COMMON RADIATION PROTECTION EQUATIONS

A DRAFT

ABOUT RADIATION EXPOSURE X & EXPOSURE RATE X*

CONTROLLED REDUCTION & PREVENTION OF THE UNWANTED EFFECTS OF IONIZING RADIATION IS THE JOB & GOAL OF RADIATION PROTECTION PROFESSION.

“Continuous improvement is the foremost prerequisite for survival.”

DeSegnac et al.

Send inquires about this presentation to Dusan desegnac@att.net
“TELLING IS NOT TEACHING”

Thoughtfully organized, illustrated, and animated presentation, given by a classroom experienced, engaging SAT enabled trainer/instructor, could help students, especially the adult ones, understand the RP concepts and their applications in practice.

The following PPT module covering EXPOSURE X and EXPOSURE RATE X* is a part of our COMMON RADIATION PROTECTION EQUATIONS series. It illustrates our abilities to create impressive and useful learning material that will keep the students aware, awake, and engaged in the process of acquiring new and/or reviewing and cementing their existing knowledge of the radiation protection science.

Our team is, also, capable of incorporating similar PPT presentations into your existing, approved lesson plans and in an engaging way. We are, also, well qualified and capable of augmenting your training team at outages and other times of need.

Please review our RP DOSE module and let us know if and, maybe, when we may be considered to help in your important efforts in RP training and qualifications of your workforce.

We are standing by!

Our references include RP Directors, Nuclear Power Plant Maintenance Managers, Maintenance Training Directors and Managers, and Lead Instructors. If and when you need our references, we will be glad to provide you with their e-mails and/or phone numbers.

Respectfully Dusan A. Radosavljevic  desegnac@att.net

“Continuous improvement is the foremost prerequisite for survival.”
The material that follows is an introductory presentation of two fundamental concepts in radiation protection Exposure X and Exposure Rate X*. It could help an RP technician build her/his understanding of other important concepts and tools that RP professionals are using in the field.

Pictures and simple animations are used for visualization of the concepts. Formulas and unit conversions are the bare minimum and should not present great difficulties while working a few numerical examples.

As always, there are unintended mistakes and errors hidden within the material. These are my own and I would appreciate to be made aware of them by you so that they can be corrected. Please let me know your impressions and concerns regarding this presentation.

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COMMON RADIATION PROTECTION EQUATIONS

ABOUT EXPOSURE X & EXPOSURE RATE X*

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**Exposure X – “ancient” definition**

Radiation Exposure X is a measure of the amount of ionization produced in 1 cm$^3$ (of air) by gamma or X-rays.

$X$ is the sum of the electric charges on all ions of one sign that are produced in a volume of air STP.

The unit of exposure was named roentgen, $R$.

$1R = 1 \text{ esu} / \text{cm}^3 \text{ STP air}$

If one ionic charge

$1 \text{ e} \sim 4.8 \times 10^{-10} \text{ esu}$

(1 esu = 1 statCoulomb)

then, how many $-e$ ions in 1 esu/cm$^3$?

$\sim 2.08 \times 10^9 \text{ -e ions/cm}^3$
Radiation Exposure \( X \) is a measure of the amount of ionization produced in 1 kg (of air too!) by gamma or X-rays.

\( X \) is the sum of the electric charges on all ions of one sign that are produced in a volume of air, divided by the mass of air in that volume.

The unit of exposure was named roentgen, \( R \).

\[
1 \text{R} = 2.58 \times 10^{-4} \text{ Coulomb / kg air}
\]

If one ionic charge, in Coulombs, measures

\[1 \text{ e} \sim 1.6 \times 10^{-19} \text{ C}\]

then, how many \(-e\) ions makes 1 \( R \)?

\[\sim 1.61 \times 10^{15} \text{ -e ions}\]

Roentgen, Wilhelm Conrad
1845 - 1923
**EXPOSURE** : “ANCIENT” **VERSUS MODERN DEFINITION**

**Exposure X** is a **measure** of the **amount of ionization** produced by gamma or X-rays.

\[ 1R = 1 \text{ esu} / 1 \text{ cm}^3 \text{ air STP} \]

\[ 1R = 2.58 \times 10^{-4} \text{ Coulomb / kg (air too!)} \]

1 cm\(^3\) air \~ 1.293\times10^{-3} \text{ g}

(Drawings not to scale)

Because 1 R was defined as the amount of ionizing radiation generating 1 electrostatic unit of free ionic charges in 1 cm\(^3\) of STP air (1.293 kg/m\(^3\)), compute 1 esu in Coulombs and 1 C in esu.

1 esu \~ 3.34 \times 10^{-10} \text{ C} \quad 1 \text{ C} \~ 3 \times 10^9 \text{ esu}

How many of ft\(^3\) holds 1 kg of air?

\~ 27.3 ft\(^3\)
**Exposure Rate**  \( X/hr = X^* \)

**Exposure Rate** \( X^* \) is a measure of the amount of ionization produced in air by gamma or X-rays, per unit of time, \( R/hr \).

\[ 1R/hr = 2.58 \times 10^{-4} \text{ Coulomb / kg (air) hr} \]

Ionized air consists of free negatively charged electrons and equally but positively charged molecules of the air constituents \( +N_2, +O_2, +H_2O \), etc.

To assess Exposure Rate, instruments equipped with an ion chamber are used. These portable rate-meters measure in units from mili roentgens/hr, mR/hr, up to many roentgens/hr, R/hr.
ABOUT RADIATION EXPOSURE RATE INSTRUMENTS

An instrument is a probe by which we may, discover, directly and/or indirectly, facts about radiation fields.

A single, careful reading of an instrument, properly calibrated in appropriate units may reveal, directly, the radiation field’s strength, but indirectly, with some additional information, a source strength, a distance from it, even the radionuclide involved.

But thorough understanding of the basic notions and units describing and measuring radiation fields is the foremost prerequisite for the task of properly reading an instrument.

A word need not be spent about interpreting the instruments’ readings without such understanding.
**Exposure Rate** \( \text{X/hr} = \text{X}* \)

\[
1 \text{R/hr} = 2.58 \times 10^{-4} \text{ Coulomb / kg (air) hr}
\]

Because electron charge is \(~1.6 \times 10^{-19}\) Coulombs, how many, either negatively or positively charged ions, is generated per second per kg of air @ STP, at the exposure rate of \( \text{R/hr} \)?

\(~1.4 \times 10^{11}\) ions/s

How many roentgens \(\text{R}\) correspond to 1 Coulomb of free charges?

\(~3.9 \times 10^{3}\) \(\text{R}\)

If 5 \(\text{R/hr}\) makes \(\approx 10^{14}\) ions/min and 1A of el. current = 1 C/sec, how many \(\mu\text{A}\) is in the ions?

\(~3.5 \times 10^{-1}\) \(\mu\text{A}\)
Concerning an energetic photon, ionization is the end of its interaction with atomic electrons, which results in ejection of an electron from the neutral atom thus making a pair of free ionic charges \( \sim 1.6 \times 10^{-19} \) Coulombs each.

The ejected electron having all or a portion of the incident photon energy, continues to move and by interacting electro-statically ionize surrounding atoms until all of its energy spent.

A common interaction of an el. neutral photon is when it impacts only a portion of its energy to the ejected electron - the Compton Effect.

The scattered photon may ionize another atoms in its path adding to the overall ionization, i.e., the number of liberated ionic charges.
The photo-electric effect is the case when an electron acquires all of the photon’s energy and spends it on ionizing atoms on its tortuous path.

For the photons of $E > 1.022 \text{ MeV}$ and heavy nuclei, creation of the $+e -e$ pairs gains in occurrence.
About IONIZATION (photon – atom interactions)

All three modes of photon - atom interactions contribute to the ionization of atoms, each contribution depending on the energy of the interacting photons. That dependency is given in the value $\frac{\mu_{en}}{\rho}$ ($\rho = \text{density g/cm}^3$) or the mass-energy absorption factor (graph.)

For $N$ photons of energy $E$, the work expanded for ionization in a material:

$$W = \left(\frac{\mu_{en}}{\rho}\right) \times E \times N$$

If $W_e$ is the work needed for ionization of an air molecule, than the number of free charges is given by

$$W/W_e = \left\{\left(\frac{\mu_{en}}{\rho}\right) \times E \times N\right\} / W_e$$
COMMON RADIATION PROTECTION EQUATIONS

**About IONIZATION (photon – atom interactions)**

For 1 second burst of \( N_p \) photons of energy \( E \), the work \( W \), spent on air ionization

\[
W_{\text{MeV}} = (\mu_{\text{en}}/\rho) \times E \times N_p \quad (\mu_{\text{en}}/\rho \text{ in m}^2/\text{kg,} \ E \text{ in MeV})
\]

If \( W_e \) is the work necessary for ionization of air, than the number of free charges is given by:

\[
N_e = W/W_e \quad W_e(\text{air}) \sim 34 \text{ eV}
\]

Because 1e charge amounts to \( \sim 1.6 \times 10^{-19} \) Coulombs the amount of free charges will be:

\[
Q_e \sim N_e \times 1.6 \times 10^{-19} \text{ C}
\]

Because Exposure \( X \) is defined as Coulombs/kg then:

\[
X \sim Q_e / m \quad \text{C/kg}
\]

Compute \( X/\text{hr} \) for 1 s burst of \( \sim 4.57 \times 10^9 \) photons/m\(^2\) of \( \sim 1.25 \) MeV each, ionizing 1kg of air of \( \mu_{\text{en}}/\rho \sim 2.67 \times 10^{-3} \) m\(^2\)/kg.

How many R/\text{hr} ?

How many Ci of \(^{60}\text{Co} \) makes that many R/\text{hr} @ 1m ?
Ionization is generated by gamma and/or X-ray photons emanated by a large variety of radioactive elements:

While the output and energies of the X-rays from Roentgen (X-ray) equipment may be regulated, radioactive elements emanate photons at different energies and at different rates, both unique to each one.
In an X-ray tube, energy of the bremsstrahlung (X-rays) generating electrons may be controlled - “tuned” - by an applied high voltage.

Energies of radioactive emanations are not “tunable” and are very unique to each radioactive isotope.
Due to uniqueness of decay and emanated photon energies, a value $\Gamma_X$ of exposure rate $X^*$ at 1 meter distance from 1 Ci source has been established for a host of radioactive isotopes:

A “point” 1 Ci source is assumed at the centre of 1 m radius sphere of $4\pi d^2 \sim 12.57$ m$^2$ of surface.

Thus a source $C = 1$ Ci effects exposure rate:

$$X^* = C \times \sum \left\{ \left( \frac{\mu_{en}}{\rho} \right) \times E \times N \right\} / 4\pi d^2$$

$E \times N =$ energy $\times$ %decimal of each photon.

$(\mu_{en}/\rho) =$ air mass-energy absorption factor.

$$\Gamma_X = \sum \left\{ \left( \frac{\mu_{en}}{\rho} \right) \times E \times N \right\} / 4\pi \sim 0.5 \sum (E \times N) \text{ Rm}^2/\text{Cihr}$$

$$\Gamma_X \sim 0.5 \sum (E \times N) (\pm 20\%) \text{ R m}^2/\text{Ci hr} \text{ (see web page)}$$

http://www.doseinfo-radar.com/Exposure_Rate_Constants_and_Lead_Shielding.Values%204.pdf
**Γₓ**, THE SPECIFIC EXPOSURE RATE CONSTANT

The **Rate of Exposure X** \( X^* \) R/hr, at a distance from a radioactive source, is the product of the radionuclide’s \( Γₓ \) and the source activity \( C \) in Ci.

\[
X^* = Γₓ × C / d^2 \text{ R/hr}
\]

Essentially, \( Γₓ \) is the unit of exposure rate @ 1m, specific to each radionuclide.

For example, a piece of rust from inside of a valve reads \( ? \text{ R/hr} \), at 1 ft. Radionuclide is \( ^{60}\text{Co} \). Find \( Γₓ \) if the source activity \( C' \sim 190 \text{ mCi} \).

\( ^{60}\text{Co} \) \( Γₓ \sim 1.29 \text{ Rm}^2/\text{Cihr} \)
**Γ_X, THE SPECIFIC EXPOSURE RATE CONSTANT**

Γ_X is computed, roughly, ±20%, as ½ of the sum of the product of the photon energies \( E \) in MeV, and fractional % values of photons per decay (37% = 0.37, 100% = 1, ...).

\[
Γ_X = 0.5 \sum (E \times N) \text{ (R m}^2\text{) / (Ci hr)}
\]

Example: sum EN for \(^{60}\text{Co}_{27}\)

\( E_1 = 1.27\text{MeV} \) @ 100% /decay N=1
\( E_2 = 1.33\text{ MeV} \) @ 100% /decay N=1

\[
\text{sum EN} = (1.27 \times 1) + (1.33 \times 1) = 2.5
\]

\[
Γ_X = 0.5 \sum (E \times N) = 0.5 \times 2.5 = 1.25 \text{ (R m}^2\text{) / (Ci hr)}
\]

By more accurate and precise computations this value is given as \( 1.29 \text{ Rm}^2/\text{Ci hr} \).
**\( \Gamma_x \), THE SPECIFIC EXPOSURE RATE CONSTANT**

\[ \Gamma_x = 0.5 \, \text{sum} \left( E \times N \right) \frac{(R \, m^2)}{(Ci \, hr)} \]

The constant \( \Gamma_x \) could be understood as the *unit of exposure rate* for 1 Ci of a *given* radionuclide at a distance of 1 meter.

Thus \( \Gamma_x \) is of different numerical value for each radionuclide.

*Example: \( \Gamma_x \) for \( ^{137}\text{Cs}_{55} \)*

\[ E_1 = 0.662 \, \text{MeV} \, @ \, 85\% /\text{decay} \]

\[ \text{sum EN} = (0.662 \times 0.85) = 0.56 \]

\[ \Gamma = 0.5 \, \text{sum} \left( E \times N \right) = 0.5 \times 0.56 = 0.28 \]

More accurate value \( 0.34 \) \((R \, m^2)/(Ci \, hr)\)
COMMON RADIATION PROTECTION EQUATIONS

\( \Gamma_X \), THE SPECIFIC EXPOSURE RATE CONSTANT \( ^{192}\text{Ir}^{77} \)

\( ^{192}\text{Ir}^{77} \) \( \rightarrow \) Three \( \beta^- \) @ 95.3% \( \rightarrow \) \( ^{192}\text{Pt} \)

T \( \frac{1}{2} \) 73.83 d \( \rightarrow \) e Capture @ 4.7% \( \rightarrow \) \( ^{192}\text{Os} \)

Emanated gamma keV: \( 205 \) @ 3.4% \( 286 \) @ 29.3% \( 308 \) @ 31% \( 316 \) @ 86.1%

\( 468 \) @ 50% \( 484 \) @ 3.1% \( 589 \) @ 4.6% \( 604 \) @ 8.9% \( 612 \) @ 5.5%

By excluding \( 205 \) & \( 484 \) \( \gamma \) and averaging \( 468, 604, \) & \( 612 \) \( \gamma \) to \( 602 \) keV @ 19% we obtain:

\[
\text{sum (ExN)} \sim 0.286 \times 0.293 + 0.308 \times 0.31\% + 0.316 \times 0.86\% + 0.468 \times 0.5 + 0.602 \times 0.19 \sim 0.8
\]

\( \Gamma_X \sim 0.5 \text{ sum } (E \times N) \sim 0.5 \times 0.8 \sim 0.4 \text{ } Rm^2/Ci \text{ hr} \)

More accurate value could be 0.46 \( Rm^2/Ci \text{ hr} \)

Multiplying \( \Gamma_X \) by any amount of radioactivity \( C \), we obtain rate of exposure @ 1 m, thus:

\( X^* \sim 0.5 \text{ } C \times \text{sum } (E \times N) \)
COMMON RADIATION PROTECTION EQUATIONS

\[ \Gamma_X, \text{ THE SPECIFIC EXPOSURE RATE CONSTANT} \quad 75\text{Se}^{33} \]

\[ 75\text{Se}^{34} \rightarrow \text{e Capture @ 100%} \rightarrow 75\text{As}^{33} \]

T \( \frac{1}{2} \) 119.8 d

Emanated significant gamma, keV:

121 @ 17.2% 136 @ 58.2% 265 @ 58.9% 280 @ 25% 401 @ 11.5%

\[ \text{sum (ExN)} \sim 0.121 \times 0.172 + 0.136 \times 0.582 + 0.265 \times 0.589 + 0.280 \times 0.25 + 0.400 \times 0.115 \sim 0.372 \]

\[ \Gamma_X \sim 0.5 \quad \text{sum (E x N)} \sim 0.5 \times 0.372 \sim 0.19 \quad Rm^2 /Ci\ hr \]

More accurate value could be 0.203 \( Rm^2 /Ci\ hr \)

Compute \( X^* \) @ 1m for 113 mCi of \( 75\text{Se}^{41} \)

\[ X^* \sim 0.5 \times \text{C} \times \text{sum (E x N)} = \Gamma_X \times \text{C} \]

\[ \sim 0.19 \times 0.113 \sim 0.021 \quad R/hr (?) \]
**COMMON RADIATION PROTECTION EQUATIONS**

\[ \Gamma_X, \text{ THE SPECIFIC EXPOSURE RATE CONSTANT } ^{169}\text{Yb}_{70} \]

\[ ^{169}\text{Yb}_{70} \rightarrow \text{ e Capture @ 100%} \rightarrow ^{169}\text{Tm}_{69} \]

\[ T_{1/2} = 32 \text{ d} \]

**Emanated significant gamma, keV:**

\[ 63 \text{ @ } 43.8 \% \quad 110 \text{ @ } 17.4 \% \quad 131 \text{ @ } 11.4 \% \quad 177 \text{ @ } 21.7 \% \quad 198 \text{ @ } 35.6 \% \quad 308 \text{ @ } 9.9 \% \]

\[ \text{sum (E x N) } \sim 0.063 \times 0.44 + 110 \times 0.174 + 0.131 \times 0.114 + 0.177 \times 0.217 + 0.198 \times 0.356 + 0.308 \times 0.099 \sim 0.201 \]

\[ \Gamma_X \sim 0.5 \quad \text{sum (E x N) } \sim 0.5 \times 0.201 \sim 0.1 \quad \text{Rm}^2/\text{Ci hr} \]

Due to the much higher absorption of 63 keV actual value could be 0.194 \( \text{Rm}^2/\text{Ci hr} \)

**Compute** \( X^* @ 1 \text{m for } 13 \text{ Ci of } ^{169}\text{Yb}_{70} \)

\[ X^* \sim \Gamma_X \times C \sim 0.19 \times 13 \sim 2.5 \text{ R/hr} \]

1 Ci

1 meter
**COMMON RADIATION PROTECTION EQUATIONS**

### $\Gamma_X$, THE SPECIFIC EXPOSURE RATE CONSTANT

$\Gamma_X \text{ Rm}^2 / \text{Ci hr}$ FOR SOME ISOTOPES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\Gamma_X$</th>
<th>$0.5 \times C \times \text{sum (E} \times N)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}\text{Co}$</td>
<td>1.29</td>
<td>0.5 × 1.29 × 1 = 0.645</td>
</tr>
<tr>
<td>$^{192}\text{Ir}$</td>
<td>0.46</td>
<td>0.5 × 0.46 × 1 = 0.23</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>0.34</td>
<td>0.5 × 0.34 × 1 = 0.17</td>
</tr>
<tr>
<td>$^{75}\text{Se}$</td>
<td>0.2</td>
<td>0.5 × 0.2 × 1 = 0.1</td>
</tr>
<tr>
<td>$^{131}\text{I}$</td>
<td>0.22</td>
<td>0.5 × 0.22 × 1 = 0.11</td>
</tr>
</tbody>
</table>

For some isotopes, $\sim 70 \text{ mCi source generates 15.4 mR/hr at 1 m}$. Which radionuclide could make it possible?

- $^{131}\text{I}$
**0.5 CEN & 6 CEN FORMULAS**

**Exposure rate** $X^*$ in R/hr, at 1 meter, is the product of $\Gamma_X$ and source activity $C$, in Ci.

$$X^* \text{ R/hr} \sim \Gamma_X \times C \sim 0.5 \times \sum (E \times N) \text{ @ 1m}$$

For $X^*$ in R/hr, at 1 foot or 0.305 meter, and source activity $C$ in Ci, applies another formula:

$$X^* \text{ R/hr} \sim 6 \times C \times \sum (E \times N) \text{ @ 1 ft}$$

Or, a little better: $X^* \text{ R/hr} \sim 11 \Gamma_X \times C \text{ @ 1 ft}$

What $X^*$ in R/hr an **873 mCi** $^{60}$Co point source generates at 1 m & at 1 ft?

$\sim 1.1 \text{ R/hr @ 1m ; } \sim 12 \text{ R/hr @ 1ft}$
0.5 CEN, 6 CEN & INVERSE SQUARE

Exposure rates at 1 m and 0.305 m ~ 1 ft are related by the squares of corresponding distances in a simple manner.

0.5 CEN × 1² ~ 6 CEN × 0.305²

\((\Gamma_x \times C) \times 1^2 \sim (11 \Gamma_x \times C) \times 0.305^2\)

Or, for any exposure rate \(X^*\) and corresponding distances (consult slide # 10):

\[X^*_1 \times d_1^2 = X^*_2 \times d_2^2\]

What is the distance in ft, where \(X^* \sim 5 \times 10^{-3}\) R/hr, if at 1 m from a ~3 Ci source \(X^* \sim ?\) R/hr?

What is the probable radioactive isotope?

\(d_2 \sim 55\) ft, \(^{192}\text{Ir}\)
COMMON RADIATION PROTECTION EQUATIONS

USE OF 0.5 CEN & 6 CEN & $\Gamma_x$ (use the table of $\Gamma_x$)

A ~ 5.6 Ci source @ 0.305 m read ~? R/hr. Which isotope makes it?

$6\text{CEN} \sim 11\Gamma_x \times 5.6 \sim 35\text{ R/hr}$

$\Gamma_x \sim 0.57$  $^{18}\text{F}$

What reading is expected @ 3.3 ft?

$0.5\text{CEN} \sim \Gamma_x \times 5.6 \sim 3.2\text{ R/hr}$

~1.6 Ci of $^{60}\text{Co}$ reads ? R/hr at what distance?

$0.5\text{CEN} \sim \Gamma_x \times C$

1 meter

How many Ci $^{192}\text{Ir}$ @ 1 m makes ? R/hr

$0.5\text{CEN} \sim 340\text{ mR/hr}$

~0.74 Ci
COMMON RADIATION PROTECTION EQUATIONS

SUMMARY: $X$, $X^*$, $\Gamma_X$, 0.5 CEN, 6 CEN

RADIATION EXPOSURE $X$ - a measure of the ionization produced in air by gamma or X-rays. The unit is roentgen $R$.

$1R = 2.58 \times 10^{-4}$ Coulomb/kg air @ STP ($1e$ charge $= 1.6 \times 10^{-19}$ C)

EXPOSURE RATE $X^*$ - a measure of the ionization produced in air by gamma or X-rays, per unit of time, $R$/hr.

$1R/hr = 2.58 \times 10^{-4}$ Coulomb/kg (air) hr @ STP.

THE SPECIFIC EXPOSURE RATE CONSTANT $\Gamma_X$ is EXPOSURE RATE determined at 1 meter from 1 Ci “point” photon emanating radioactive source.

EXPOSURE RATE constant $\Gamma_X$ is different for each radionuclide.

$\Gamma_X$ is computed by the formula $\sim 0.5 \times \text{sum} (E \times N) (\pm 20\%) \text{ R m}^2 / \text{Ci hr}$

0.5 CEN $\sim \Gamma_X \times C$ in $R$/hr Exposure Rate at 1m for $C$ of radioactivity in Ci.

6 CEN $\sim 11\Gamma_X \times C$ in $R$/hr Exposure Rate at 1ft for $C$ of radioactivity in Ci.

http://www.doseinfo-radar.com/Exposure_Rate_Constants_and_Lead_Shielding_Values%204.pdf
Congratulations for persevering!

CONTROLLED REDUCTION & PREVENTION OF THE UNWANTED EFFECTS OF IONIZING RADIATION IS THE JOB & GOAL OF RADIATION PROTECTION PROFESSION.

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“Continuous improvement is the foremost prerequisite for survival.”

DeSegnac et al.