Overview of Lecture

- Exposure
- \((W/e)_{\text{air}}\)
- Exposure and Air Kerma

Exposure

- Exposure is symbolized as \(X\) and defined by the ICRU as “the quotient of \(dQ\) by \(dm\), where the value of \(dQ\) is the absolute value of the total charge of the ions of one sign produced in (dry) air when all the electrons liberated by photons in air of mass \(dm\) are completely stopped in air”

\[ X = \frac{dQ}{dm} \]

Exposure is the ionization equivalent of the collision kerma in air for photons.
As an electron slows down in a gas, it loses energy by ionizing the gas. The quantity $W$ is the mean energy expended in the gas per ion pair formed, usually expressed in units of eV per ion pair. For air, this quantity is found to be a constant, independent of the electron energy above a few keV. The value is $W_{air} = 33.97 \text{ eV/ion pair}$.

A more useful form of this quantity is in terms of the charge released

$$(W/e)_{air} = 33.97 \text{ J/C}$$

$(W/e)_{air}$ is the number of joules of energy deposited in the air per coulomb of charge released. Alternatively, $(e/W)_{air}$ is the number of coulombs released per joule of energy deposited in air.

The definition of collision kerma states that it gives the energy transferred (less radiative losses) to charged particles per unit mass. Multiplying by $(e/W)_{air}$, the number of coulombs of charge created per joule of energy deposited will give the charge created per unit mass of air, i.e., the exposure.

$$X = (K)_{air} \left( \frac{e}{W} \right)_{air}$$

For CPE
Exposure and Air Kerma

- The relationship between air kerma and exposure is
  \[ K_{\text{air}} = \frac{W}{e} X \]
  or
  \[ (1-g) K_{\text{air}} = \frac{W}{e} X \]
  where \( K_{\text{air}} \) is the collisional part of air kerma, \( K_{\text{air}} \) is the total air kerma, and \( g \) is the fraction of initial kinetic energy of electrons radiated as bremsstrahlung.

Exposure and Air Kerma

- The amount of energy radiated as bremsstrahlung is not included in exposure because exposure is a measure of ionization finally produced by the secondary electrons.
- However, kerma is the initial kinetic energy of all secondary electrons so the total kerma includes the fraction \( g \) radiated as bremsstrahlung.

Exposure and Air Kerma

- In any event, \( g \) is a small value.
- Some values:
  - \(^{60}\text{Co}\)
    - \( g = 0.003 \)
  - \(^{137}\text{Cs}\)
    - \( g = 0.002 \)
  - orthovoltage
    - \( g = 0.0 \)
- The numerical relationship between air kerma and exposure for \(^{60}\text{Co}\) is
  \[ (1-0.003) K_{\text{air}} \text{ (J/kg)} = 33.97 \text{ (J/C)} X \text{ (C/kg)} \]
  \[ 8.997 K_{\text{air}} \text{ (Gy)} = 33.97 \times 2.58 \times 10^{-6} X \text{ (R)} \]
  \[ 8.997 K_{\text{air}} \text{ (Gy)} = 8.79 \times 10^{-3} X \text{ (R)} \]
Exposure and Air Kerma

- Similarly we can show
  \[ K_{\text{air}} (\text{Gy}) = 8.78 \times 10^{-3} \times X (\text{R}) \]
  for \(^{137}\text{Cs}\) gamma rays, and
  \[ K_{\text{air}} (\text{Gy}) = 8.76 \times 10^{-3} \times X (\text{R}) \]
  for orthovoltage and lower energy x-rays.

Measurement of Exposure

- The figure illustrates a schematic of a free-air ionization chamber.
- Ionization is collected from the volume between the dotted lines.
- This collecting volume must be far enough removed from the diaphragm that electronic equilibrium is established.

\[
X_D = \frac{Q}{\rho A_e L}
\]

Measurement of Exposure

- This distance, denoted by \(D\) in the figure, must be greater than the maximum range of secondary electrons created.
- The plate separation must be twice this distance.
- Under these conditions, electrons will expend all their energy before striking the collector.

\[
X_D = \frac{Q}{\rho A_e L}
\]
Measurement of Exposure

- The definition of the Roentgen is in terms of mass of air.
- The use of the term “air” implies what some have termed “dry air.” Humidified air is a mixture of the components of air and water vapor.

Measurement of Exposure

- Correction factors must be applied for measurement conditions other than those of the definition.
- At normal operating temperature and pressure, the perfect gas law may be used.
- If the mass of air in the definition is taken as a unit mass, then the number of units in a volume $V$ of “dry air” is

$$\frac{273.2 \cdot PV}{T} \frac{760}{P}$$

Measurement of Exposure

- Because of differences in W' values and electron densities between air and water vapor, a correction must be applied for humid air.
- In this case the number of unit masses of volume $V$ is

$$\frac{273.2 \cdot (P - 0.238P_v)V}{T} \frac{760}{P}$$

where $P_v$ is the vapor pressure of moisture in the air in mm of mercury.
Measurement of Exposure

- The collection volume is defined by the entrance aperture and the length of the collecting electrode.
- If the cross-sectional area of the X-ray beam is \( A_d \) at point \( P \) inside the chamber, then the exposure at that point is:

\[
X_d = \frac{Q}{\rho A_d L}
\]

where:
- \( Q \) = collected charge
- \( \rho \) = density of air
- \( L \) = length of collecting electrode

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Measurement of Exposure

- The exposure at the entrance diaphragm is:

\[
X_o = \frac{Q}{\rho A_d L} \left( \frac{S_2}{S_1} \right)^2
\]

where:
- \( S_2 \) = distance from source to point \( P \) inside chamber
- \( S_1 \) = distance from source to entrance diaphragm \( D \)

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Measurement of Exposure

- The area of the entrance diaphragm is equal to \( A_d \) times an inverse square factor:

\[
A_d = A_o \left( \frac{S_2}{S_1} \right)^2
\]

where:
- \( A_o \) = area of entrance diaphragm
Measurement of Exposure

• Then the exposure at the entrance diaphragm is given by

\[ X_d = \frac{Q}{\mu_{eq}(S_d)} \left( \frac{S_d}{S_a} \right)^a \]

• This relation tells us that the exposure at the entrance diaphragm is equal to the charge collected from the free-air ionization chamber divided by the product of the air density, the area of the entrance diaphragm, and the length of the collecting electrode.

Measurement of Exposure

• The basis of an air-wall chamber is that the air surrounding the active volume can be "condensed" into a "solid air" wall.
• A wall thick enough to provide electronic equilibrium permits measurement of exposure with cavity chambers.
• The definition of an air-wall chamber is a chamber whose walls interact with radiation in the same manner as air interacts.
• This condition means that the mass energy absorption and mass attenuation coefficients for the material should be the same as that of air.

Measurement of Exposure

• To ensure that the walls are equilibrium thickness and to correct for wall attenuation, measurements must be made for a number of wall thicknesses.
• If the first wall thickness is less than equilibrium thickness, then as the thickness increases, the signal will increase until the equilibrium thickness is reached.
• Then the signal will decrease with increasing wall thickness because of absorption of the primary photon beam in the wall.
• The exposure corrected for wall attenuation is found by extrapolating the attenuation curve back to zero wall thickness.
Measurement of Exposure

- Chambers were constructed of high-purity graphite with closely fitting shells used for wall absorption measurement.
- There were 8 chambers and with their shells made possible six exposure rate determinations.

Bragg-Gray Theory

- The use of cavity chambers to measure exposure is based in the Bragg-Gray relation.
- Basically, Bragg-Gray theory relates the energy absorbed in a medium to energy absorbed in a cavity in that medium.
- In the equation below, consider the medium to be material $w$ and the cavity to contain a gas $g$. The energy absorbed in the gas is equal to the number of ion pairs (or ionization) per unit mass of the gas times the average energy to create the ion pair. The energy per unit mass, absorbed dose, is given by

$$D_w = J_g \left( \frac{W}{e} \right) \left( \frac{S_g}{e \rho_g} \right)$$

Bragg-Gray Theory

- In this equation
  - $D_w$ = absorbed dose in material $w$
  - $(S/g)_w$ = ratio of the mass stopping power of the electrons in material $w$ to that in the gas $g$
  - $W/e$ = average energy absorbed per unit charge of ionization produced
  - $J_g$ = the ionization charge of one sign produced per unit mass of the cavity gas
Bragg-Gray Theory

- In an exposure measurement the medium \( w \) is the wall of the chamber when the wall is thick enough to provide electronic equilibrium.
- The dose in air in the chamber cavity is then given by
  \[
  D_{aw} = D_w \left( \frac{\mu_{en}}{\rho} \right)_w
  \]
  where \( (\mu_{en}/\rho)_w \) is the ratio of the mass energy absorption coefficients, air to wall.

Bragg-Gray Theory

- Combining the two equations yields
  \[
  D_{aw} = \int f \left( \frac{w}{g} \right) \left( \frac{1}{\rho} \right)_w \left( \frac{\mu_{en}}{\rho} \right)_w dE
  \]

Relationship to Exposure

- If air is the cavity gas, then the \( g \) may be replaced by \( \text{air} \) in all places in the previous equation.
- The current definition of the Roentgen is \( 2.58 \times 10^{-4} \) coulomb per kilogram of air.
- The previous equation can be rewritten in terms of exposure as
  \[
  X = \frac{D_{aw}}{w} = \frac{1}{2.58 \times 10^{-4}} \int f \left( \frac{g}{\rho} \right)_w \left( \frac{\mu_{en}}{\rho} \right)_w dE \prod k
  \]
Relationship to Exposure

\[ X = \frac{D_{air}}{W} = \frac{1}{2.58 \times 10^{-4} J/C} \int \left( \frac{\rho}{\rho} \right) \sum k \]

- The quantity | | is the product of correction factors including stem scatter, recombination, wall thickness, and the correction that takes into account the mean center for electron production in the chamber wall.

Relationship to Exposure

- Consider the relation between absorbed dose and exposure.
- One Roentgen deposits energy in air to create ionization of \(2.58 \times 10^{-4}\) coulomb per kg of air.
- The presently accepted value for the W-value of air is 33.97 joules per coulomb, where the W-value is defined as the average energy required to create an ion pair.
- Then
  \[ 1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg} \times 33.97 \text{ J/C} = 0.876 \times 10^{-2} \text{ Gy for air} \]

Relationship to Exposure

- In SI units, 1 C/kg – 1 C/kg x 33.97 J/C = 33.97 J/kg.
- Air exposed to 1 R receives 0.876 cGy and air exposed to 1 C/kg receives 33.97 Gy.
- If some other material is exposed to 1 R, the absorbed dose in the medium will be
  \[ D_{med} = D_{air} \left( \frac{\rho}{\rho} \right)_{med} \]
Relationship to Exposure

- For an exposure of X R
  \[ D_{\text{med}} = 0.876 \left( \frac{H_{\text{eq}}}{\rho} \right)_{\text{med}} X \text{ cGy} \]

- For an exposure of 1 C/kg
  \[ D_{\text{med}} = 33.97 \left( \frac{H_{\text{eq}}}{\rho} \right)_{\text{med}} \text{ Gy} \]

Relationship to Exposure

- The conversion factors have been assigned a special terminology; they are called the I-factor.

- For higher energy photon beams, an additional factor is required – \( A_{\text{eq}} \).
- This factor represents the attenuation of the primary photon beam in reaching \( d_{\text{max}} \) in the medium.
- The equation for determining dose to a small mass of water large enough to establish electronic equilibrium from an exposure measurement is
  \[ D = f A_{\text{eq}} \]
- For \(^{60}\)Co, \( f = 0.967 \) and \( A_{\text{eq}} = 0.989 \).