Colorado State University

Radiation Control Office

Radiation Safety Training

Module 5 - Dosimetry

Outline

- State Rules and Regulations pertaining to Dosimetry Training
- Review of occupational radiation dose limits
- Radiation Use Application
- External Radiation Exposures
  - Alpha, Beta, Gamma Dose Calculations
  - Example Calculations
  - Methods of Reducing External Exposure
- Internal Radiation Exposures
  - Pathways
  - Dose Equivalent Quantities
  - Example Calculations
- Methods of Reducing Internal Exposure
- Peer Example of Radiation Safety Plan Dose Calculations

CDPHE - Rules & Regulations


NOTICE TO EMPLOYEES

Instructed in health protection problems associated with exposure to radiation

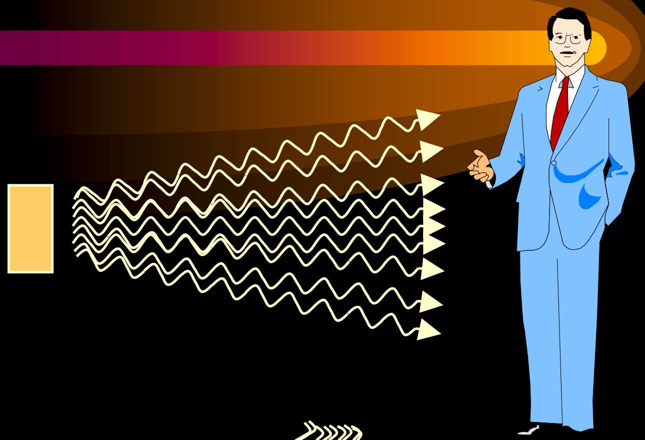
Purposes and functions of protective devices employed.

Instructed in applicable provisions of rules and regulations

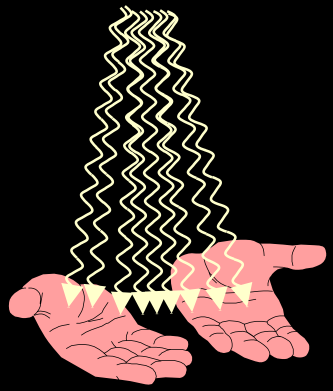
Instruction will commensurate with potential radiological health protection problems

Occupational Dose Limits for Radiation Workers

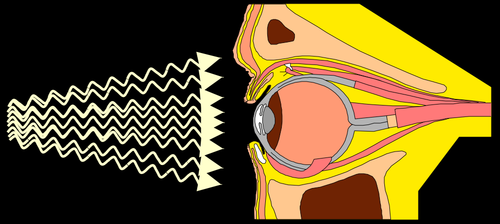
Whole Body Dose Limit = 5 rem or 5000 mrem



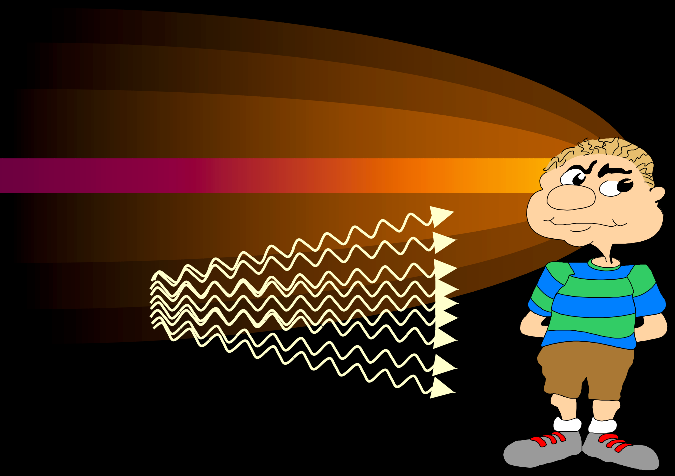
Extremity or Skin Dose Limit = 50 rem or 50,000 mrem



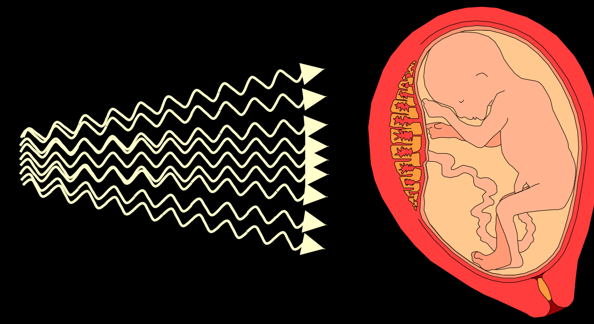
Lens of the Eye Limit = 15 rem or 15,000 mrem



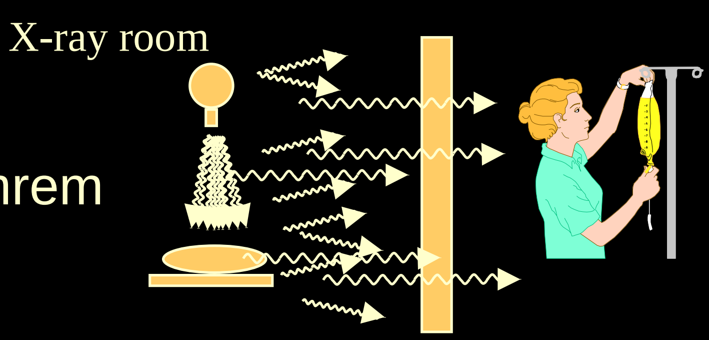
Occupational Dose Limits



Dose Limit for Minors – Under 18 = 500 mrem



Dose Limit for Unborn Fetus = 500 mrem



Dose Limit for General Member of Public = 100 mrem

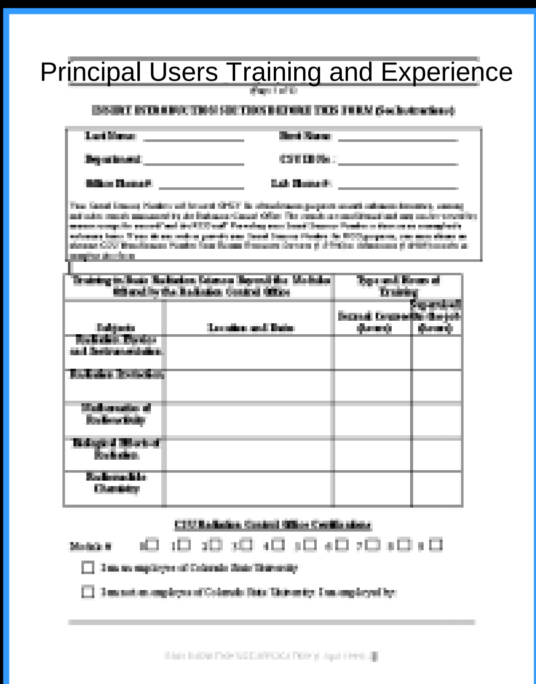
RADIATION CONTROL Manual

- Purpose
- Policy
- Responsibilities

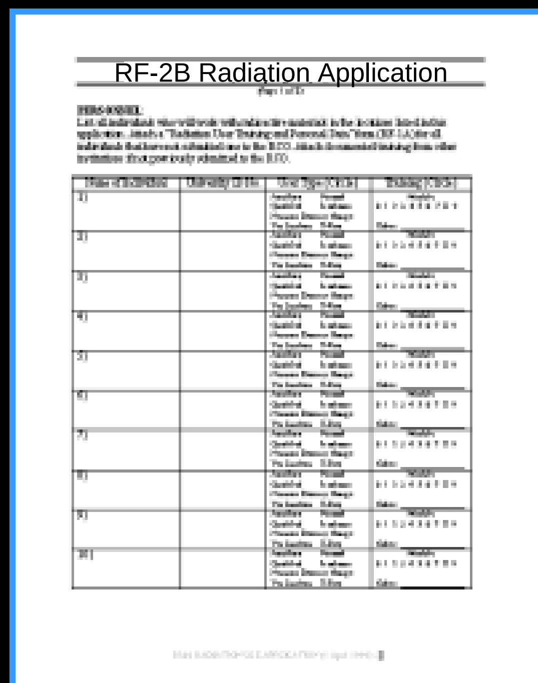
- ***Individuals must be informed of their potential doses***
- ***Required through a Radiation Safety Plan submitted by P.U.***
- ***Individual must follow safe work practices, to be aware of actual or potential radiation exposures and to keep all exposures to levels that are ALARA.***
- ***Each individual is responsible for:***
- ***Knowing basic properties of the material used, e.g. half-lives, type of radiation emitted, the ALI and shielding requirements***
- ***Be aware of actual or potential exposures***

RADIATION USE APPLICATION

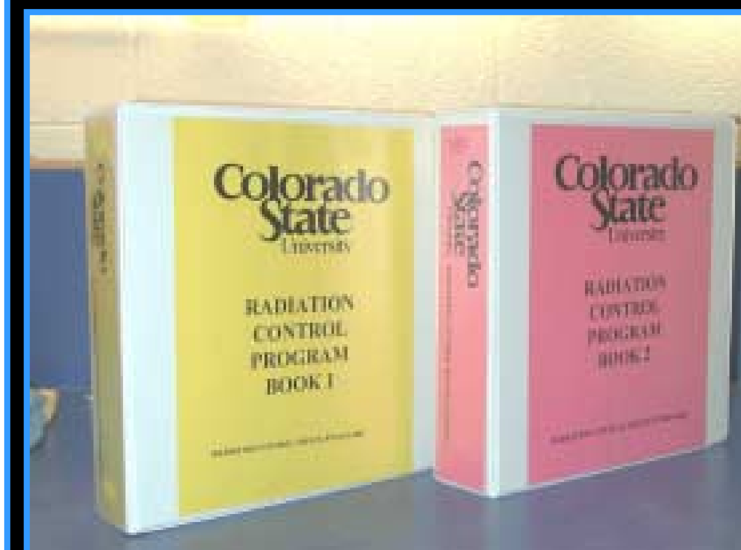
Must clearly show the calculations for the expected doses for all project members. Include both internal and external calculations. List *worse case* and *normal use scenarios*.



Principal Users Training and Experience

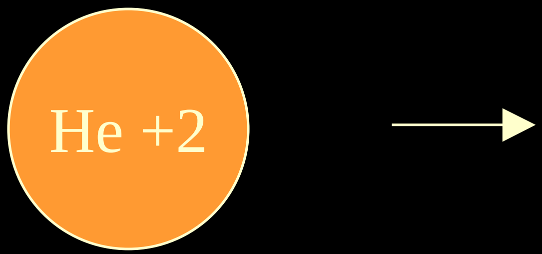


RF-2B Radiation Application



Major Types of Ionizing Radiation
Alpha, Beta, Gamma

Alpha Particle – Helium Nucleus that has a +2 charge

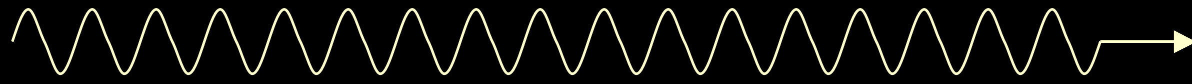


Large Mass (nuclei)
Range 1-2 centimeters in air

Beta Particle – electron that originates from inside the nucleus

Small Mass
(subatomic particle)
Range 0-2 meters in air

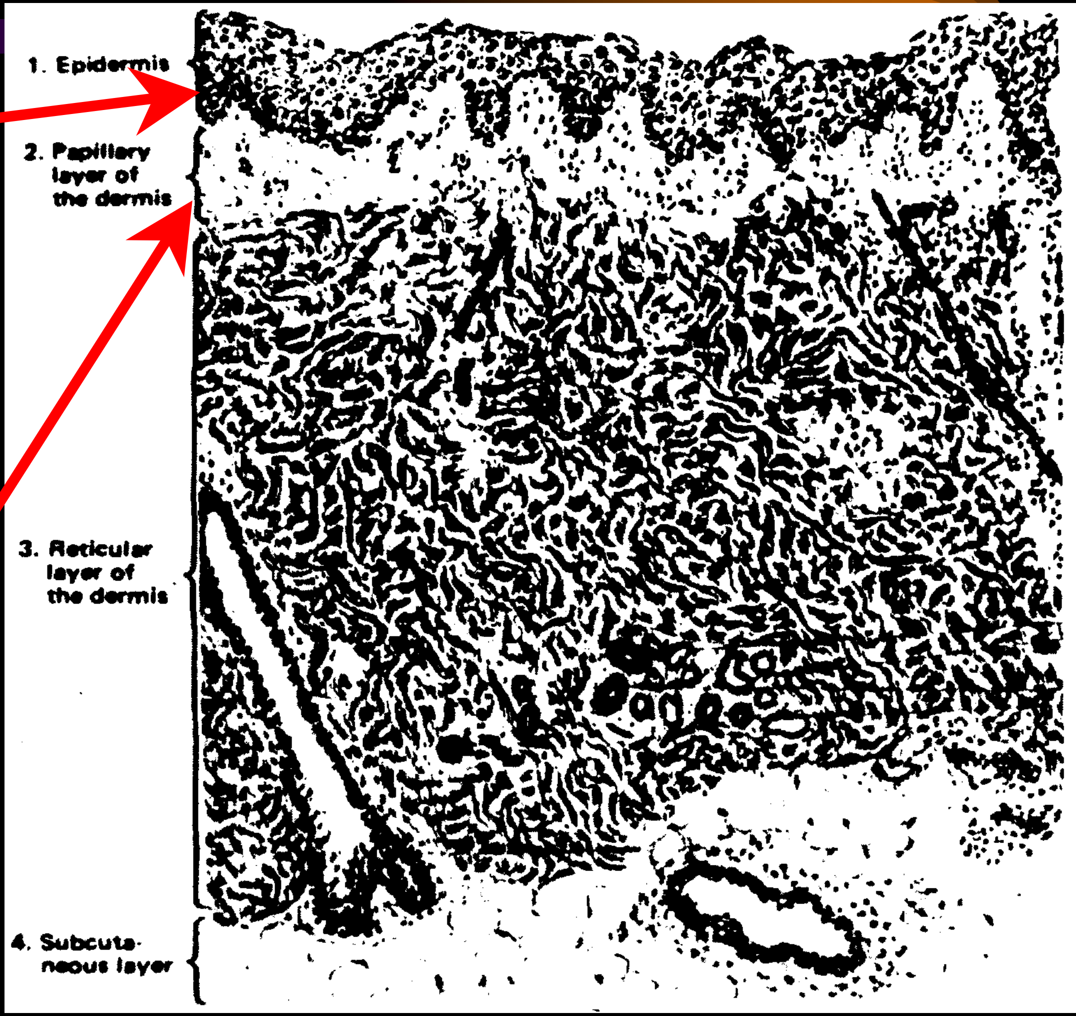
Gamma Photon
and X-Rays



Electromagnetic Radiation – No mass; Range of meters in air

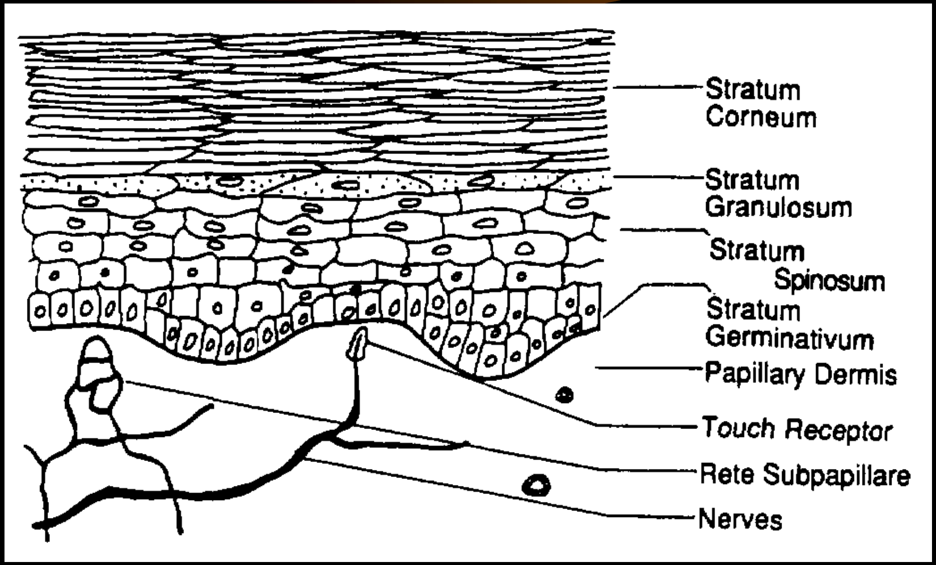
Skin Biology: Dermis

- **Epidermis is composed of viable and nonviable cells**
- **Significant blood flow in papillary dermis for temperature regulation**

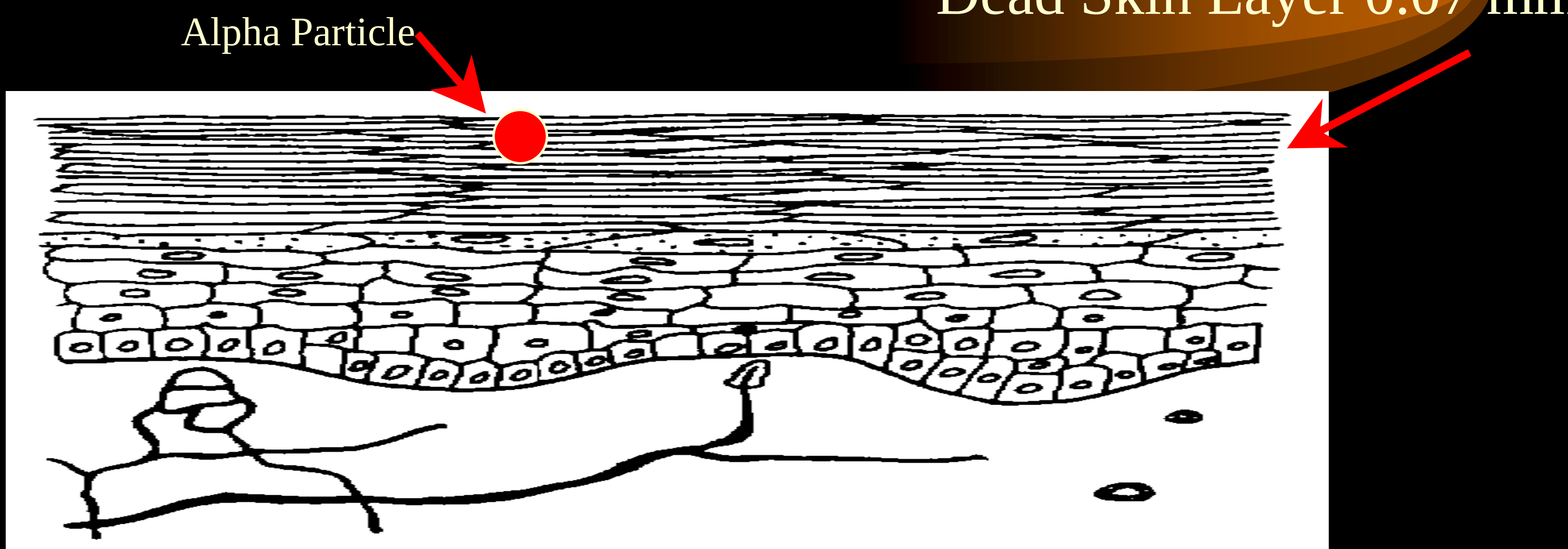


Skin Biology: Epidermis

- **Outer layers of dead cells constitute 25% of the epidermis**
- **Basal cells (stratum germinativum and stratum spinosum) determine the radiation response of skin**



ESTIMATION OF EXTERNAL α RADIATION DOSE



- External doses not generally required; Most Cases – No Alpha Dose!
- Minimum of 7.5 MeV to penetrate dead skin layer
- Thorium has 8 MeV alpha, yet no dose effects are observed even at high doses
- Contact RCO for high energy α particles

ESTIMATION OF EXTERNAL β RADIATION DOSE NOT IN CONTACT WITH SKIN

- Rule of thumb, valid over a wide range of beta energies

$$\dot{D} = \left(27 \frac{rad * m^2}{Ci * hr} \right) \frac{A}{d^2}$$

Activity (Ci)

Distance from source (m)

Dose Rate (rad/hr)

- Assumes point source and no attenuation to air or source material

- Expect large errors beyond 1 m (overestimates absorbed dose)

EXTERNAL β RADIATION DOSE IN CONTACT WITH SKIN

Use this formula:

$$\dot{D} = C_f \frac{A}{\alpha}$$

- Dose Rate (rad/hr): $\dot{D}$
- Dose Rate Conversion Factor: C_f
- Activity on skin (uCi): A
- Area of contamination on skin (cm²): α

To use the formula, some additional information is needed:

There is a 0.07 mm (7 mg/cm^2 – density thickness) dead skin layer that acts as shield to the betas

Complex empirical formulas are used to compute skin dose for beta radiation

Recommend using the Varskin ™ Chart to determine the Dose Rate Conversion Factor (C_f)

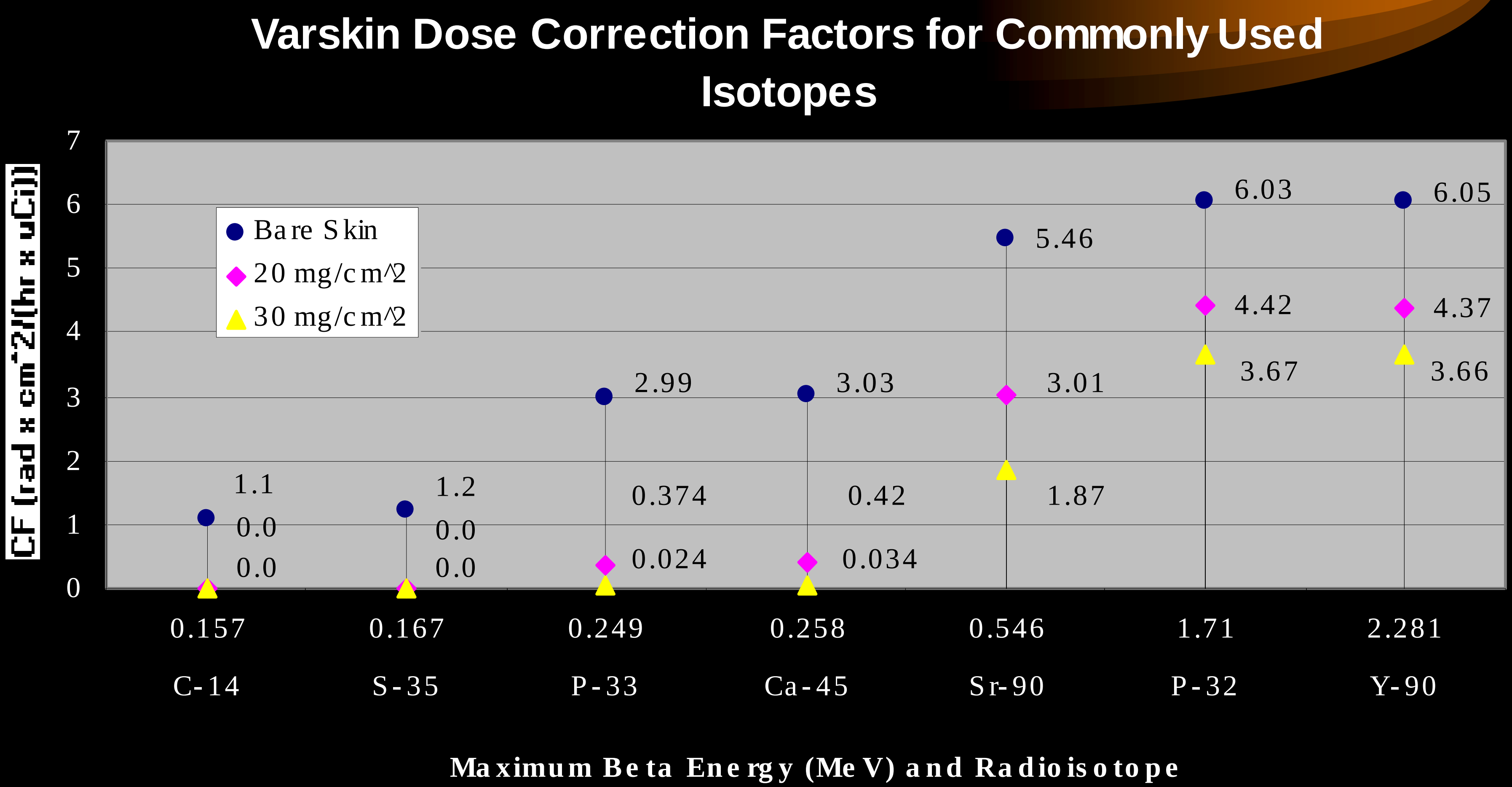
The Varskin Chart is used for:

Infinitely thin area sources (liquid on skin) and for several shield thicknesses

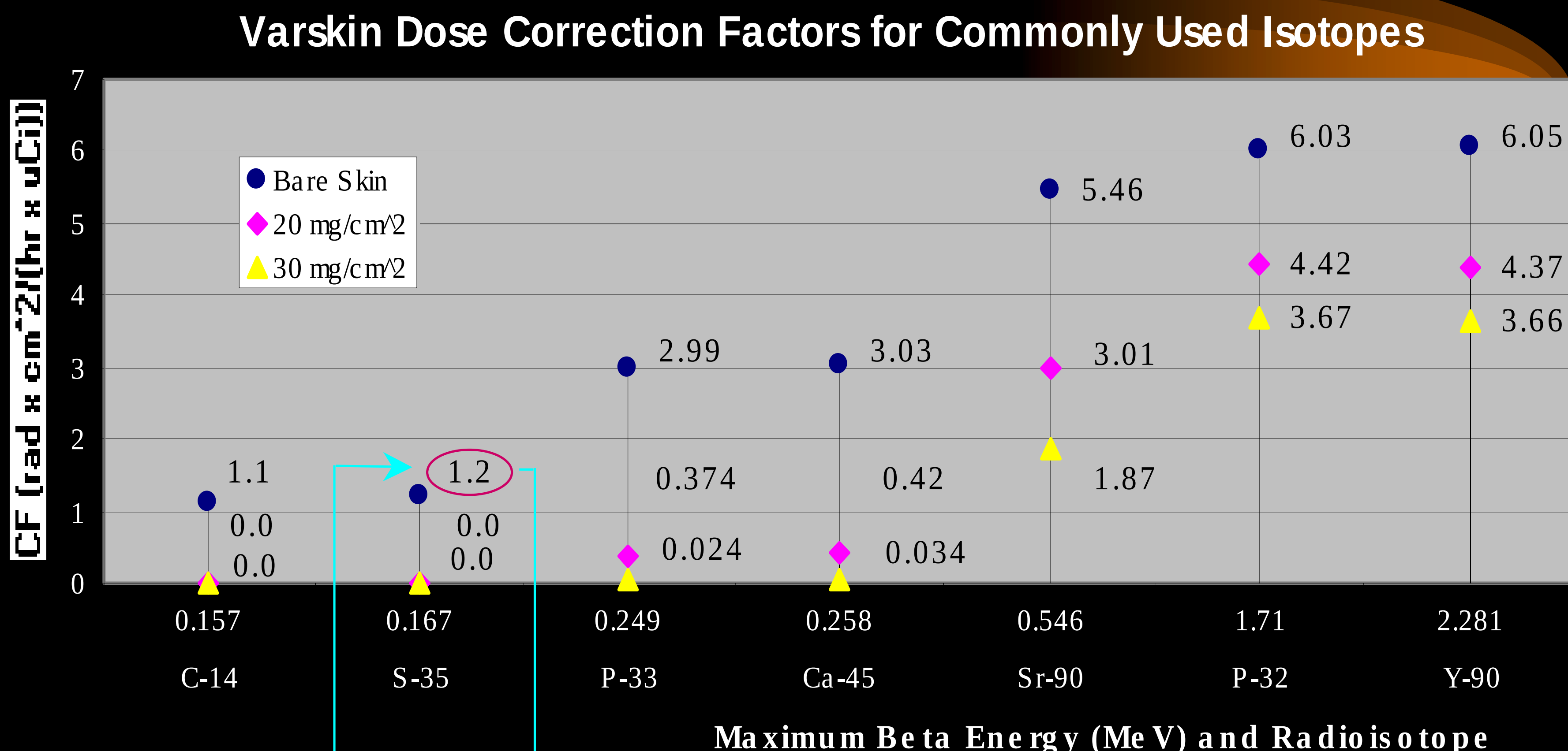
7 mg/cm^2 → dead skin layer shield

20 and 30 mg/cm^2 → dead skin layer + latex gloves

EXTERNAL β RADIATION DOSE IN CONTACT WITH SKIN



ESTIMATION OF EXTERNAL β RADIATION DOSE IN CONTACT WITH SKIN



Determine Isotope and Skin Shielding factor to be used – (here S-35 on bare skin)

$$\dot{D} = C_f \frac{A}{\alpha}$$

Determine activity on skin (µCi)

Estimate area contaminated (cm^2)

ESTIMATION OF EXTERNAL β RADIATION DOSE

IN CONTACT WITH SKIN

Estimation of Skin Dose using the preceding formula is NOT Valid for the following beta emitting isotopes:

Hydrogen-3

H-3 does not have a maximum energy beta high enough to penetrate the dead skin layer. Thus, there is
No external dose associated with H-3.

Dose Units and Quantities: Alpha, Beta, and Gamma

To this point, all of our doses are calculated in units of rad/ hr. We must convert rad/ hr to rem/hr when analyzing a radiation dose to a human being. This will be shown in a later slide.

"Rad" is an acronym that stands for "Radiation Absorbed Dose". It is a measurement of the amount of energy deposited by any type of radiation in any material. It does not take into account the biological effectiveness of different radiations into the human body, thus we must convert to "rem" which stands for "Radiation Equivalent Man" or "Roentgen Equivalent Man"

The unit "Roentgen" (R) is a measurement of the specific ionization of air molecules by photons. It only applies to gamma or x-ray photons in air. See the next slide.

ESTIMATION OF EXTERNAL γ RADIATION DOSE

To determine Gamma Dose, we must first calculate "Exposure" (R) of The photons in air.

•Unshielded point source

$$\dot{X} = \Gamma \frac{A}{d^2}$$

Exposure Rate (R/hr)

Activity (Ci)

Distance from source (m)

Specific gamma-ray constant provided in table ($(R\ m^2)/(hr\ Ci)$)

Specific Gamma-Ray Constant for Some Commonly Encountered Gamma Emitters

Nuclide	Γ (R m^2)/(hr Ci)	Nuclide	Γ (R m^2)/(hr Ci)
^{133}Ba	0.24	^{125}I	0.07
^{51}Cr	0.116	^{131}I	0.22
^{137}Cs	0.33	^{192}Ir	0.48
^{57}Co	0.09	^{54}Mn	0.47
^{60}Co	1.32	^{226}Ra	0.825
^{198}Au	0.23	^{22}Na	1.20

Converting a Gamma-Ray Exposure Rate to Dose Equivalent Dose Rate

Three depths

1.0 cm	used for "Deep" absorbed dose
0.3 cm	used for dose to lens of the "Eye"
0.007 cm	used for "Shallow" or skin dose

Dose Equivalent rate (rem/hr)

$$\dot{H} = C_d \dot{X}$$

Exposure Rate (R/hr)

Conversion factor from table (rem/R)

Rem/R Conversion Factors (C_d)

Photon Energy (keV)	Conversion Factors at Depth (rem/R)		
	1.0 cm ("Deep")	0.3 cm (Lens of Eye)	0.007 cm ("Shallow")
15	0.28	0.67	0.9
20	0.58	0.79	0.94
30	1.00	1.07	1.11
40	1.28	1.29	1.34
50	1.46	1.46	1.50
60	1.47	1.47	1.52
70	1.45	1.45	1.50
80	1.43	1.43	1.48
90	1.41	1.41	1.45
100	1.39	1.39	1.43
110	1.37	1.37	1.40
120	1.35	1.35	1.36
130	1.33	1.33	1.34
140	1.32	1.32	1.32
150	1.30	1.30	1.30
662	1.03	1.03	1.03

Factors Increase W/ Photon Energy

Factors Decrease W/ Photon Energy

Worse Case Dose Factor Use this for calculations

Photon Energy High All Factors Equal

Cs-137

Example Calculations

β External Dose Equivalent Dose Rate Unshielded, Not in Contact With Skin for ^{32}P

What is the Dose Rate to a person who sits 30 cm from 10 microcuries of ^{32}P ? (Assume there is no shielding from air or the source vial)

$$\dot{D} = \left(27 \frac{rad * m^2}{Ci * hr}\right)\frac{A}{d^2}$$

$$\dot{D} = \left(\frac{27\, rad * m^2}{hr * Ci}\right)\frac{10\,x10^{-6}\,Ci}{(0.3m)^2}$$

10 μCi

30 cm from the source

$$\dot{D} = 0.003\frac{rad}{hr} = 3\frac{mrad}{hr}$$

Converting from Absorbed Dose to Dose Equivalent is done By multiplying the Abs. Dose by a Quality Factor

$$\dot{H} = \dot{D}Q$$

For beta particles, Q=1

$$\dot{H} = 3\frac{mrem}{hr}$$

Example β Calculation - External Dose Equivalent Dose Rate Unshielded, In Contact With Skin

What is the dose incurred by spilling 50 uCi of P^{32} on a gloved hand? The latex had a thickness of 5 mils and only one pair was worn. The glove was removed after 10 seconds.

Calculate the Density Thickness of the glove:

First, calculate the thickness in cm (‘mils’ = “milli-inches”) = 0.005” = ***0.0127 cm***

Second, we will assume that the density of latex is equal to that of water, or ***1 g/cm³***

Density Thickness is calculated by multiplying the two together:

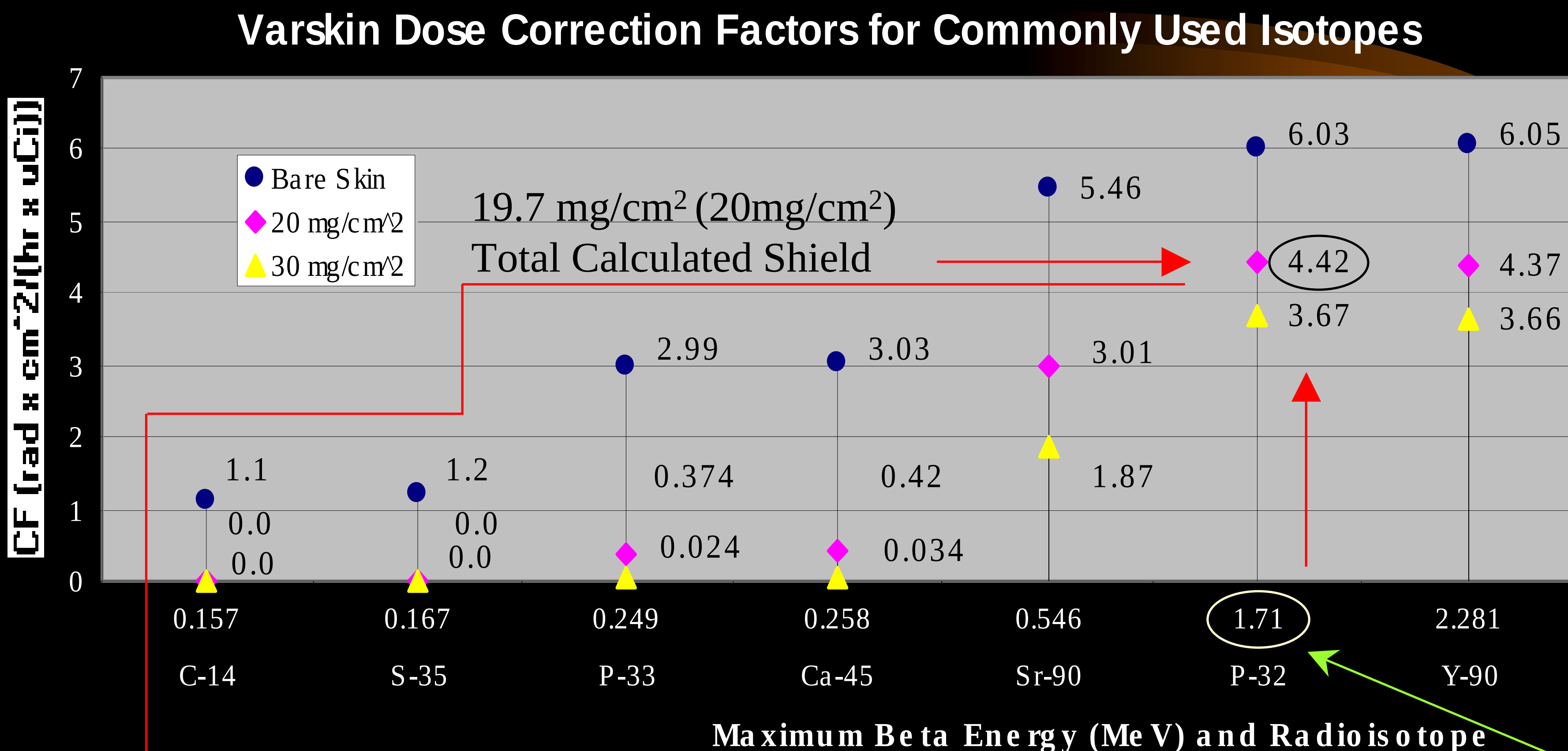
$x_m = \rho x = (1\ g/cm^3)\ (0.0127\ cm) = 0.0127\ g/cm^2 =$ ***12.7 mg/cm²***

Total shield from glove and dead skin layer:

$X_{m,tot} = (\ 12.7 + 7\ )\ mg/cm^2 =$ ***19.7 mg/cm²***

Maximum energy of ^{32}P beta = 1.71 MeV

Example β Calculation (Continued)



Maximum beta energy

Activity on skin = 50 μCi

For beta particles, Q=1

$$\dot{D} = \left(4.42\,\frac{rad * cm^2}{hr * \mu\,Ci}\right)\frac{50\,\mu\,Ci}{1\,cm^2} = 221\,\frac{rad}{hr} = 221\,\frac{rem}{hr} * \frac{10\ \sec}{3600\ \sec/hr} = 614\ mrem$$

Final Dose to Skin after 10 seconds

Skin area contaminated = 1 cm²

Example γ Calculation External Dose Equivalent Dose Rate Unshielded for ^{137}Cs

What is the dose rate from a 0.53 uCi ^{137}Cs source that is 30 cm away From the individual ?

Maximum energy of ^{137}Cs gamma = 0.662 MeV

Specific Gamma-Ray Constant for ^{137}Cs

Nuclide	Γ (R m^2)/(hr Ci)
^{137}Cs	0.33

Rem/R Conversion Factors (C_d)

Photon Energy	Conversion Factors at Depth		
	1.0 cm (“Deep”)	0.3 cm (Lens of Eye)	0.007 cm (“Shallow”)
662	1.03	1.03	1.03

Example γ Calculation External Dose Equivalent Dose Rate Unshielded for ^{137}Cs

Exposure Rate (R/hr)

Specific gamma-ray constant provided in table

Activity = 0.53 μCi

$$\dot{X} = \Gamma \frac{A}{d^2}$$

$$\dot{X} = \left(0.33 \frac{R * m^2}{hr * Ci}\right) \frac{0.53x10^{-6} Ci}{(0.30m)^2}$$

Distance from source = 30 cm

$$\dot{X} = 1.94 \text{ x } 10^{-6} \text{ R/hr}$$

$$\dot{H} = C_d \dot{X} = 2.00 \ \mu\text{rem/hr}$$

Does this concern you?

Conversion factor from table = 1.03 (rem/R)

Natural Background from Cosmic Radiation = 15-20 μrem/hr

Reducing External Radiation Exposure

- Time:
  reduce time spent in radiation area

- Distance:
  stay as far away from the radiation source as possible

- Shielding:
  interpose appropriate materials between the source and the body

Reduction of Exposure Time

- Training:

  training improves efficiency should include full rehearsal of the procedures outside of the radiation area to improve efficiency and confidence

- Power and automated equipment

- Lab design

allows easy access to the equipment and components

- Task modifications from ALARA review

Control of Distance

- remote operation

  manipulating devices, remote handling tools

- moving away from sources

  remain near a source only when it is being used

- remove other radiation sources

  waste containers

  unnecessary sources

Shielding

Basic principle:
Place materials between the source and person to absorb some or all of the radiation

- α radiation: no shield required for external exposures; dead skin layer stops α's

- β radiation: ranges of meters in air; some can penetrate dead skin layer; thin plexiglass shields adequate

- x and γ radiation: highly penetrating, best shields are high atomic number materials (lead)

Other Methods for Controlling External Exposure

Inventory Limitations:

Reduce activity stored in work area

Separate into multiple containers and store elsewhere

Centralize storage

Good Practices:

Restrict access

Limit personnel

Post areas

Post procedures

Buddy system

INTERNAL RADIATION EXPOSURE

Deposited in the body

Pathways

Inhalation of dust, mists or fumes
Ingestion of contaminated food or water
Injection via puncture wound
Absorption through skin or via a wound

INTERNAL RADIATION EXPOSURE

- Rarely any method to reduce exposure once in the body
- If long physical and biological half-life, may irradiate individual for rest of life

Estimates of dose are complex

- Quantity of intake usually not known
- Complex biological process of elimination and concentration
- High biological variability
- Fraction of energy released deposited in other organs

INTERNAL DOSIMETRY CALCULATIONS

Two aspects make dose estimate methods very different compared to external exposures:

- **Metabolic processes are important in eliminating and/or concentrating radioactivity (radiosensitivities of all organs and tissues are not the same)**
- **Exposure internally may continue for a lifetime (activity is changing in time due to both physical decay and complex metabolic processes)**

DOSE EQUIVALENT QUANTITIES

- **Differences in radiosensitivity are addressed using risk based weighting factors: *Effective Dose Equivalent***

- **Duration of exposure is addressed by integrating the exposure over 50 years: *Committed Dose Equivalent***

- **Both problems are simultaneously addressed using the concept of *Committed Effective Dose Equivalent***

DOSE EQUIVALENT

Organs and Tissues:

$$H_T = QD_T$$

EFFECTIVE DOSE EQUIVALENT

Sum of products of dose equivalent to organ or tissue (H_T) and weighting factors (w_T) applicable to each organ or tissue that is irradiated:

$$H_E = \sum_T w_T H_T$$

WEIGHTING FACTORS (w_T)

Proportion of risk of stochastic effects resulting from irradiation of that organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly

Organ or Tissue	w_T
Gonads	*0.25*
Breast	*0.15*
Red Bone Marrow	*0.12*
Lung	*0.12*
Thyroid	*0.03*
Bone Surfaces	*0.03*
Remainder	*0.30*
Whole Body	*1.00*

COMMITTED DOSE EQUIVALENT

$H_{T,50}$ is the dose equivalent to an organ or tissue (T) that will be received from an intake of radioactive material by an individual during the 50-year period following the intake:

$$H_{T,50} = \int_{t_0}^{t_0+50} \dot{H}_T(t)\,dt$$

Determined by physical decay of the nuclide and metabolic models:

•Models based on *reference man* include:

respiratory tract model

gastrointestinal tract model

Bone model

Systemic biokinetic and excretion models

MODELS

Mathematical descriptions of the transfer of materials within the body and their elimination

Depend on:

Chemical form - impacts on solubility and transfer to and from the blood

Particle size - distribution for inhalation which impacts where the particles lodge in the respiratory tract

Biochemistry

First principle calculation beyond the scope of this course.

An easy to use quantity is the ALI (Annual Limit on Intake)

COMMITTED EFFECTIVE DOSE EQUIVALENT

$H_{E,50}$ is the dose equivalent to an organ or tissue (T) that will be received from a single intake of radioactive material that Addresses both the radiosensitivity of the organs to a particular isotope as well as the time duration of exposure over a 50-year period following the intake:

CEDE = (A/ ALI) x 5 rem for whole body exposure

CEDE = (A/ ALI_T) x 50 rem for a target organ

ANNUAL LIMIT ON INTAKE (ALI)

Derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year.

ALI is the smaller value of intake of a given radionuclide in a year by reference man that would result in:

•a committed effective dose equivalent of 5 rem

or

•a committed dose equivalent of 50 rem to any individual organ or tissue

READING ALI TABLES

Chemical form - self-explanatory

Classes - inhalation for an aerosol with median diameter of 1 μm and for 3 retention times in the pulmonary region of the lung:

- **D - days - clearance half-times <10 days**
- **W - weeks - clearance half-times of 10 to 100 days**
- **Y - years - clearance half-times > 100 days**

If organ is listed then 50 rem limit to that organ applies

If organ is not listed then 5 rem limit applies

ALI TABLES

Part 4 Appendix B of the State Rules and Regulations

Examples

Atomic No.	*Radionuclide*	*Class*	*Oral Ingestion ALI (μCi)*	*Inhalation ALI (μCi)*
6	*Carbon-14*	*Monoxide*	*-*	*2E+6*
		Dioxide	*-*	*2E+5*
		Compounds	*2E+3*	*2E+3*
53	*Iodine-125*	*D, all compds*	*4E+1*	*6E+1*
			Thyroid (1E+2)	*Thyroid (2E+2)*

EXAMPLE CALCULATION

Accidental ingestion of 1 μCi ^{14}C labeled organic compound

$$H_{E,50} = (A/ALI_g)5 \text{ rem}$$

Intake activity (μCi) → A

ALI from table (μCi) → ALI_g

There is no target organ so 5 rem is used

$$H_{E,50} = (1 \mu Ci / 875 \mu Ci)(5 \text{ rem}) = 5.7 \text{ mrem}$$

EXAMPLE CALCULATION

Accidental inhalation of 1 μCi ^{125}I in the elemental form

$$H_{thyroid,50} = (A/ALI_g)50 \text{ rem}$$

Intake activity (μCi)

ALI from table (μCi)

There is a target organ so 50 rem is used

$$H_{thyroid,50} = (1\ \mu Ci / 60\ \mu Ci)(50{,}000 \text{ mrem}) = 833 \text{ mrem}$$

To thyroid

$$H_{E,50} = (1\ \mu Ci / 200\ \mu Ci)(5{,}000 \text{ mrem}) = 25 \text{ mrem}$$

To body

Control of Internal Exposure

- Expend effort to prevent any intake of radioactive material

- 2 Types of contamination must be controlled

removable surface contamination

airborne contamination

- suspension
- resuspension
- sputtering of fluids
- vaporization

Methods for Control of Contamination

- design features associated with the lab
- routine contamination surveys
- decontamination of objects and individuals
- air-sampling and air-monitoring
- use of PPE
- administrative guidelines

Example of Dose Calculations From a Lab (External)

The license or registrant shall demonstrate compliance with the dose limits by summing external and internal doses.

Procedure	Activity (µCi)	Distance (cm)	Time (secs)	Number of Procedures
1) Open Bottle	1000	10	0.5	1
2) Remove 5 µl	1000	10	2	2
3) 5 µl in reaction	50	10	5	2
4) Mix compnents	50	3.5	10	2
5) Thermal block	50	3.5	5	2
6) Remove reaction	50	3.5	5	2
7) Pipette reaction	50	3.5	10	2
8) Mix tube contents	8.4	3.5	5	12
9) Remove tube	8.4	3.5	10	12

Example of Dose Calculations From a Lab (External) (Continued)

Procedure	Activity (µCi)	Distance (cm)	Time (secs)	Number of Procedures
10)Cap indiv. tubes	2.1	3.5	5	48
11)Move to cycler	2.1	3.5	2	48
12)Remove tube fr. cycler	2.1	3.5	5	48
13)Place tube in heat block	2.1	3.5	2	48
14)Load Aliquot.	2.1	3.5	5	48
15)Remove gel	8.4	80	60	1
16)Discard gel	8.4	50	10	1

Example of Dose Calculations From a Lab (External)

Procedure	mrem/hr	Total mrem
1	2700	0.4
2	5400	3
3	270	.4
4	2204	6.1
5	2204	3.1
6	2204	3.1
7	2204	6.1
8	2222	3.1
9	2222	6.2
10	2222	3.1
11	2222	1.2
12	2222	3.1
13	2222	1.2
14	2222	3.1
15	0.4	0.0
16	0.9	0.0
Total		43.1

Example of Dose Calculations From a Lab (Internal)

Accidental oral ingestion of 1 μCi of ^{32}P

$$H_{E,50} = \left(\frac{1\mu Ci}{30\mu Ci} \right) 5000\, mrem = 167\, mrem$$

Accidental inhalation of 1 μCi of ^{32}P

$$H_{E,50} = \left(\frac{1\mu Ci}{900\mu Ci} \right) 5000\, mrem = 5.55\, mrem$$

Example of Dose Calculations From a Lab (Internal)

5 volumes handled and amounts on previous pages for ^{32}P in DNA sequencing procedures

	Activity (µCi)	Committed Dose Equiv. Oral Ingest.	Committed Dose Equiv. Inhalation
Whole Bottle	1000	8333	5556
Labeling Reaction	50	417	278
Sequencing Reaction	10	83	56
One Deoxy Reaction	2.5	21	14
One Loading on sequencing gel	1	8	6

Questions ???

See our Website – http://www.ehs.colostate.edu/radiation

Please Feel Free to Contact: The Radiation Control Office

133 General Services Bld.
CSU Main Campus
Fort Collins, CO. 80523-6021

Environmental Health Services: 491-6745

Radiation Safety Officer: 491-3736

Alt. Radiation Safety Officer: 491-3928

Radiation Control Technician: 491-4835

VTH Radiation Technician: 491-4439

Colorado State University

Module 5: Dosimetry

Prepared by James C. Graham, R.S.O.
James P. Abraham, Alternate R.S.O.
Radiation Control Office
Environmental Health Services