Health Physics 3321 Radiologic Physics

Spring Semester Class Time: Friday 1:00 - 2:50 Place: TBD

Text:

Steward C. Bushong;

Radiologic Science for Technologists, Physics, Biology, and Protection (latest edition)

Instructor: Richard R. Brey Ph.D., C.H.P. /Professor of Health Physics AVP Operations and Safety Office: CH 234 Telephone: 282-2667

Office Hours: Monday through Thursday 10:00 to 11:00 or by appointment. Informal open door policy.

Course Description:

PHYS 321 Radiologic Physics (2 credits) Basic Physics of x-ray production and the interaction of x-rays with matter. Includes topics in medical imaging. Available to juniors in Radiographic Sciences.

PREREQ: PHYS 1100. S

Tentative Course Schedule

TOPIC	READINGS (Bushong)
Grading Policy, Testing Format, Homework Policy, Expectations.	
Basic Radiation Physics	
Physics/Mathematics Review	
Concepts of matter/ atomic and nuclear structure	
Radioactive decay	Class Notes
Types of Radiation	
Interactions of Radiation with matter	
Fundamentals of Radioactivity	
Test 1	
Generation, interactions, and behavior of characteristic and Continuous X-Rays	
Test 2	
Health Physics practice, instrumentation & dosimetry	
Regulations	Class Notes
Radiobiology	
Test 3 (Cumulative Final)	

HPHY 3321 Class Policy

1) Homework will represent 30% of the overall class grade.

a) Homework should be expected frequently.

i) Students are encouraged to work together on homework.

ii) Homework problems can and may be the basis for test questions.

iii) Homework assignments are not considered to be group projects. Each student should do their own work, merely consulting with others as appropriate.

- A photocopy of the work of someone else is not acceptable.

** The instructor is a resource during office hours or by appointment.

b) All homework assignments must be completed.

i) Students who don't complete all homework assignments can expect an incomplete grade in the course at the discretion of the instructor.

c) Questions completed correctly will be awarded an appropriate number of points.

Assignments will typically include several multi-part questions or inter-related questions.

* Students are encouraged to write out the assigned questions.

* All work is to be shown.

* The student is encouraged to carry units along with the solution of the problem, and provide a neat easy to follow answer.

- homework which is too difficult to follow will be returned with a zero grade until completed in an acceptable fashion.

* Answers must be given with the appropriate units.

* All answers are to be circled.

2) There will be two full lecture period tests and a cumulative final examination.

a) Tests will cover topics on homework, lectures, and assigned reading.

b) Each test will be worth 20% of the final class grade.

c) The cumulative final examination will be worth 30% of the final class grade.

d) At the discretion of the instructor, any evidence of dishonesty are grounds for failing tests or examinations, and subject to other university disciplinary actions.

3) Final Class grade

a) Grades will be based on:

Homework	30%
Tests	40%
Final	30%

b) Tentatively, grades will be earned based on a straight scale grading policy:

≥ 97% ....+A
≥ 93% ....A
≥ 90% ....-A
≥ 87% ....+B
≥ 83% .... B
≥ 80% ....-B
≥ 77% ....+C
≥ 73% ....C etc.

c) The instructor reserves the right to change the grading scale, and assignment weighing. Such changes will be:

i) based on profession judgement
ii) applied across the board to all students
iii) in favor of the students

4) Reading assignments should be completed prior to lecture.

a) Students are encouraged to apply the SQ3R study method.

SQ3R:

Survey the literature
Develop **Q**uestions prior to reading and based on the survey
Read the material answering your own questions
Recite what was read
periodically **R**eview the material

6) Lectures:

a) Bring pertinent questions on the literature, personal experiences, and current affairs, which do not have self-evident answers, to lecture.

b) Students can expect to be asked questions about the topics at hand while attending lecture so please be prepared.

i) This lecture style is intended to build student confidence.

- It is not intended to embarrass, intimidate, or belittle, students. It is okay not to have an answer, but not okay to leave it at that.

c) Take advantage of the opportunities available - You have paid for them!

Idaho State University is committed to providing equal opportunity in education for all students. If you have a diagnosed disability or if you believe you have a disability physical, learning, hearing, vision, psychiatric) that might require reasonable accommodation in this course, please contact the Disability Services Center, Rendezvous Building, Room 125 (282-3599) or on the web at http://www.isu.edu/ada4isu.edu It is the responsibility of students to contact instructors during the first week of each semester to discuss appropriate accommodations.

Academic integrity is expected of all individuals. Behavior beyond reproach must be the norm. Academic dishonesty in any form is unacceptable. Academic dishonesty includes, but is not limited to, cheating and plagiarism. Procedures for determination of academic dishonesty and imposition of penalties for academic misconduct are outlined in the Student Code of Conduct:

Health Physics 3321 Radiologic Physics

<u>Introduction and Definitions</u>

Matter is anything that occupies space.

We consider matter to be composed of atoms.

Atoms are composed of neutrons, protons, and electrons.

We categorize atoms into different types referred to as elements. For example hydrogen, oxygen, carbon.

Elements vary according to the number of protons contained within the nuclei of their atoms.

The number of protons in an atom largely determine its properties. The properties of atoms with different numbers of protons vary in a predictable fashion.

We have developed the Periodic Table of the Elements based upon this observation.

There are variations of the atom types within elements. Although any atom of an element will have the same number of protons, the number of neutrons within atoms of a particular element may vary.

Elements of atoms (all having the same number of protons) but with different numbers of neutrons are referred to as isotopes f an element. Hence we have C-14, C-13, C-12.

Overview of the Atom

A) Consideration of the electron

1. Electrons are considered to be fundamental particles.
2. they move in a wavelike motion about the nucleus.
   (a) this is described using wave mechanics.

(b) this motion is confined to specific geometric orbitals which are a definite distance
from the nucleus.
(c) these distances are referred to as energy states or energy levels. Only certain states are allowed.
(d) one may speak of the probability of finding an electron at a given distance from the nucleus or at a certain energy level.

3. The mass of the electron is about 1/1837 that of the hydrogen atom or about $9.1x10^{-28}$g.

4. The electron, because of its electromagnetic nature does not have a definite radius.

(a) any measurement of the electron's radius will be somewhat dependent on the experimental procedure used.

(b) the radius of the electron is taken to be less than $1x10^{-16}$cm.

5. The charge of the electron:

(a) It was once thought that the quantity of charge carried by an individual electron could not be further divided.

(b) there is evidence that this is no longer the case. It is now known that smaller units of charge than the possessed by the electron exist.

(i) The evidence of this is the existence of quarks.
(ii) Six different quarks and their anti-quarks have been named these are:

NAME	Approximate Mass		
	(grams)	(GeV/c^2)	Electrical charge
up (U)	$7.1x10^{-27}$	$4x10^{-3}$	2/3
down (d)	$1.2x10^{-26}$	$7x10^{-3}$	-1/3
charm(c)	$2.7x10^{-24}$	1.5	2/3
strange (s)	$2.7x10^{-25}$	0.15	-1/3
top (t)	$1.6x10^{-22}$	>0.89	2/3
bottom (b)	$8.4x10^{-24}$	4.7	-1/3

note; the top quark has not yet been observed.

Quark theory along with several conservation laws can be used to explain the composition and behavior of many of the elementary particles thought to exist.

Families of Elementary Particles

Fundamental particles are composed of elementary particles.

There are several ways to classify elementary particles.
Elementary particles can be classified according to:

1) The types of interactions the particles undergo during their reactions and decay.

   a) weak interactions

   b) electromagnetic interactions

c) nuclear or strong interactions

2) According to their rest mass

a) Lightest group: Leptons

b) Middle mass group: Mesons

c) Heaviest group: Baryons

3) Intrinsic spins

4) Life times of those particles that are unstable with respect to decay

a) as a rule the stronger the forces involved, the shorter the half-life:

Interaction Type	Typical Half-life range
Strong Interactions	10^{-23} to 10^{-20}s
Electromagnetic Interactions	10^{-18} to 10^{-15}s
Weak Interactions	10^{-10}s to 15 min

5) nature of the associated antiparticle

The classification scheme which encompasses many of the others employs segregation by rest mass. This scheme includes the Lepton, Meson, and Baryon families. The following table summarizes this classification scheme of elementary particles.

Consideration of the Nucleus

A) The nucleus is composed of protons and neutrons. The collective term for these is nucleons.

B) Nucleons are a sub-set of the baryon family of elementary particles.

(a) They have relative long half-lives compared to other members of the baryon family and are consequently considered to be stable.

C) A proton is similar to the nucleus of the ordinary hydrogen atom (protium).

(a) It is positively charged.

(b) A proton may be thought of consisting of two up quarks and one down quark.

(c) The magnitude of the charge is the same as that on the electron.

(d) Its mass is 1836 times that of an electron. or about $1.6726485x10^{-24}g$

D) Originally it was thought that nuclei were merely multiplies of the proton.

1. Under this false assumption the mass number of the hydrogen proton was assigned a value of one.

2. Accordingly the mass numbers of subsequent nuclei should have simply been merely multiples of the hydrogen proton.

3. However, the nuclear mass numbers were found to be about twice as great as the corresponding atomic numbers.

(a) This ratio became relatively greater as the atomic numbers increased.

E) Another problem with the assumption that the nucleus was composed entirely of protons was an inconsistency, and subsequent need to account for the stability of the nucleus, when the Coulombic forces among the nuclear protons

1. Consider a simple calculation comparing the Coulombic force of repulsion and the gravitational force of attraction acting between two protons.

(a) The Coulombic force of repulsion is given as:

$$F = k_o q_1 q_2 / r^2$$

(b) The gravitational force of attraction is given as:

$$F = Gm_1m_2/r^2$$

2. It is clear when considering the magnitude of these two forces that unless some other forces are involved that an atom composed of protons should not be capable of existing.

F) This enigma was solved by James Chadwick in 1932 when he discovered the neutron

1. The neutron has roughly the same mass as the proton, but its mass is just slightly greater than that of the proton.

2. The proton's mass is $1.62726485 x 10^{-27}$kg

3. The neutron's mass is $1.6749544 x 10^{-27}$kg.

4. A neutrons mass is about 1837 times that of an electron.

G) The neutron is thought to be composed of two down quarks and one up quark.

H) A neutron has no charge; it is electrically neutral.

(ii) A description of the neutron in terms of fundamental particles indicates (as mentioned above) that the neutron consists of two down quarks and one up quark.

(iii) This combination gives it a neutral charge.

(I) The presence of neutrons within an atom supplies the attractive nuclear forces otherwise known as the strong forces.

1. Nucleons are bound together in the nucleus by the action of the nuclear force.

2. Nuclear forces are cohesive force acting over extremely short ranges (2 to $3x10^{-13}$cm) which holds the nucleus together overcoming the repulsive Coulombic forces discussed above.

3. The strong force or nuclear force is thought to be generated by the exchange of gluons with quarks.

4. The strong force or nuclear force is one of the basic forces of nature.

(J) The four basic forces in nature are:

1. Gravitational force - between two masses

2. Electromagnetic force- charged particles.

3. Weak forces - beta decay processes.

4. Strong forces - Nuclear force.

In field theory it is thought that the force arising between objects arises from the exchange of certain particles.

1) The strong (sometimes called the nuclear) interaction between nucleons is through to arise from the interchange of pi-mesons or pions.

2) The graviton is thought to be interchanged by objects having gravitational attraction.

3) The vector boson caries the weak interaction.

4) The electromagnetic field is carried by photons.

5) Quarks are thought to be held together by the exchange of particles whimsically named gluons.

CONVENTIONS FOR DESCRIBING NUCLEONS

A) In an undisturbed atom the number of extranuclear electrons is equal to the number of protons.
B) The atom as a whole is electrically neutral.
C) The number of protons in the nucleus of an atom determines the type of element.
D) This number is called the atomic number of the element.
    1. Atomic number has the designation Z.

One may alternately say a particular substance has a high z or a high atomic number.

E) The number of protons plus neutrons in the nucleus of an atom is called the mass number.
    1. The mass number is designated by the letter A.
F) The number of neutrons is equal to A-Z and is called the neutron number.
    1. The neutron number is designated by the letter N.
G) The mass number of the nucleus of an atom is not the same as its atomic mass.
    1. The atomic mass of an atom is the mass of the atom compared to the mass of ^{12}C.

^{12}C mass = 12 amu.

^{12}C was adopted in 1962.

2. That is to say that the modern scale of atomic and molecular weights is set by stipulating that the gram atomic weight of the carbon 12 isotope, 12C, is exactly 12.000g.

H) The radius of the nucleus of an atom of atomic mass number A is given approximately by the formula:

$$r \equiv 1.3A^{1/3} x 10^{-13} cm$$

1. The radii of atoms are about $1x10^{-8}$cm
2. The radii of nuclei are about 10^{-13}cm to 10^{-12}cm.

I) Although the nucleus is small compared to the atom, the nucleus contains all the mass of the atom. An atom is mostly empty space.

Consider the following analysis:

We know that the volume of a sphere is equal to $4/3\prod r^3$ hence the ratio of the:

Volume of atom/volume of the nucleus = $\left[4/3\prod(10^{-8})^3\right]/\left[4/3 \prod (10^{-12})^3\right] = 10^{12}$

The correction for the volume of electrons is negligible. Therefore, only 1 part in about 10^{12} is matter.

This reality is important to keep in the back of your mind particularly when we start to speak about the interaction of radiation with matter.

(J) It is good to remember that matter, the items we call solid objects for instance, are predominantly composed of empty space. The density of nuclear matter, the material in the nucleus - the nucleons - is about 10^8 tons/cm^3.

1. The emptiness of the atom is the reason small particles can penetrate matter.

(K) We should all remember that a gram atomic weight of any element contains Avogadro's number, $N_o = 6.023x10^{23}$, of atoms.

1. And that a gram molecular weight of any gas contains Avogadro's number of molecules and occupies a volume of 22.4136L at standard temperature and pressure. (e.g. 273K and 760 torr where 1 torr=1 mm Hg).

(L) Each species or nucleus is designated by its nuclear composition this may be observed in its proper designation.

1. The most commonly used method of designation was approved in 1960 by the International Union of Pure and Applied Chemistry (IUPAC) (J.AM.Chem.Soc.82,5526(1960)).
2. A full designation uses the following items:

Symbol for the element: the central point of the designation

Mass number: left upper index
Atomic number: left lower index
Ionic charge: right upper index
Number of atoms in molecule: right lower index.

Example:

Which may be found in the molecule $Ca_3(PO_4)_2$.

Usually the atomic number is omitted since the symbol for the element designates the number of protons.

It should also be noticed that the ionic charge is indicated as n+ rather than +n, where n is some integer.

In some of the older literature the mass number is written as a right upper index.

This was done primarily in the United States. This method is no longer used.

3. Another acceptable method is to write the element name or write out the elemental symbol followed by the mass number, for example:

Ca-45

or

Calcium-45.

(M) Originally it was thought that for a given element all of the atoms were identical.

1. It is now known that even for a given element there can be many different species.
2. The different species differ in the number of neutrons present in the nucleus.
3. These different species are called isotopes.

Note: Do not refer to isotopes alternately as species the words are not interchangeable it is done here for discussion purposes only.

Isotopes are species of nuclei with the same atomic number but different mass number.

Examples of isotopes are as follows:

^{9}C ^{10}C ^{11}C ^{12}C ^{13}C ^{14}C ^{15}C ^{16}C

4. Isotopes are species of the same element.
5. The chemical and physiological properties of an element depend upon the number of electrons.
6. The isotopes of a given element all have the same number of electrons.
   (a) Therefore, for practical purposes the chemical and physiological properties of all the isotopes of an element are the same.

However, at low Z a small mass effect may be observed in some circumstances.

(b) This is the basis for using isotopes as tracers in chemical and biological work.

Examples: The thyroid uses iodine, ^{127}I is stable.

If we give someone ^{131}I instead of ^{129}I this difference cannot be distinguished by the thyroid.
However, we can detect the radiation emitted from ^{131}I and study the iodine uptake kinetics of a thyroid.

(N) Isobars are species of nuclei with the same mass number but different atomic number.

$$x_6^{14}C \quad and \quad x_7^{14}N$$

Example:

(O) Isotones are species of nuclei with the same number of neutrons.

$$x_6^{14}C \qquad and \qquad x_7^{15}N$$

Example:

(P) Isomers are species of nuclei with the same atomic and mass numbers but with different energy levels.

Example: $x_{51}^{124}Sb \qquad x_{51}^{124m}Sb \qquad or \qquad phantom x_{43}^{99}Tc \qquad x_{43}^{99m}Tc$

1. These are called metastable isomers because they have measurable half-lives.

(Q) A Nuclide is any species of nucleus characterized by its composition, in particular by the number of protons and neutrons, but also the energy level of the nucleus.

1. The term nuclide is a general term.

2. It should always be used when no relationship to another nuclear species is intended.

Example:

C-12 may be referred to as a nuclide.
C-12 and C-13 are isotopes.
C-12 is an isotope of carbon.

They are isotopic to each other.

C-14 and N-14 are isobars.
C-14 and I-131 are nuclides. Except for being radioactive they are not related.

The term isotope is commonly misused.

(R) There are presently (as of November 29, 1993) 109 elements recognized by the American Chemical Society.

(S) The combinations of neutrons and protons which are stable are called Stable Nuclides.

1. Those nuclides which are rare, on the atom percentage basis present in the natural mixture, can be used as tracers.
2. These are referred to as rare stable isotopes.
   (a) However, the use of rare stable isotopes is a complicated technique requiring highly sensitive, and expensive, equipment such as mass spectrometers.

(T) Elements with atomic number through 92 (uranium) exist in nature with the exception of 43 (Technetium) and 61 (promethium).

1. Elements with atomic numbers 93 and 94 have been separated from pitchblende in very small amounts.
    (a) These result from neutron interactions.

(U) Elements with atomic numbers 93 (Neptunium) through 109 have been synthesized.

1. Many more will probably be synthesized.

(V) All elements greater than 83 (Bismuth) are radioactive.

1. These radionuclides have no stable isotopes.

(W) There are several elements with atomic numbers 83 and less that are naturally radioactive because they contain small percentages of naturally radioactive isotopes.

1. To exist in nature a radioactive nuclide must either:
    (a) Be continuously produced by some process
    (b) Have a half-life comparable to the age of the earth, somewhere around $4.5x10^9$y.

X) Those combinations of neutrons and protons which are not stable are called radioactive nuclides or simply radionuclides.

1. Their instability may be overcome by a transformation in the nucleus leading to a different species of nucleus.

2. This transformation is called radioactive decay.

All things being equal, the essential aspect of matter that we can realize is mass.

In physics we actual realize three fundamental base quantities:

1) Mass

2) Length
3) Time

Base quantities allow us to describe objects.

Mass is defined as the quantity of matter contained within an object. The MKS system uses the unit of kilograms to measure quantities of mass.

Mass should not be confused with the idea of weight.

Weight actually is the experience of force.

You should remember that

Force = Mass x Acceleration

The unit of force in the MKS system is the newton. An object with a 10 kg mass on the planet earth is associated with a force of:

$$F = (10kg)(9.80m/s^2) = 98.0\ kg\text{-}m/s^2 = 98.0\ \text{Newtons}$$

where $9.80m/s^2$ is the acceleration due to the force of gravity experienced on the planet earth.

In the old English system, the acceleration due to the force of gravity experienced on the planet earth is 32.2 $feet/s^2$
The unit for mass is the slug. Force is given in units of pounds.

What is your mass in slugs?

If you were on the Moon, would your mass change?

Would your weight change in these two circumstances?

The unit second is used to measure time.

The unit meter is used to measure length. A meter is defined as the wavelength of orange light emitted from an isotope of krypton, Kr-86.

We use base quantities to develop derived quantities.

Derived quantities are concepts that allow us to describe experiences, such as motion.
The derived quantities of greatest interest are:

Velocity
Acceleration
Force
Momentum
Work
Energy
Power

Velocity is simple length divided by time.

Acceleration is the rate of change of velocity.

Force is the product of mass and acceleration.

Momentum is the product of mass and velocity

Work is the product of force and distance

Power is the quotient of work divided by time.

Energy is the ability to do work. We experience energy in either the form of Kinetic Energy or Potential Energy.

We can say that kinetic energy is the energy of motion.

Kinetic energy = $(1/2)mV^2$

Potential Energy is the capacity to do work.

Potential energy = mass x acceleration x height

Your book describes several situations in which we commonly experience either kinetic energy or potential energy:

Form of energy	Way it is experienced
Chemical Energy	
Electrical Energy	
Thermal Energy	
Nuclear Energy	
Electromagnetic energy	

Heat is defined as the kinetic energy of randomly moving molecules. The calorie is the unit of heat. A calorie is the energy necessary to raise one gram of water one degree Celsius. In dieting we often talk about calories but we are actually referring to kilocalories.

Temperature is a scalar measurement of heat; we commonly use two different unit systems for measuring temperature. The Celsius scale and the Fahrenheit scale. A third absolute scale exist referred to as the Kelvin scale. At sea level, water boils at 100°C, 212 °F, and 373 K. At sea level water freezes at 0°C, 32°F, and 273 K

Heat energy is transferred in three ways,

1) Conduction:
2) Convection:
3) Thermal radiation:

Conduction is the transfer of heat energy along or between touching objects. Convection is the mechanical transfer of heat energy by rapidly moving gas or liquid.

Radiation: Energy emitted from a source as waves or particles and transmitted through space.

Radioactivity: The phenomenon of spontaneously emitting radiation as a result of changes in the nuclei of atoms that are energetically unstable.

This change is called Radioactive decay or radioactive disintegration or just decay or disintegration.

The word spontaneous is important. Nuclei can be made to change into different nuclei, but the change is not spontaneous.

Example: Co-60

A) Transformation Kinetics

1. The rate of transformation of a radionuclide, the rate of decay, is a first order reaction.

2. The rate of decay is a function of the number of radioactive elements present in a sample.

3. More formally, the rate of decay (dN/dt) is proportional to the total number N of atoms in a radioactive sample:

$$\frac{dN}{dt} \propto N$$ where:

dN/dt = the number of atoms decaying per unit of time, the rate of decay.

N = the total number of atoms present

4. It can be observed that the number of radioactive atoms decreases as time passes.

5. With this information we can make a specific statement:

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

(a) This is the instantaneous rate of decay at any time.

(b) The negative sign N decreases as the time increases.

(c) λ is called the decay constant.

(i) The decay constant is a property of each radionuclide.

(ii) The rate of decay is not altered by any known physical or chemical means. Neither pressure, temperature, chemical changes, gravitational fields, electrical fields, nor magnetic fields, effect the rate of decay.

(d) Radioactive decay is a random process.

(e) We can never determine when an individual atom will decay.

(f) Given a population of atoms we can predict when a fraction of the population is likely to decay.

(g) Radioactive decay is a stochastic process.

(h) If we consider a population of atoms, and plot the number of atoms which decay in each finite increment of time following some initial starting point this plot will have a Poisson distribution.

(B) The rate of decay is actually used to describe the quantity of radioactive material present.

1. We may call the rate of decay the activity (A) of the sample.
2. The old unit of activity is the Curie (Ci).

(a) Originally the unit curie was based in the measured number of atoms disintegrating per unit time from one gram of Ra-226_.

(i) This unit was named in honor of the Curies who discovered radium.

(b) Today, one curie is defined to be equal to 3.7×10^{10} disintegrations/second.

(c) Here we are using the word disintegration interchangeably with the word transformation.

3. The SI unit of activity is the becquerel (Bq).

(a) A becquerel is one disintegration per second.

(b) There are 3.7×10^{10}Bq per 1.0Ci.

$1.0Ci = 3.7 \times 10^{10}Bq$

(c) Alternately, we may write:

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

4. This in itself is a useful expression, given any two variables in this equation we can determine the instantaneous value of the third variable.

(a) For instance, using this equation we can determine the instantaneous number of atoms present in a sample given the activity and the value of λ.

(b) The equation:

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

is a first order differential equation.

(c) We can solve this equation as follows:

First separate variables:

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

Then we integrate both sides of the equation:

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

this result of this operation is:

$$\ln(N) + Const_1 = -\lambda t + Const_2$$

where ln is the natural log function.
lets allow $Const_2 - Const_1$ to equal $\ln(C)$, doing so allows the equation to be rewritten as:

$$\ln(N) = -\lambda t + \ln(C)$$

We know as an initial condition that at time is equal to 0,
$t = 0$ and we can denote the number of atoms at time equals 0 as N_0 hence, the equation becomes:

$$\ln(N_0) = 0 + \ln(C)$$

therefore; $\ln(N_0) = \ln(C)$, or $N_0 = C$. We can rewrite the equation as:

$$\ln(N) = -\lambda t + \ln(N_0)$$

this is the same as:

$$\ln(N) - \ln(N_0) = -\lambda t$$

which is the same as:

$$\ln(\frac{N}{N_0}) = -\lambda t$$

raising both sides by exp yields:

$$\frac{N}{N_0} = \exp^{-\lambda t}$$

This expression is sometimes called the exponential radioactive decay law.
Incidently, since A = -λN we may also write this as:

$$\frac{A}{A_0} = \exp^{-\lambda t}$$

$$A_0 \exp^{-\lambda t}$$

5. The number of disintegrations which have occurred over a period of time

$$A_0 \exp^{-\lambda t}$$

may be found by integrating the expression:

wrt to time from the beginning of the time of interest (t_1)to the end of the time of interest (t_2) as follows:

$$\int_{t_1}^{t_2} A_0 ext^{-\lambda t} dt = \left[\frac{A_0}{-\lambda} exp^{-\lambda t}\right]_{t_1}^{t_2}$$

When $t_1 = 0$ this becomes:

$$\frac{A_0}{\lambda}(1 - exp^{-\lambda t_2})$$

6. We have already mentioned that the decay constant is a property of each radionuclide.

(a) There are several different ways to describe the decay constant.

(b) Consider a plot of the ratio of A/A_o versus time.

(c) It can be observed that A/A_o decreases as a smooth function of time.

(i) This is the exponential decay function.
(ii) If we look at any ratio of A/A_o and than at the ratio $(0.5)(A/A_o)$ we can define the time it takes for one-half of atoms of a particular radionuclide to decay.
(iii) This time is the radionuclide's half-life.
(iv) Sometimes the half-life is called the physical half-life.

(7) The half-life can be used to describe the decay constant.

(a) Initially, we can state that in one half-life ($t_{1/2}$) only one half of the activity we had initially (A_o) will be present.
(b) That is to say that the ratio of A/A_o will be one half of the original value
(c) Under these conditions the exponential radioactive decay law can be written as:

$$\frac{1}{2} = \exp^{-\lambda t_{1/2}}$$

taking the natural log of both sides of the equation produces:

$$\ln(\frac{1}{2}) = -\lambda t_{1/2}$$

this is equal to:

$$-0.693 = -\lambda t_{1/2}$$

consequently:

$$\lambda = \frac{0.693}{t_{1/2}}$$

(d) This is one definition of the decay constant.

8. The half-life of a radionuclide is commonly found in the literature.

(a) Several sources include:

The Chart of the Nuclides
The Health Physics and Radiological Health Handbook
The CRC Handbook of Chemistry and Physics
The Radiological Health Handbook (of 1970)

9. Another methods of describing the decay constant is sometimes also encountered.
(a) This is the average or mean life (τ):
(i) The average or mean life is the reciprocal of the decay constant (i.e)

$$\tau = 1/\lambda.$$

10. Hypothetically, one could speak of the tenth-life or fifth-life or any other such thing.

(a) Such a parameter would be defined similarly to the half-life parameter.

11. It is interesting to point out two items when discussing the exponential radioactive decay law and the half-life.

(a) First since the exponential decay law describes exponential decay and since exponential function never reaches 0. items which are radioactive will always be radioactive theoretically.

(b) That being said what does it mean.

It means that if we had billions and billions of radioactive atoms we cannot predict when the very last atom in the population will decay (nor exactly when any atom oin the population will decay).

The exponential function is asymptotic to the zero value.

(c) The expression $exp^{-\lambda t}$ can be thought of as the probability of a number of atoms decaying within a certain period of time.

(i) As t gets large this probability becomes very small.

(d) As a rule of thumb we say that after the tenth half-life a radioactive material is considered to decay away "completely".

(i) This obviously applies when dealing with medium to small sources of radioactivity.

(ii) For very large sources of radioactivity even after the tenth half-life there may still be a considerable amount of radioactive material present relatively speaking.

12. A second interesting item is an argument:

(a) Some argue that every atom in the universe is in reality radioactive.

(b) What we refer to as stable species simply have half-lives which are so long that we can not measure them.

(c) Students are encouraged to think about this idea for a while.

(i) Half-life values for radionuclides range from fractions of a (i.e 10^{-13}s) second to billions of years (i.e. $2x10^{18}$y - Bi-209).

****

Wilhelm Konrad Roentgen (Germany) is given credit for his November 8, 1895 discovery of x-rays.

While working with a Crooke's tube Roentgen notices that a small nearby screen coated with barium platinocyanide fluoresced when the Crooke's tube was operated.

Roentgen recognized that this was caused by a previously unknown agent which he named x rays.

Within a few days he was able to describe the basic properties of x rays.

1) High penetrating power in light materials
2) Stronger absorption in soft tissue and bone.
3) X rays affected photographic plates.
4) X rays are not deflected by magnetic fields
5) X rays caused an electroscope to lose its charge

Taking advantage of these properties Roentgen developed the famous picture, shown in your text which contrasts the differential absorption of x rays in soft tissue and bone.

Henri Becquerel (France) was given credit for his 1896 discovery of Radioactivity.

While studying the phosphorescence of potassium uranyl sulfate he observed that a crystal of this salt darkened a photographic plate even when this assembly was kept in the dark.

1) It was found that the source of this radiation was the uranium metal itself.
2) The radiation was emitted spontaneously in apparently undiminished intensity.
3) This radiation could discharge an electroscope.

In 1898 Pierre (France) and Marie (Poland) Curie started an intensive study of radioactive material.

They observed that thorium was also radioactive. They found that pitchblende (an ore containing about 75% U_3O_8) contained two new elements which were much more strongly radioactive than uranium. These elements were polonium and radium.

Polonium is named in honor of Poland, Marie Curie's country of origin. Radium is a Latin word indicating radius - ray.

The discovery of x rays was a scientific bombshell. Experimenters and physicians, laymen and physicists set up x-ray generating apparatus and proceeded about their labors with seemingly lack of concern regarding potential dangers.

There was nothing in previous experience to suggest that x rays would be potentially dangerous. How could a ray which was undetectable by human senses be damaging to a person?

Soon after the widespread and unrestrained use of x rays began, deleterious human effects were reported.

1) Reports of skin erythema, epilation, and similar effects began to appear in the literature early in 1896.

2) Blood changes, tumor induction, and leukemia were reported in the early decades following the turn of the century.

By the turn of the century the first organizations to study the potentially harmful effects of radiation were established.

These were followed by a string of committees who are still periodically producing and publishing scientific reports on the health effects and safety recommendations concerned with the use of radiation by humans.

1) 1899 (three years after discovery of x rays) the British Roentgen Society.

2) 1900 American Roentgen Ray Society (ARRS) founded.

3) 1915 British Roentgen Society adopts x-ray protection resolution.

4) 1920 ARRS establishes standing committee for radiation protection.

5) 1921 British X-ray and Radium Protection Committee presents its first radiation protection rules.

6) 1922 ARRS adopts British rules.

7) 1925 First International Congress of Radiology establishes ICRU.

8) 1928 ICRP established under auspices of the Second International Congress of Radiology.

9) 1931 The roentgen adopted as unit of x-radiation.

10) 1934 ICRP recommends daily tolerance dose.

11) 1942 Manhattan District begins work on first atomic bomb.

12) 1946 U.S. Atomic Energy Commission created.

13) 1946 NCRP formed.

14) 1948 NCRP introduces recommendations and introduces risk/benefit concept.

15) 1953 ICRU Introduces concept of absorbed dose.

16) 1955 Health Physics Society formed.

17) 1955 UNSCEAR established.

18) 1956 ICRP lowers basic permissible occupational dose to present.

19) 1958 First UNSCEAR report.

20) 1977 ICRP 26 published.

21) 1978 ICRP 30 published.

22) 1980 BEIR III published.

23) 1988 BEIR IV published.

24) 1990 BEIR V published.

Sources of Radiation Exposure

Humans are now, and have always been, continuously exposed to ionizing radiation. This radiation comes from natural radionuclides in the earth's crust, from cosmic sources including cosmically produced radionuclides, and from human activities.

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Sources of radiation exposure

Terrestrial radiation

1) natural decay chains
    A) Three natural decay chains
        a) Uranium series (U-238)
        b) Thorium series (Th-232)
        c) Actinium Series (U-235)
    B) Totally 46 types of nuclides are involved in these three decay chains.
    C) Radon is a member of the uranium decay chain.
    D) A fourth series no longer occurs naturally this is the Neptunium series (Pu-241).

2) Singly occurring radionuclides
    A) There are at least _____ types of naturally occurring radionuclides.
    B) Most radiometrically important singly occurring radionuclides.
        a) _______
        b) _______

Cosmic radiation

A) Galactic radiation
    a) Direct exposure: high energy particles, the majority of which are stopped in the atmosphere, produces some direct exposure.
    b) The process of stopping high energy particles in the atmosphere produces secondary particles which contribute significantly to human radiation exposure.
    c) Cosmic secondary particles beside being a source of direct exposure may interact with atoms in the atmosphere or on earth to produce cosmogenic radionuclides. There are several cosmogenic, radionuclides the four most radiometrically important radionuclides produced in this fashion include:

i) ______

ii) ______ (also known as tritium)

iii) Na-22

iv) Be-7

B) Solar radiation

a) Normally stopped in the earths magnetic field.

Anthropogenic

General categories of human activities which produce radiation or radioactive material increasing population exposure

A) Medical arts

B) Industrial processes and testing

C) Scientific research

D) Energy generation

E) Military applications

Fractions of total human radiation exposures from various sources

Reference NCRP 160: "Reprinted with permission of the National Council on Radiation Protection and Measurements, http://NCRPonline.org).

NCRP says: that there is a total dose received by all Americans of about 187,000,000,000 person-millirem.

- There are about 300,000,000 Americans

- Hence the average dose delivered is about 620 millirem

This is a factor of about 1.7 times higher than the average estimated in 1980. The difference is mostly associated with increased medical exposures.

The distribution in dose among individuals is heavily skewed

Annual exposure to external sources of radiation in North America – 120 mrem
Annual exposure to internal and external sources of radiation exposure about 620 mrem
Typical chest x-ray 30 mrem
Typical dental x-ray 10 mrem to head
Annual occupational limit for radiation workers 5,000 mrem (5 rem)
$LD_{50/30}$ 450,000 mrad (450 rad)

SPECIFIC ACTIVITY

1. The concept of specific activity can sometimes be useful to express exactly how much radioactive material is present in a particular sample.

2. Neither the Becquerel nor curie, although used as a unit of quantity, mention anything about the mass or volume of the radioactive material in which the specified number of transformations occur.

3. The concentration of radioactivity, or the relationship between the mass of radioactive material and the activity________________________.

4. Specific activity is the quantity of activity divided by a unit volume or unit mass.

5. The specific activity of a _________ radioisotope, that is a radioisotope that is not mixed with any other isotope of the same element, may be calculated as follows:

$$\text{Specific Activity} = \frac{(0.693)(6.022x10^{23})\ \frac{atoms}{moles}}{(t_{1/2})\ A\frac{g}{moles}}$$

$$\text{Specific Activity} = \frac{(\lambda)(6.022x10^{23})\ \frac{atoms}{moles}}{A\frac{g}{moles}}$$

where:

A is the atomic weight of the isotope

and λ is expressed in s_{-1} , $t_{1/2}$ in units of s.

I) Properties of Ionizing Radiation

Introduction

There are three common types of radiation emitted from the nucleus of radionuclides. These radiations are sometimes called ionizing radiation because they can cause the ionization of matter, they have sufficient _______or impart sufficient ________ to produce ion pairs.

1) Alpha particles – α

a. Alpha particles are equivalent to the nucleus of the helium atom. The alpha

particle consists of ____ protons and ______ neutrons which are tightly bound together. The alpha particle is a very stable particle.

2) Beta Particles – β

a. There are two kinds of beta particles:

(1) Negatrons – β^{-}, e^{-}

The negatron is a negatively charged electron indistinguishable from the electron ordinarily found in matter.

(2) Positrons – β^+, e^+

---

3) Gamma rays – γ

a. Gamma rays are a type of __________ radiation. Gamma rays are similar to x rays.

(1) The difference between gamma rays and x rays is their origins.

gamma rays originate from the nucleus of the atom.

x rays are generated within the electron orbitals of the atom.

4) In addition to the three types of radiation listed above there are a few radionuclides which emit either protons or neutrons.

(a) for example:

$^{53m}Co \rightarrow {}^{52}Fe$ + proton

Emission of protons is rare.

(b) ^{252}Cf undergoes spontaneous fission.

Although this is fission rather than radioactive decay it is an example of a the release of neutrons.

II) Modes of Radioactive Decay:

1) Radioactive nuclides decay by one of several modes.

(a) Each radionuclide has its own characteristic sequence of decay modes.

A) **Alpha Transitions**

1) When an alpha particle is emitted during radioactive decay it may or may not be accompanied by a gamma ray.

(a) Alpha decay does not occur in nuclei with A $\leq$ 140.

(b) It is thought that all nuclei with A $\geq$ 140 undergo alpha decay, but for some the decay rate is so slow that alpha particle emission has not been detected.

(c) Alpha decay schemes are usually complicated:

2) During alpha decay, A decreases by 4 and Z decreases by 2.

3) Because of the requirement that A_____, alpha decay does not occur in nuclides frequently used in biological work.

a. Alpha emitters are high in the periodic table.

b. These elements in general are not used in biological systems and in fact are usually toxic to biological systems.

B) **Isobaric Transitions**

Isobaric Transitions does not lead to a change in A but it does cause a change in Z.

1. One definition of beta decay is that it is a decay leading to a change in _____ without a change in _____.

2. Gamma ray emission may or may not accompany beta decay.

3. There are three common types of Isobaric Transitions.

a. Negatron decay occurs when there is a ______ n/p ratio.

(1) During negatron decay Z increases by one and an isobar is formed.

(2) In beta decay transitions occur between isobar.

(3) In negatron emission, there is a transition of a nucleon from its neutron to its proton energy state.

(4) The negatron is emitted at high velocities.

(5) An ________________ is emitted simultaneously with the negatron during negatron decay.

(6) Both the negatron and the antineutrino are created as the instant they

are emitted since they cannot exist as such in the nucleus.

(7) During negatron decay, recoil of the nucleus is negligible.

Example: P-32 a pure negatron emitter.

More commonly, excited states are formed after negatron emission. These excited states loose energy by gamma emissions.

(8) Negatron emission is common with reactor produced radionuclides.

(a) Reactor produced radionuclides generally have high n/p ratios.

b. <u>Positron decay</u> occurs in nuclei with ________ n/p ratios.

(1) During positron decay Z decreases by one.

(2) Positron decay leads to isobar formation.

(3) During positron emission, there is a transition of a nucleon from its proton to its neutron energy state.

(4) The positron is emitted at high velocities.

(5) During positron decay both a positron and a ____________ are emitted simultaneously.

(6) Both the positron and the neutrino are created at the instant the are emitted since they cannot exist
as such in the nucleus.

(7) In positron emission there is always a _______-MeV difference in the kinetic energy of the positrons and the Q value.

a. The reason is that the parent atom loses a positron in the nuclear transition and the daughter atom loses an electron to become electrically neutral since Z decreases by one.

b. An energy of 1.02 MeV is equivalent to the ________ of an electron and a positron.

(8) Positron emission cannot occur unless Q is at least ____________ MeV.

(9) Positron emission is common with accelerator produced radionuclides, many of these have _____ n/p ratios.

c. Electron capture, sometimes known as K-capture, is an alternate mode of decay to positron emission.

(1) Electron capture occurs when there is a ________ n/p ratio.

(2) Electron capture decreases Z by one.

(3) Electron decay results in isobar formation.

(4) During electron capture the nucleus captures an extranuclear electron, usually from the K-level.

a. In the nucleus, a nucleon is transformed from its proton to its neutron energy state.

b. The neutrino is the only radiation that is emitted from the nucleus (unless the daughter is formed in an excited state).

c. There can also be L-capture, but this is less probable than K-capture.

[1] Electrons at the K-level are more likely than any other to be found near the nucleus.

* The amplitude of the wave function of a k-level electron is higher near the nucleus than that of an L-level electron.

[2] If Q is less than the binding energy of the K-level electrons, then only L-capture can occur.

(5) The capture of an electron leaves a vacancy in the level from which the electron was captured.

a. This vacancy is filled by an electron from the next higher energy level.

b. This electron readjustment produces _______________ of the product nucleus.

(6) Rather than an x ray being emitted, the energy may be transferred to an electron at a higher energy level.

a. This electron is then emitted with an energy equal to the characteristic x-ray energy minus its own binding energy.

b. The electron emitted is called an _________________ electron.

Example: In the decay of Fe-55, x rays and auger electrons are the only radiations emitted from the atom, other than the neutrino. Had the daughter, Mn-55 been formed in an excited state, gamma rays would be emitted. Auger electrons have such low energies that they are usually not detected by the common radiation detectors. Neutrinos react poorly with matter. Consequently, only x rays can be detected.

Example: Na-22, frequently, electron capture and positron emission occur together.

(7) Generally, the Q value for both positron emission and electron capture is listed as Q_{EC} on the decay scheme.

a. This practice avoids misunderstandings as to whether or not the rest mass of the positron
and negatron is included in the Q value for positron emission.

(8) If the Q value for a nuclide with a low n/p ratio is less than 1.02 MeV, only electron capture can occur.

(9) Above 1.02 MeV, positron emission competes with electron capture more effectively the higher the Q value.

(10) On the other hand, ________ in atomic number favor electron capture. With high Z, positron
emission is rare. The potential barrier against positron emission increases with Z.

a. The reason is that with higher Z, electron orbits are smaller, and there is a greater probability for an electron to be within the nuclear volume.

c. The overall process where by an energetically excited nucleus releases energy without a change in the structure of the nucleus, just a decrease in the energy level of the nucleus is known as Isomeric transition.

1) During _______________ transition there is no change in A or Z.

(a) The nucleus goes from an excited energy state to a lower energy state or a ground state.

2) The transitions between excited states of nuclei usually occur within a very short time, probably about 10^{-13} to 10^{-16} seconds.

(a) These transitions proceed in accordance with the exponential decay law and have a characteristic half-life.

(b) If these half-lives are measurable, the excited states are called isomers, or metastable isomers.

3) There are two categories of Isomeric transition:

(a) When the excited nucleus emits a gamma ray and goes to a lower energy state or to a ground state this is called_______________transition.

(b) Radiative transition can be sub-divided into two processes:

i) Gamma ray emission is the emission of one photon from the nucleus.

ii) When two gamma rays are emitted within a very short period of time from the same radionuclide these are called ______________ gamma rays. These must be emitted from the same nuclide and there may be two or more.

4) A second type of isomeric transition is called __________________.

5) During _____________________the nucleus interacts with an ________________ electron.

(a) This electron may be in the K, L, M, etc., level but the K level predominates. The reason is the same as for electron capture.

(b) The electron is emitted with an energy equal to the disintegration energy minus its own binding energy.

These electrons are called ____________________ electrons.

(c) Both x ray and auger electrons accompany internal conversion. Both are produced in a manner identical to their production in electron capture.

(d) In internal conversion the excited nucleus interacts electromagnetically with the electron. No gamma ray is produced.

(e) Internal conversion is an alternate to ___________________.

(f) frequently, a nuclide decays by both isomeric transition and internal conversion.

(g) The internal conversion coefficient is the ratio of the number of conversion electrons to the number of gamma rays emitted.

(1) It is designated by the symbol α or e/γ. It may have any value between 0 and ∞.

(h) Internal conversion is favored by _______ atomic number and by _____ Q values.

d. Less common modes of decay.

1) Proton Emission (very rare)

2) Spontaneous fission (this process occurs only with very heavy elements).

(a) Delayed neutron emission occurs with nuclides with a high n/p ratio.

(b) In such a negatron is emitted first.

(c) The product nucleus is left with an energy in excess of the binding energy of one of its neutrons.

(d) Several neutrons are emitted promptly, these are referred to as prompt neutrons.

(e) Other neutrons are emitted in a very short time after fission and these neutron are referred to as a delayed neutron.

(1) Delayed neutrons are used in the control of nuclear reactors.

Properties of Electromagnetic Radiation

A. Both Gamma-rays and X-rays are a types of electromagnetic radiation.

1. There are many types of electromagnetic radiations:

a. Visible light
b. Infrared light
c. ultraviolet light
d. gamma rays
e. x rays

2. Electromagnetic radiations consist of oscillating ___________ and ___________ fields.

a. A field is a region where a certain kind of force is exerted.

3. All electromagnetic fields can travel at the same velocity.

a. This is the velocity of light:

b. $c = 3.0x10^{10} cm/s = 3.0x10^{8} m/s$

(1) this is the velocity of light in a vacuum

c. The energy of electromagnetic radiation is proportional to the frequency of oscillation of the electric and magnetic fields:

$E = hf = h\nu$

E = energy in ergs
h = Planck's constant (6.625×10^{-27} erg-sec).
$\nu = f$ = frequency of radiation s^{-1}.

d. Frequency is inversely proportional to the wavelength:

$f = c/\lambda$

c = velocity of light
λ = wavelength of wave (cm)

4. The energy of electromagnetic radiation is quantized.
   a. This was proposed by the quantum theory.

   b. The energy of electromagnetic radiation is carried in little "bundles" or packets.

      (i) Each little bundle or packet is called a photon or quantum.

      (ii) The energy of a photon or quantum is given by the expression
      $E = hf = h\nu$ or $E = hc/\lambda$.

      (iii) A photon cannot be further subdivided. It either exists, or it disappears completely when it undergoes various interactions.

5. Photons are classified by their ____________________, not their energy.

a. Photons involved with radioactive nuclides include gamma rays and x rays.

b. The gamma rays from radioactive nuclides have energies that range from about 10 keV to about 3 MeV.

c. There are two types of x rays:

i) characteristic x rays, which are emitted from extranuclear electrons in transitions between different energy levels.
Their energies range from a few keV up to a about 100 keV (a little higher for the artificial elements).

ii) Bremsstrahlung or continuous x rays; these are emitted during acceleration of charged particles, usually electrons (beta particles).
Their energies range from zero up to some maximum value. These maximum values are the energies of the charged particles which emit bremsstrahlung.

d. Gamma rays are monoenergetic.

i) Their energy depends on the nuclear transitions which form them.
ii) There can be more than one energy group even for a given radionuclide. Within each group all the gammas have the same energy.

e. Characteristic x rays are monoenergetic. Their energies depend upon the energy level transitions from which they originated.

f. Bremsstrahlung radiation is not _______________. It exhibits a continuous spectrum.

6. Gamma rays and x rays interact with matter in essentially the same manner.

a. Both interact with matter ______________ compared to alpha and beta particles.

b. gamma and x rays can penetrate great thicknesses of matter.

7. Gamma rays and x-rays have no charge.

a. Gamma rays do not have the same force fields that are associated with charged particles.

b. The fact the gamma rays do not have mass is immaterial since gravitational force generally is not significantly involved in the interaction of radiation.

8. Gamma rays do not produce excitation and ionization in the same manner that charged particles do.

a. They cannot lose their energy in small amounts, since they must give up all their energy or none at all.

9. Gamma rays do have an electromagnetic force field.

a. This force field allows gammas to interact with matter.
b. Electromagnetic radiation interact with matter in three principal ways:

i) The photoelectric effect

ii) The Compton effect
iii) The pair production effect

10. The Photoelectric effect

a. An incident gamma ray interacts with the whole atom to which an electron is bound.

(1) An incident photon __________ be totally absorbed by a free electron.

(2) Total absorption can only take place when the target electron is initially bound in an atom.

b. All of the gamma ray's energy is transferred to the atom

c. The gamma ray disappears.

d. The electron is ejected from the atom with an energy equal to the gamma ray energy minus its own binding energy.

(1) The ejected electron is known as a photoelectron.

$$E_e = E_\gamma - B_e$$

Where:

E_e = energy of photoelectron
E_γ = energy of incident photon
B_e = binding energy of the electron

(2) The photoelectron can produce excitation and ionization of matter in a manner similar to the beta particle.

(3) The binding energy of the ejected electron is eventually observed as either the energy of a **characteristic x ray** or the energy of an **auger electron** when the vacancy created by the ejection of the electron is filled.

(4) The momentum of this interaction is conserved by the recoil of the entire residual atom. However, the kinetic energy gained by the ________________ is negligible.

(5) As might be expected, the most tightly bound electrons have the greatest probability of absorbing a photon which is incident upon an atom.

(i) It has been found experimentally and theoretically that about _____ of the photoelectric absorption processes take place in the K shell, provided that the incident photon energy clearly exceeds the K-shell binding energy.

(ii) Schematically the photoelectric process appears as follows:

(6) When the photoelectric effect occurs the energy of the photoelectron is usually absorbed within the material from which it was __________________.

(7) The photoelectric process is the predominant mode of interaction for gamma rays (or x rays) of relatively _____ energy.

(8) The photoelectric process is enhanced for absorber materials of _______ atomic number (Z).

(9) Although no analytic expression is valid for the determination of the probability of photoelectric absorption per atom for all Z and over all energy ranges a rough approximation is given by the expression:

$$\tau \cong Const.\frac{(Z^n)}{(E_\gamma^3)}$$

where:

τ = the probability of photoelectric absorption
Z = the atomic number of the absorber
n = an exponent with a value of between 4 and 5 over the gamma ray energy region of usual interest.
$E\gamma$ = Energy of the incident gamma

(i) This severe dependence of the photoelectric absorption probability on the atomic number of the absorber is a primary reason for the preponderance of high-Z materials (such as lead) in gamma ray shields.

(ii) The following figure is an approximate graph showing the probability of photoelectric absorption for a popular gamma ray detection material {NaI(Tl)}. The following items should be observed:

* In the low-energy region, discontinuities in the curve or "absorption edges " appear at gamma ray energies which correspond to the binding energies of the of electrons in the various shells of the absorber atom.

- The edge lying highest in energy corresponds to the binding energy of the K-shell electrons.

- For gamma rays with energies above the edge, the photon energy is sufficient for the photoelectric effect to occur with K-shell electrons.

- For gamma rays with energies below the edge, the photon energy is insufficient for the photoelectric effect to occur with K-shell electrons.

- Similar absorption edges occur at lower energies for the L, M.....electron shells of the atom.

11. The Compton Effect

a. The compton effect consists of the following events:

(1) A photon collides with a bound electron of an atom.

(a) a free electron cannot totally absorb a gamma ray because ________cannot be conserved in such a collision.

(2) The energy of the photon is partially acquired by the electron and partially acquired by a scattered photon.

(3) The scattered photon and electron move away from the atom producing further ______________________.

b. Schematically the compton effect appears as follows:

c. The scattered electron is called a compton electron, recoil electron, or struck electron.

(1) The energy relationships associated with the compton effect are given by the expression:

$E_e = E_\gamma - E_\gamma'$

where:

E_e = the energy of the compton electron

E_γ = the energy of the incident photon

E_γ = the energy of the scattered photon

(a) Unlike the case of the photoelectric effect, the binding energy of the electron involved in the Compton effect is insignificant compared to the typical energies of the incident photon, the scattered photon, and the Compton electron's energy. Therefore, the binding energy of the Compton electron is usually ignored.

(2) The energy of the Compton electron varies from 0 up to a maximum value as a function of the angle of scatter relative to the path of the incident photon.

(a) The maximum energy of the Compton electron is given by the following expression:

$$E_e = \frac{E_\gamma}{1+\frac{0.511}{2E_\gamma}}$$

1. This maximum energy occurs when the Compton electron experiences a scattered angle θ' of 180°.

2. This is called a ___________ collision of the photon and the electron.

(3) The scattered photon does not have the same direction as the original photon and is said to be scattered.

(a) The angle of scatter depends on the amount of energy lost by the original photon.

12 Pair Production

a. Above incident photon energies of 1.02 MeV, a third type of interaction, known as pair production, becomes increasingly important.

(a) In pair production the photon is _______ absorbed and in its place appears a positron-negatron pair whose total energy is just equal to the incident photon's energy.

$$E_\gamma = (KE_{negatron} + m_o c^2) + (KE_{positron} + m_o c^2)$$

(b) Schematically the overall process is as follows:

(c) The pair production process occurs only in the field of charged particles, mainly in the nuclear field but to some degree in the field of an electron.

(1) The presence of this "particle" is necessary for _______ conservation.

(2) When pair production occurs in the nuclear field the minimum energy requirement is $E_\gamma \geq 1.02$ MeV.

- In the typical case of pair production, pair production occurs in the nuclear field.

(3) Pair production can occur in the field of an electron. However, this is relatively ________.

- The minimum energy requirement for this is: $E_\gamma \geq$ ______MeV. This great energy requirement results from momentum considerations.

(d) Pair production can be thought of as the reverse of annihilation.

(e) Pair production is favored by high energies ($E_\gamma \geq 5$ MeV) and by ______atomic number.

$$\kappa \cong Const.(Z^2)(E_\gamma - 1.02)$$

where:

κ = the probability of pair production

Z = the atomic number of the absorber

Eγ = Energy of the incident gamma

Note: this is not the same constant employed an a similar expression for the photoelectric effect
and the Compton effect

Attenuation, absorption, and scattering coefficients

a. Photon penetration in matter is governed statistically by the probability per unit distance traveled that a photon interacts by one physical process or another.

1. This probability is denoted by the Greek symbol μ (mu).

2. μ - is called the linear attenuation coefficient.

3. μ - has the dimensions of ____________________ (cm^{-1}).

4. The coefficient μ depends on photon energy and is the sum of the probabilities of the photoelectric effect, Compton scattering, and pair production for the medium in question under the conditions of concern. .

5. The coefficient μ depends on the material being traversed.

b. Consider a narrow beam of monoenergetic photons which are incident on a slab of material as drawn below:

1. Where; $N(x)$ is the number of photons which reach a certain distance x within the material without undergoing any interactions and N_o is the initial number of photons incident on the slab.

2. If dN is the change between the number of photons incident on the slab and measured at point x then we may write the following expression:

$$dN \propto N dx$$

3. In words, the change in the number of photons is ________l to the number of photons and the thickness of the absorber material.

4. If we use the linear attenuation coefficient as a constant of proportionality this expression becomes:

$$dN = -\mu N dx$$

(a) In this expression the negative sign indicates a _________ in the number of photons due to a combination of scattering and absorption processes.

(b) The solution of this expression is as follows:

(i) Separate variables:

$$\frac{dN}{N} = -\mu dx$$

(ii) Integrate both sides:

$$\int \frac{dN}{N} = -\int \mu dx$$

$$\ln N + C_1 = -\mu x + c_2$$

(iii) Letting $C_2 - C_1 = C$ we obtain the expression:

$$\ln N = -\mu x + c$$

(iv) Consider the initial conditions; at x = 0
N = No, hence:

$$\ln N_o = c$$

(v) applying this expression we obtain:

$$\ln N = -\mu x + \ln N_o$$

(vi) which is equal to:

$$\ln N - \ln N_o = -\mu x$$

and

$$\frac{\ln N}{\ln N_o} = -\mu x = \ln \frac{N}{N_o}$$

or:

$$\frac{\ln N}{\ln N_o} = -\mu x = \ln \frac{N}{N_o}$$

(vii) employing the exp function we obtain:

$$N/N_o = exp^{-\mu x}$$

and therefore

$$N = N_o\ exp^{-\mu x}$$

Example:

What attenuation can be expected in a steel plate if a narrow beam of 1.0-MeV photons with a particle fluence of 10,000 photons/cm^2 impinges on a steel plate 2-cm thick (neglecting attenuation in air). μ = 0.460 cm^{-1}.

$$N = N_o\ exp^{-\mu x}$$

$$= (10{,}000\ cm^{-2})exp^{-(0.460/cm)(2\ cm)}$$

$$= 3985\ cm^{-2}$$

(c) In these expressions any unit which is a function of particle number can be substituted in place of the N values.

(d) There is some special nomenclature associated with a description of attenuation.

(i)

$\frac{1}{\mu}$ = *Mean Free Path*

This is the average distance traveled by a photon before interaction.

In fact μ, the linear attenuation coefficient, is sometimes referred to as the inverse mean free path.

(ii) The Thickness of shield for which the photon intensity in a narrow beam is reduced to 1/e of its original value is called the relaxation length.

(iii) The ratio of I/I_o is called the transmission factor.

Note: The relaxation length and the mean free path are related numerically although they are concerned with very different ideas.

(iv) The numerical relationship of interest:

At one relaxation length, $I/I_o = 1/e$

$I/I_o = e^{-\mu x}$

consider one mean free path: $1/\mu$

at a distance of one mean free path $x = 1/\mu$

Hence:

$$I/I_o = e^{-\mu x} = I/I_o = e^{-\mu(1/\mu)} = e^{-1} = 1/e$$

It is observed that at one mean free path the reduction in the transmission factor corresponds to the reduction experienced from one relaxation length.

The energy absorption coefficient is useful when trying to determine the amount of energy deposited in air or deposited within a tissue or other material.

Example:

What fraction of the energy in a 40 keV x-ray beam is deposited in 15 mm of soft tissue?

The linear energy absorption coefficient for a 40 keV photon beam passing through tissue is about 0.09 cm^{-1}.

15 mm = 1.5 cm.

N/N_o the fraction of the beam **passing through** the 1.5-cm thick tissue.

$$\frac{N}{N_o} = \exp^{-\mu_{en} x} = \exp^{-(\frac{0.09}{cm})(1.5\,cm)}$$

= 0.874

The fraction absorbed is therefore: 1 - 0.874 = **0.126**

Often when individuals describe the required shielding thickness to reduce the intensity of radiation the speak of "half-value" layer or "tenth value" layer thickness'.

A half-value layer (HVL) is the thickness of a particular material that will reduce the intensity a particular energy of electromagnetic to one-half of its initial intensity.

i.e., the transmission factor is 1/2.

A tenth-value layer (TVL) is the thickness of a particular material that will reduce the intensity a particular energy of electromagnetic to one-tenth of its initial intensity i.e., the transmission factor is 1/10.

The following table taken from NCRP-49 Appendix C, lists HVL and TVL values for photons associated with various x ray tube operating energies and also those for the photons associated with selected radionuclides.

TABLE 27—*Half-value and tenth-value layers*

Approximate values obtained at high attenuation for the indicated peak voltage values under broad-beam conditions; with low attenuation these values will be significantly less.

Peak Voltage (kV)	Lead (mm)		Concrete (cm)		Iron (cm)	
	HVL	*TVL*	*HVL*	*TVL*	*HVL*	*TVL*
50	0.06	0.17	0.43	1.5		
70	0.17	0.52	0.84	2.8		
100	0.27	0.88	1.6	5.3		
125	0.28	0.93	2.0	6.6		
150	0.30	0.99	2.24	7.4		
200	0.52	1.7	2.5	8.4		
250	0.88	2.9	2.8	9.4		
300	1.47	4.8	3.1	10.4		
400	2.5	8.3	3.3	10.9		
500	3.6	11.9	3.6	11.7		
1,000	7.9	26	4.4	14.7		
2,000	12.5	42	6.4	21		
3,000	14.5	48.5	7.4	24.5		
4,000	16	53	8.8	29.2	2.7	9.1
6,000	16.9	56	10.4	34.5	3.0	9.9
8,000	16.9	56	11.4	37.8	3.1	10.3
10,000	16.6	55	11.9	39.6	3.2	10.5
Cesium-137	6.5	21.6	4.8	15.7	1.6	5.3
Cobalt-60	12	40	6.2	20.6	2.1	6.9
Radium	16.6	55	6.9	23.4	2.2	7.4

Another way to reduce the fluence from a source is to increase the distance between the source and the item of concern.

Depending on their relative dimensions many sources of radiation may be treated as point sources without introducing too much error into an estimation.

X-ray tubes are generally always treated like point sources of radiation.

The intensity of radiation decreases as distance from the source increases.

Consider, a point source of radiation in space (within a vacuum). Lets say this source has an activity of 2 Ci and with every decay we obtain one photon.

How many photons would be expected per unit area at 100 cm away from this source.

$1.0\ Ci = 3.7x10^{10}$ dis./sec.

The total number of photons being emitted per unit time from this source is therefore:

$(2.0\ Ci)(3.7x10^{10} dis/sec./Ci)(1\gamma/dis) = 7.4x10^{10}\ \gamma/sec.$

The surface area of a sphere is given by the expression $4\pi r^2$.

The surface area of a sphere with a 100-cm radius and the point source located in the exact center is:

$4\pi r^2 = 4\pi(100\ cm)^2 = 1.26x10^5\ cm^2$.

The number of photons experienced per cm^2 at any unit area on the surface of this 200-cm sphere (100-cm radius) is:

$\{(7.4x10^{10}\ \gamma/sec.)\}/\{1.26x10^5\ cm^2\} = 5.87x10^5\ \gamma/(sec. - cm^2)$

Notice this relationship, activity divided by area is fluence rate.

This may be written as Act./Area = fluence rate.

Or we may say: Act. = (fluence $rate_1$)($area_1$)

What would be the story at 300 cm away from the point source.

The area of a sphere with a 300-cm radius is:

$4\pi r^2 = 4\pi(300\ cm)^2 = 1.13x10^6\ cm^2$.

The number of photons experienced per cm^2 at any unit area on the surface of this 600-cm sphere (300-cm radius) is:
$\{7.4x10^{10}\ \gamma/sec.\}/\{1.31x10^6\ cm^2\} = 5.65x10^4\ \gamma/(sec. - cm^2)$

Again notice this relationship, activity divided by area is fluence rate.

this may be written as Act./Area = fluence rate.

Or we may say: Act. = (fluence $rate_2$)($area_2$) This is an interesting relationship.

Lets consider the two relationships just observed.

Act. = (fluence $rate_1$)($area_1$)

and

Act. = (fluence $rate_2$)($area_2$)

These two expressions are equal since the activity in both expressions is the same quantity. Hence:

(fluence $rate_1$)($area_1$) = (fluence $rate_2$)($area_2$)

Remember the expression for area $4\pi r^2$, and lets let the fluence rate equal the variable "I". This expression becomes:

$(I_1)(4\pi r_1^2) = (I_2)(4\pi r_2^2)$

lets divide both sides by 4π this results in the new expression:

$(I_1)(r_1^2) = (I_2)(r_2^2)$

This relationship applies too any two distances away from a point source hence we can substitute the variable "d" for distance in place of the variable "r" for radius resulting in the equation:

$(I_1)(d_1^2) = (I_2)(d_2^2)$

This is the expression of the inverse square law.

Example,

Say that you measure the fluence rate 250 cm away from a point source to be 50,000 photons /sec-cm^2. What is the expected fluence rate at 100 cm and 300 cm away from this source (neglect air absorption)?

A) 100 cm:
$(I_1)(d_1^2) = (I_2)(d_2^2)$
(50,000 photons/sec-cm^2)$(250\ cm)^2 = (I_2)(100\ cm)^2$

$(50{,}000 \text{ photons/sec-cm}^2)(250 \text{ cm})^2/(100 \text{ cm})^2 = I_2$

$I_2 = 312{,}500 \text{ photons/sec-cm}^2$

B) 300 cm

$(I_1)(d_1^2) = (I_2)(d_2^2)$

$(50{,}000 \text{ photons/sec-cm}^2)(250 \text{ cm})^2 = (I_2)(300 \text{ cm})^2$

$(50{,}000 \text{ photons/sec-cm}^2)(250 \text{ cm})^2/(300 \text{ cm})^2 = I_2$

$I_2 = 34{,}722 \text{ photons/sec-cm}^2$

In real situations when we encounter point sources both the inverse square relationship and attenuation effect the fluence rate measured at different distances away from the source.

Incidently:

Time
Distance
Shielding

Continuous and Characteristic x rays

A) Roentgen discovered that x rays are produced when a beam of electrons strike a target.

1. x rays are an example of electromagnetic radiation.

2. x rays have sufficient energy to both excite and ionize the electrons of an atom.

3. Excitation is the process of causing an electron to jump to a higher energy level by providing it with energy.

4. Ionization is the process by which sufficient energy is imparted to an

orbital electron to cause it to be completely removed from the atom.

(a) During ionization:

(i) the atom becomes positively charged.

(ii) the electron becomes a free independent entity.

B) X rays can be categorized as either continuous or discrete.

1. The energy spectrum of x rays depends on the mechanism by which they were generated.

Photon Energy (keV)

C) Characteristic x rays:

1. characteristic x rays have discrete wavelengths characteristic of the atoms from which they were produced.

2. characteristic x rays are produced when an electron undergoes excitation

to

a higher energy level.

(a) when the excited atom de-excites, the electron jumps down to a lower energy level, a photon is produced from this orbital transition.

(b) they are usually produced when vacancies are filled in a K, L, or M shell.

(c) the photon released has a discrete wavelength corresponding to the difference in energy states between the initial and final energy states of the transition.

3. Advantage can be taken of the phenomena of characteristic x-rays.

(a) element identification

(i) x-ray fluorescence

(ii) dispersive x-ray analysis

4. This is similar to the mechanism producing light.

(a) x-rays are a form of electromagnetic radiation.

5. Ways in which characteristic x rays might be generated:

(a) bombardment of an atom
(b) photoelectric effect
(c) internal conversion
(d) electron capture

D) Continuous x rays:

1. According to classical theory, whenever a charge experiences an Acceleration it will radiate energy.

(a) Whenever an incident charged particle is deflected from its path

or

has its velocity changed it emits electromagnetic radiation whose amplitude is proportional to the acceleration.

2. It is more accurate to describe this radiation as bremsstrahlung radiation.

(a) bremsstrahlung radiation is a German word meaning: braking radiation.

(b) The total bremsstrahlung per atom varies as the inverse square of the mass of the incident particle.

(c) Thus protons and alpha particles will produce far less radiation

than

the bremsstrahlung of an electron of the same velocity.

i) because of the strong inverse mass dependence, bremsstrahlung is almost completely negligible for all swift particles other than electrons.

(d) Bremsstrahlung intensity (I) is such that:

$$I \propto Z^2 z^2 / M^2$$

where:

Z = the atomic number of the target nucleus
z = the particle charge number
M = the mass of the particle

(e) In an individual deflection by a nucleus, the incident particle can radiate any amount of energy from zero up to its maximum kinetic energy.

(f) The intensity of radiation that an x-ray tube produces is a function of the voltage applied across the tube, the cathode filament current, and the duration of the applied voltage.

(g) Since energy is supplied with alternating current:

i) the output of the tube has an alternating nature.

* Pulses typically follow the 60 hz line frequency in the United States unless a high frequency circuit is used to power the unit.

** Using external rectifiers increases the effective frequency of the alternating high voltage power supply. It is possible to increase the high voltage power supply's effective frequency to 120 hz.

(h) Because high voltage is applied with an alternating current the tube's intensity of x-ray output is proportional to a $\sin^2$ function.

i) the machine's intensity is also proportional to the square of the
potential difference applied across the tube:

$I_1/I_2 = (kVp_1/kVp_2)^2$

Example: A certain procedure requires 110kVp at 10mAs and will produce 32mR of exposure. What would be expected if the potential were increased to 125 kVp?

(i) X-ray quantity is directly proportional to the product of filament current and exposure time. (mAs = mC/s*s = mC)

$$I_1/I_2 = (mAs_1/mAs_2)$$

Example: A certain procedure requires 110kVp at 10mAs and will produce 32mR of exposure. What would be expected if the product of filament current and exposure time were changed to 20 mAs?

(j) The current and time product as well as the potential difference across the anode and cathode are referred to as technical factors.

"In practice, radiographic technical factors are selected from a narrow range of values, usually between 40 to 150 kVp. In theory, to double the x-ray intensity by kVp manipulation alone, the kVp must be increased by 41%. However a 41% increase in kVp to double the intensity does not work in practice. As kVp is increased, the penetrability of the x-ray beam is increased as well, which results in fewer x-rays absorbed in the patient. More x-rays go through the patient, do not interact with tissue, and are recorded on the image. To maintain a constant exposure of the film, an increase of 15% in kVp should be accompanied by a one half reduction in mAs." (Bushong 1997 p141-142 required course text see syllabus for more details on text.)

So a combination of the previous two expressions is perhaps the most important for operation:

$$I_1/I_2 = (mAs_1/mAs_2)(kVp_1/kVp_2)^2$$

Example: A certain procedure requires 80kVp at 30mAs and will produce 135mR of exposure. What would be expected if the potential were increased to 92 kVp and the current time product reduced to 15mAs?

(k) Radiation intensity from an x-ray tube varies inversely with the square of the distance form the target:
$I_1/I_2 = (d_2)(d_1)^2$

Example: If an x-ray examination that normally is conducted at a 100-cm patient to tube-filament distance produces an exposure of 12.5 mR, what would be the exposure if the patient to tube-filament distance were changed to 91 centimeters?

(i) Thus, the maximum quantum energy $(hf)_{max}$ at the short wavelength limit of the continuous x-ray spectrum is:

$(hf)_{max}$ = KE

where:

KE is the kinetic energy of the electron.

(l) Continuous x ray spectrums associated with bremsstrahlung radiation are not like discrete energy patterns.

(m) An estimate of radiation yield can give an indication of the potential bremsstrahlung production of electrons:

(i) $Y \approx 6x10^{-4}ZT/(1 + 6x10^{-4}ZT)$

3. X-ray tubes produce a continuous energy-spectrum of x-rays.

a) The low energy component of this spectrum is not useful.

(i) The low energy component is not capable of penetrating the human body. Instead this energy is deposited in tissue without any useful contribution to the quality of the x-ray image.

b) Filtration of the beam is necessary to cut out the low energy component of the x-ray tube energy spectrum.

c) X-ray units have aluminum filters between 1 to 3-mm thick positioned between the x-ray tube and the patient.

(i) The purpose of the filter is to attenuate low energy photons before they irradiate the patient.

(ii) Filtration of an x-ray beam can be described as having two components:

1. Inherent filtration: is provided by the glass of the x-ray tube.

- Specially designed tubes with beryllium windows are sometimes used to decrease the inherent filtration of a beam when very low energy x-rays are appropriate for imaging such as in the case of mammography.

2. Added filtration: reflects the effect of the added sheets of Aluminum described above.

- Added filtration can be sub-divided into two components whose sum is equivalent to 2 or 3 mm of aluminum.

- 1 or 2mm is installed permanently in the port of the x-ray tube housing.

- In a conventional light-localizing variable-aperture collimator the collimator contributes about 1-mm of aluminum equivalent filtration. This is associated with the silver mirror in the collimator.

3. Sometimes when a body that varies in thickness of tissue composition must be x-rayed additional filtration is used to compensate for differences in radio-opacity.
- Several different filters have been developed for this purpose referred to as <u>compensating filtration</u> including:
    + wedge filters - applied to body parts varying in thickness like the foot.
    + trough filters - applied to chest radiography a thin central region of the wedge is positioned over the mediastinum.
    + bow-tie-shaped filters - applied with CT scanners to compensate for the shape of the head.
    + Conic filters - either concave or convex used in digital fluoroscopy.
    + step-wedge filters -applied when long sections of anatomy are imaged with several separate films.

d) When the low energy component of the x-ray tube spectrum is removed it is sometimes said that the beam is <u>hardened</u>.

(i) Beam hardening shifts the effective (or average) energy of the photon spectrum to which patients are exposed to higher energies.

(ii) It may be said that a hardened beam has greater penetrability.

(iii) Penetrability refers to the attenuation of x-rays in tissue. Higher energy x-rays are able to penetrate through tissue easier than lower energy x-rays.

(iv) consider the following graph showing the probability of photon interactions versus photon energy.

D) X-ray machines

1. There are many physical processes that result in the production of x rays,

the process of most value for medical purposes is electron bombardment of a target through the use of an x-ray tube.

(a) x-ray tubes are relatively small

(b) They produce a very intense x-ray source.

(c) The closer an x-ray source can be made to approach a point source,

the sharper is the image that can be produced in radiography.

(d) The higher the intensity of the source, the shorter is the exposure time required.

2. There are several major sections of a stationary x-ray machine:

a) the ceiling support - two sets of two rails positioned perpendicularly to one another that allow longitudinal and transverse movement of the machine.

- a telescoping column attaches the x-ray tube housing to the ceiling support rails. The tube housing serves several purposes:

+ it provides a window where x-rays are intented to pass out of the housing in the direction of the patient.

+ The remainder of the housing reduces leakage radiation - or that radiation emitted in every direction except the one of interest.

+ the housing also helps prevent electrical shock.

+ It provides mechanical support, some housing surround the x-ray tube that both electrically insulates the tube and provides "thermal cushion".

- The distance from the tube to the x-ray film of cassette is called the source to image receptor distance of (SID). In the older literature this is referred to as the focal-film distance (FFD).

- when the tube is locked into position it is said to be in detent. Positions other than detent can be chosen by the operator.

b) The floor to ceiling support system consists of a single column with rollers attached to each end one on a ceiling rail and one on a floor rail that allows the x-ray tube to move horizontally and vertically.

c) the floor mount system as an alternate to the floor to ceiling column mount system of (b).

d) sometimes machines include a fluoroscopic x-ray tube that is

mounted

underneath the radiographic table. This is interlocked with a image intensifier tower.

e) x-ray tubes may be mounted in many different ways one common method is the use of the C-arm.

3. The heart of the X-ray machine is the x-ray tube which consists of:

(a) a positively charged anode target which are struck by electrons from the cathode.

(i) usually a copper molybdenum, graphite, or tungsten block.

- Tungsten (W) is favored because:

+ it has a high atomic number; 74. Although molybdenum and graphite have lower atomic numbers their advantage in weight is important if the target is to be rotated.

+ it has good thermal properties of thermal conductivity.

+ It has a high melting point 3400°C versus 1,100°C for copper (Cu).

(ii) the anode may be stationary or rotate.

- the anode is an electrical conductor

-the anode provides mechanical support for the target.

-the anode must be a good thermal conductor. (99% of the energy obtained by electrons moving from the cathode to the anode is experienced as heat and not as electromagnetic radiation.)

(b) a heated cathode filament usually composed of copper, or tungsten.

(i) the cathode is heated to incandescence at around 2000°C by passing an electric current through it to cause the release of electrons by thermionic emission.

(ii) the cathode is accompanied by a focusing element or focusing cup. This negatively charged metal shroud surrounding the filament condenses the electron beam to a small area of the anode target.

- an alternate to a focusing cup is employed in some units capable of producing multiple exposures at precise exposure times, this alternate is referred to as a grid and such units are called grid-controlled units.

- One problem with low potential x-ray tubes is the problem of moving electrons generated at the filament away from the filament.

The problem is that electrons remaining in the vicinity of the filament provide a space-charge that restricts further filament electron production. Such machines are said to be space-charge limited as they suffer from a space-charge effect.

- To some extent all machines at some point are limited by the maximum current that may be produced by the filament. The current at which this is experienced is referred to as the saturation current.

(iii) Commonly, an x-ray tube will have two filaments, such a machine is referred to as a dual-focus tube. A machine with two filaments will have two focal spots.

- the focal spot is the area of the target actually being hit with electrons and is the source of x-rays.

- The smaller the focal spot the better the spacial resolution of the image.

- However, the smaller the focal spot the more intense is the regional heating of the target. Several steps are taken to increase the area of the focal spot to enhance heat removal without actually increasing the area over which the beam strikes the target.

- One approach to this is the line focus principle , which angles or bevels the target to increase its effective surface area. The usually bevel angle is between 5 and 15 degrees. A biangle target is one manufactured with different two bevel angles on the same anode and two focal spot sizes.

    + a problem with the line focus principle is the heel effect. The heel effect relates to the depth in the target from which x-rays arise. Those arising at greater depths have more target to emerge from and hence are more heavily attenuated than those produced closed to the surface. The smaller the bevel angle the less the heel effect.

Consider the following figure:

- The <u>effective target area</u> or <u>effective focal spot</u> projected onto the patient and the image receptor.

- The smaller of the two focal spots will be used when better spatial resolution is necessary. These range from 0.1 to
0.5 mm.

- The larger focal spot will be used when technical factors are likely to produce higher heat lodes on the anode (usually at greater than 400 mA).   These range from 0.4 to 1.2 mm.

+ The selection of large or small focal spot is usually made with the mA selector on the operating console or with a focal spot selection switch.

(c) these components are enclosed within a glass envelope in which a vacuum is maintained.

Causes of tube failure include the following:

1. Excessive heating resulting in surface and melting of the anode. This results in variable and reduced radiation intensity. This is often associated with single excessive exposure.

2. Long exposure times may also result in tube failure. Typically the problem in this case is excessive heat transfer to the bearing of the anode rotor resulting in increased friction which ends as rotor imbalance.

-bearing damage itself with time is another cause of tube failure.

3. Thermal stress of the tube may cause failure. This is common with fluoroscopic systems when the thermal capacity of the heat removal system is exceeded. The effect may be bearing failure, or cracks in the glass housing.

4. Filament vaporization is another cause of tube failure. Vaporization of the filament with subsequent plating of the filament metal on the tube glass envelope is the most frequent cause of tube failure.

To reduce rates of tube failure:

1. To prevent pitting and cracking, maximum radiographic technical factors should never be applied to a cold anode. A good warm up procedure is to conduct three exposures - 3 seconds apart at 200 mA for one second at 80kVp. X-ray tube housings generally have a maximum heat capacity between 1 to 1.5 million heat units (HU).

- One heat unit for single phase units
  (HU) = (kVp)(mA)(time in seconds)

One heat unit for three phase units 6-pulse units
(HU) = 1.35 (kVp)(mA)(time in seconds)

One heat unit for three phase units 12-pulse units
(HU) = 1.41 (kVp)(mA)(time in seconds)

2. Always maintain operation of radiologic units inside the operating

envelope described by radiographic rating charts applicable to the x-ray machine being used.

(d) A high voltage power supply is also necessary.

(i) this supplies the potential for the anode and cathode system and supplies current for the cathode filament.

(ii) usually a high voltage system employs a high voltage step up transformer.

(iii) This supplies an alternating potential difference between the cathode and target.

(iv) During each cycle while the target is positive with respect to the cathode, electrons under the influence of the coulombic force are accelerated across the tube and strike the anode.

(v) this leads to the production of bremsstrahlung radiation as the electrons are deflected from their paths by the target atoms.

(vi) if the tube voltage is sufficient, some of the electrons being accelerated across the tube may ionize the target material resulting in the production of characteristic x rays.

(vii) Most of the radiation leaving the tube is bremsstrahlung radiation, characteristic x rays are only a relatively small component of the total spectrum.

(viii) The energy of the radiation leaving the tube ranges from 0 to that corresponding to the maximum energy of an electron striking a target.

(e) the x-ray machine comes with an milliampere meter by which one measures the filament current.

(i) one milliampere is equal to 6.25×10^{15} electrons per second.

(ii) Dental x-ray machines are generally operated between 5 and 15 mA.

(iii) Medical x-ray machines are typically operated between 50 and 1,000 mA.

(f) Typically less than 1% of the energy imparted to electrons accelerated from the cathode to the anode results in the production of useful x rays.

(i) The fraction is approximately:

$$RFP = (EE)(Z)(1x10^{-3})$$

where:

RFP = radiation fraction produced
Z = the atomic number of the target
EE = the energy of the electron in MeV.

(ii) The balance of energy lost in electronic collisions is converted into heat which must be removed from the anode.

(iii) This heat is handled in the following ways:

* anodes are sometimes beveled over the target area, this increases the surface area over which the electron beam strikes the target, allowing for better heat removal.

** anodes are sometimes cooled by rotating them. Usually anodes rotate at about 3,400 rpm. This increases the surface area of the target struck by accelerated electrons moving between the cathode and anode. Rotation is achieved using an induction motor located inside the x-ray tube.

*** circulating coolant through anodes is another method used to keep the temperature lower.

Regulations considering the use of radioactive materials, and radiation producing machines.

Perhaps the first definitive federal regulation regarding radiation exposures was established in 1946.

A) The Atomic Energy Commission (AEC) was created by congress in 1946.

B) The AEC was given the authority to regulate the use of:

1) Byproduct Material

2) Special nuclear material

3) Source Material

C) The AEC was also given authority to promote the use of these materials. In fact the set up two divisions to promote the use of radioactive material:

1) Division of Biology and Medicine

2) Division of Isotope Development

D) The AEC was reorganized in 1975. It was divided into two new groups:

1) The Nuclear Regulatory Commission (NRC)

2) The Energy Research and Development Administration (ERDA)

a) ERDA has since been incorporated into the Department of Energy (DOE)

E) The NRC has primary responsibility for regulating byproduct material, special nuclear material, and source material. The NRC dose not control the use of:

1) Naturally occurring radioactive material (NARM)

2) Accelerator produced radioactive material.

3) Radiation producing machines

F) There are several other organizations with regulatory authority over the use of radioactive material or with authority to set recommended standards of practice in certain areas involving radiation, radiation producing machines, or radioactive material, these include:

1) The Center for Devices and Radiological Health regulates radiation producing devices and medical devices:

a) TV sets

b) microwave ovens,

c) X-ray units..etc..

2) The Department of Labor

a) i.e. OSHA

3) The Department of Transportation (DOT)

4) The Environmental Protection Agency

5) The Food and Drug Administration

6) The Department of Defense

7) The Department of the Interior

G) Additionally, States have laws governing the use of radiation and radioactivity.

1. The use of radiation producing machines are generally governed by state regulations.

In Idaho the state regulations can be found in IDAPA 16 published by the Department of Health and Welfare referred to as 16.02.27 - Idaho Radiation Control Rules DOCKET NO. 16-0227-9701. A copy of these rules may be found at:

http://www2.state.id.us/adm/adminrules/bulletin/jul97/160227.htm

2. Should the states not regulate certain aspects of radiation sources, and the nature of the sources is such that they are not regulated by the Nuclear Regulatory Commission than these activities could be regulated under the OSHA act and the appropriate regulations would be listed under 29CFR1910.96.

l) The regulations of the federal agencies are published first in the Federal Register after being promulgated. But may always be found in the code of Federal Regulations.

The regulations of most interest for radiation protection are:

1. 10CFR 20 Part 19, Notices, Instructions, and Reports to Workers; Inspections

2. 10CFR Part 20, Standards for Protection Against Radiation

3. 10CFR Part 30, Rules of General Applicability to Domestic Licensing of Byproduct Material

4. 10CFR Part 31, General Domestic Licenses for Byproduct Material

5. 10CFR Part 33, Specific Domestic Licenses of Broad Scope for Byproduct Material.

6. 29CFR Part 1910.96 of subpart G of the General Industrial Standards -the ionizing radiation section.

c) These regulations are laws and violations or noncompliance can result in:

1. revocation of license

2. Fines

3. Imprisonment

4. or any combination of the above.

Chemical and Biological Effects of Radiation

INTRODUCTION

1. When considering the effect of ionizing radiation on humans it is convenient to categorize potential effects. One common scheme for this is as follows:

A. Stochastic Effects

a. The term stochastic implies a random outcome or an outcome related to the probability of occurrence

b. The probability of the occurrence of a stochastic effect is a function of dose. The higher the dose the larger the probability of an effect.

- For regulatory purposes it is assumed that the relationship between the probability of occurrence and the dose received is a linear non-threshold relationship.

* This is a conservative approach.

* According to ICRP 30 and ICRP 60 this relationship is more likely to be sigmoidal in shape.

* There is an increasing body of literature which support the theory that a threshold of response exists.

* There is some information supporting the idea that low-dose of radiation are beneficial and necessary. This idea is called radiation hormesis.

c. For stochastic effects the severity of the effect is independent of the dose received.

- One only considers the probability of the event occurring, not its severity.

d. The primary stochastic effect of concern is development of malignant tumors.

- A stochastic effect experienced by the exposed individual is referred to as a somatic stochastic effect.

e. Another important sub-category of stochastic effects are hereditary effects. These are effects which may be experienced by the off spring of exposed individuals.

- Hereditary effects have been observed in some lower species following exposure to ionizing radiation. These have never been observed in humans exposed to ionizing radiation.

- Hereditary effects should not be confused with teratogenic effects.

- Teratogenic effects are associated with the exposure of an embryo or fetus while in its mothers womb.

  * An example of a teratogenic effect observed in atomic bomb survivors was mental retardation.

B. Non-stochastic Effects or deterministic Effects

1. Non-stochastic effects are those associated with large doses of radiation, typically delivered in a short time.

2. The occurrence of a non-stochastic effect depends on the dose received.

3. The severity of a non-stochastic effects is dependent on the dose received.

4. Non-stochastic effects have observable thresholds

5. Examples of non-stochastic effects include lens opacities (cataract), skin erythema, the acute radiation sickness syndrome, etc.

In summary one may experience or observe the following categories of radiation effects in exposed populations or individuals.

Stochastic Effects

Somatic

Heredity

Non-Stochastic Effects or Deterministic Effects

In the remainder of this lecture series we will discuss the details of how radiation interacts with biological material and how biological systems respond to this stress.

STOCHASTIC RISKS

A) Dose Response Relationships

1. There is no consensus concerning the response of humans and the expected response.

2. ICRP takes a very conservative approach and assumes a linear no-threshold response regarding stochastic effects.

a. The ICRP recommendations are valid only on the basis of this assumption - and the concurrent assumption that the severity of each type of stochastic effect is independent of dose.

i) The added risk from a given dose increment depends on the slope of the dose response relationship.

3. The ICRP in ICRP 26 indicates that there is strong evidence to support a view that the dose response relationship for stochastic processes may be better described as a sigmoid relationship rather than a linear relationship.

4. This sigmoid response may be represented by the expression:

$$E = aD + bD^2$$

where:

E = The effect
D = the dose
a and b = constants which are not yet well defined.

5. In this expression the quadratic portion is the bD^2 part and the linear part is the aD part.

a. The quadratic term predominates at high absorbed dose (generally above a gray) and at high absorbed dose rates, on the order of one gray per minute.

b. The linear term and the slope that it represents predominate as the dose and dose rate are reduced.

6. Human data is still too limited to enable confident prediction of the dose response relationship at low doses and low dose rates.

a. The values of the constants a and b are not well known.

b. So the use of linear extrapolations, from the frequency of effects observed at high doses, is employed.

c. This provides to some extent, in light of the discussion given above, provides an upper limit of risk by which the benefit of a practice - or alternately the risk or detriment of a practice - can be compared to another to an alternative practice.

i. The potential problem with this approach, as mentioned by the ICRP is that an over estimate of risk may result in a choice of an alternate practice which is in fact more hazardous. Great caution must be used when making risk estimates and decisions that compare alternatives.

IMPLICATIONS OF ASSUMPTIONS ABOUT DOSE-RESPONSE RELATIONSHIPS

A) ICRP uses the mean dose to an organ when considering stochastic effects.

1. It is the opinion of the commission that for stochastic effects the absorption of given quantities of radiation are "less effective" when due to a series of hot spots then when uniformly distributed

a) This is because of the effect of high doses in causing the loss of reproductive capacity or the death of cells.

2. The commission developed a procedure under which account of the total risk attributable to the exposure of all tissues irradiated is considered.

a) The risk factors for different tissues are based on upon the estimated likelihood of inducing:

fatal malignant disease
non-stochastic changes
substantial genetic defects expressed in live born
Decedents.

B) THE RISK TO SPECIFIC ORGANS

1. Gonads may experience three different types of deleterious effects.

a) tumor induction

b) impairment of fertility in the irradiated individual

c) hereditary effects

2. Human gonads have a low radiosensitivity, radiocarcinogenesis has not been demonstrated.

a) Impairment of fertility varies with age in the female.

i) Induction of menopause with permanent cessation of fertility could result from an absorbed dose of 3 Gy low LET radiation in a 40 year old woman but this dose would only cause temporary amenorrhoea in a 20 year old woman. Amenorrhoea is an abnormal absence or suppression of the menstrual discharge

ii) A depression of sperm count in males is expected after a high dose rate delivery of 0.25 Gy of low LET radiation in the male, but permanent sterility requires an absorbed dose of at least 2.5 Gy.

b) Gonadal tissue is involved in the production of radiation-induced gene mutations and chromosomal changes leading to hereditary defects.

i) Such effects have been observed in small mammals and lower organisms.

ii) We know which naturally occurring hereditary and partially hereditary diseases might be affected by radiation

iii) ICRP estimates that hereditary detriment is likely to be less than the detriment is likely to be less than the detriment due to somatic injury in the irradiated individual.

iv) The risk of serious hereditary ill health within the first two generations following the irradiation of either parent is taken to be about $1x10^{-2}$ Sv^{-1} and the additional damage to later generations to be of the same magnitude.

2. RED BONE MARROW

a) Red bone marrow is thought to be the tissue mainly involved in the causation of radiation-induced leukemia; other blood-forming tissues are thought to play a minor role in leukaemogenesis.

b) The risk of radiation induced leukaemia reaches a peak a few hears after irradiation and then returns to pre-irradiation levels after about 25 years.

c) The risk factor for leukaemia is taken to be $2x10^{-3}$ Sv^{-1}.

d) The average dose equivalent to the haematpooietic marrow within trabecular bone is thought to be a good representation of the dose to hematopoietic cells uniformly distributed throughout this tissue.

3. BONE

a) The radiosensitive cells in bone are the endosteal cells and the epithelial cells on the bone surfaces.

b) Dose equivalent in bone should apply to the endosteal cells and cells on bone surfaces and should be calculated as an average over tissue up to a distance of 10μm from the relevant bone surfaces.

c) The bone is thought to be much less sensitive than breast, red bone marrow, lung and thyroid.

d) The risk factor for bone cancer is taken to be $5x10^{-4}$ Sv^{-1}.

4. LUNG

a) Cancer of the lung has been demonstrated to be caused in uranium miners exposed to high concentrations of radon and its decay products.

b) Cancer of the lung clearly attributable to radiation exposure has not been reported in people who have worked with radioactive materials in particulate form, such as plutonium, even though some of them were exposed above current limits.

c) The risk seems to be much higher for uniformly distributed sources than in situations were the dose arises from localized "hot spots". Hence, exposure of the lung from an external source is not insignificant in regard to risk.

d) The indication is that the risk of lung cancer is about the same as that for the development of leukaemia.

e) The risk Cancer for lung cancer is taken to be $2x10^{-3}$ Sv^{-1}.

5. Pulmonary Lymphoid Tissue

a) The major issue for lymphoid tissue is the retention of inhaled particles containing insoluble compounds in bronchopulmonary lymph nodes.

b) The dose delivered by these particles is non-uniform and involves a lower hazard than if it were uniformly distributed throughout the lymphoid system.

i) For lymphocytes themselves this non-uniformity is less extreme due to their circulation through the lymph system.

c) Lung and lymphoid tissues should be considered jointly due to their functional and physical relationship.

i) In many cases the concentration of particles will be greater in lung tissue then in lymphoid tissue. An example is inhaled plutonium particles.

ii) Lung tissue is more radiosensitive than lymphoid tissue.

iii) ICRP 26 indicates that the trachea, bronchi, pulmonary region and pulmonary lymph nodes are to be treated as one composite organ of mass 1 kg to which dose limitations for the lung should apply.

6. THYROID

a) The epitheal cells of the thyroid follicles are considered to be the most radiosensitive according to ICRP 26 but in most cases the dose to the whole gland will be substantially the same as the dose to these cells.

b) The sensitivity of the thyroid to the induction of cancer is even higher than that of the red bone marrow but cancer induced in the thyroid is rarely fatal because it is readily treated and the slow progress of thyroid tumors.

c) The overall mortality risk factor for radiation protection purposes is taken to be $5x10^{-4}$ Sv^{-1}.

7. BREAST

a) ICRP considers the breast to be one of the most sensitive tissues of the human body during the reproductive life of the human female.

b) The risk factor for breast cancer is a few times higher than that for leukaemia.

c) The risk factor for breast cancer is taken to be $2.5x10^{-3}$ Sv^{-1}.

8. RISK OF CANCER IN ALL OTHER TISSUES

a) There are several tissues (e.g. stomach, lower large intestine, salivary glands and liver) in which exposure to radiation may result in carcinogenesis - however, estimates of risk can be made.

i) These risk factors are felt to be very low.

b) There are other tissues in which there is no evidence of any tumor induction by radiation these include muscle and adipose tissues.

c) The collective risk of inducing tumors in these organs is taken to be $5x10^{-3}$ Sv^{-1}.

d) No single tissue is responsible for more than one-fifth of this value.

9. TOTAL STOCHASTIC RISK FROM UNIFORM WHOLE BODY IRRADIATION

a) The mortality risk factor for radiation-induced cancers is about $1x10^{-2}$ Sv^{-1} as an average for both sexes and all ages.

b) The average risk factor for hereditary effects, as expressed in the first two generations, is taken as $4x10^{-3}$ Sv^{-1}.

c) Although there is a difference in the risk factors between workers and the general public, primarily caused by differences between the age demographics between these two populations, it is not sufficiently large to warrant separate risk values for protection purposes.

10. LENS

a) If the lens is irradiated with either high or low LET radiation over the occupational life time it is concluded that a total dose equivalent of 15 Sv would be below the threshold for the production of lens opacification that would interfere with vision.

b) In adults the most sensitive region of the eye is the equatorial portion of the anterior epithelium.

i) For radiation protection purposes the lens of the eye can be considered to lie 3 mm behind the surface.

11. Skin

a) In comparison to other tissues the skin is the least likely to be susceptible to fatal cancer development.

b) The skin may develop "unacceptable" cosmic changes with absorbed dose of 20 Gy or more delivered over a period of weeks or months to limited portions of the skin. Using 20 Gy as the limit over the entire occupational life time should prevent these non-stochastic changes.

c) The basal layer of the skin is taken to be the part of the skin most at risk.

i) This is taken to exist at a depth of 50-100μm below the surface. A depth of 70μm is recommended as an reasonable mean value.

12. CHILDREN AND FOETUSES

a) Exposure before growth or during childhood may interfere with growth. This time period is also one in which the individual is more susceptible to induction of malignancies.

13. Tissues of low sensitivity

a) Some tissues have a very low radiosensitivity. The dose limitations for these tissues are based on the possible damage to vascular or other deleterious changes.

14. OTHER EFFECTS

a) Life shortening - no conclusive evidence

b) Tumor induction other than those listed - inconclusive.

c) Overlooked? Not likely based on the last 30 years plus of observation

NON-STOCHASTIC EFFECTS

(A) THE INTERACTION OF RADIATION WITH CELLS

1. The major constituent of the human body is water.

Mammalian Cells are:

a. 70 to 85% water
b. 10 to 20% protein
c. about 10 % carbohydrates
d. 2 to 3 % lipids

Therefore, the majority of radiation interactions with the body will be those occurring in water. Some interactions will also occur with the molecules forming the cells in the body.

2. We can divide the action of radiation with the body into two groups: direct action, and indirect action.

a. Direct action involves the ionization or excitation of target molecules within the cell. An example would be the case of ionizing an electron and breaking a bond in a DNA molecule.

b. Indirect action involves the ionization of water.

Ionized and excited states of the water molecule may lead to free radical formation.

i. These free radicals in turn may diffuse throughout the cell an react with the aforementioned target molecules.

ii. Target molecules consequently suffer a risk of change caused by radiation, even if they have not been directly involved with radiation interaction.

c. Indirect action is more likely than direct action and is consequently more important than direct action.

d. Interactions within the cell happen very rapidly.

i. Free radicals are formed and react within a microsecond.

ii. Free radical reactions are completed with biological molecules within a millisecond.

iii. Biochemical changes all occur within a second.

3. The response of a cell to irradiation will depend on whether cellular molecules are ultimately altered by the experience and, if so, which of them are altered by the experience.

a. If important molecules are changed, a loss of function and perhaps a change in behavior of the irradiated cells might be expected.

- It is this loss and change which are known as radiation effects.

b. The type of effect which is to be expected depends on several factors including:

- The quantity of radiation energy deposited.

- The type of radiation depositing the energy and the pattern of energy deposition.

* A key measurement of this is the LET or linear energy transfer. This is a measure of energy loss per unit path length (keV/μm).
LET varies as the square of the charge of a particle and inversely as its velocity.

- The age and kind of tissue irradiated.
- The stage of the cells life cycle during which irradiation occurred.
- The capacity of an individual cell to repair radiation damage.
- The rate of cellular division.
- the availability of oxygen

4. The Interaction of Ionizing Radiation with Water - The genesis of indirect action.

a. When irradiated, water, like any other material is ionized. An electron is removed from the molecule, leaving behind an ionized water molecule.

b. The ions subsequently formed are not stable. They will dissociate into free radicals rapidly, within a microsecond.

c. Free radicals are distinguished by the presence of a single, unpaired orbital electron. The electron is unpaired from the point of view of direction of spin on the electron's own axis.

i. Free radicals are extremely important in the study of radiation effects, for it is through them that the indirect action of radiation occurs.

d. Consideration of the formation of free radicals from ionized water:

i. The outer electron orbits of ionized water molecules may be represented in the following manner:

e. These ions almost immediately dissociate into two subunits:

i. Each water ion will yield one smaller ion and one free radical.

ii. The free radicals formed are responsible for the indirect action of radiation.

iii. They are extremely reactive: in pure water they ordinarily react within $1x10^{-5}$ seconds.

5. The reaction of free radicals.

a. The reactions of free radicals are indiscriminate; a free radical may interact with another free radical, with a molecule already damaged by radiation, or with an intact molecule.

b. The reactions of free radicals can be subdivided into five categories.

(1) Interactions among free radicals themselves

(2) Interactions of free radicals with the water in which they are formed.

(3) Interactions of free radicals with their own products.

(4) Interactions of free radicals with oxygen

(5) Interactions of free radicals with organic molecules

6. The products of free radical interactions:

a. Not all the products of free radical interactions are harmful to living systems.

i. water is a potential product of free radical interactions which is not harmful to the cell, as is molecular hydrogen.

b. Some products of free radical interactions are poisons to cells.

i. For instance H_2O_2 (hydrogen peroxide) is a cell poison and if present in sufficient quantities can materially interfere with metabolism.

c. Other free radicals may represent not only changed molecular constituents of the cell, but also substances that are free to attack other such constituents and spread molecular change still further.

7. Sources of Radiation-Produced Free Radicals.

a. Cellular water is the primary source, but not the only source of free radicals.

b. The ionization of nearly any cellular component can result in free radical formation which, in turn, will contribute to the indirect action of radiation.

8. The influence of Ion Density on Free Radical Formation.

a. The interaction of free radicals both among themselves and with their own reaction products is dependent primarily on how closely together the free radicals have been formed.

b. After free radicals are created they diffuse through the medium in which they were formed until they encounter something with which they may interact.

i. Densely ionizing radiations, those with high LET values such as alpha particles, protons, and electrons, will produce clusters of ions that are very close together.

ii. The result of this is a high probability of interactions between free radicals with free radicals and with the product of precious radical-radical interactions.

iii. Sparsely ionizing radiation, such as x-rays and gamma rays will also produce clusters of ions formed but these will be much more widely separated than those of densely ionizing radiation.

- The probability of interaction between the resultant free radicals is much smaller than that following irradiation with densely ionizing particles. A different population distribution of free radical products is expected.

9. The energy required to generate the various species of free radical products is known fairly well. This is expressed as the G value. The G value is:

G value = the number of a given species/100 eV of energy loss.

Radiations of different energies will produce slightly different distributions of species of free radical products in water.

Advantage is taken of this fact when using chemical dosimeters.

The differences in chemical speciation are due entirely to the different spatial patterns of initial energy deposition expressed by different particles.

Radiation damage is delivered by either the direct interaction of the radiation with cellular macromolecules such as DNA or through the indirect effects of the radiolytic byproduct of radiation and water reactions.

The radiolytically produced cytotoxins of radiation and water reactions may disrupt the same cellular constituents as expected from direct radiation interactions.

The impact of these kinds of interactions on the cell may range anywhere from no effect, cellular death to genetic mutation.

In general, when considering low radiation doses, cellular death is of little consequence. Cellular death of more consequence at higher radiation dose where deficits in cellular populations effect tissue or organ system function.

The outcome of genetic effects on the cellular level may range from no out come to deviations in the cellular structure or performance in subsequent generations of that particular cell line.

About 95% of cellular mutations on deleterious and usually result in loss of the cells reproductive capability.

When is generally little significance to the loss cellular reproductive capacity on the microscale.

Greatest concern is on cellular systems that are mutated and are capable of successfully passing a deleterious mutation in progeny generations.

The worse case scenario is that such mutated cells, under the narrow circumstances of promotion lead to uncontrolled sub populations of cells which may be called tumors or cancer.

P. The effects on Tissues and Organs.

a. The responses of organized tissues and organs to irradiation are largely due to the effects of the reproductive mechanisms of certain cells in the tissue.

i. The cells of most tissues can be organized into three categories:

* Stem cells

- stem cell compartments within tissue are usually very mitotically active.

* differentiating cells

* mature functional cells.

b. Tissues and organs that respond most to irradiation are those tissues and organs in which function is most dependent on the reproductive capacity of cells in the stem cell compartment.

i. This in turn depends in the natural life span of mature cells in the tissue.

c. The Law of Bergonie' and Tribondeau

i. Radiation sensitivity of tissues depends on

* the number of undifferentiated cells in the tissue
* the degree of mitotic activity in the tissue
* the length of time cells of the tissue stay in active proliferation.

Q. Immediately Lethal Effects in the Total Organism

a. The principle affect of whole body exposure to ionizing radiation is the shortening of the life span of the exposed individual.

b. The dose required to produce lethality among individuals depends on several independent parameters including:

i. species differences
ii. age
iii sex

iv. time in the circadian cycle in which the exposure occurred.

c. The observed effect from large doses of irradiation are primarily dose dependent.

d. Typical observed effects include:

i. nausea
ii. sometimes vomiting
iii. hair loss
iv. loss of appetite
v. malaise
vi. soreness in the throat
vii. petechiae
viii. weight loss/moderate emaciation

e. effects severe enough to cause death are expected as the following levels for the species listed below.

Organism	LD 50/30 Rads
pig	250
goat	250
dog	250
burro	300
man	300 to 450
monkey	500
mouse	600
rat	700
rabbit	700
frog	800
newt	3000

f. The time of survival after a dose large enough to start causing lethality has considerable variability.

i. Some typically responses can be expected.

ii. When mean or average survival times are reviewed for doses of radiation greater than that which begins to cause death, a pattern, consistent for nearly all species of mammals studied emerges. This is shown below.

iii. This pattern of response has three clearly defined components.

* Initially, over a dose of ________ rads, the response is dose __________

- mean survival times, as dose increases, decreases from weeks to days.

* The second phase, extending over the wide range of approximately 1000 to 10,000 rads is a plateau.

- Mean survival at any dose in that range is about 3 to 4 days.

- This response appears to be ________ of dose.

* The last phase is dose ________________.

- A s the dose increases mean survival time _______ from a period of days to hours and finally even to minutes.

g. The three regions of the dose-response pattern reflect the radiation damage to, and the failure of, three different organ systems after irradiation.

i. In the first region death may occur because of failure of the _________ system

ii. In the second region death is associated with damage and failure of the __________ system

iii. In the third region ___________ system damage causes death.

Q. The Hematopoietic Syndrome

1. The hematopoietic syndrome is associated with a large acute dose of penetrating radiation uniformly distributed over the whole body.
   a. Under this type of exposure the effect on the _________is of key importance.
2. Manifestations of the hematopoietic syndrome
   a. Disturbance in the function of the _________________is expected to occur within a few hours post irradiation.
   b. This may _______ period persists for a few hours or few days will include:
      i. ______________________________
      ii. ______________________________
      iii. ______________________________

   c. This is followed by a _____ period of variable length.
   The individual experiences no obvious symptoms during this period but there are lethal effects in progress, destruction of the bone marrow is beginning.

   d. The latent period is followed by a period of __________. The following signs and symptoms are expected and may in fact precede death:

      i. gastrointestinal disturbance reappears.
      ii. diarrhea, often bloody, sometimes quite severe, begins.
      iii. Hemorrhage into the tissues occurs
      iv. fluid imbalance accompanies the hemorrhage
      v. serious infection ultimately follows.
      vi. weight loss
      vii. loss of hair

viii. depression of spermatogenesis or oogenesis

e. At death nearly all organs in the body have been affected, however, death occurs principally as a result of the failure of ________________.
f. Histologic Changes

1. The degree of the histologic changes experienced are a function of the dose received.
2. Immediately after irradiation the structure and architecture of the bone marrow are disrupted.

(a) marrow normally contains nucleated cells, a small amount of fatty material, and some circulating blood in vessel-like channels

(b) after irradiation there is a significant reduction in the amount of cellular material.

i. This decrease in the number of cells is compensated for by:

- ____________________

- and by hemorrhage of blood into the cell-depleted regions.

- and by an increase in the amount of ___________

i. If the dose is large enough cell depletion is severe and the marrow becomes acellular.

- The marrow space becomes filled with pooled blood.
- Circulation of blood becomes extremely sluggish
- reabsorption of extra vascular blood is limited.

iii. Obviously, even in very large dose cases, not all of the cells in the marrow will be killed.

- some start to undergo _____ at an attempt in regeneration.
* At higher doses these attempts at regeneration usually fail or abort. These clusters of dividing cells regresses and disappears.

- Later in time regeneration will again begin. Precursors of red and white cells will appear after a general hyperplasia which characterizes this "real" regeneration. This regeneration does not mean the animal will escape death.

3. Lymphoid tissue is also severely effected by the dose-range that produces the hematopoietic syndrome. The required dose for this is less species dependent than that of the hematopoietic syndrome.

i. Shortly after the a total-body dose:
- the node become severely depleted of cells.
- node architecture is completely disrupted

ii. Regeneration of the nodes occurs soon after irradiation, and usually in a rapid fashion.

Cytologic Changes

1. One aspect of the Hematopoietic system is a predictable change in the mitotic frequency in the bone marrow.

i. Initially the mitotic frequency drops.

ii. The mitotic frequency then rises. The time at which the rise occurs is very much a function of the absorbed dose.

- The slope ofthe rise in frequency is also a function of dose.

- The rapid rise in mitotic frequency results in an overshoot of the normal frequency.

iii. There is then a second fall in the mitotic frequency in the bone marrow which in turn is followed by a second rise. Eventually, the mitotic frequency is restored to the normal unirradiated frequency.

2. Many of the cells in a rebounding populations are abnormal.

i. However, a large number of abnormal cells are not readily apparent in the regenerating bone marrow.

- Undoubtedly, some of the damaged chromosomes are quickly repaired.
- More likely, many of the injured cells are quickly eliminated.
- Some cells with damaged chromosomes survive and continue to multiply.
    * These can be detected many years later.

3. Within a few hours after irradiation and well before bone-marrow regeneration a range of nuclear abnormalities of cells in the bone marrow may be observed.

i. The nuclei of some of these cells may be shrunken, their chromatin will be clumped.

ii. The nuclei of others will appear faint, as if their chromatin were diluted or dissolving. These cells are dying, the injury from radiation has killed them even before they were able to divide.

iii. Some cells will display aberrant chromosomes.

- some chromosomes will be swollen
  + Chromosome bridges will be present
  + Broken chromosomes will be present.
  + Some cells will have spindles with more than two poles.
  + Other grossly- abnormal cells will be present at this time.
- Most of these directly damaged cells will be quickly eliminated.
- The elimination of cells directly following irradiation is primarily responsible for the loss of total cellularity in marrow.

h. The Latent Period

1. Degenerative changes in the bone marrow and attempts at early regeneration occur during the prodromal and the latent periods.

2. Death, as a result of the hematopoietic syndrome, is believed to be due to the loss or failure of the bone marrow to carry out its function; supplying the organism with the functional cells that it needs in its circulating blood.

i. There is a direct loss of some red and white blood cell precursors.

ii. There is a later loss of some of the remaining red and white blood cells due to injury to their nuclei (mutations and chromosome aberrations).

iii. There is an inhibition of mitosis at various times post irradiation.

3. The combination of these three processes results in a critically short supply of circulating cells, this is true for several reasons:

i. Circulating cells have limited life spans.

ii. Most circulating cells are highly specialized.

iii. Most circulating cells do not divide.

- The body depends on stem cells of the bone marrow, a set of undifferentiated frequently dividing cells.

+ The stem cells are the cells which are directly eliminated.

i. The Blood Count

1. The loss of precursor cells in the bone marrow is reflected in the number and kind s of cells in the circulating blood.

2. After irradiation, there is a drop in blood count (anemia); its severity depends on dose.

3. Anemia, as associated with the hematopoietic syndrome does not arise initially from the destruction of bone marrow and the subsequent drop in the production of red cells.

- There is a drop in the production of red cells but this is nor initially noticeable as mature blood cells have relatively long life.

- Red cells are lost from circulation because of:

+ a large number of small hemorrhages into tissue (petechiae) related to the breakdown of the capillary walls.

+ More importantly, there is a deficiency in the number of platelets resulting in an increase in clotting time.

j. Infection is the terminal phase of the hematopoietic syndrome.

1. fever is common.
   - temperature rise above 105° F are typical.
   - overwhelming infection can be expected.

2. Normal intestinal flora have been isolated as an infectious agent in large animals.

3. Bacteremia in the blood stream of smaller animals is expected.
   - This has not been observed in man, probably because of differences in analysis techniques, although they may be present.

4. Infection greatly influences the time course of survival of irradiated mammals.

5. Treatment of animals with antibiotics both prior to irradiation or post irradiation increases their mean survival time.
   - Germ free animals have been shown to have higher survival rates for given radiation doses than animals that are not germ free.

6. It may be concluded that the irradiated animals receiving large doses of radiation have increased susceptibility to organisms not normally pathogenic and normally pathogenic.
   - Infection, therefore, is extremely important in regard to the mortality associated with irradiation.

   - Infection after total body irradiation is correlated with the loss of circulating blood cells namely granulocytes.

7. Death associated with the hematopoietic syndrome is related to:

- a failure of the bone marrow.
- failure of the body systems to combat infection.

8. The effects of irradiation on immunity

- The immune system is responsible for the bodies defence against harmful environmental agents.
- The immune system can be viewed as being composed of two categories, an innate system and an acquired system.

    + The innate category is a product of genetic makeup and is an expression of the experiences of past generations.

    + Acquired defense is related to an individuals own experience.

- The fundamental aspect of the immune system is the antigen-antibody reaction.

    + Immune response is initiated when a foreign body, referred to as an antigen enters the body and stimulates the lymphoid-macrophage system.

- Under appropriate conditions the antigen stimulates the formation of antibodies.
    + These are specific proteins which have the ability of neutralizing or reacting with the antigen.
    + Antibodies are antigen specific. An antibody capable of defeating one type of antigen is ineffectual against another type of antigen.
    + The specific antibodies formed after the initial antigen insult are maintained and spring into action if that specific antigen again challenges the body. This is referred to as acquired immunity.
    +The initial response may be relatively slow the first time a particular antibody is formed. Due to acquired immunity, any subsequent response is expected to occur in a much more rapid and effective fashion.

- Radiation acts as an immunologic suppressive

+ Because the lymphoid system is in the same range of radiosensitivity as the hematopoietic system, whole body radiation at high doses results in a rapid death of large numbers of lymphocytes and inhibition of cellular reproduction in many others.

+ In mammals, doses of whole body radiation on the order of 500 rads will cause rapid degeneration of lymphoid cells.

+Active proliferation of lymphoid cells does not restart until 3 or 4 weeks post irradiation.

+ If an antigen is introduced after irradiation, the formatio of antibodies is delayed until the capacity for mitotic activity is recovered.

+ Cells that are actively synthesizing antibodies may continue to be active even after massive doses of radiation.

+Acquired immune responses are relatively resistant to radiation, however, the appearance of antibodies may be delayed following a large acute dose to radiation.

+ The depression of the immune response following exposure to large doses of ionizing radiation can be significantly modified by partial shielding of the lymphoid tissue in the body or by the injection of living lymphoid cells after the irradiation event.

+ The depression in the immune response probably plays the largest role in the death of exposed animals. This is primarily related to enhanced susceptibility to infection.

R. The gastrointestinal syndrome

1. The primary manifestations of the gastrointestinal syndrome are the failure of two systems:

- The cells lining the intestinal tract (the mucosa)
- The cell renewal system of the bone marrow.

2. The true or complete gastrointestinal syndrome can be obtained only after total-body irradiation.

3. However, irradiation of the gastrointestinal tract alone can be fatal, but the full syndrome must involve the cell renewal system of the bone marrow as well.

4. The syndrome demonstrates the following initial signs after irradiation:
   a. Lack of appetite
   b. sluggishness
   c. diarrhea
   d. signs of infection and dehydration
   e. loss of weight
   f. retained food and water in the stomach for long periods of time
   g. very low absorption of the food eaten.

5. At the same time the number of circulating white blood cells will drop to nearly zero.
6. The terminal phase of the syndrome happens rapidly, often lasting for less than a day, it includes:
   a. Severe diarrhea
   b. severe dehydration
   c. distinct emaciation
   d. vomiting
   e. essentially inert behavior

7. Death will occur with regularity in most species between 3 and 4 days after irradiation. It will be observed post mortem that:
   a. Blood volumes have changed
   b. Electrolyte levels in the serum will be altered
   c. There will be evidence of bacteremia (bacteria in the blood) in many species.
   d. Severe wasting and dehydration

e. Stomachs will show the retention of food and water

f. The small bowl itself may be swollen and may contain a bile colored, bad smelling, liquid tainted with blood

g. The large bowl may contain liquid stools that are often bloody

h. There will be a large quantity of mucus in the gut

i. The mucosal layer of the small intestine will be badly damaged

- The villi will be flattened and shrunken
- Some areas will lack the cellular lining altogether
- Many of the crypts which are usually active in cell proliferation will be empty

j. In the stomach and rectum, some areas will be denuded of cells and will be ulcerated

k. The bone marrow is formless, completely without structure.

8. Cellular structure of the gastrointestinal tract.

a. The mature functional cells of the gut epithelium are those lining its villi, in particular at the ___ of the villi.

b. The crypts, much like the bone marrow, are _______ centers. Crypt cells are:

i. Undifferentiated

ii. In general, unspecialized

- The specialized functional cells of the villi (in particular those of the small intestine) have a short life.
- Normally they wear out and our sloughed into the intestinal lumen only a few days after they become functional.

c. The gut lining may be said to undergo ______ renewal.

i. The cells of the crypt:

- have a high ______ rate

- are the source of replacement of the rapidly renewing epithelial lining.

ii. There is a an orderly procession of cells from the crypts up the villi through a region in which they mature, through another in which they function, to the villus tips where they are extruded and sloughed.

Schematic diagram of the regions of a normal intestinal villus

d. As in the case of the bone-marrow syndrome, radiation strikes at the cells that are the source of differentiated functional cells.

1. This is to be expected because:
   - These cells are most frequently active in mitosis
   - These cells are most frequently active in DNA synthesis.
   - These cells are undifferentiated.

e. Effects of irradiation on the cellular mitosis with the small intestine.

1. After irradiation the rate of cellular mitosis drops drastically.
   - In many species there will be no cells undergoing mitosis ____minutes post exposure.

2. The length of time for which mitosis is inhibited is a function of dose.
   - The larger the dose the longer mitosis will be ____________.

3. It is expected that the mitotic rate will rise sharply after the inhibition time has passed.   This will be followed by a second depression in the

mitotic rate. This is similar to the circumstances expected in the bone marrow post irradiation.

- Many of the cells taking part in the first "increased mitotic rate" have nuclear abnormalities such as broken, lagging, or sticky chromosomes.

- These cells and most of their progeny die after ____________

4. Death is thought to occur in an irradiated animal by the gastrointestinal syndrome if a critical number of crypt cells become irradiated.

5. Cells in the bone-marrow are grievously damaged by doses producing the gastrointestinal syndrome.

- damage to the bone marrow is an integral part of the gastrointestinal syndrome.

- The bone-marrow renewal systems are completely depleted within a few days after irradiation at the gastrointestinal syndrome level.

- Consequently, there is a major lack of important hematopoietic cells, primarily _________, when the brunt of the gastrointestinal syndrome's signs occur.

9. Degenerative Changes in the Lining of the Small Intestine.

a. The following changes may be observed after exposures large enough to experience the gastrointestinal syndrome:

CRYPT CELLS

i. Within the first day one may observe progressive destruction in the nuclei of the cells that line the crypts of the intestine.

- The chromatin agglomerates into an _______ masses which is densely straining.

ii. Both the nuclei and cytoplasm swell, some dissolution may be observed within the damaged cells.

iii. The dead and dying cells produce a measurable decrease in the number of cells of the ______ lining.

i. The cells which remain have abnormal nuclei and are often swollen and enlarged.

iv. Few crypt cells are observed to be in mitosis, this is unusual because crypt cells normally have a high rate of mitosis. Those cells in mitosis are often abnormal.

v. Initially one observes many dead crypt cells, but eventually they are sloughed off and are passed down the intestine.

i. Since mitosis is occurring at a slow rate these dead cells are not replaced and areas void of cells appear.

ii. The cells remaining often appear abnormal.

INTESTINAL VILLI

vi. The villi of the intestinal wall begin to lose cells progressively with time. They begin to shorten and shrink.

i. The rate of cell loss is proportionally to the magnitude of dose.

vii. At death, the villi are nearly flat and almost completely free of living cells.

b. The precise time schedule of these effects and the time required prior to observing them depends on:

i. Total dose

ii. Species

c. The intestine can be expected to be denuded of cells in most mammals who have received a "gastrointestinal syndrome sized dose" in ________. for man this is typically up to 4 or 5 days post irradiation.

10. Regeneration in the Gastrointestinal Tract.

a. Even after extremely large doses of radiation not every crypt cell is going to be killed.

i. Some which remain will be severely damaged and unable to reproduce.

ii. Some which remain will be heavily damaged but still able to reproduce.

- These cells will form the nucleus on a focus of regeneration of the gut.

iii. Unfortunately, at gastrointestinal syndrome sized doses the attempt at regeneration is too little too late.

- At lower doses ranges, say between the hematopoietic and gastrointestinal syndrome ranges, _________ regeneration doses occur

iv. During regeneration the following occurs:

- There is an increase in the mitotic rate
- Epitheal linings of the crypt begin to be repopulated from the cells still capable of division.
- The newly regenerated cells begin to move into the villi to replace those that have been sloughed.
- New nest of cells start to appear, these represent new crypt.

v. If the dose is very low, clearly within the hematopoietic syndrome range, it is possible for regeneration of the whole intestinal lining to occur.

- However, this does not preclude death associated with ____________________.

11. The remainder of the small intestine undergoes a pattern of changes similar to those observed in the small bowel.

a. The main difference is that the changes occur more slowly so that, when death comes following a gastrointestinal syndrome sized dose, the large intestine is rarely completely denuded of its epithelium.

b. This is consistent with the renewal requirements and turnover of mature cells in the large and small bowels.

12. Fluids and Electrolytes:

a. When near death, animals experiencing the gastrointestinal syndrome, suffer from profound ________.

- The reduction in body fluids is so severe that the blood becomes exceedingly thick. Some observe that obtaining blood samples is even difficult in this situation.

b. Fluid loss/electrolyte imbalance is attributed to several concurrent items:

- ____.

-____________________. This prompts severe fluid loss.

* It is though that this is brought about by the inability of the distal end of the small intestine (distal ileum) to reabsorb bile salts and the resulting irritation of the colon by these salts.

* diarrhea has been prevented in irradiated animals clamping the bile duct.

- ____

13. Infections: Animals irradiated to dose-levels resulting in the gastrointestinal syndrome may be expected to become infection prone.

    - Infection plays a major role in causing the depth of animals exposed to large enough dose to cause the gastrointestinal syndrome.
    - In order to evaluate the potential for infection during the gastrointestinal syndrome one needs only consider the following state of affairs:

        * ____________________________________

        * ____________________________________

        * ____________________________________

14. Death occurs within 3 to 4 days for most mammals post irradiation when exposed to large enough radiation fields to deposit doses within the gastrointestinal syndrome range.

    a. Death is due to:

    - ____________________________
    - ______________________________
    - ______________________________

    b. The irradiated animal dies of __________________________

S. The Cerebrovascular Syndrome

1. The mean survival time post irradiation for a dose large enough to bring on the cerebrovascular syndrome is dose dependent.
2. The threshold for this syndrome for most species is in excess of 5000 rad.
3. The signs and syndromes elicited are characteristic of damage to the central nervous syndrome.
4. Manifestations of the Cerebrovascular syndrome include:

a. Periods of agitation alternating with remarkably apathetic behavior.
b. ____________________
c. upsets of equilibrium
d. loss of coordination of muscular movement (ataxia)
e. diarrhea
f. vomiting
g. tetanic spasms of the muscle of the back
h. ____________________

i seizures
j. prostration
k. _______________
l. death
m. salivation (occasionally)
n. diarrhea (occasionally)
o. oscillatory movement of the eyes - nystagmus (occasionally)

Histologic and Inflammatory Changes Observed During The Cerebrovascular Syndrome

A. Blood cells filter into the meninges.

1. In particular, one may observe the following formed elements within the meninges:
   a. Granulocytes
   b. mononuclear types
   c. macrophages

2. Along with the granulocytic infiltration, inflammation of the meninges is observed initially, increasing to a maximum, and then decreasing slightly

B. Inflammation of blood vessels and lymph tissues (vasculitis) may be observed a few hours after a high radiation dose.

1. Veins and arteries of all sizes undergo changes which involve infiltration of granulocyte in foci about the vessel.

2. Damage to blood vessels leads to changes in capillary permeability.

a. This results in leakage into the brain.

i. It is a question if the damages observed are critical to the death of the exposed individual or are incidental.

b. This leakage into the brain, edema, is responsible for some local cell damage.

c. There is an increased water content of the brain in those whose heads have been irradiated. This is reflected in changes in specific activity.

C. One observes profound alterations in the cerebrum:

1. The cerebellum, brain stem and spinal cord seem less involved.

2. Alterations appear first in gray matter, ultimately white matter becomes seriously involved.

D. The choroid plexuses are quickly affected by the radiation.

1. edema and infiltration of leukocytes occur soon after irradiation.

a. This is probably associated with the creation of micro-hemorrhages and necrosis.

E. The Immediate Cause of Depth

1. The exact cause of death from the cerebrovascular syndrome is not known for certain.

2. The Cerebrovascular Syndrome is truly a total body syndrome.

a. Segregated head doses without whole body exposures in the cerebrovascular syndrome range do not produce lethality.

3. Death is presumed to result from events taking place within the skull:
    a. swollen meninges
    b. damaged blood vessels
    c. blood leakage in the brain, edema and interracial pressure
    d. obvious damage to sections of the brain

4. Although many cells have received lethal doses of radiation there is no evidence of necrotic areas.
    a. Although neurons may have been lethally irradiated there does not appear to have been a loss of function prior to death, this does not therefore cause death.

Effects on Developing Embryos

A. The embryo probably represents the most radiosensitive stage in the life of any organism.

1. This is true for several reasons:

    a. Many of the cells in the embryo are differentiating
        i. According to Bergonie' and Tribondeau differentiating cells are highly radiosensitive.

2. There is a high rate of mitotic activity in the embryo, the embryo system is proliferative.

    a. Mitosis is a sensitive time of the cells life cycle.
    b. It can be generalized that the organ system undergoing differentiation will acquire great radiosensitivity.

3. The cells of the embryo will have a long ancestral future.

a. They serve as the ancestral cells to vast numbers of cells in the adult.
b. If an embryonic cell is killed, at any time in the development of certain embryos and after certain stages of development of nearly all embryos- the cells for which it would have been an ancestor will not be formed.

i. sometimes another cell can and will take over the functions of the lost cells.

ii. Embryo's are usually capable of much greater regeneration than those of adults.

- The loss of individual cells typically does not result in the loss of progeny functions but it will serve as a stress on the embryo.

- This stress is expressed as the observed smaller embryo size.

+ This smaller embryo will appear grossly normal however they will display both cytologic and histologic damage when examined closely.

* Their life span will be shortened.
* Certain behavioral performances will not be on par with their unirradiated peers.

4. There are several teratogenic agents other than ionizing radiation.

a. In most cases the abnormality produced is often more characteristic of and dependent upon the system developing when the embryo-deforming agent is used rather than upon the agent itself.

b. The reactions of the system (damage to the cells in it) will always be expressed in the same way - incomplete or abnormal development of the system.

5. Expected Developmental Abnormalities

a. Irradiation of the developing embryo before it becomes implanted into the uterus usually results in death rather than the production of abnormalities.

- It has been observed in mice that preimplanted cells are very sensitive to radiation exposure. At doses as low as 200 Rad in mice 80% of the preimplanted cells will die.

b. Irradiation of the embryo during organogenesis lads to malformations and to neonatal death (rather than prenatal death).

- Organogenesis occurs in humans between about the 7 to 12 week after fertilization.

For mice and rats the following table reflects the type of teratogenic effect expected if the exposure occurs at different times after fertilization:

Time Post Fertilization	Effect
Mice	
day 7 to 8	microphthalmia (tiny eyes) skeletal anomalies
day 9 to 10	coloboma (fissure of the eye) spina bifida occulta (a defect in the closure of the spinal cannel)

hernia, urogenital anomalies

Rats

day 9, 10, and 11 — anencephaly (the absence of cerebrum and cerebellum)
flat bones in the skull anophthalmia (missing eye or eyes)
hydrocephalus (fluid in and around the brain)

day 12 — microcephaly (pin head)
(this corresponds to the fourth week in humans)

c. During the first third of pregnancy the embryo is the most vulnerable.

d. In the second third it is less sensitive.

e. In the last third it is relatively resistant.

f. in utero exposure at Hiroshima and Nagasaki resulted in the following conditions:

i. mental retardation
ii. less than expected head circumferences
iii. strabismus (an abnormality of the eyes in which the visual axes do not meet at the desired objective point. This is felt to be consequence of in-coordinate action of extrinsic ocular muscles)
iv. Congenital malformations of the hips
v. increased incidence of congenital heart disease
vi. increased incidence of fetal death

Remember these observations are associated with very large acute exposures. These occurred primarily to survivors between than 1200-meters to 2000-meters to ground zero.

Treatment of Irradiated Organisms

A. Lethality associated with total-body irradiation induced syndromes has been ascribed to cells of all tissues of the body.

B. However, death is primarily from radiation damage to and failure of the cell renewal systems of the hematopoietic and gastrointestinal systems.

C. Therefore, a reasonable course of treatment may be to somehow mitigate the consequences associated with the failure of these two systems.

a. This assumes that the damaged can and will be eventually regenerated.
b. Additionally, it is assumed that both primary and secondary manifestations of acute radiation sickness can be treated.

D. The Treatment of Secondary Manifestations

a. The secondary manifestations which must be treated if even short-term survival is to be possible include:

1. the deficit in granulocytes (granulocytopenia)
2. the deficit of thrombocytes (i.e. platelets, red blood cells) - called thrombocytopenia
3. anemia
4. fluid loss
5. electrolyte imbalance

E. An organism receiving large doses of radiation is much more susceptible to infection by nearly any kind of bacteria this is correlated to:

a. The break down in various types of barrier tissues
b. The depression of granulocytes

F. For these reasons replacement therapy, the replacement of lost granulocytes via transfusion, in theory would seem to mitigate the consequences of the bacterial infection following lethal exposure.

a. The actual application of this, however, has produced somewhat disappointing results.

i. This is thought to be associated with the short half-life of mature granulocytes in man, between 6 and 8 hours.

ii. The implication of this short half-life is that if transfusion is going to be useful copious numbers of granulocytes will have to be introduced into the exposed individual's system during the whole period of time granulocyte depression is experienced.

iii. The principle, nevertheless, is valid to modify the course and extent of infection.

G. Treatment of Infection with drugs.

a. Antibiotics may be used during the period of granulocyte depression to help control bacterial infection.

i. They should be administered at the first signs of fever.
ii. Because bacteria rapidly becomes resistant to antibiotics it is not unusual to observe secondary increases in temperature with time.
ii. It is recommended that combinations of bacteria

b. A combination of antibiotics and blood platelets has been used effectively in dogs to prevent death from massive radiation exposures.

c. Antibiotic therapy in general has shown mixed results.

i. In some instances it has been very effective, in other cases it was of limited, or nor observable, benefit.
ii. The principle, however, is valid.

H. Control of Hemorrhage

a. Even if granulocyte and antibiotic therapy is successful in avoiding infection the hazard of hemorrhage due to thrombocytes remains.

b. A treatment to prevent lethal hemorrhage involves platelet transfusion.

i. The difficulty is that platelets rapidly loose the qualities needed in the treatment of radiation exposure.
ii. When repeated transfusions are performed the life of transfused cells decreases and the transfusion becomes less and less effective.

- This is associated with the development of antibodies in both the radiated and unirradiated host which agglutinate and destroy the transferred cells.

- The platelets of mammals typical have a life of about 5 days.

I. Treatment of Dehydration

a. During the late portions of the gastrointestinal syndrome the gut becomes denuded of cells. This is accompanied by severe fluid loss.

b. This severe water loss must be compensated for if time is to be given to the gut lining to replenish itself.

c. Fluid replacement combined with antibiotic therapy is useful.

i. Dogs which have received large acute doses of radiation have enhanced survival rates and survival times following this treatment if administered slightly before the start of infection.

J. Bone-Marrow Replacement

a. The transfusion of bone-marrow cells to lethally irradiated individuals may confer benefit to irradiated individuals.

b. The degree of success experienced with bone marrow transplants is associated with the quantity of marrow transplanted.

i. The more marrow transplanted the higher and more rapid the success.

c. The problem is finding an acceptable source of unirradiated marrow. A genetically appropriate donor is necessary.

d. Autotransplants, using the irradiated individuals own marrow obtained prior to irradiation are expected to be successful.

e. Chernobyl experiences with bone-marrow transplants were not encouraging

K. In general the treatments of radiation syndrome are treatments of the signs and symptoms.

a. The goal is to prolong the window of opportunity for regeneration of damaged tissues.

i. The damage, nevertheless, has occurred in the individual and despite treatment may often be to extensive to avoid death.

ii. With treatment, suffering can be reduced even if the patient has little chance for survival.