FUNDAMENTAL QUANTITIES & UNITS FOR IONIZING RADIATION

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INTRODUCTION

• A unit is necessary for the measurement of any physical quantity.

• International Commission of Radiation Units and Measurements (ICRU)
  • Reviews and updates the concepts related to quantities and their units in radiation physics, dosimetry and radiological protection.
CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protectional Quantities
- Operational Quantities
- Radiometric Quantities
- Interaction Coefficients
DOSIMETRIC QUANTITIES
EXPOSURE

• Exposure is a quantity which measures the photon (X or γ radiation) flux at any point in air.
• It is defined as that quantity of x or γ radiation that produces in air, ions carrying 1 coulomb (C) of charge of either sign per kg of air.
• The S.I. unit of exposure is CKg⁻¹.
• The old unit of exposure is Roentgen (R).
DOSIMETRIC QUANTITIES
EXPOSURE (X)

• Measurement of ionization produced in air by photons
• Quotient of \( dQ \) by \( dm \)

\( dQ \)- The absolute value of the total charge of ions of one sign produced air, when all the electrons liberated by the photons in a volume of element of air having mass \( dm \) are completely stopped in air

\[
X = \left( \frac{dQ}{dm} \right)
\]

Unit: C.kg \(^{-1}\)
DOSIMETRIC QUANTITIES
EXPOSURE

• *One roentgen* is defined as the amount of X or γ radiation which would liberate 1 e.s.u of charge of either sign in 1cc of air at STP.

  • 1 R = 1 esu per cc of air at STP
  • 1 R = 2.58 x 10⁻⁴ CKg⁻¹

• Exposure is not defined above photon energies of 3 MeV.
DOSIMETRIC QUANTITIES

ABSORBED DOSE

• The effects of radiation depend (physical, chemical and biological) not so much on the energy transferred to the medium, but on the energy absorbed by it.

• Absorbed dose (simply dose) is defined as the amount of energy absorbed per unit mass of the matter at the point of interest.
DOSIMETRIC QUANTITIES
ABSORBED DOSE (D)

Energy absorbed from ionizing radiation per unit mass
Quotient of $dE$ by $dm$

$dE$- Mean energy imparted by the ionizing radiation to the mass $dm$

$$D = \left( \frac{dE}{dm} \right)$$

Unit: J.kg$^{-1}$

The quantity absorbed dose has been defined to describe the quantity of radiation for all types of ionizing radiation including charged and uncharged particles
DOSIMETRIC QUANTITIES
ABSORBED DOSE

• The special name of the unit of dose is Gray (Gy).
  – 1 Gy = 1 Jkg\(^{-1}\)

• The old Unit of absorbed dose is rad.
  – Energy absorption of 100 erg per gram of material
  – 1 rad = 100 ergs/gm
  – 1 rad = 1 cGy = 10\(^{-2}\) Jkg\(^{-1}\) = 10\(^{-2}\) Gy
  – 1 Gy = 100 rads
DOSIMETRIC QUANTITIES

KERMA

• The field of indirectly ionizing radiations at any point in matter is given by the quantity “Kerma”.

• Kinetic Energy Released in a Medium

• It is defined as the sum of initial kinetic energies of all charged particles liberated by radiation (uncharged particles) in a material of mass 1 kg.
DOSIMETRIC QUANTITIES
KERMA (KINETIC ENERGY RELEASED IN THE MEDIUM)

Quotient of $dE_{tr}$ by $dm$

$dE_{tr}$ - the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged particles in the material of mass $dm$

$$K = \left( \frac{dE_{tr}}{dm} \right)$$

Unit: J.kg$^{-1}$
DOSIMETRIC QUANTITIES
KERMA

• The SI unit is Joules per kilogram (Jkg\(^{-1}\)).

• The special name of the unit is Gray (Gy).
  – 1 Gy = 1 Jkg\(^{-1}\)

• If the reference material is air, the quantity is called “air kerma”.

DOSIMETRIC QUANTITIES
KERMA & ABSORBED DOSE RELATION

\[ D \text{ and } K^{\text{col}}, \beta = 1 \]

\[ \beta < 1 \quad \beta > 1 \]

Buildup Region  
Equilibrium Region
DOSIMETRIC QUANTITIES
KERMA & ABSORBED DOSE RELATION

- Kerma is maximum at surface and decreases with depth.
- Dose initially buildup to a maximum value and decreases at the same rate as kerma.
- Because of the increasing range of electrons complete electronic equilibrium does not exist within MV photon beam.
- At depth greater than the maximum range of electrons, there is a region of Transient electronic equilibrium.
CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protectional Quantities
- Operational Quantities
- Radiometric Quantities
- Interaction Coefficients
RADIOACTIVITY QUANTITIES

- Radioactivity refers to the phenomena associated with spontaneous transformations that involve changes in the nuclei of atoms.

- The energy released in such transformations is emitted as nuclear particles (alpha particles, electrons, and positrons) and/or photons.
The activity of a radioactive material is a measure of its spontaneous transformation. It is defined as the number of nuclear transformations (or disintegrations) per second. The SI unit for activity is the Becquerel (Bq). 1 Bq = 1 disintegration per second.
RADIOACTIVITY QUANTITIES
ACTIVITY (A)

Quotient of $dN$ by $dt$

$dN$ - the mean change in the no. of nuclei in that energy state due to spontaneous nuclear transformations in the time interval $dt$

$$A = -\frac{dN}{dt}$$

Unit: $Sec^{-1}$

Special unit: Becquerel (Bq) and Curie (Ci)

$$1Ci = 3.7 \times 10^{10}Bq$$
The old unit of activity is Curie (Ci).

- 1 Curie (Ci) = $3.7 \times 10^{10}$ disintegrations/sec
  = $3.7 \times 10^{10}$ dps
  = $3.7 \times 10^{10}$ Bq or 37 GBq

- 1 millicurie = 37 MBq
- 1 microcurie = 37 kBq
RADIOACTIVITY QUANTITIES

The activity $A$ is equal to the product of the decay constant, $\lambda$, and the number $N$ of nuclei in that state.

$$A = \lambda N$$

DECAY CONSTANT ($\lambda$)

quotient of $-\frac{dN}{N}$ by $dt$

$-\frac{dN}{N}$ – Mean fractional disintegration taking place in the time interval $dt$

$$\lambda = -\frac{dN}{N} \frac{1}{dt}$$

Unit: Sec$^{-1}$
CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protection Quantities
- Operational Quantities
- Radiometric Quantities
- Interaction Coefficients
PROTECTION QUANTITIES

- Effect of radiation depends upon amount of energy and also on absorbed spatial distribution of ion pairs

- Damage due to same dose of radiation
  1. Varies with radiation type
  2. Vary with radio-sensitivity of tissue

- Two factors were introduced to consider these variations such as:
  - Radiation weighting factor \((W_R)\)
    - accounts effectiveness of radiation
  - Tissue weighting factor \((W_T)\)
    - accounts radio-sensitivity of organs
PROTECTION QUANTITIES
EQUIVALENT DOSE

• Effect of radiation depends
  – Not only on the amount of energy absorbed
  – But also on the spatial distribution of ion pairs.
• Hence the biological damage caused by the same
dose of different radiation are different.
  – Alpha radiation – higher charge and mass
    • Greater ionization per unit path length
PROTECTION QUANTITIES
EQUIVALENT DOSE

• In radiation protection, the Radiation Weighting Factor, \((W_R)\) accounts for the variation in the effectiveness of different types of radiations.

• The product of the absorbed dose, \(D\) and radiation weighting factor, \((W_R)\) of a particular radiation gives the measure of its biological damage.

• The weighted absorbed dose is called the Equivalent Dose \((H_T)\).
PROTECTION QUANTITIES
EQUIVALENT DOSE

• \( H_T = \sum R W_R \cdot D_{TR} \)
  
  – \( D_{TR} \) is the absorbed dose in tissue ‘\( T \)’ for radiation ‘\( R \)’ of radiation weighting factor \( W_R \).
  
  – \( W_R \) is a dimensionless quantity
    • Formerly called as Quality factor (QF).

• The special unit of Equivalent Dose is Sievert (Sv).
  
  – 1 Sv = 1 Jkg\(^{-1}\)
PROTECTION QUANTITIES
EQUIVALENT DOSE

• In radiation protection
  – 20 mGy of gamma dose, 1 mGy of alpha dose and 10 mGy of proton dose are equivalent.

• Equivalent dose in $\text{Sv} = \text{Dose in Gy} \times W_R$

• The old unit of equivalent dose is rem.
  – Roentgen Equivalent Man
  – Equivalent dose in $\text{rem} = \text{Dose in rad} \times QF$

• $1 \text{ Sv} = 100 \text{ rem}$
PROTECTION QUANTITIES
EFFECTIVE DOSE

• Exposure to radiation may occur to the whole body (uniform irradiation) or to individual organs of the body (non-uniform irradiation).

  – Non uniform radiation will have to be restricted in order to protect against not only deterministic effects but also to reduce stochastic effects.

  – ICRP recommends dose limits for both stochastic and deterministic effects.
# PROTECTION QUANTITIES

## RADIATION WEIGHTING FACTORS ($W_R$)

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Radiation Weighting Factor ($W_R$) based on ICRP 103</th>
<th>Radiation Weighting Factor ($W_R$) based on ICRP 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons, Electrons &amp; Muons</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Protons &amp; Charged Pions</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, heavy ions</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Neutrons</td>
<td>Continuous function of neutron energy</td>
<td>&lt;1 MeV $2.5+18.2 , e^{-[\ln(E)/6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 to 50 MeV $5.0+17.0 , e^{-[\ln(2E)/6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;50 MeV $2.5+3.25 , e^{-[\ln(0.04 , E)/6}$</td>
</tr>
</tbody>
</table>
PROTECTION QUANTITIES
EFFECTIVE DOSE

• The Effective dose assesses risk by modifying the equivalent dose using a tissue weighting factor $W_T$.

• It is defined as the sum of the equivalent dose in all tissue and organs of the body multiplied by the corresponding tissue weighting factor.

\[
E = \sum_{T} W_T \cdot H_T
\]

\[
E = \sum_{R} W_R \cdot D_{TR} \cdot W_T
\]
The unit of equivalent dose is $\text{Jkg}^{-1}$.

The special unit of equivalent dose is Sievert (Sv).

The old unit of equivalent dose is rem.

$1 \text{ Sv} = 1 \text{ Jkg}^{-1}$

$1 \text{ Sv} = 100 \text{ rem}$
PROTECTION QUANTITIES
EFFECTIVE DOSE

• $W_T$ values are useful in converting equivalent dose received by one or more tissues (partial body exposure) to effective dose (whole body exposure equivalent).

• This equivalent to be used only for estimation of stochastic effects for radiation protection purpose only.
# Protection Quantities

**Tissue Weighting Factors** ($W_T$)

<table>
<thead>
<tr>
<th>ORGANS</th>
<th>ICRP 30 (136) 1979</th>
<th>ICRP 60 (13) 1991</th>
<th>ICRP 103 (16) 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.25</td>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>Red Bone Marrow</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>colon</td>
<td>-</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>-</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Breast</td>
<td>0.15</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>-</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Liver</td>
<td>-</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Oesophagus</td>
<td>-</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Skin</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone Surface</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Salivary gland</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Brain</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Remaining body</td>
<td>0.30</td>
<td>0.05</td>
<td>0.12</td>
</tr>
</tbody>
</table>
CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protection Quantities
- Operational Quantities
- Radiometric Quantities
- Interaction Coefficients
OPERATIONAL QUANTITIES

- Protection quantities in human body can not practically be measured
- Operational quantities are introduced to estimate Protectional quantities reasonably
- These quantities are determined at defined locations in defined phantoms
- While doses are estimated from area monitoring,
  1. Ambient dose equivalent $H^*(d)$
  2. Directional Dose equivalent $H^*(d,\Omega)$
- While doses are estimated from individuals,
  1. Personal Dose equivalent $H_p(d)$
OPERATIONAL QUANTITIES

AMBIENT DOSE EQUIVALENT $H^*(D)$

The dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at a depth $d$ in mm on radius opposing the direction of the aligned field.

\[
\frac{d\Phi}{dE}(E) = f_P(E)
\]

At point $P$: $\Phi = \Phi_P$

Corresponding expanded and aligned field:

\[
\frac{d\Phi}{dE}(E) = f_P(E)
\]

at any point in sphere

$H^*(10)$ is the Dose Equivalent $H$ at 10 mm depth
Special unit: Gray (Gy)

Gray – The transfer of one joule of radiation energy per kg of medium

\[ K = \psi \left( \frac{\mu_{tr}}{\rho} \right) \]

\( \mu_{tr}/\rho \) - Mass energy transfer coefficient for the medium averaged over the energy fluence spectrum of photons \( \psi \)

Energy transfer to ionizing particles may be:

- Collisional interaction results ionization & excitation
- Radiative interaction results bremsstrahlung

\[ K = K_{col} + K_{rad} \]
The dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth d in mm in a specified direction Ω.

This is of particular use in the assessment of dose to the skin and eye lens.

**Unit:** J/kg and Sievert (Sv)
OPERATIONAL QUANTITIES
PERSONAL DOSE EQUIVALENT $H_p(D)$

- The dose equivalent in soft tissue at an appropriate depth $d$ below a specified point on the body.

- $H_p(d)$ measured with a detector which is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material.

Operational quantities, the depth of measurement is:

- For strongly penetrating radiation, $d$ is 10mm
- For weakly penetrating radiation, $d$ is 0.07mm
- For eye lens $d$ becomes 3mm
CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
- Protectional Quantities
- Operational Quantities
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- Interaction Coefficients
• Radiation fields are characterized by radiometric quantities that apply in free space and in matter.

• The Radiometric quantities are:
  1. Particle Number, Radiant Energy
  2. Flux, Energy Flux
  3. Fluence, Energy Fluence
Particle Number (N):
The number of particles that are emitted, transferred, or received

Radiant Energy (R):
The energy of the particles that are emitted, transferred or received

- For particles of energy E, the radiant energy, R, is equal to the product of NE.

\[ R = N \cdot E \]
RADIOMETRY

Flux (N):

Quotient of $dN$ by $dt$

$dN$ - the particle number in the time interval $dt$

$$N = \frac{dN}{dt}$$

Units: $\text{Sec}^{-1}$

Energy Flux (R):

Quotient of $dR$ by $dt$

$dR$ - the increment of radiant energy in the time interval $dt$

$$R = \frac{dR}{dt}$$

Units: $\text{W}$
RADIOMETRY

**Fluence (φ):**

Quotient of \( dN \) by \( da \)
\[ \phi = \frac{dN}{da} \]

Unit: \( m^{-2} \)

**Fluence rate (φ’):**

Quotient of \( d\phi \) by \( dt \)
\[ \phi' = \frac{d\phi}{dt} \]

Unit: \( m^{-2}\text{Sec}^{-1} \)
**RADIOMETRY**

**Energy fluence (\(\varphi\)):**

Quotient of \(dR\) by \(da\)

\(dR\) - the radiant energy incident on a sphere of cross-sectional area \(da\)

\[
\varphi = \frac{dR}{da}
\]

**Unit:** J/m\(^2\)

**Energy fluence rate (\(\varphi'\)):**

Quotient of \(d\varphi\) by \(dt\)

\(d\varphi\) - the increment of the energy fluence in the time interval \(dt\)

\[
\varphi' = \frac{d\varphi}{dt}
\]

**Unit:** J/m\(^2\)
CLASSIFICATION

- Dosimetric Quantities
- Radioactivity
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- Interaction Coefficients
Interaction process occur between radiation and matter.

Either energy or direction of the incident particle is altered or particle is absorbed.

Interactions is characterized by various coefficients which specifies interaction process, type and energy of radiation and material.

Various interaction coefficients are defined such as:

- Linear Attenuation Coefficient
- Mass Attenuation Coefficient
- Mass Energy Transfer Coefficient
- Mass Energy Absorption Coefficient
- Stopping power
- Mass Stopping Power
- Linear Energy Transfer
- Radiation Chemical Yield

Uncharged Particle

Charged Particle
The interaction coefficients (uncharged particle) attenuating per unit path length in medium

Let

- \( N \) = No. of photons incident on medium
- \( dN \) = Reduction of photons
- \( L \) = Length of the medium

The linear attenuation coefficient is defined as:

\[
\mu = \left( \frac{dN}{N} \right) \left( \frac{1}{dL} \right)
\]

Unit: \( \text{cm}^{-1} \)

\( \mu \) depends on density of the medium
INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)

MASS ATTENUATION COEFFICIENT (M/P)

Quotient of $\mu$ by $\rho$

$\mu$ – Linear Attenuation Coefficient
(fraction of photons attenuated per unit path length in medium)

$\rho$ – Density of medium

Unit: cm$^2$g$^{-1}$

$$\frac{\mu}{\rho} = \left(\frac{dN}{N}\right)\left(\frac{1}{\rho \cdot dL}\right)$$
INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)
MASS ENERGY TRANSFER COEFFICIENT \( \left( \frac{M_{\text{TR}}}{P} \right) \)

Quotient of \( dR_{\text{tr}}/R \) by \( \rho dL \)

\[ \frac{dR_{\text{tr}}}{R} \] – The fraction of incident energy that is transferred as the kinetic energy of charged particles, in traversing a distance of \( dL \) in the medium of density \( \rho \)

\[ \frac{\mu_{\text{tr}}}{\rho} = \left( \frac{dR_{\text{tr}}}{R} \right) \left( \frac{1}{\rho dL} \right) \]

Unit: \( m^2 kg^{-1} \)

- The binding energy of the liberated charged particles are not included in \( dR_{\text{tr}} \)
**INTERACTION COEFFICIENTS (UNCHARGED PARTICLE)**

**MASS ENERGY ABSORPTION COEFFICIENT** \((\mu_{\text{en}}/\rho)\)

- Product of mass energy transfer co-efficient \((\mu_{\text{tr}}/\rho)\) and \((1-g)\)

- \(\mu_{\text{tr}}/\rho\) – Mass energy-transfer Coefficient

- \(g\) – Fraction of the energy lost in Radiative process in the medium (bremsstrahlung)

\[
\frac{\mu_{\text{en}}}{\rho} = \left(\frac{d\mu_{\text{tr}}}{\rho}\right)(1-g)
\]

Unit: \(m^2\text{kg}^{-1}\)
INTERACTION COEFFICIENTS (CHARGED PARTICLE)
STOPPING POWER (S.P)

Quotient of $\textbf{dE}$ by $\rho \textbf{dL}$

$dE$ - Mean energy lost by the charged particles in traversing a distance $\textbf{dL}$ in the medium

$$\textbf{S.P} = \left( \frac{\textbf{dE}}{\textbf{dL}} \right)$$

**Unit:** $\text{J.m}^{-1}$ or $\text{MeV.m}^{-1}$

**Mass Stopping Power (S.P}/\rho):**

Quotient of S.P by $\rho$

$$\frac{\textbf{S.P}}{\rho} = \left( \frac{\textbf{dE}}{\textbf{dL}} \right) \cdot \left( \frac{1}{\rho} \right)$$

**Unit:** $\text{Jm}^2\text{kg}^{-2}$ or $\text{MeV.m}^2\text{.kg}^{-1}$
INTERACTION COEFFICIENTS (CHARGED PARTICLE)
LINEAR ENERGY TRANSFER (LET)

Energy lose per unit path length in medium

Energy lost is due to electronic collisions of charged particle in traversing medium

\[ \text{LET} = \left( \frac{dE}{dL} \right) \]

Unit: keV/\(\mu\text{m}^{-1}\)
Quotient of \( n(x) \) by \( \varepsilon \)

\( n(x) \)- Mean amount of substance of the entity produced, destroyed, or changed in a system by the mean energy imparted \( \varepsilon \), to the matter of that system

\[
G(x) = \left( \frac{n(x)}{\varepsilon} \right)
\]

Unit: \( \text{mol}.\text{J}^{-1} \)

- \( G \) value is the mean number of entities produced, destroyed or changed with an imparted energy of 100 eV
## SUMMARY

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>OLD UNIT</th>
<th>NEW UNIT</th>
<th>RELATIONSHIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radioactivity</td>
<td>Ci</td>
<td>Bq</td>
<td>$1 \text{ Bq} = 0.27 \times 10^{-10} \text{ Ci}$&lt;br&gt;$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$</td>
</tr>
<tr>
<td>Exposure</td>
<td>R</td>
<td>Ckg$^{-1}$</td>
<td>$1 \text{ Ckg}^{-1} = 3876 \text{ R}$&lt;br&gt;$1 \text{ R} = 2.58 \times 10^{-4} \text{ Ckg}^{-1}$&lt;br&gt;$1 \text{ Air Kerma} = 114 \text{ R}$</td>
</tr>
<tr>
<td>Absorbed Dose</td>
<td>rad</td>
<td>Gy</td>
<td>$1 \text{ Gy} = 100 \text{ rad}$&lt;br&gt;$1 \text{ Gy} = 1 \text{ Jkg}^{-1}$</td>
</tr>
<tr>
<td>Equivalent dose / Effective dose</td>
<td>rem</td>
<td>Sv</td>
<td>$1 \text{ Sv} = 100 \text{ rem}$&lt;br&gt;$1 \text{ Sv} = 1 \text{ Jkg}^{-1}$</td>
</tr>
</tbody>
</table>
Thank You