Environmental Radioactivity

expanded from LA-UR-00-502, Mike McNaughton, Los Alamos National Lab.

Outline

This course is an introduction to monitoring the environment for radioactivity.

Section 1 provides an introduction to the vocabulary and key concepts of radioactivity.
Section 2 discusses the four basic types of radiation: alpha, beta, gamma, and neutron.
Section 3 discusses the units used to measure radiation and radioactivity.
Section 4 discusses natural and anthropogenic radioactivity.
Section 5 discusses the biological effects of ionizing radiation.
Section 6 outlines the relevant regulations.
Section 7 instructs you how to keep exposure as low as reasonably achievable (ALARA).
Section 8 outlines the pathways of radioactive material from the lab. to the environment.
Sections 9 and 10 provide overviews of uranium and plutonium.
Section 11 discusses environmental monitoring.
Section 12 is a hands-on exercise in the use of detectors.

Each section contains questions. As part of the learning process, please pause and think about these questions. The questions serve two purposes.

- They ensure that you understand the key points before moving on.
- They make the process active; it is easier to learn by playing a game than by watching it.

Time will be allocated for discussion and hands-on exercises. As much as possible, this course should lead to dialog among the participants.

Numerical data

Numerical data are essential to this course. From a scientific perspective, we cannot say "radioactivity is safe" or "radioactivity is dangerous" without specifying how much radioactivity.

Pictures

This course needs pictures. I would appreciate your suggestions. In fact, I would appreciate your suggestions and comments on all topics. You may contact me
by phone: (505)667-6130; or
by email: mcnaught@LANL.gov

Note for information about tritium, see:
http://eshtraining.lanl.gov/esh13/esh13_documents/11952.pdf

1. Introduction

Objective: establish a common vocabulary for discussions about radioactivity.

1.1 Atoms

All matter consists of atoms. Atoms are made of three types of particles: *protons*, *neutrons*, and *electrons*. The protons and neutrons are in the atomic nucleus, at the center of the atom. The electrons surround the nucleus.

The number of protons, neutrons, and electrons determine the type of atom.

In its usual, neutral state, an atom has an equal number of protons and electrons. This number is called the *atomic number*, Z. For example, hydrogen always has one proton and one electron, so Z=1. Similarly, for nitrogen, Z=7; for iron, Z=26; and for uranium, Z=92, etc.

The atomic number, Z, determines the type of *element*. Atoms of the same element have the same chemical properties. For example, every atom with Z=26 is iron and behaves the same whether it is in steel, rust, or hemoglobin.

Each element has a unique symbol consisting of one or two letters. For example, hydrogen is H, nitrogen is N, iron is Fe, and uranium is U.

1.2 Isotopes and Nuclides

The number of neutrons does not affect the type of element, but it may affect the radioactive properties. Atoms of the same element but with different numbers of neutrons are called *isotopes*. For example, hydrogen has three isotopes: most hydrogen atoms have no neutrons; deuterium is an isotope of hydrogen with one neutron; tritium is an isotope of hydrogen with two neutrons.

Note that isotopes are not always radioactive. For example, deuterium is not radioactive.

If we want to specify both the element and the isotope, we need to specify the number of protons and the number of neutrons, as follows.

> First, we write the element symbol, e.g., H for hydrogen; this specifies the number of protons, which is equal to the atomic number, Z.
>
> Next, we specify the number of neutrons (N) plus protons (Z). This is called the *mass number* (A) because it determines the mass of the atom.

$$A = N + Z$$

For example, tritium has one proton and two neutrons so its mass number is 3. We write tritium: ^{3}H, or H-3, or hydrogen-3.

The word "*nuclide*" is sometimes used instead of "isotope". A nuclide is a type (or species) of nucleus with a specific number of neutrons and protons. for example, the nuclide with exactly one proton and two neutrons is tritium. Tritium is also an isotope of hydrogen because it has the same number of protons (Z=1) as hydrogen.

Note: when we say "isotope", we must specify the element, e.g., "isotope of hydrogen".

Radionuclide is short for radioactive nuclide.

Demonstrations: show a periodic table of the elements and a chart of the nuclides.

Discussion: What elements are familiar? Where are they on the periodic table and the chart of the nuclides? What radionuclides are familiar? What are they used for?

Viewgraph

- Atoms: protons, neutrons, and electrons
- Atomic number, Z:
  - number of protons
  - (number of electrons)
- Element: unique Z
- Element symbol
- Isotope: number of neutrons, N
- Mass number: A = N + Z
- Nuclide: specific A, N, and Z

Review

We have discussed the following key concepts. It is important to understand them before moving to the next section. For each concept, try writing some key points that you can think of or find in the previous section. Then answer the practice questions on the next page.

atom

proton

neutron

electron

atomic number, Z

element

element symbol

isotope

nuclide

mass number

Practice Questions

1. Atoms are made of which three types of particles?
a. protons, neutrons, and electrons
b. elements, nuclides, and isotopes
c. alphas, betas, and gammas

2. The number of protons in the atom determines the type of
a. neutron
b. mass number
c. element

3. The atomic number, Z, is equal to the number of ______ in the atom.
a. neutrons
b. protons
c. neutrons plus protons

4. The mass number is equal to the number of ______ in the atom.
a. neutrons
b. protons
c. neutrons plus protons

5. Different isotopes of an element have different numbers of
a. protons
b. electrons
c. neutrons

6. Which of the following is a way of writing an isotope of uranium?
a. U
b. UO_2
c. ^{238}U

7. Symbols such as H, Fe, Au, or U specify a particular
a. isotope
b. nuclide
c. element

8. Which word means a type of nucleus with a specific number of neutrons and protons?
a. electron
b. nuclide
c. element

9. For nitrogen, Z=7. How many neutrons are in each nitrogen-14 (N-14) atom?
a. 1
b. 7
c. 14

1.3 Radiation

Radiation is energy in the form of particles or waves that travels from one object to another. For example, sunlight is radiation that travels from the Sun to the Earth.

1.4 Ionization

To understand how radiation affects matter, you must first understand the process of ionization. *Ionization* is the process of removing electrons from atoms to make charged atoms called *ions*.

Normally, atoms have an equal number of protons (+ charge) and electrons (- charge) so the total charge is zero. If enough energy is supplied to remove electrons from the atom, the remaining ion has a positive charge.

Too many ions in human tissue can cause sickness. This is discussed in section 5.

1.5 Ionizing Radiation

Radiation that causes ionization is called *ionizing radiation*. Examples of types of ionizing radiation are:
- alpha particles,
- beta particles, and
- gamma rays.

Radiation that does not cause ionization is called non-ionizing radiation. Examples of non-ionizing radiation are:
- radar,
- radio waves,
- microwaves, and
- visible light.

Note that non-ionizing radiation such as microwaves can cause harm. However, because it is not ionizing radiation, it causes harm in a different way from ionizing radiation.

The particles in ionizing radiation are like speeding bullets; neither the particle nor the bullet is in itself dangerous; however, the energy resulting from their speed is dangerous. After the particle stops, it becomes harmless.

1.6 Radioactive Atoms

Some atoms have too many or too few neutrons for their given number of protons. The resulting atoms are not stable. The unstable atoms will become stable by giving off excess energy in the form of ionizing radiation.

These unstable atoms are known as *radioactive* atoms. They emit ionizing radiation.

For example, tritium has two neutrons and one proton. This is too many neutrons for the given number of protons, so tritium is radioactive. It emits ionizing radiation, in the form of a beta particle, to become stable.

The beta particle can cause harm by ionizing atoms in its path, until it eventually stops and becomes a harmless electron. After emitting the beta particle, the tritium becomes helium, which is also harmless.

- A radioactive atom is like a live bullet waiting to go off.
- When it goes off, the radiation is like a speeding bullet, which can cause harm.
- After it stops, the particle is like a spent bullet and is harmless.

1.7 Radioactive Material and Contamination

Radioactive material is material (or matter) containing radioactive atoms. Radioactive material emits ionizing radiation.

Radioactive contamination is radioactive material in an unwanted location; it is outside its proper storage place in the lab. For example, contamination might be in the air, soil, or water in the environment.

It is important to distinguish radioactive material from radiation, as follows.

Radioactive material is matter	Radiation is energy
Radioactive material is like a box of live bullets	Radiation is like speeding bullets
Radioactive material is like glowing charcoal	Radiation is like the heat emitted

Demonstration: laser, infrared lamp, microwave oven, radio or cell phone, radioactive material and detector(s). Question: when is a stone dangerous?

Discussion: What types of radiation are familiar? Which are hazardous? How are they hazardous? Which are ionizing?

Viewgraph

- Radiation
- Ionization, ion
- Ionizing radiation
  - alpha, beta, gamma
- Nonionizing radiation
- Radioactive atoms
- Radioactive material
- Radioactive contamination

Review

It is important to understand the following concepts before continuing. It is especially important to distinguish radiation from contamination. Try writing the key points for each concept. Then answer the practice questions, below.

radiation

ionization

ionizing radiation

radioactive material

radioactive contamination

Practice Questions

1. Radiation is a form of
a. energy
b. material
c. isotope

2. Contamination is
a. energy
b. material
c. radiation

3. The process of removing an electron from an atom is called
a. contamination
b. ionization
c. radiation

4. Which of the following is an example of non-ionizing radiation?
a. alpha particle
b. beta particle
c. gamma ray
d. radio wave

5. Which of the following is an example of ionizing radiation?
a. radio wave
b. microwave
c. visible light
d. gamma ray

6. Which of the following is like a speeding bullet, it is hazardous because of its speed but after it stops it is harmless?
a. radioactive material
b. radioactive contamination
c. radiation

7. Radioactive material in an unwanted location is called
a. radiation
b. ionization
c. contamination

1.8 Half Life

The *half life* is the time it takes for one-half of the material to decay or disintegrate. This concept applies to radioactive material that decays by emitting ionizing radiation and to the radiation itself, because the radiation is always proportional to the amount of material. The concept also applies to chemicals such as pesticides and herbicides that decay by changing into other chemical compounds, and to chemicals that are removed from the body in urine. You could even apply it to buildings that decay or disintegrate by the actions of wind and rain and eventually become ruins like those at Chaco Canyon.

Game

To illustrate the mathematics, take 16 coins to represent 16 radioactive atoms. Shake them in your hand, and throw them on a table. On average, half should show heads and half tails. Assume 8 show heads and have disintegrated; they are out of the game so remove them.

Take the remaining 8 coins, shake them, and throw again. On average, 4 should show heads and 4 tails. Those that show heads are out of the game. Take the remaining 4 that showed tails and shake again.

Each shake is like one half life. After one half life, half the original number of atoms remains; after two half lives, one quarter remains; after three half lives, one eighth remains; and so on.

Calculation

To calculate the amount of material, A, remaining after time t, use the following equation.

$$A = A_0\, 0.5^{-t/h}$$

A_0 is the amount of material at time $t = 0$ and h is the half life.
Note: A must be in the same units as A_0 and t must be in the same units as h.

Exercise: use a scientific calculator or a spreadsheet program such as Excel to make a table and a graph of A versus t. Assume A_0 is 1024 grams and calculate A for $t = 0, h, 2h, 3h, 4h$, etc.

The same equation can be used for any type of half life. With radioactive material, it can be used to calculate the amount of material, for example if A and A_0 are in grams. It can also be used to calculate the activity or the amount of radiation if A and A_0 are in any of the units discussed in Section 3.

Radioactive half life

Each type of radioactive nuclide has a characteristic half life. For example, the half life of tritium is 12 years, and the half life of plutonium-239 (Pu-239) is 24,000 years. The half life of every radioactive nuclide is listed in the Chart of the Nuclides:

http://www2.bnl.gov/CoN/ or http://ie.lbl.gov/toibook.html .

Which is more hazardous, a radioactive material with a short half life or a long half life? For example, Pu-238 has a half life of 88 years and Pu-239 has a half life of 24,000 years. Pu-239 persists for a longer time so this might suggest it is more hazardous; but because Pu-238 emits all its radiation in a shorter time, its radiation is more intense, so it is more hazardous.

On the other hand, consider oxygen-15, which is emitted from the Los Alamos Neutron Science Center, LANSCE into the air and is carried with the wind. Oxygen-15 has a 2-minute half life, so its radiation is very intense for a while, but by the time it reaches populated areas it is almost all gone, so it is not hazardous. In summary, there is no easy answer.

We also refer to *biological half life.* Following an intake of radioactive contamination, the biological half life is the time for one half of the atoms to be removed from the body by natural biological processes. For tritium, this time is 10 days. For plutonium, it is 200 years. Thus, if plutonium gets into a human body, most of it is there for life.

Chemicals also have a half life. For example, the pesticide DDT has a half life in the environment of about 20 years. You can still find DDT in places that were sprayed 60 years ago, though 7/8 of the material has decayed to other chemical forms.

Materials: the game needs 16 coins per person
Discussion: make a list of radioactive nuclides you have heard about and find their half lives. Which are of the most concern to you?
Lab: collect radon decay products on a balloon and measure the half life.

Practice questions

1. The half life of Cs-137 is 30 years. What fraction remains after 60 years?
a. ½
b. ¼
c. 0

2. The biological half life of uranium in bone is about 1 year. If 1,000 atoms of uranium are in a bone, how long will it be before there are 125 atoms of uranium remaining?
a. 1 year
b. 2 years
c. 3 years
d. 8 years

1.9 Confidence level

If we take 100 coins and play the “half-life game” described in the last section, do we get exactly 50 coins showing heads and 50 showing tails? The answer is no; we sometimes get 60 and 40. However, 70 and 30 is unlikely.

Statistics allows us to predict results that are likely and those that are unlikely. We usually write the expected number of coins that show heads as:

50 ± 10 with a 95% confidence level.

This notation means: statistics predicts a result between 50–10 and 50+10 (i.e., between 40 and 60) 95% of the time. 5% of the time the result will be greater than 60 or less than 40. However, only 0.01% of the time will the result be greater than 70 or less than 30.

If we start with 100 coins and shake 6 times, each time removing the coins that show heads, we will likely have a coin that still remains after 6 shakes, having come up tails every time. It might even survive for several more shakes. Is this coin a special, lucky coin because it showed tails every time? The answer is no, this happens sometimes.

Unusual events can be thought of as "statistical storms". Meteorologists predict the chance of a storm, but they are sometimes wrong.

Every measurement in science has an uncertainty associated with it. Professional scientist estimate the uncertainty and include it with their answer.

One way to estimate the uncertainty is to ask several people to measure the same quatity using methods and apparatus that are as independent as possible. A scientific calculator or a spreadsheet program such as Excel can then be used to calculate the average and standard deviation.

In summary, randomness is expected. Statistics predicts how much randomness to expect.

Exercise: use the results of the half-life game in Section 1.8 to calculate the average and standard deviation for each step in the game.

Demonstration: compare the rhythm of metronome and a radiation detector.

Discussion: how do the uncertainty and confidence level apply to the incidence of cancer in a town? Does it matter if the town is large or small?

Lab: Use a handheld detector to obtain several measurements of natural radioactivity, and calculate the mean, the standard deviation, and the uncertainty with the required confidence level.

Practice Questions

1. If a scientist says the number of elk in Los Alamos county is 200 ± 20 with a 95% confidence level, this means the number is
a. certainly less than 220
b. certainly less than 180
c. probably less than 220
d. probably less than 180

2. If a public school has exactly 1,000 students and a mathematician is asked to estimate, with a 95% confidence level, the number of girls at the school, which answer is most likely?
a. 500 ± 0
b. 500 ± 30
c. 500 ± 500

3. If an exact count is taken later and it is determined there are actually 535 girls at the school, would this show the mathematician is incompetent?
a. yes
b. no

2 Types of Radiation

Objective: distinguish the four basic types of radiation.

There are four basic types of ionizing radiation:
- alpha,
- beta,
- gamma, and
- neutron.

Each has distinct properties.

2.1 Alpha

Each alpha particle consists of two protons and two neutrons and is identical with the nucleus of a helium atom. Like a speeding bullet, when it is moving rapidly it can do harm by ionizing atoms but once it stops it becomes ordinary helium which is harmless. In fact, the helium used to fill balloons comes from alpha particles emitted long ago by natural radioactive materials such as uranium.

Alpha particles do not travel far before they stop. In air, they travel 1-2 inches. In skin, they travel 1-2 thousandths of an inch. This is less than the thickness of skin, so alpha particles cannot penetrate the skin. They are completely stopped by skin, paper, or clothing.

By analogy with a gun, the maximum distance is called the *range*.

As a result of their short range, alpha particles are not an *external* hazard, i.e., they are not hazardous if they remain outside the body. They are, however, an *internal* hazard, they are hazardous if radioactive material gets inside the body. Internal and external hazards will be discussed later.

2.2 Beta

Each beta particle consists of a speeding electron. When it is moving rapidly, it can do harm by ionizing atoms, but once it stops it is no different from any other electron in matter; once it stops, it is harmless.

Beta particles travel about 20 feet in air; in fat or muscle they travel about a quarter of an inch. If the radioactive material is outside the body, betas can damage the skin but not the internal organs, which are more than half an inch deep.

Beta particles are shielded by about half an inch of a solid material such as soil, plastic, wood, or metal. Almost any wall contains enough material to stop betas.

Strictly speaking, there are two types of beta: beta-plus and beta-minus. The beta-plus is also called a positron. The difference is not important for this course. Beta-plus particles are unusual, and behave much like beta-minus particles.

2.3 Gamma

Gammas may be called gamma rays or gamma photons; in some ways, photons are like particles, but this detail is not essential for this course.

Gammas are the same as x rays. The difference is only in how they are produced. Gammas come from the protons and neutrons in the atomic nucleus, x rays come from the electrons in the atom. Once they leave the nucleus or the atom, gammas and x rays are the same.

Gammas and x rays consist of electromagnetic energy. Like alphas and betas, they cause harm while they are traveling, but once they are absorbed into matter, they become harmless.

Some gammas and x rays are more penetrating than others.

At most industrial and medical facilities, gammas are generally more penetrating than x rays, but there are exceptions. For example, the gammas from plutonium are less penetrating than the x rays used by dentists, whereas the x rays used to look inside a nuclear weapon are more penetrating than the gammas used to examine steel at a factory. In summary, assume gammas and x rays are essentially the same, but ask: how penetrating are they?

Gammas and x rays from plutonium are easily shielded by a sheet of lead, like that inside the walls of the x-ray room at a hospital or the cabinet of the x-ray devices at the airport. However, gammas and x-rays from devices used to look inside a weapon must be shielded by a concrete wall, several feet thick.

2.4 keV and MeV

The character of gammas and x rays is specified in keV or MeV; 1 MeV = 1,000 keV. This is similar to how a radio station is specified in kilohertz (kHz) or megahertz (MHz): KRSN is 1490 kHz, KUNM is 89.9 MHz, and KHFM is 96.3 MHz.

The number of keV or MeV determines how penetrating the gamma or x ray is.

For example:

- 40 keV x rays are used at a hospital to take pictures of soft tissue and are shielded by 1/16 inch of lead;
- 70 keV x rays are used by dentists to take pictures of teeth and are shielded by ¼ inch of lead;

- 1 MeV (1,000 keV) x rays or gammas are used to take pictures through the steel casing of a weapon and are shielded by several inches of lead.

MeV and keV can also refer to alphas, betas, and neutrons. Briefly:
- there is very little difference among alphas so it is generally not important;
- some betas are less penetrating and therefore difficult to detect, e.g., tritium;
- neutrons are complicated and not usually found in the environment.

We will return to these details in later sections.

2.4 Neutrons

Neutrons are generally the most penetrating of all the types of ionizing radiation. They are shielded by several feet of concrete or earth.

There are only a few areas of Los Alamos where measurable amounts of neutrons are emitted, most notably: technical areas (TA) #18 and #53.

In section 8, we will discuss the use of time, distance, and shielding to keep the dose from penetrating radiation as low as reasonably achievable, ALARA.

2.5 Summary

The four types of radiation, from least penetrating to most penetrating, are: alpha, beta, gamma, and neutron. Their penetrating ability is summarized by the following table which gives the typical amount of shielding.

Type	**Typical Shielding**
Alpha	1-2 inch air, skin, paper, cloth
Beta	Half-inch of muscle, fat, or almost any wall
Gamma	special wall, e.g., a lead-lined wall
Neutron	3 ft thick wall

Demonstration: radioactive sources, detectors, and typical shielding materials; show how alphas are stopped by paper or 1-2 inches of air.

Discussion: Which type of radiation is more hazardous? Are gammas more hazardous than x rays? What are some typical sources of the various types of radiation?

Viewgraphs

Alpha:	short range
Beta (or positron):	medium range
Gamma or x ray:	long range
Neutron:	most penetrating

Internal or external hazard

Picture of skin

Gammas and x rays: how penetrating are they?
40 keV: soft tissue medical x ray
70 keV: dental x ray
1 MeV: steel casing of a weapon

Lab: Use handheld detectors to measure the range and attenuation of different types of radiation.

Practice Questions

1. Alpha, beta, gamma, and neutron, are types of
a. element
b. radioactive contamination
c. radioactive material
d. radiation

2. Which of the following travels only 1-2 inches in air and cannot penetrate the skin?
a. alpha
b. beta
c. gamma
d. neutron

3. Radiation that is not a hazard if the radioactive material remains outside the body but is a hazard if the material gets inside the body is described as an
a. outside hazard
b. external hazard
c. internal hazard

4. Which of the following is not an external hazard but can be an internal hazard?
a. alpha
b. x ray
c. gamma
d. neutron

5. Which of the following travels only about 20 feet in air and only about ¼ inch in fat or muscle?
a. alpha
b. beta
c. gamma
d. neutron

6. Which of the following is completely shielded by about half an inch of solid material such as a wooden wall?
a. x ray
b. beta
c. gamma
d. neutron

7. Gammas are essentially the same as
a. alphas
b. betas
c. neutrons
d. x rays

8. Which is most likely to be used in a hospital to look for tumors inside soft tissue?
a. 40 keV alphas
b. 40 MeV alphas
c. 40 keV x rays
d. 40 MeV x rays

9. which is most likely to be used to take pictures inside a nuclear weapon?
a. 1 keV alphas
b. 1 MeV alphas
c. 1 keV gammas
d. 1 MeV gammas

10. Which is the most penetrating?
a. alphas
b. betas
c. positrons
d. neutrons

3. Quantities and Units

Objective: understand how radiation and radioactivity are quantified and reported.

If you ask: "how much?", the answer "eight ninety five" is ambiguous unless you know the units, e.g., \$8.95, \$895, or 895 Francs. Similarly, when measuring radiation or radioactivity, you must state both the number and the units.

Radiation and radioactive material are measured with different units.

3.1 Measuring Radiation

Radiation is measured in units of R, rad, or rem. As a first approximation, assume they are approximately the same:

$$1 \text{ R} = 1 \text{ rad} = 1 \text{ rem}.$$

Experts say 1 R equals 0.88 rad in air, 0.96 rad in muscle, and 0.97 rad in water, but this detail is not usually important because the uncertainty in the measurement is usually larger than this.

1 rad can be as much as 20 rem, but in this case the value is reported in rem, which is the unit we are really interested in. The letter "e" in rem stands for "equivalent"; the equivalent or effective dose is best measured in rem.

In later sections we will return to the question of why R, rad, and rem are sometimes different.

Specialists say R is used for "exposure", rad for "dose", and rem for "dose equivalent" or "equivalent dose". In this course, we will use one word, dose, for all three.

It is very important to notice the prefix: m for milli or µ for micro;

m means a thousandth,

µ means a millionth.

Thus mrem means milli-rem, which is a thousandth of a rem, and µrem means micro-rem, which is a millionth of a rem.

It may be helpful to visualize distances of a meter, a millimeter, and a micrometer. A meter is about a yard, a millimeter is about the thickness of the letter **I**, and a micrometer is the about smallest you can see with the best optical microscope.

Just as "miles" are different from "miles per hour", so too "mrem" is different from "mrem per hour".

Exercise: if you drive at 60 miles per hour for 3 hours, how far will you travel?
If you receive 60 mrem per hour for 3 hours, how much dose will you receive?

The international units are gray, Gy, and sievert, Sv.

1 Gy = 100 rad
1 Sv = 100 rem

The metric prefix c means "1/100" so we can write

1 rad = 1 cGy
1 rem = 1 cSv

3.2 Measuring Radioactive Material and Contamination

The amount of radioactive material is measured by its *activity*, i.e., its rate of radioactive disintegration. For example, we often measure the number of "disintegrations per minute", dpm, or "disintegrations per second", dps.

The international unit for radioactive material is the becqerel, Bq:

1 Bq = 1 dps = 60 dpm

Another common unit for radioactive material is the curie, Ci. These units are often written with metric prefixes:

1 Ci	= 1E0 Ci	= 37E9 Bq	= 2.22E12 dpm
1 mCi	= 1E-3 Ci	= 37E6 Bq	= 2.22E9 dpm
1 µCi	= 1E-6 Ci	= 37E3 Bq	= 2.22E6 dpm
1 nCi	= 1E-9 Ci	= 37 Bq	= 2,220 dpm
1 pCi	= 1E-12 Ci	= 37 mBq	= 2.22 dpm
1 fCi	= 1E-15 Ci	= 37 µBq	= 0.0022 dpm
1 aCi	= 1E-18 Ci	= 37 nBq	= 0.0000022 dpm

Exercise: if you have 1 aCi of radioactive material, how long would you expect to count the material before you detected one disintegration?

Demonstration: meter stick marked in mm. Detectors marked with various units.

Discussion:
Why do different detectors use different units?
Why do we need different units for radiation and contamination?
Is it possible to convert from one set of units to another, e.g., $ to Francs, cpm to dpm, dpm to rem, etc.?
Does it make sense to measure all types of radiation with one unit, the rem? Is 1 mrem from a medical x-ray device the same as 1 mrem from a radiation source at Los Alamos?
Are hazards best expressed in mrem or in mrem/h?

Viewgraph

Measuring Radiation
First approximation, assume: 1 R = 1 rad = 1 rem

m	milli	1/1,000
µ	micro	1/1,000,000

- Sv, Gy
- Measuring Radioactive Material and Contamination
  - dpm, dps, Bq, Ci
  - metric prefixes

Lab: Use handheld instruments and NEWNET to compare and convert data measured in various units.

Practice Questions

1. Which is the smallest?
a. 1 rem
b. 1 mrem
c. 1 μrem

2. The size of a grain of sand is about
a. 1 meter (1 m)
b. 1 millimeter (1 mm)
c. 1 micro-meter (1 μm)

3. The size of the smallest object that can be seen with an optical microscope is about
a. 1 meter (1 m)
b. 1 millimeter (1 mm)
c. 1 micro-meter (1 μm)

4. Which is used to measure the dose (or strictly the dose equivalent) from ionizing radiation?
a. rem
b. cpm
c. cps
d. dpm

5. Which is used to measure the amount (or activity) of radioactive material?
a. rem
b. rad
c. R
d. dpm

6. cps, cpm, and dpm are all used to measure the amount of
a. dose
b. dose equivalent
c. radiation
d. radioactive material

7. R, rad, and rem are all used to measure the amount of
a. ionizing radiation
b. non-ionizing radiation
c. radioactive material
d. radioactive contamination

Estimating radiation from a point source.

Radiation travels from a source, such as radioactive material, and travels in all directions until it hits a "target", such as a person. If we know the number of curies, C, of radioactive material, we can estimate the number of rad/hour, H, using the equation

$$H = 0.5\ CE/r^2$$

E is the number of MeV emitted per disintegration and r is the number of meters from the source to the target.

For example, what is the dose rate, H, from C=4 Ci of Cs-137, for which E=0.5 MeV? The answer is listed in the table as a function of the distance, r.

r (meters)	H
1	1 rad/h
10	10 mrad/h
100	100 µrad/h
1,000	1 µrad/h

Distance is very effective at reducing the dose. Almost every quantity decreases in this way as the distance increases. For example: as you increase the distance from a light source, the light decreases; and as you increase the distance from a speaker, the sound decreases.

3.3 Calculating radiation from contamination

It is possible to calculate the amount of gamma radiation that will result from contamination in the ground or air. If you only want the simple conclusion, skip the derivation in the next paragraph.

C is the concentration in Ci/kg and *E* is the energy in MeV/disintegration. Multiply *C* by 37E9 to convert Ci to Bq and by 3600 to convert s to h. Multiply *E* by 1.6E-13 to convert MeV to joules (J). *CE* is now in J/(kg•h), which is the definition of Gy/h, so multiply by 100 to convert to rad/h. If the ground is below and the air is above, each is a hemisphere so divide by 2. The resulting conversion factor for either the ground or the air is 1066.

The simple conclusion is: if
C is the concentration in **Ci/kg**, and
E is the energy in **MeV/disintegration**, then
1066*CE* is the dose rate in **rad/h**.

Air at high altitudes has a density of 1 kg/m^3 so 1 Ci/kg is 1 Ci/m^3. Therefore if
C is the airborne concentration in **Ci/m^3**, and
E is the energy in **MeV/disintegration**, then
1000*CE* is approximately the dose rate in **rad/h**.

Finally, here are the values of *E* for various materials.

Natural thorium with all its decay products:	*E* = 2 MeV
Natural uranium with all its decay products:	*E* = 1.5 MeV
Natural radon with all its decay products:	*E* = 1 MeV
Mixed fission products:	*E* ≈ 1 MeV
Cesium-137:	*E* = 0.56 MeV
Potassium-40:	*E* = 0.15 MeV
Enriched uranium:	*E* = 0.1 MeV
Americium-241:	*E* = 0.02 MeV
Depleted uranium:	*E* = 0.01 MeV
Plutonium with ≈5% Americium-241:	*E* ≈ 0.001 MeV.

3.4 Typical radiation from radioactive material in the environment

Here are some typical concentrations, *C*, and the resulting external gamma radiation.

Radioactive material	*C*	μrad/h
Natural potassium in the earth	25 pCi/g	4
Natural thorium in the earth	2 pCi/g	4
Natural uranium in the earth	2 pCi/g	3
Cs-137 in DP Canyon (Los Alamos)	2 pCi/g	1
Radon in the air	1 nCi/m^3	1

Note that *external* radiation is not normally the important health hazard from contamination. The important hazard is *internal* dose, which happens if the contamination gets inside you. This is discussed in sections 4.3, 4.4, and 7.1.

The point of sections 3.3 and 3.4 is that hand-held detectors that measure gamma radiation are not suitable for measuring contamination.

In summary, radiation (see sections 1.3 and 1.5) should be thought of separately from contamination (see section 1.7).

Exercise
Select data from the Environmental Surveillance Report and calculate the external radiation.

Discussion
Why are the results in sections 3.3 and 3.4 in rad instead of rem? Hint: these calculations only yield part of the dose.

Lab
Measure actual dose rates and compare with calculations.

Practice Questions

1. Internal dose happens
a. if contamination gets inside you
b. if contamination stays outside you
c. only when there is external radiation
d. only when it can be measured with a hand-held detector

2. Why should you think about radiation and contamination separately?
a. they are normally measured in different units
b. they are normally measured with different detectors
c. the hazard from one might be small while the other is large
d. all of the above

4. Natural and Artificial Radioactivity

Objective: identify the origins and typical amounts of natural and artificial radioactivity.

The Earth is a radioactive planet and always has been. Humans have always lived in the presence of radiation from natural sources. The four major sources of natural radiation are discussed below; these are

- cosmic radiation (from outer space),
- terrestrial radiation (from the earth),
- internal sources (from food), and
- radon.

This is followed by a discussion of four major types of artificial radiation:

- medical,
- consumer products,
- nuclear weapons, and
- industrial uses.

Artificial radioactivity is sometimes called “manmade” or “anthropogenic” radioactivity. Naturally occurring radioactive material is called by the acronym NORM.

4.1 Cosmic Radiation

Cosmic radiation comes from the Sun and distant stars. High-speed particles are emitted from the Sun and stars and hit the Earth’s atmosphere, which acts as a partial shield. At sea level, the dose rate to each individual is about 3 μrem/hr. At higher altitudes, the amount of atmospheric shielding is less so the dose is more. At Los Alamos, the dose rate is 7 μrem/hr; on a 10,000-ft mountain it is 10 μrem/hr; and in an airplane at an altitude of 12 km and a latitude of 50 degrees it is about 500 μrem/hr. The following equation was used by Bouville and Lowder (Rad. Prot. Dos. 24(1988)293) to calculate the dose rate, H, in μrem/hr as a function of the altitude, z, in km.

$$H = 3.2[0.21\exp(-1.649z)+0.79\exp(0.4528z)]$$

The dose rate from neutrons is not normally included in these estimates because it is small and has not been measured precisely. It is estimated to be 1 μrem/hr at sea level and 2 μrem/hr at an altitude of 2 km.

Most cosmic rays are high-energy muons, which can penetrate a meter of lead shielding. Even inside a lead storage vault, the dose rate from cosmic-ray muons is about 3 μrem/hr.

4.2 Terrestrial Radioactivity

Terrestrial radioactivity refers to the activity of natural radioactive material in the soil, primarily uranium, thorium, and potassium. These have very long half-lives. They were formed when the Earth formed, and have not yet decayed.

When uranium and thorium disintegrate, the decay products are also radioactive. The products of radioactive disintegration are called decay products, or sometimes daughters. For example, two of the decay products of uranium are radium and radon.

In the US, the average dose rate from terrestrial radioactivity is 3 µrem/hr. The western part of the US has larger amounts of natural potassium, uranium and thorium in the soil, so the average terrestrial dose rate in New Mexico is about 10 µrem/hr. In Los Alamos, natural uranium and thorium concentrations range from 0.7-3 pCi/g and potassium-40 ranges from 12-30 pCi/g, which results in terrestrial radiation from 5-15 µrem/hr.

There are parts of the world where the dose rate is higher. For example, in Kerala, India, 100,000 people live in a region where the terrestrial dose rate is more than 100 µrem/hr, and the dose rate from the monazite sands on some beaches of Espirito Santo, Brazil, and near Ramsar, Iran, is about 1 mrem/hr. The people who live in these areas have been examined and no increase in cancer has been found.

The terrestrial dose rate depends on the shape of the ground. In a canyon, terrestrial radiation comes from the canyon walls as well as the floor. In the canyons of the Pajarito Plateau, the typical terrestrial dose rate is about 15 µrem/hr.

4.3 Internal Radioactivity

All living things contain natural potassium-40, which is radioactive. Food, which is derived from living things, contains potassium-40, and so our bodies contain potassium-40. Radioactivity inside the body is called *internal radioactivity.* All humans receive about 4 µrem/hr from internal radioactivity, most of which is from potassium-40.

4.4 Radon

Radon comes from the radioactive decay of natural uranium and thorium, which are present in all soil. Because radon is a gas, it diffuses from the soil and collects in buildings and homes from where it gets inside the body. The average dose rate to each person in the US from radon decay products is about 20 µrem/hr.

The largest concentrations of radon occur when the gas is trapped in a building, cave or mine. Concentrations vary by more than a factor of 100, depending on the air circulation.

Typical outdoor concentrations in the western US are about 0.5 nCi/m^3. During a hot summer day, the sun heats the ground, the hot air near the ground rises and radon is mixed throughout the troposphere, resulting in radon concentrations of about 0.1 nCi/m^3. Conversely, during an atmospheric inversion, radon is trapped near the ground, especially in a canyon, resulting in radon concentrations of more than 1 nCi/m^3.

Rain or snow fall sweeps radon decay products, which are attached to dust particles, down to the ground where an estimated concentration of 1 µCi/m^2 results in an external dose rate of up to 10 µrad/hr. The radon decay products in turn decay with a half life of less than 0.5 hours. Thus, during a rain or snow storm, the NEWNET data show a characteristic pattern: an increase of 1-10 µrad/hr followed by an exponential decay for one or two hours.

Although the external dose rate from radon can be calculated by the equation in section 3.3, the internal dose rate is more difficult to estimate. Most of the dose results from radon decay products such as polonium that stick to the bronchial epithelium or deeper in the lungs. In the early years of uranium mining, this problem was not recognized, and many miners in poorly ventilated mines suffered from lung cancer.

4.5 Medical

A typical radiation dose from a single chest x ray is about 10 mrem. The average person in the US receives the equivalent of several chest x rays per year from various medical procedures, including diagnostic x rays.

4.6 Consumer Products

Many common household items emit ionizing radiation. Modern televisions, luminous-dial watches, and smoke detectors result in dose rates less than 0.1 μrem/hr. Building materials such as granite contain natural uranium and thorium, resulting in individual doses of about 1 μrem/hr inside the building. On average, each person in the US receives about 1 μrem/hr from various consumer products.

4.7 Nuclear Weapons

Almost all the radiation received from nuclear weapons is from the radioactive fallout from nuclear weapons tests in the atmosphere. The earliest atmospheric test was in 1945 at White Sands, New Mexico. This was followed by tests at the Nevada Test Site, the Pacific islands, and many other places, mostly in the 1950s and early 1960s. Later tests were underground and therefore released much less radioactivity. Above-ground tests released about 3 tons of plutonium into the atmosphere.

Radioactive fallout containing plutonium, tritium, strontium-90, and cesium-137 has now spread throughout the world. In the early 1960s, the average individual dose rate from fallout was about 1 μrem/hr but this has now decreased to less than 0.1 μrem/hr. This dose rate is too small to be detected with hand-held detectors.

Within the boundaries of Los Alamos National Lab, LANL, there are locations where cesium-137 can be detected. For example, at Material Disposal Area T the dose rate is about 10 μrad/hr above background.

4.8 Industrial Radiation Uses

Industrial uses of radiation include the use of x-ray devices to inspect materials for small defects, sterilization of food or medical supplies, and the production of electricity from nuclear power. The average individual dose from all these sources is less than 0.1 μrem/hr.

At Los Alamos National Lab (LANL) radiation is used for a wide variety of purposes. However, most of the sources are far from public locations and so cannot be detected. At a typical LANL technical area, clerical workers who are limited to 100 mrem/year work within 10 meters of radioactive sources, whereas the public is restricted to locations more than 100 meters away. Using the equation in section 3.3, if the distance is increased by a factor of 10, the dose is decreased by a factor of 100 to 1 mrem/year or less. Generally, this is too small to be detected.

The only exception is at LANL technical area TA-18. About once a month, an experiment at TA-18 emits a burst of radiation that is detected by NEWNET. Because it is a short burst, it stands out as a peak on the NEWNET graph, although the total dose is usually less than 1 mrem.

Summary

The average radiation dose to a member of the general population is 40 µrem/hr. About 50% of this is from radon decay products. In addition, each of the following contributes about 10%: medical x rays; potassium-40 in the body; cosmic rays; and natural uranium and thorium in the soil. The contribution from nuclear power and nuclear weapons is smaller than 1%.

Demonstration: show sources of alphas such as thoriated lantern mantles, smoke detectors, uranium ore, etc. If you blow up a balloon, give it a static charge by rubbing it on cloth or wool, and carry it around the room, it will collect radon products which can be detected with an alpha detector. Also, a beta-gamma detector will detect cosmic rays and a sodium-iodide spectrometer such as the Exploranium will detect the 1.46-MeV gamma from potassium-40 from wooden tables, people, the ground, etc.

Discussion: What are the implications of the fact that there is natural radioactivity all around and inside us? Does this influence the way we think about radioactivity?

Lab: Use NEWNET and handheld detectors to measure examples of natural and artificial radiation.

Viewgraphs

Natural Radiation

- cosmic radiation (from outer space)
- terrestrial radiation (from the earth)
- internal sources (from food)
- radon

Artificial radiation:

- medical
- consumer products
- nuclear weapons
- industrial uses

Practice Questions

1. Which of the following is artificial, i.e., made by humans?
a. cosmic radiation
b. terrestrial radiation
c. radon

d. radioactive fallout

2. Which of the following is artificial, i.e., made by humans?
a. uranium
b. thorium
c. potassium-40
d. cesium-137

3. Natural terrestrial radiation comes mostly from
a. uranium and thorium
b. strontium and cesium
c. plutonium and tritium
d. deuterium and hydrogen

4. 4 μrem/hr of internal radiation from natural radioactive material in the body comes mostly from
a. potassium-40
b. strontium-90
c. cesium-137
d. plutonium-239

5. Natural radon comes from the radioactive decay (or disintegration) of
a. potassium
b. hydrogen
c. carbon
d. uranium

6. The average person in the US receives a total of about
a. 4 rem/hr
b. 40 mrem/hr
c. 40 μrem/hr
d. 4 μrem/hr

7. In Los Alamos and Santa Fe, the average member of the public receives about twice the US-average dose from cosmic rays because of the
a. high altitude
b. type of soil
c. plutonium
d. nuclear weapons

8. In New Mexico, the average member of the public receives about twice the US-average dose from terrestrial radiation because of the
a. high altitude
b. type of soil
c. plutonium
d. nuclear weapons

5.0 Biological Effects

Objective: understand the biological effects of ionizing radiation.

This section discusses the effects of ionizing radiation on living organisms in general and humans in particular.

5.1 Cells

All living organisms, including plants, animals, and humans, have cells that are essentially similar in their basic biology. The cells are enclosed by a membrane, contain DNA, and use similar methods to reproduce themselves.

Radiation causes damage to cells by ionization of atoms in the cell. Ionization can change the chemical properties of atoms. In some cases, the chemical changes inside a cell are minor, in other cases they can injure or kill the cell.

Radiation might strike a vital part of the cell, like the DNA, or a less vital part, like a water molecule. To take an analogy, a bullet might strike a vital part of the body like the head or a less vital part like a toe.

When radiation strikes a living cell,

- some cells are damaged,
- most cells repair the damage, and
- some cells die as a result of the damage.

A human body contains billions of cells. Every day, thousands of cells die and are replaced by new cells. Most cells die naturally. A few cells die from damage caused by external sources including cuts, bruises, bacteria, chemicals, and radiation.

As long as the number of cell deaths is small, the body can adapt successfully. However, when the damage is extensive the body may take time to repair the damage and sickness may result. Radiation sickness occurs after a dose of more than 100 rad (100,000 mrad) is received in a short time.

5.2 Dose and Dose Rate

The effects of radiation depend on the dose. In general, the greater the dose, the greater the effect.

Biological effects also depend on how fast a radiation dose is received, i.e., the dose rate. This is like the effects of alcohol; the effect of five drinks spread over five hours is different from the effect of five drinks in five minutes. If a dose is spread over a long time, the body has time to repair the damage.

Radiation dose is grouped into two categories:

- Chronic dose is received over a long time, typically years;
- Acute dose is received in a short time, typically hours or less.

The immediate effects of a large acute dose are summarized as follows.

Acute dose (rad)	**Acute dose (mrad)**	**Immediate Effect**
0 - 50	0 - 50,000	No symptoms expected
50- 100	50,000 - 100,000	temporary changes in the blood
100- 200	100,000 - 200,000	possible radiation sickness
200- 300	200,000 - 300,000	probable radiation sickness
300- 600	300,000 - 600,000	possible death
600- 1,000	600,000 - 1,000,000	probable death
> 1,000	> 1,000,000	death

5.3 Cancer

When an individual receives small amounts of radiation over a long time (chronic dose) the body has time to repair the damage. In most cases, the repair is successful. However, if the body does not repair the damage correctly, there is a possibility of cancer.

In the 1920s, young women were employed to make luminous instrument dials by painting them with radium (a radioactive decay product of uranium). They were not warned of the hazards of radioactive materials so they habitually licked the tips of the paintbrushes to make a fine point. As a result, they swallowed large amounts of radium. Of those who received between 2,000 and 20,000 rad, 30% died of cancer.

By far the best source of information on radiation and cancer comes from the study of the 80,000 survivors of the atom bombs on Hiroshima and Nagasaki. Those who received doses of 30 rad are 2 to 3% more likely to die of cancer than those who received no dose.

Another source of information is gradually becoming available from Russia. In the early 1950s, several thousand workers producing plutonium at Chelyabinsk received doses of about 100 rad per year. Preliminary data indicate that those who received 100 rad (total) are 3% more likely to die of cancer. This is a smaller cancer rate than for the atom-bomb survivors, probably because the doses at Chelyabinsk were chronic, allowing the body time to repair the damage.

An increase in thyroid cancer has been observed among children who lived close to the Chernobyl reactor at the time of the accident in 1986. More details are available at: http://www.iaea.org/worldatom/inforesource/other/chernoten/index.html

The most recent report on cancer in Los Alamos was completed in 1999 by the University of New Mexico (UNM) and the New Mexico Department of Health. This report is available at http://hsc.unm.edu/epiccpro/presentations.html

This report concluded that all types of cancer in Los Alamos are consistent with or below average except for melanoma of the skin. The expected number of annual melanoma cases is 2; the actual number is 5.

Melanoma of the skin is caused by ultra-violet (UV) radiation in sunlight. Because of its high altitude and sunny days, people in Los Alamos receive more UV radiation than average. In the opinion of UNM doctors, this is a likely explanation for the higher-than-average number of melanomas.

Ten years ago, the incidence of thyroid cancer in Los Alamos was higher than average, though it is now close to average. The expected number is 1 per year; the actual number was 3 per year, and is now 1 per year.

Thyroid cancer is known to be caused by radioactive isotopes of iodine, but these have not been found in significant quantities in Los Alamos. UNM doctors surmise that workers from Los Alamos were probably exposed to radioactive iodine while observing nuclear-weapons tests at the Nevada Test Site or the Pacific Islands.

Many other cases are discussed in detail in the report Argonne National Lab. Report ANL-92-23, the National Academy of Sciences reports by the Committee on the Biological Effects of Radiation, BEIR, and the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR.

5.4 Low Doses and Dose Rates

We know that an acute dose of 30,000 mrem results in 2 to 3% more cancers. Does a chronic dose of 3,000 mrem result in 0.2 to 0.3% more cancers? The simple answer is: we don’t know.

It is often assumed that 10% of the dose causes 10% of the effect, i.e., the cause and effect are “linear”, they follow a straight-line graph. However, straight-line graphs are rare in biology.

Effects smaller than 1% are extremely difficult to measure. Despite extensive studies, there is no reliable conclusion on the possible effects of doses smaller than 10,000 mrem; the possible effects are too small to measure.

5.5 Individual Sensitivity

Some individuals are more sensitive to radiation than others, and some parts of the body are more sensitive than others.

As a general rule, rapidly dividing and non-specialized cells are the most sensitive. For this reason, children and fetuses are more sensitive than adults, possibly by as much as a factor of ten.

Some survivors of Hiroshima and Nagasaki who were exposed to radiation while in the uterus suffered irreversible damage. Those exposed to more than 100,000 mrem while in the uterus have an average IQ of 70. However, those exposed to less than 50,000 mrem have normal IQs.

The specialized reproductive cells, sperm and ova, are expected to be more sensitive to radiation. However, extensive studies have never shown a measurable effect in humans. For example, the children of Hiroshima and Nagasaki who were not actually in the uterus at the time of the atom bombs are not measurably different from other children.

5.6 Summary

In summary, we know that doses of 30,000 mrem or more are harmful. Despite extensive studies, there is no evidence that smaller doses are harmful.

Discussion: discuss your feelings about this chapter.

Viewgraphs

When radiation strikes a living cell,

- some cells are damaged,
- most cells repair the damage, and
- some cells die as a result of the damage.

Picture of cell
Table from page 25

Chronic:
Cancer
Effects on children and a fetus
Effects of low dose and dose rate

Practice Questions

1. A dose received in a short period of time, typically hours or less, is called
a. a chronic dose
b. an acute dose
c. an equivalent dose
d. a lethal dose

2. An acute dose of 70,000 mrem is likely to cause
a. no immediate symptoms
b. temporary changes in the blood
c. radiation sickness
d. death

3. How much acute dose will cause possible radiation sickness but not death
a. 1,000 mrem
b. 10,000 mrem
c. 100,000 mrem
d. 1,000,000 mrem

4. How much acute dose might possibly result in death?
a. 300 mrem
b. 3,000 mrem
c. 30,000 mrem
d. 300,000 mrem

5. Of the individuals who survived the atom bombs on Hiroshima and Nagasaki and who received 30,000 mrem, how many got cancer?
a. all
b. 2 to 3% in total
c. 2 to 3 % more than average
d. none

6. What do scientists know about the number of cancers that will result from exposing people to 3,000 mrem?
a. all of the exposed people will get cancer
b. none of the exposed people will get cancer
c. 3% of the exposed people will get cancer
d. the possible effects are too small to measure

7. Which of the following is the most sensitive to the effects of ionizing radiation?
a. a man
b. a woman
c. a child
d. a fetus

8. What is the effect on people who were in the uterus at the time of the atom bombs in 1945 at Hiroshima and Nagasaki?
a. all got cancer
b. all are mentally retarded
c. some are mentally retarded
d. there is no effect

6. Legal limits

Objective: identify the legal limits for radiation and radioactive contamination in the environment.

International standards and Federal regulations specify limits on radiation and radioactivity, both in the laboratory and in the environment. The International Commission of Radiation Protection (ICRP) and the National Council on Radiation Protection (NCRP) publish guidance. The Department of Energy (DOE), National Regulatory Commission (NRC), Environmental Protection Agency (EPA), and Department of Transportation publish regulations.

6.1 Dose

According to Federal regulations, workers who are officially designated as radiological workers may receive an annual occupational dose up to 5,000 mrem.

Members of the public are not allowed to receive more than 100 mrem per year as a result of routine operations at a laboratory.

Regulations also specify annual limits from specific sources:
25 mrem from radioactive waste,
10 mrem from the air, and
4 mrem from drinking water.

The ICRP is considering a proposal to a designate dose <3 mrem per year as "trivial" and "exempt".

Recall that the average dose from natural radioactivity is about 40 μrem/hr, which amounts to 360 mrem per year. Careful measurements are needed to distinguish the dose caused by Laboratory operations from the dose caused by natural radioactivity.

6.2 Radioactive Contamination

In general, radioactive contamination is controlled at a much lower level than required to satisfy the regulations on doses. The reasoning behind this is essentially: if a workplace looks dirty, workers are being sloppy.

If the amount of radioactive material can be detected, workers try to control it. Radioactive material that can be detected will not usually result in exceeding the dose limits, but it should be kept as low as reasonably achievable (ALARA).

The table, below, is a simplified summary of the limits for removable contamination in the environment; (100 cm^2 is about the size of a typical detector).

Type	Removable Contamination in 100 cm^2
Alpha particle emissions	20 dpm
Beta and gamma emissions	1,000 dpm

6.3 Radioactive Material

Confusion arises over what is meant by “radioactive material”.

Every sample of matter that is large enough to be seen contains radioactive atoms. For example, every speck of earth from anywhere in the world contains millions of atoms of uranium, thorium, potassium-40, and carbon-14, all of which are naturally radioactive. Every living thing contains radioactive potassium-40 and carbon-14. So in one sense, everything is radioactive.

When regulators say something is non-radioactive they mean the amount of radioactivity is less than the official limits and standards discussed above.

Discussion: are the legal limits set too high or too low? How do they compare with the dose received from natural radioactivity?

Exercise: all human bodies contain 3 pCi/g of potassium-40. Use section 3.3 to calculate the dose rate from external radiation you receive when you hug another person.

Viewgraphs

Annual Limits on Radiation

RadWorkers	5,000 mrem
Public	100 mrem

Annual Limits on Contamination

Type	Removable Contamination in 100 cm^2
Alpha particle emissions	20 dpm
Beta and gamma emissions	1,000 dpm

Everything is radioactive!

Practice Questions

1. As a result of routine operations in one year, a radiological worker is not allowed to receive more than
a. 5,000 rem
b. 5,000 mrem
c. 100 mrem
d. 100 µrem

2. As a result of routine operations in one year, members of the public are not allowed to receive more than
a. 5,000 rem
b. 5,000 mrem
c. 100 mrem
d. 100 µrem

3. Identify the limit for removable alpha contamination (e.g., from plutonium) in 100 cm^2 of the environment.
a. 5,000 dpm
b. 1,000 dpm
c. 200 dpm
d. 20 dpm

4. Identify the limit for removable beta contamination (e.g., from strontium-90) in 100 cm^2 of the environment.
a. 5,000 dpm
b. 1,000 dpm
c. 200 dpm
d. 20 dpm

5. According to the legal definition, "non-radioactive" material must not contain
a. a single radioactive atom
b. any type of isotope
c. more than the official limits

7. ALARA

Objective: understand the methods used to minimize the dose from radiation.

Our policy is to keep radiation doses *as low as reasonably achievable,* ALARA. The standard techniques for this are as follows.

7.1 Internal Dose

Avoid taking radioactive material into the body. If radioactive material is in the body, it radiates the body from the inside. This is called *internal dose*. There are four routes for radioactive material to enter the body:

the skin,
cuts,
eating, and
breathing,

Skin is very good protection against almost all material so it is very rare for radioactive material to enter the body through the skin. Nevertheless, the protection is easy: when working with contamination, wear coveralls or a lab. coat, and gloves. Because it is easy to do, and because of the ALARA policy, this is standard practice in nuclear industries.

It is easier for contamination to enter the body through a cut than through intact skin. Again, protection is straightforward: cover the wound with a bandage.

It is also straightforward to avoid eating undesirable material. Don't eat in contaminated places, and wash your hands before eating.

The other method for contamination to enter the body is by breathing. The protection is to wear a respirator. When you see a worker wearing yellow coveralls, gloves, and a respirator, it may give the impression that the work is exceptionally hazardous. But because of the policy of keeping all doses ALARA, this is standard practice, even when the risk is extremely small.

7.2 External Dose

It is more difficult to protect a person from *external dose,* which is dose received from outside the body. Recall, alphas are shielded by skin or clothing, betas are shielded by almost any wall; these two are easy to shield. But it takes a very thick or special wall to shield gammas and neutrons.

There are 3 standard methods to keep external dose ALARA:

- time,
- distance, and
- shielding.

Minimize the time. Do not stay in a radiation area for a longer time than you need to.

Increase the distance. Most sources are "point sources", which means the radiation comes from one point; in this case, every time you increase the distance by a factor of 2, you reduce the dose by a factor of 2 times 2, which is 4. If you increase the distance by a factor of 100 you reduce the dose by 100 times 100, which is 10,000.

For example, close to the target of the Los-Alamos DARHT accelerator, an unshielded worker could receive 1,000 mrem. The public highway is 100 times as far away, so (assuming no shielding) the dose at the highway would be 0.1 mrem.

The third method is: **use shielding**. For example, the target is surrounded by earth mounds more than 10 feet thick, to reduce the dose even further.

Demonstration: show typical anti-C clothing and equipment.

Discussion: scientists believe the hazard is small from small amounts of radioactive material; in this case, should workers be required to use protective equipment?

Viewgraphs

ALARA

Internal dose, via
- the skin
- cuts
- eating
- breathing

External dose
- time
- distance
- shielding

Effect of distance on a point source

distance (ft)	dose (mrem)
1	1024
2	256
4	64
8	16
16	4
32	1

Practice Questions

1. ALARA means
a. As Long As Radiation is Around
b. A Large Amount of Radio Activity
c. As Low As Reasonably Achievable

2. The ways that radioactive material might enter the body and cause internal dose are
a. time, distance, and shielding
b. alpha, beta, gamma, and neutron
c. breathing, eating, through cuts, and through skin

3. The ways to minimize radiation that causes external dose are
a. time, distance, and shielding
b. alpha, beta, gamma, and neutron
c. breathing, eating, through cuts, and through skin

4. If radiation comes from a "point source" and you double the distance from the source, the dose ______ by a factor of ____ .
a. increases, 2
b. increases, 4
c. decreases, 2
d. decreases, 4

5. Which of the following is typical shielding for alphas
a. skin
b. almost any wall
c. a specially designed, thick wall

6. Which of the following is typical shielding for betas
a. skin
b. almost any wall
c. a specially designed, thick wall

7. Which of the following is typical shielding for gammas and neutrons
a. skin
b. almost any wall
c. a specially designed, thick wall

8. Pathways to the Environment

Objective: understand the common pathways of radioactive contamination into the environment.

Radioactive contamination is radioactive material in an unwanted location. So long as it remains in its proper containment in the lab., it is not "contamination".

In the context of environmental radiation protection, a *pathway* is a route that radioactive contamination follows from a *source*, such as the workplace, to the environment. The air, water, food, and waste pathways will be discussed.

8.1 Air

Radioactive material can be suspended in the air and carried by the wind. It may then be inhaled by people or animals, or settle on plants or the ground.

Particle size is a key to the behavior of particles in air. Small particles are more easily transported by wind and inhaled into the lungs. Large particles fall quickly to the ground, and if inhaled, stick in the nose or throat; from there, they are quickly expelled from the body.

For example:
- smoke particles have a median diameter less than 1 µm (1 micrometer) so smoke travels many miles in the air and is inhaled deep into the lungs;
- dust is typically in the range 0.01 to 0.1 mm; it settles slowly to the ground and sticks mostly in the nose and throat from where it may be sneezed or coughed out;
- sand is about 1 mm in diameter; it settles quickly to the ground and sticks mostly in the mouth and nostrils, causing you to spit or blow your nose.

Thus, smoke is generally more hazardous than dust or sand.

Airborne particles travel with the wind, so wind direction is important. Wind direction is defined by specifying one of 16 sectors: N, NNE, NE, ENE, E, etc. Airborne particles released from a source such as a smoke stack usually spread over about a sector, e.g., if the wind is toward the north, most of the smoke from a stack will spread from about 10 degrees west of north to about 10 degrees east of north.

Note: we often specify the direction the wind is coming from, not going to. For example, in New Mexico, the wind often comes from the west-south-west (WSW) sector.

Wind speed is an important variable. In Northern New Mexico, sustained wind speeds vary from 0 to 30 mph with an average of about 6 mph.

The stability of the air is also important. At night, the air is usually still because cold air stays close to the cold ground; at night, smoke or mist can often be seen floating near a fixed height, a condition known as an inversion. During stable conditions, particles spread about half as much as normal, over about half a sector. During the day, the sun heats the ground and the air close to the ground, the hot air rises, and so the air becomes unstable. During unstable conditions, particles spread about twice as much as normal, over about two sectors.

8.2 Example: Airborne Radioactivity from an Accelerator

As an example, consider the airborne radioactivity from the Los Alamos Neutron Science Center (LANSCE) accelerator.

Air consists mostly of the elements nitrogen, N, oxygen, O, and argon, Ar; the common isotopes are N-14 ,O-16, and Ar-40. The accelerator knocks neutrons out of N-14 to make N-13, and out of O-16 to make O-15. It also adds a neutron to argon to make Ar-41. These radioactive isotopes travel with the wind to East Gate industrial park, half a mile to the north-east. A person who spends 24 hours per day for 365 days at this location would receive several mrem from this radioactive air.

The half life of N-13 is 10 minutes. Because this nuclide has a short half life, it disintegrates quickly, so the dose is smaller to people who live further away. For example, if the wind were blowing at 6 mph toward the north-west, it would take an additional 10 minutes to reach the nearest houses, which are 1.5 miles away. In this time, half of the N-13 would have decayed. Furthermore, after 1.5 miles, the air is at least 3 times as diluted compared with the air at 0.5 miles. Thus, the dose to the residents is much less than 1 mrem/yr.

In this example, for every additional mile, the N-13 is reduced by half, so after 10 miles the remaining N-13 is reduced by a factor of 1,000. Also, for every mile, the air is diluted by a factor of 3, so after 10 miles the dose from N-13 is much less than a millionth of the amount at Eastgate.

The detailed calculations involve many nuclides with different half lives (see Chapter 4 of the environmental surveillance reports referred to in Section 11, below). Computers are used for detailed calculations, but the general conclusions are the same: the dose close to the source is a few mrem/yr, the dose further from the source is much smaller.

8.3 Water

In principle, water can provide a pathway for radioactive material from the workplace into food or drinking water. Water in the environment may be separated into three categories: surface water in streams or rivers, ground water in soil and sediment, and aquifers. Aquifers are about 1,000 ft underground; in western parts of the US they are our main source of drinking water.

At Los Alamos, from 1945 to 1951, water containing radioactive material was discharged into Acid Canyon, which flows into Pueblo Canyon and from there to the Rio Grande. At present, the water discharged from the liquid-waste treatment facility at TA-50 into

Mortandad Canyon contains a small amount of residual radioactive material which is monitored closely to ensure it does not leave DOE property or get to the aquifer. The data are reported in the annual environmental surveillance reports, as described in section 11.

8.4 Food

Radioactive materials in the soil, water, and air can be taken up by plants and so enter the food chain. Natural potassium-40 from the ground and natural carbon-14 from the air are present in all plants, animals, and food. It is important to avoid significant amounts of other radioactive materials in food.

Radioactive isotopes behave chemically and biologically like the other isotopes of the same element; for example, potassium-40 behaves like any other isotope of potassium and tritium behaves like the other isotopes: hydrogen and deuterium. The periodic table (familiar to chemistry students) defines which elements are chemically and biologically similar. For example, cesium behaves like potassium and strontium behaves like calcium.

8.5 Waste

If radioactive waste is not disposed of properly, radioactive material can enter the air, water, or food. As much as possible, air- and water-borne waste is converted to the more stable solid form before disposal.

Solid waste is carefully sorted into separate containers designated either for non-radioactive waste or for waste that might be radioactive. If there is any doubt, it is assumed to be radioactive. It is then placed in sealed containers and stored or buried, e.g., at Area G of Los Alamos or the waste isolation pilot plant, WIPP.

Area G is deliberately located on a dry mesa top so the buried waste is kept clear of ground water. Similarly, WIPP is located in salt beds because it is known that these have been relatively dry for geological time spans.

Liquid waste is separately disposed of as either non-radioactive or possibly radioactive waste. Radioactive liquid waste is transferred to a liquid-waste treatment plant where almost all the radioactive material is removed, solidified, and sent to a solid-waste disposal site. At Los Alamos, the liquid residue, which still contains some radioactive material, is discharged into Mortandad Canyon.

Airborne radioactive material is captured by high-efficiency particulate air (HEPA) filters, which are more than 99.97% efficient.

Demonstration: show air filters and other environmental monitoring equipment. Show various filters. Show wind roses from Environmental Survey Report. Show periodic table of the elements.

Discussion: how does radioactivity from Los Alamos affect you? How can Los Alamos National Lab. respond better to your concerns?

Viewgraphs

Review:
Radiation vs. Radioactive Material
Radioactive Material vs. Radioactive Contamination

Pathways for material
- Air
- Water
- Food
- Waste

Particle size

smoke: inhaled deep into lungs
dust: sticks in nose and throat
sand: sticks in nostril and mouth

Wind
- Direction
- Speed
- Wind roses
- Spreads over about a sector

Water
- Rivers
- Sediment
- Aquifers

Food
- tritium is like hydrogen
- potassium-40 and cesium-137 are like sodium
- strontium-90 is like calcium

Waste
- segregated into rad and nonrad at source
- solidified
- sealed and buried in dry location

Practice Questions

1. Which type of particle is most likely to be expelled quickly from the body?
a. very small particles which stick in the deepest recesses of the lungs
b. dust particles which stick in the throat
c. sand particles which stick in the mouth and nostrils

2. If the wind is from the SW, airborne particles will
a. move exactly toward the NE
b. spread through most of the NE sector
c. spread evenly everywhere from the SW to the NE

3. In Los Alamos, most of our drinking water comes from
a. surface water
b. ground water
c. aquifers

4. which element behaves most like calcium?
a. potassium
b. tritium
c. cesium
d. strontium

5. Which element behaves most like potassium?
a. uranium
b. tritium
c. cesium
d. strontium

6. Before disposal, waste is converted to which form?
a. air
b. water
c. solid
d. food

7. At Los Alamos, the solid-waste disposal area (Area G) is located on a mesa top to keep the radioactive waste away from the
a. ground
b. cosmic rays
c. ground water

9. Uranium

Objective: identify the important properties of uranium related to environmental monitoring.

Uranium is a natural element that is used as the primary fuel for nuclear energy and nuclear weapons.

9.1 Uranium Isotopes

The three naturally-occurring uranium isotopes are U-234, U-235, and U-238. Their half lives and natural abundance are in the table, below. Both U-235 and U-238 have long half lives, so uranium formed when the earth was made still exists today. U-234, which has a shorter half life, is a decay product of U-238 so it is continually replenished by the disintegration of U-238.

Isotope	Half Life	Natural Uranium	Depleted Uranium
U-234	0.246 million years	0.0055%	0.001%
U-235	700 million years	0.72%	0.2%
U-238	4,468 million years	99.725%	99.8%

Natural uranium has the isotopic composition listed in the table. Natural uranium is present in the soil throughout the world at an average concentration of 2 parts per million (ppm), which is 0.7 pCi/g. In the Rocky-Mountain states, the concentration is 1-3 pCi/g. Concentrations of natural uranium are often greater near the bottom of the canyons than at the top. This is one reason why radiation readings are usually greater in a canyon.

The uranium used as nuclear fuel or in nuclear weapons is called *enriched uranium* because it is enriched in U-235; the amount of U-235 in enriched uranium ranges from about 2% to more than 90%. Enriched uranium is tightly controlled and so is unlikely to get to the environment.

The most common type of uranium produced by the DOE is called *depleted uranium* (DU) because it is has less U-235 than natural uranium. DU has the same properties as other types of uranium except it cannot become *critical*, i.e., it cannot sustain a chain reaction and so spontaneously release a large amount of energy, as in a nuclear bomb or reactor. So DU is safer than the other forms of uranium. Experts agree that for DU the chemical hazard is worse than the radioactive hazard and that DU is approximately as hazardous as lead.

Because DU is less radioactive than natural uranium, for many years it was officially considered to be “non-radioactive”. Now that it is officially considered “radioactive”, efforts are being made to clean it up.

9.2 The Natural Reactor at Oklo

Billions of years ago, in a place called Oklo, in the country of Gabon, in Africa, a nuclear reactor formed naturally. Deposits of uranium ore collected in a river delta, and the combination of uranium and water were sufficient to allow the uranium to become critical, as in a nuclear reactor. In essence, the conditions were similar to those in the US-designed light-water reactors. For millions of years, this reactor generated heat and made plutonium. Then conditions changed and the reaction stopped.

At that time, natural uranium contained more U-235 than at present. A natural reactor is not possible today because natural uranium does not contain enough U-235. At present, natural uranium can only become critical when mixed with deuterium oxide (heavy water) as in the Canadian-Deuterium-Uranium (CANDU) reactors, or with very pure graphite as in the obsolete Chernobyl reactors.

9.3 Radioactive Emissions from Uranium

All uranium isotopes decay by emitting an alpha particle, but many uranium decay products emit betas and gammas. Betas and gammas are much easier to detect than alphas. Therefore, uranium is best detected by looking for the beta particles or gammas emitted by the uranium decay products.

The beta dose rate from a large amount of pure uranium is about 200 mrem/hr. However, if the concentration in the environment is 10 ppm, the beta dose rate is about 2 µrem/hr. It is difficult to detect such a low level with a portable detector.

Uranium may also be detected by a technique called gamma spectroscopy, which will be discussed in section 11.5.

More information about uranium may be obtained from the self-study course at: http://eshtraining.lanl.gov/esh13/esh13_documents/12324.pdf

Demonstration: show uranium ore and consumer products containing uranium.

Viewgraph

- Uranium, U
    - natural uranium
    - enriched uranium
    - depleted uranium (DU)
    - alpha emissions
    - beta emissions from decay products

Practice Questions

1. Compared with enriched and natural uranium, depleted uranium has less of which isotope?
a. U-234
b. U-235
c. U-238

2. Which type of uranium cannot become critical?
a. enriched uranium
b. natural uranium
c. depleted uranium

3. The amount (ppm) of natural uranium in Los Alamos county is about how much compared with the world average?
a. a quarter
b. half
c. same
d. twice

4. Natural and depleted uranium may be detected by looking for
a. alphas or betas
b. neutrons
c. non-ionizing radiation

5. The dose rate from the small amount of natural uranium in the environment is about
a. 200 mrem/hr
b. 2 mrem/hr
c. 200 µrem/hr
d. 2 µrem/hr

10. Plutonium

Objective: identify the important properties of plutonium related to environmental monitoring.

Extremely small amounts of natural plutonium exist in uranium ore, much too small to be worth extracting; a cubic yard of ore contains about 1,000 dpm of natural plutonium. (A 1-µm-diameter particle of plutonium-239 has an activity of 1 dpm).

Most plutonium that exists today is artificial. About 3 tons of plutonium were released into the atmosphere by nuclear-weapons tests from 1945 through the early 1960s. This plutonium has spread throughout the world, so, in addition to natural plutonium, every square yard of dirt now contains about 1,000 dpm of plutonium from nuclear-weapon fallout. This is still much less than the amount of uranium; there is about one atom of plutonium for every 10-million atoms of uranium in the environment.

10.1 Plutonium Isotopes

The four plutonium isotopes of most interest are as follows.

Pu-238 is used as a heat and energy source, for example in the Cassini space probe. Until the 1980s, it was also used in cardiac pacemakers and was implanted into the chests of more than 1,000 patients. Many of these pacemakers are still in use today. The radiation level outside the patient's chest is about 1 mrem/hr.

Pu-239 is used for nuclear weapons. Like U-235, it can also be used as an energy source in a nuclear reactor.

Pu-240 is an undesirable byproduct. The amount of Pu-240 is minimized in high-quality weapons-grade plutonium because it greatly increases the radioactivity and greatly reduces the effectiveness of the weapon. Plutonium produced in commercial reactors contains large amounts of Pu-240 and so is undesirable for nuclear weapons.

Pu-241 decays to americium-241 (Am-241), which is used in commercial smoke detectors. All plutonium contains Pu-241 and Am-241, so plutonium may detected by the characteristic 60-keV gammas emitted from the Am-241.

Isotope	Half Life	Comment
Pu-238	88 years	Heat source
Pu-239	24,000 years	Weapons grade
Pu-240	7,000 years	undesirable byproduct
Pu-241	14 years	decays to americium-241

10.2 Properties of Plutonium

Plutonium is an alpha emitter. Therefore, if plutonium is on the ground or even on your skin, the alpha particles are stopped by the skin. If plutonium gets inside the body, however, the alphas are no longer stopped by the skin, and it becomes much more hazardous.

If plutonium is eaten, less than 0.1% is absorbed into the body. This is because most forms of plutonium are almost insoluble.

The most significant route by which plutonium can enter the body is from the air. However, for the plutonium to stay in the body, the particles must be about the size of smoke particles. Larger particles (the size of dust or sand) would stick in the nose or throat and be expelled when you blow your nose or cough.

Plutonium is kept in glove boxes, which are sealed boxes with fitted gloves that allow workers to handle plutonium without direct contact. The glove boxes are contained in specially designed rooms and the rooms are contained in specially designed buildings, so if the glove box leaks, the plutonium is still contained.

The amount of airborne plutonium in the environment is small. The largest amount at Los Alamos is at Area G where waste is being processed to send to WIPP. At this location, the concentration is about 0.0015 dpm/m^3.

Is this amount hazardous? To answer this question, we need some math. If you prefer, you may skip the next paragraph.

The Derived Air Concentration, DAC, for each nuclide is published in the Code of Federal Regulations. For Pu-239, the value is 4.4 dpm/m^3. The DAC is the air concentration that will cause a committed dose equivalent (CDE) of 5,000 mrem, if breathed for 2,000 hours. Therefore, the dose from breathing air with 0.0015 dpm/m^3 for 2,000 hours would be: (5,000 mrem)(0.0015 dpm/m^3)/(4.4 dpm/m^3) = 1.7 mrem (CDE).

At other outside locations, the amount of plutonium is 1,000 times smaller than in this example. In conclusion, the plutonium in the environment is not hazardous.

More information about plutonium may be obtained from the self-study course at: http://eshtraining.lanl.gov/esh13/esh13_documents/11579.pdf

Viewgraph Plutonium, Pu
    Natural Pu
    Heat-Source Pu
    Weapons-grade Pu
    Reactor-grade Pu
    alpha emission from Pu
    60-keV gamma from Am-241

Discussion: how do you feel about natural compared with man-made plutonium?

Practice Questions

1. Which plutonium isotope is used mostly as a heat and energy source?
a. Pu-238
b. Pu-239
c. Pu-240
d. Pu-241

2. Which plutonium isotope is most useful for nuclear weapons?
a. Pu-238
b. Pu-239
c. Pu-240
d. Pu-241

3. Which plutonium isotope is produced in commercial reactors but is undesirable for nuclear weapons?
a. Pu-238
b. Pu-239
c. Pu-240
d. Pu-241

4. Which plutonium isotope decays to Am-241?
a. Pu-238
b. Pu-239
c. Pu-240
d. Pu-241

5. Which is the most significant route by which plutonium can enter the body?
a. breathing
b. eating
c. through the skin

11. Environmental Monitoring

Objective: identify the methods used to monitor the environment for radioactivity.

A large number of techniques are used to monitor air, soil, water, sediment, and food for radiation and radioactive material. The most important methods are discussed in this section and in the annual environmental surveillance reports which are available on the world-wide web: http://lib-www.lanl.gov/pubs/Environment.htm . (From the LANL home page, click "Library", then "Laboratory Publications", then "Environment". They may also be found by searching for the "Technical report no.": the 1999 report is: LA-13775-ENV.)

11.1 Background Measurement

Background refers to the radiation or radioactive material that is always present but is not the major focus of interest. It is like the background in a portrait.

The background makes it more difficult to detect the particular material you are looking for. For example, it may be difficult to detect plutonium because the detector is responding to a background of natural uranium or thorium.

Ideally, you should measure the background in a location which is identical to the location of interest, except for the particular item you are looking for. For example, if you are looking for plutonium in a canyon, you should compare your results with other, similar canyons. In practice, this is difficult because there are many variables: altitude, moisture, soil type, shape of canyon walls, etc.

It is much easier to control the background in a well designed laboratory, where the detectors are shielded. For this reason, the most accurate measurements are made by collecting samples and analyzing them in the controlled conditions of the laboratory.

11.2 Monitoring for External Radiation

Recall the difference between radiation and contamination, see sections 1.3 through 1.7.

NEWNET stations continuously measure radiation in the environment at 19 locations in New Mexico. The data may be accessed from http://newnet.lanl.gov/ . Environmental radiation is also monitored by thermo-luminescent dosimeters (TLDs) as reported in the annual environmental surveillance reports.

Units

Detectors designed to measure radiation use the units R or rem. Notice that units of radiation include the letter r.

Alpha

Because alphas cannot penetrate the skin or the windows of most radiation detectors, they do not cause external radiation.

Beta Detectors

Some radiation detectors have a thicker window or protective cover and therefore cannot measure betas. For example, the Exploranium GR-130 and NEWNET cannot measure betas.

Some detectors have a movable "beta shield", typically ¼ inch sheet of plastic, that may be put in place to shield betas or removed to measure them. To check if you are measuring betas, record the reading with and without a ¼ inch sheet of plastic between the detector and the source. The difference between the two readings is the beta reading.

Gamma Detectors

Some gamma detectors are designed to measure penetrating gammas (see sections 2.3 and 2.4) and so are inaccurate for less-penetrating gammas. This is an important consideration when measuring the 60-keV gammas from Am-241, which accompany plutonium. Some detectors over-respond to Am-241 by a factor of 10, i.e., if the true Am-241 dose rate is 100 µrem/hr, some detectors will read 1,000 µrem/hr. Other detectors under-respond by a factor of 2.

Neutron Detectors

Neutrons require a specially designed detector. Almost all neutron detectors are surrounded by a large piece of polyethylene, several inches thick, and so are usually bulky and heavy. Furthermore, neutrons are rare in the environment. For these reasons, neutron detectors are not usually chosen for environmental monitoring.

11.3 Monitoring for Radioactive Contamination

Detectors designed for radioactive contamination have two important features:
- They have thin windows;
- They use units of cpm, cps, or dpm.

Note: most radiation units include the letter r; contamination units begin with b, c or d.

Alpha
Alpha detectors have very thin windows. This is because alphas will not penetrate a normal window. Also, alphas will not penetrate more than about an inch of air. For this reason, it is important to hold an alpha detector within ¼ inch of the source.

Betas

Many alpha detectors are deliberately designed so they will not detect betas. Others, such as the E600, can report the alphas and betas separately. This is to reduce the background. The background of betas from cosmic rays would obscure the small alpha signal from plutonium or uranium. By eliminating the cosmic-ray background, we can detect smaller amounts of alpha-emitting material.

Gammas

Some gamma detectors simply count the total number of gammas. The problem with this is: gammas are not equally hazardous; e.g., each 662-keV gamma from Cs-137 is ten times as hazardous as each 60-keV gamma from Am-241. The best gamma detectors measure each type separately. This will be discussed in more detail in section 11.5.

Neutrons

Radioactive contamination does not emit significant neutrons, so there are no neutron-contamination detectors.

11.4 Environmental Samples

The best way to find small amounts of radioactive contamination in the environment is to collect samples from the air, water, sediment, and food, and analyze them for radioactivity in low-background laboratories.

Samples are processed to concentrate the radioactive material and give an accurate measurement of extremely small amounts. The amount that can be detected is millions of times smaller than the amounts that would be a health hazard. This provides advance warning, to deal with potential problems while they are still small.

The radioactivity is measured in a variety of ways. The simplest methods count “gross alpha”, i.e., all alpha emitters are counted together, whether from uranium, thorium, radon, or plutonium. Other methods can measure each individual nuclide separately, as follows.

11.5 Gamma Spectrum

A *spectrum* is a picture which reveals the characteristic energies of the particles or waves emitted from a material. A gamma spectrum can be used to identify individual nuclides. During the hands-on section of this course, you will have an opportunity to see and understand a spectrum.

Almost all radioactive nuclides emit a characteristic spectrum of gammas. Each gamma is identified by a specific number of keV or MeV (see section 2.4). For example, Am-241 emits 60-keV gammas, Cs-137 emits 662-keV gammas, and K-40 emits 1.461-MeV (1,461-keV) gammas. The spectrum, which is a graph of the number of each type emitted, is like a signature or a fingerprint. The spectrum uniquely identifies the nuclides present.

In principle, this technique can give a list of nuclides and the amounts of each. In practice, it may be necessary to count for more than an hour in a well-shielded enclosure, and to use a very high quality detector.

The Exploranium GR-130 detector uses gamma spectroscopy to identify nuclides. In order to make it portable, however, some compromises are necessary. The “signature” or “fingerprint” provided by the Exploranium is "blurred" and not as "sharp" as that obtained from higher-quality and less-portable germanium detectors.

The degree of sharpness of a spectrum is known as the *resolution*. Each characteristic gamma is shown as a peak in a spectrum, much like peaks in a range of mountains. In reality, each peak is a very narrow and tall spike, more like a radio antenna than a mountain. With a perfect detector, each spike would be distinct; with an actual detector, one peak merges into the next.

In science, the best way to confirm a result is to repeat it. Reproducibility is essential. Therefore, an interesting spectrum should be stored or recorded so others can view it, discuss it, and try to reproduce it.

Demonstration: show various detectors

Discussion: which detectors do you think are most useful?

Viewgraph

- Monitoring Radiation
  - background is important
  - units include the letter r
  - alphas: not relevant
  - betas: movable beta shield
  - gammas: over-response to low energies
  - neutrons: bulky, rare in the environment

- Monitoring Contamination
  - thin (fragile) windows
  - units: cpm, cps, dpm
  - background is important
  - alpha: low background, short range
  - take samples to low-background location
  - use spectrum to identify nuclides

- Gamma Spectrum
  - nuclide identification
  - like a "fingerprint"
  - Resolution: blurred or distinct

Gamma spectrum

- In science, reproducibility is essential

Practice Questions

1. Detectors that measure radiation rather than contamination use which units?
a. cpm
b. Ci/m^3
c. µR/hr
d. cps

2. Detectors that measure contamination rather than radiation use which units?
a. R/hr
b. mrem/hr
c. cpm
d. µR/hr

3. Which type of detector has the lowest background count rate?
a. alpha
b. beta
c. gamma

4. Which delivers the largest total dose?
a. 100 60-keV gammas from Am-241
b. 100 662-keV gammas from Cs-137
c. They are both the same

5. How far should an alpha detector be from the source of alpha particles?
a. ¼ inch
b. 2 inches
c. 1 foot
d. 1 meter

6. Most neutron detectors have a
a. very thin, fragile window
b. window about as thin as skin
c. movable beta shield
d. bulky layer of polyethylene

7. The least amount of background is usually found in which location?
a. in canyons
b. on mesa tops
c. at high altitudes
d. in a well-shielded laboratory

8. Which of the following is like a unique "fingerprint" that allows individual nuclides to be identified?
a. its spectrum
b. its dose rate
c. its count rate

12. Detectors

This section provides specific hands-on training in the use of the Exploranium GR-130 and the Eberline-E-600detectors.

Generally, the following 5 checks should be performed before making a measurement.

1. Check the calibration date.
2. Check for physical damage.
3. Check the battery.
4. Check the response to a source of radioactivity.
5. Check the background.

12.1 Exploranium GR-130

The Exploranium "GR-130 minispec" is a sodium-iodide gamma detector which uses gamma spectroscopy to detect individual nuclides. There are 3 main modes of operation, each with different units and uses, as follows.

Mode	Units	Used to …
SURVEY	cps	search for radioactive material
ANALYSIS	none	identify nuclides
DOSE METER	µR/h or mR/h	measure dose rate

Survey mode is used to find unusual amounts of radioactive material. The display is a graph (histogram) of the count rate as a function of time. Unusual amounts of radioactive material stand out as peaks above the background from terrestrial sources and cosmic rays (see in section 4).

Note: randomness is expected, as discussed in section 1.9. Occasional peaks about ¼ inch high will occur randomly. The key to science is reproducibility; unless a clear peak always appears every time the detector is at a certain location, it is not significant.

Analysis mode is used to identify specific nuclides. The spectrum always shows a broad peak toward the left; this is background from terrestrial sources and cosmic rays. If there is nothing but background, the nuclide identification report will state: no nuclides have been found. If you see any interesting peak, select "store spectrum" to allow others to look at it later.

Note: if Cs-137 is identified, ensure that the Cs-137 check source provided with the Exploranium is far from the detector.

Dose meter mode is used to measure the dose rate; 10-15 µR/h is typical. Dose-meter mode is similar to survey mode, except the units are different and there is no graph.

12.2 Exercise: Using the Exploranium in Survey Mode

1. Turn on the Exploranium and select SURVEY mode.

2. Wait about a minute for the count-rate graph to establish the background. Record the background count rate, including the units, and sketch the graph shown on the Exploranium display.

Background count rate: _____________

Sketch the graph here:

3. Place the Exploranium 1 foot from a gamma source, record the count rate, and sketch the graph.

Count rate: ______________

Sketch the graph here:

4. Place the Exploranium 2 feet from the source, record the count rate, and sketch the graph.

Count rate: ______________

Sketch the graph here:

5. Place the source 4 feet from the Exploranium and record the count rate, and sketch the graph.

Count rate: ______________

Sketch the graph here:

6. Remove the source, record the background count rate again, and sketch the graph.

Count rate: _______________

Sketch the graph here:

7. Discuss your data with the instructor. Instructor's initials: ____________

12.3 Exercise: Using the Exploranium in Analysis Mode

1. Turn on the Exploranium, select STABILIZATION, and follow the instructions.
2. Select ANALYSIS.
3. Place the source close to the Exploranium. Sketch the graph:

4. After a minute, return to the menu and select NUCLIDE IDENT; record the nuclide identified by the Exploranium.

NUCL. IDENT. ____________

5. If time permits, move the Exploranium close to other types of radioactive material, and repeat steps 2 through 4. Record your observations below.

6. Discuss your results with the instructor. Instructor’s initials: ___________

12.4 Exercise: Using the Exploranium in DOSE METER mode

1. Turn on the Exploranium and select DOSE METER mode.
2. With the Exploranium far from the sources, record the background reading, including the units.

Background dose rate: ______________

3. Move the Exploranium 1 foot from a source of gammas and record the reading, including the units.

Gamma dose rate: ________________

4. If time permits, repeat step 3 with the Exploranium at different distances from different samples of radioactive material; record the dose rate, the type of material and the distance.

5. Discuss your results with the instructor. Instructor's initials: ___________

12.5 Eberline E-600

The Eberline E-600 is used in a variety of modes and with a variety of detectors. It has many options, more than most users need, so it is easy to become confused. If the E-600 is behaving unusually, look carefully at all the symbols on the display, especially the following.

The symbol α, β, or γ (which are the Greek letters alpha, beta, and gamma) shows which type of particle is being detected. If this is not what you want, press the "Chnl" button once or twice.

The units are shown to the right of and below the number. If the units are not what you expect, press the “Chnl” button once or twice.

You can turn the speaker on or off by pressing the “Spkr” button.

The most useful modes are as follows.

This mode ...	is used to …
Check	check the battery
Ratemeter	make a quick measurement of count or dose rates
Scalar	make a 1 minute measurement of count or dose rates

The E-600 comes with a variety of probes.

Probe	Particle(s)	Units	Used to …
SHP380AB	αβ	dpm	search for contamination
SHP330	αβ	dpm	search for contamination
SHP270	βγ	μR/h	measure radiation dose rates
SPA3	γ	μR/h	measure dose rates

The SHP380 and SHP330 can be used for alpha, beta, or both. To change, press the “Chnl” button on the handle.

The SHP270 can be used for beta or gamma. To measure beta, slide the cylindrical cover away from the cable to expose the thin window. To measure gamma, slide this cover toward the cable to cover the window.

12.6 Using the E-600 with SHP380AB

1. Turn the power off, connect the SHP380AB to the E-600, turn on, and check the battery. Before you perform each step, try to predict if the count rate will be zero or not.
2. With the cover in place and the "Chnl" set to α, record the count rate.

Count rate: ________

3. With the cover still in place and the probe ¼ inch from a source of alphas, record the count rate.

Count rate: ________

4. Remove the cover, and record the count rate ¼ inch from the source of alphas.

Count rate: ________

5. Move the probe 3 inches from the source of alphas and record the count rate.

Count rate: ________

6. Change the "Chnl" to β, replace the cover, move the probe far from the radioactive materials and record a background count rate.

Count rate: ________

7. With the cover still in place, move the probe to a source of betas and take a reading at a distance of ¼ inch from the source of betas.

Count rate: ________

8. Remove the cover, and record the count rate at a distance of ¼ inch from the source of betas.

Count rate: ________

9. Move the probe 3 inches from the material and record the count rate.

Count rate: ________

10. Move the probe 3 feet from the material and record the count rate.

Count rate: ________

11. With the probe far from the radioactive material, record the background count rate.

Count rate: ________

12. Discuss your data with the instructor. Instructor's initials: ______

12.7 Using the E-600 with SHP330

1. Turn the power off, connect the SHP330 to the E-600, turn on, and check the battery. Before you perform each step, try to predict if the count rate will be zero or not.
2. With the "Chnl" set to α and the probe far from the radioactive material, record the count rate.

Count rate: _______

3. Shield the probe with a piece of paper and move the probe to a distance of ¼ inch from a source of alphas.

Count rate: _______

4. Remove the paper and record the count rate at a distance of ¼ inch from the source of alphas.

Count rate: _______

5. Move the probe 3 inches from the material and record the count rate.

Count rate: _______

6. Change the "Chnl" to β, move the probe far from the radioactive materials, and record a background reading.

Count rate: _______

7. Move the probe to a source of betas and take a reading at a distance of ¼ inch from the source of betas.

Count rate: _______

8. Move the probe 3 inches from the material and record the count rate.

Count rate: _______

9. Move the probe 3 feet from the material and record the count rate.

Count rate: _______

10. discuss your data with the instructor. Instructor's initials: _______

12.8 Using the E-600 with SHP270

1. Turn the power off, connect the SHP270 to the E-600, turn on, and check the battery.
2. With the probe far from the radioactive material, record the background dose rate.

Dose rate: __________

3. With the cylindrical slide open, move the probe 1 foot from a source of betas and gammas and record the dose rate.

Dose rate: __________

4. With the cylindrical slide closed, place the probe 1 foot from the source of betas and gammas and record the dose rate.

Dose rate: __________

5. With the cylindrical slide open, place the probe 2 feet from a source of betas and gammas and record the dose rate.

Dose rate: __________

6. With the cylindrical slide closed, place the probe 2 feet from a source of betas and gammas and record the dose rate.

Dose rate: __________

7. Discuss your data with the instructor. Instructor's initials: _______

12.9 Using the E-600 with SPA3

1. Turn the power off, connect the SPA3 to the E-600, turn on, and check the battery.

2. With the probe far from the radioactive material, record the background dose rate.

Dose rate: __________

3. Move the probe 1 foot from a source of gammas and record the dose rate.

Dose rate: __________

4. Move the probe 2 feet from the source of gammas and record the dose rate.

Dose rate: __________

5. Move the probe 4 feet from the source of gammas and record the dose rate.

Dose rate: __________

6. Discuss your data with the instructor. Instructor's initials: _______

12.10 Detailed Notes on nuclide identification with the Exploranium GR-130

Th-232 is very difficult to identify. Try setting the scale to 0-3 MeV. Then:
Cs-137 (662 keV) is at channel 55;
K-40 (1.461 MeV) is at channel 116-117.
If you count for a long time (10 minutes) you might see the following Th products.
channel 21, 239 keV Pb-212
channel 28-29, 334 or 338 keV Ac-228 (weak)
channel 42, 510 keV Tl-208 (very weak)
channel 48, 583 keV Tl-208
channel 74-79, a pair of peaks, 911 and 969 keV from Ac-228 (rejected by the analysis)
channel 126, 1.588 MeV from Ac-228 (weak)
channel 200, 2.615 MeV from Tl-208

Ra-226 is contained in uranium ore.
The 242-keV, 295-keV, and 352-keV peaks are from Pb-214.
The 609-keV and 1120-keV peaks are from Bi-214.
The 1.32-MeV peak from Po-214 is also visible, but is not in the Exploranium library.
The 1765-keV peak from Bi-214 is also visible, but is not in the Exploranium library.

DU. Ra-226 and its decay products are not detectable from DU.
The 186-keV peak from U-235 is visible.
There are several peaks near 100 keV from U-235, U-238, and decay products.
There is a peak at 1000 keV that the Exploranium calls "U-235", actually Pa-234m.
There is also a peak near 760 keV, perhaps Pa-234m also

In the **environment**, you can usually see the following.
Low energy background. The low-energy peaks are usually lost in the background.
The 583-keV peak from Tl-208 (Th product) and 609-keV peak from Bi-214 (Ra product) tend to overlap, so neither is identified as a valid peak.
The 911-keV and 969-keV peaks from Ac-228 also overlap so neither is identified.
The 1120-keV and 1.765-MeV peaks from Bi-214 (Ra product) are usually visible, but this is only two out of the three required peaks, so Ra-226 is not usually identified.
The 2.615-MeV peak from Tl-208 (Th product) is usually visible, but this is only one out of the three that are required, so Th is not usually identified.
The 1.461-MeV peak from K-40 is usually visible and identified if you count for more than 5 minutes.

Glossary

acute dose. Typically a large radiation dose received in a short period (less than a day) and not as well tolerated by the body as chronic dose.

alpha particle. A positively charged particle emitted from the nucleus of an unstable atom. Range of about 1 to 2 inches in air; stopped by a sheet of paper or the dead layer of skin. Considered an internal hazard.

as low as reasonably achievable (ALARA). A radiological control concept to manage and keep exposures to the work force and the general public as low as is reasonable, taking into account social, technical, economic, practical, and public factors.

atom. The smallest part of an element that still retains the chemical properties of that element. The atom is made up of three subatomic particles: protons, neutrons, and electrons.

atomic number, Z. The number of protons in the atom.

beta particle. A negatively charged particle emitted from the nucleus of an unstable atom. Physically identical to an electron. Range of about 10 feet in air; stopped by a typical sheet of plastic, glass, or almost any wall.

biological half life. The time it takes for one-half of the material to be removed by biological processes; see also "radioactive half life".

cell. The smallest structural unit of an organism that is capable of independent functioning.

chronic dose. Typically, a small dose of radiation received over a long period (months or years) and better tolerated by the body than an acute dose.

contamination. Radioactive material in an unwanted location.

counts per minute (cpm). The number of ionizing events detected by an instrument in one minute.

criticality. A sustained nuclear fission chain reaction.

curie (Ci). A unit of measurement for radioactivity (2.22×10^{12} dpm).

derived air concentration (DAC). The concentration of a radionuclide in air that, if breathed over a period of a work year (2,000 hours), would result in the annual-limit-on-intake for that radionuclide being reached.

disintegration (radioactive). The change that occurs when a radioactive atom emits ionizing radiation; also called radioactive decay.

disintegrations per minute (dpm). The number of disintegrations an atom in a radioactive source undergoes per minute.

dose. The amount of energy deposited in the body from ionizing radiation.

dose equivalent. Expressed in rem, the product of the absorbed dose and a quality factor based on the type of radiation.

dose rate. The amount of ionizing radiation (dose) received per unit of time.

dosimeter. A device used to assess radiation dose.

dpm. See "disintegrations per minute".

electron. A negatively charged particle that surrounds the nucleus of the atom. Electrons determine the chemical properties of an atom.

element (chemical). A substance composed of identical atoms, each with a specific number of protons and chemical properties, e.g., hydrogen, iron.

element symbol. A one- or two-letter code that designates a particular element, e.g., H for hydrogen and Fe for iron.

embryo. The developing human from the time of conception through the eighth week of pregnancy.

exposure. Usually expressed in roentgens, it is a measure of the amount of ionization caused by gamma/x-rays in air.

external radiation. Radiation emitted from a source outside the body.

fetus. The developing human from the ninth week after conception through birth.

gamma ray. A highly penetrating, chargeless electromagnetic wave or photon emitted from the nucleus of an unstable atom. Long range in air; shielded by dense materials such as lead, concrete, or steel. Considered an external hazard.

half life. The time it takes for one-half of the material to be removed (biologically) or decay (radioactively). See "radioactive half life" and "biological half life".

heritable effect. An effect that appears in the future children of the exposed individual.

internal dose. Dose from a source that has been taken into the body.

ion. An atom that has an electrical charge because an electron has been removed (or added).

ionization. The process of removing (or adding) an electron from (or to) an atom.

ionizing radiation. Radiation that has enough energy to cause ionization of an atom with which it interacts.

isotope. One of two or more atoms of the same element that has the same number of protons but a different number of neutrons.

manmade radiation. Radiation that has been generated or produced by humans. Examples include medical x-rays or treatments, consumer products, atmospheric testing of nuclear weapons, and industrial radiography.

mass number. The number of protons plus neutrons in a nucleus; it is used to designate a particular isotope or nuclide, e.g., U-238 has a mass number of 238.

microrad (μrad). 1/1000 mrad.

microrem (μrem). 1/1000 mrem.

microroentgen (μR). 1/1000 mR.

millirad (mrad). 1/1000 rad.

millirem (mrem). 1/1000 rem.

milliroentgen (mR). 1/1000 R.

natural background radiation. Radiation that comes from naturally occurring radioactive materials in the rocks and soil of the earth, from food and water, from radon, and from cosmic rays from the sun and other sources in space.

nCi. nano-curie: 1E-9 Ci; also 2,222 dpm.

neutron. A particle with no electrical charge located in or removed from the nucleus of the atom. The number of neutrons determines the isotope of an element.

neutron (as a form of radiation). A highly penetrating particle with no electrical charge from the nucleus of an atom. Long range in air; shielded by materials such as concrete. Considered an external hazard.

nonionizing radiation. Radiation that does not have enough energy to cause ionization to an atom with which it interacts.

nucleus. The central portion of the atom, which contains protons and neutrons.

nuclide. A type of atom or atomic nucleus with a specific number of neutrons and protons.

occupational radiation dose. The radiation dose received by a worker whose assigned duties involve exposure to radiation and/or radioactive material. Does not include dose received from natural or manmade background radiation. Limited to 5 rem per year.

pCi. pico-curie: 1E-12 Ci; also 2.22 dpm.

prenatal exposure. Radiation exposure to the unborn child.

protective clothing. Clothing provided to workers to minimize the potential for contamination to skin or personal clothing. Also referred to as anticontamination clothing, or anti-Cs.

proton. A positively charged particle located in the nucleus of the atom. The number of protons determines the element.

quality factor. A modifying number, multiplied by the number of rad to determine the number of rem, which accounts for the different levels of biological damage associated with each type of radiation.

rad (radiation absorbed dose). The unit used to measure the absorbed dose in any material from all types of ionizing radiation.

radioactive contamination. Radioactive material in an unwanted location.

radioactive decay. The transformation of a nuclide into a different energy state or into a different nuclide, which results in the emission of radiation and a decrease, over time, of the original radioactive atoms. Also known as disintegration.

radioactive half-life. The time it takes for one-half of the radioactive atoms present to decay (by radioactive decay).

radioactive material. Any material containing unstable, or radioactive, atoms that emit radiation.

radioactivity. The spontaneous decay of unstable, or radioactive, atoms that emit ionizing radiation as they attempt to become stable.

rem. The unit of dose equivalence used for human exposures, which considers the biological effects of different types of radiation on the body.

roentgen (R). The unit of exposure used to measure ionization caused by gamma/x-rays in air.

thermoluminescent dosimeter (TLD). A radiation monitoring device used to assess the dose from high-energy beta, gamma, x-ray, and neutron radiation.

Answers to multiple-choice questions

Section 1 page 5. 1a, 2c, 3b, 4c, 5c, 6c, 7c, 8b, 9b.
Section 1 page 9. 1a, 2b, 3b, 4d, 5d, 6c, 7c.
Section 1 page 11. 1c, 2b, 3b.
Section 2. 1d, 2a, 3c, 4a, 5b, 6b, 7d, 8c, 9d, 10d.
Section 3 page 19. 1c, 2b, 3c, 4a, 5d, 6d, 7a.
Section 3 page 21. 1a, 2d.
Section 4. 1d, 2d, 3a, 4a, 5d, 6c, 7a, 8b.
Section 5. 1b, 2b, 3c, 4d, 5c, 6d, 7d, 8c.
Section 6. 1b, 2c, 3d, 4b, 5c.
Section 7. 1c, 2c, 3a, 4d, 5a, 6b, 7c.
Section 8. 1c, 2b, 3c, 4d, 5c, 6c, 7c.
Section 9. 1b, 2c, 3d, 4a, 5d
Section 10. 1a, 2b, 3c, 4d, 5a.
Section 11. 1c, 2c, 3a, 4b, 5a, 6d, 7d, 8a.