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Overview:

The Three “R’s”: Radiation, Radioactivity, and Risk Assessment

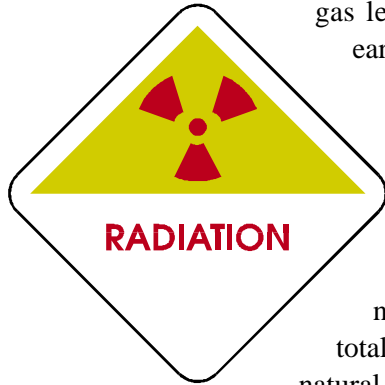
Since the beginning of time, all life on earth has thrived amid a constant exposure to radiation from naturally occurring sources. The sources of this radiation include the sun and outer space, the ground beneath our feet, the food we eat, and the air we breath. Everything in our world contains small amounts of radioactive atoms that are either left over from the creation of the world (like Uranium and Radium) or are the result of interactions with cosmic radiation from outer space (like Carbon 14 and Tritium). Over the past hundred years, we have come to know more about this form of energy thanks to the work of scientists such as Roentgen, Becquerel, the Curies, Rutherford, and others. However, radiation continues to be a topic of interest or concern to many people. Perhaps because it is invisible and cannot be detected by our senses, people are not familiar with radiation and its properties and are not familiar with evaluating its risks. A clearer understanding of radiation can be gained by examining the “Three R’s,” radiation, radioactivity, and risk assessment, and how they relate to each other.

Radiation

Radiation as used here refers to ionizing radiation — like the x-rays that are used at the doctor or dentist. Ionizing radiation deposits enough energy when it is absorbed in a material that the atoms in the material can have some of their electrons stripped off, thus creating electrically charged ions. Many kinds of radiation to which we are exposed are nonionizing; i.e., when this type of radiation is absorbed in a material, it lacks the energy to strip the atoms of electrons. Examples of nonionizing radiation are: sunlight, radio waves, microwaves, low frequency power line radiation, and heat or infrared waves. The other basic types of ionizing radiation are gamma radiation and the high energy particles emitted from the nucleus of the atom (alpha radiation, beta radiation, and neutron radiation).

How is radiation measured? The amount of radiation received is measured in terms of the energy absorbed by the material. The radiation energy absorbed is called the dose and when considering doses to human tissue, it is measured in units of “rems.” The ions formed by a radiation dose in the molecules of living cells can go on to react with other atoms in the cell causing damage. A rem is a measure of this damage caused by the deposited energy. While neutron and alpha radiation are more biologically damaging than gamma and beta radiation, the unit chosen to measure radiation dose, the rem, is used because it has the advantage that it includes the factor for biological damage for each type of radiation and we do not have to

know which type of radiation is causing the exposure. Doses from different types of radiation that have the same amount of rems cause the same amount of damage. Frequently when considering doses, the unit used is the millirem which is one one-thousandth (1/1000) of a rem. While the actual definition of a millirem corresponds to a specific amount of energy deposited per body mass, a better grasp of what a millirem means can be gained from a comparison of the dose levels received in various situations (see Table 1).



What are the levels of radiation? We are constantly exposed to a normal background of radiation. We receive radiation from cosmic rays from outer space, from radon gas leaking out of the earth into our homes, from radioactive material in the earth, from medical exposures, and from the food we eat and drink. The average dose to an individual in the U.S. including all these sources of radiation is approximately 360 millirem per year. The actual dose an individual receives depends on their location and lifestyle. Those living at higher elevation receive a little more cosmic ray radiation; those who smoke receive a larger dose to the lungs from the radioactive Polonium in tobacco smoke. Actually, a reactor operator on a submerged nuclear submarine while receiving a small extra dose from the reactor, has a total dose less than his civilian friends due to the decrease in cosmic and other natural radiation sources! At low doses, such as received every day from background radiation, the cells in the body rapidly repair any damage and the effects of very low doses of radiation cannot be distinguished from the natural variations occurring

in the population. At higher doses (up to 100,000 millirem), the cells might not be able to repair the damage and may be either permanently changed or die. A sufficiently high dose of radiation can kill any living organism. This is a very useful property that is used in industry to sterilize prewrapped food, medical supplies, and medical instruments; and is also used in medical treatments to kill unwanted cells. Examples of products that use high radiation doses for sterilization include: most sterile disposable medical equipment (bandages, needles, scalpels), tampons, facial cosmetics and mascara, artificial eye lashes, hair creams, and contact lens cleaning solutions. Little food is currently treated with radiation in the U.S. but more than 40 other countries treat foods such as onions, wheat, potatoes, cereal grains, spices, and fish.

The amount of time over which a radiation exposure occurs is also important. A large dose spread out over a year has less effect than a dose received within a few hours (an “acute” dose). This is similar to other common experiences such as exposure to the sun. Sunbathing at the beach for half an hour every few days during the summer is something most people would consider doing without thinking and has a small effect. But receiving the same total “dose” of sunlight by sunbathing for 8 hours a day, everyday for a week could lead to second-degree sunburns and severe illness if no precautions were taken. The importance of the time of exposure is why radiation dose limits often specify a time limit (quarter or year).

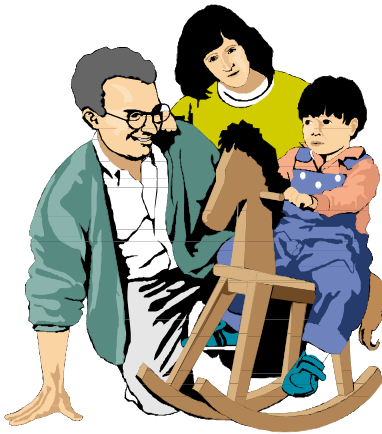
Because the long term effects of low dose exposures are unknown, a conservative regulatory policy is also used in addition to the fixed limits. This policy states that radiation exposures should be as low as reasonably achievable (ALARA principle).

Radioactivity

Just as atoms can exist in many different forms as elements, many elements can exist in more than one form and are known as isotopes. Certain of these forms, or isotopes, have unstable nuclei that can sponta-

neously change into other elements or into another form of the same element. Often this occurs as a result of a nuclear reaction with the unstable nuclei emitting one of the basic types of ionizing radiation (alpha, beta, neutron, or gamma). This spontaneous emission of ionizing radiation is called radioactivity. The nuclei of radioactive atoms have an excess of energy and are unstable. By emitting their surplus energy in the form of ionizing radiation, they change or “decay” or “disintegrate” until they become stable atoms. The time when an atom will decay is independent of both its past history and external influences such as temperature or pressure; there is no way of predicting when any one nucleus will change. However, since all the radioactive atoms of the same type will have the same probability of decaying spontaneously, we can describe this random or statistical process by the time it takes for one-half of a large number of the radioactive atoms to change or decay. We call this time the “half-life,” the time for the amount of radioactivity in a material to decrease by a factor of two to one-half (1/2) of its previous value. Half-lives of radioactive isotopes vary from fractions of a second to billions of years (see Table 4 for some examples).

How is radioactivity measured? The amount of radioactivity in a material is measured in terms of the number of nuclei disintegrating in each second, in units called curies. One curie is the quantity of material that has 37 billion disintegrations per second (d/s) taking place. The amount of radioactivity in a material can vary from the very low levels of some everyday things (9 d/s in a banana, 3000 d/s in a human adult) to the very high levels of unique items (100 trillion d/s in a radiotherapy source). See Table 3 (Radioactivity of Some Natural and Man-Made Materials) for other examples.



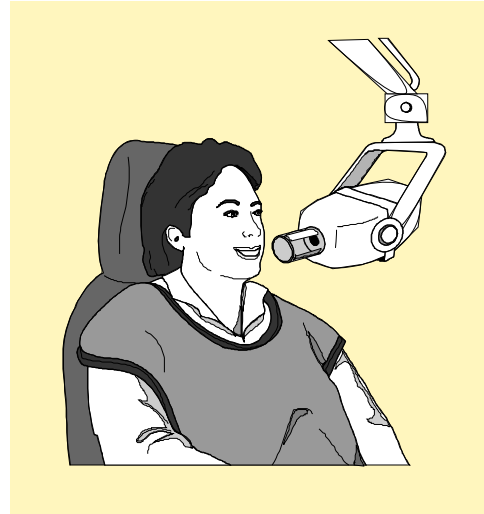
Risk Assessment

Risk evaluation is a process we undertake in many daily situations and is simply the process of making a judgment that balances the risks with the benefits. When we want to go somewhere in a hurry, we accept the risks of flying or driving for that benefit. When we want to eat fat foods, we accept the risk of heart disease. Radiation is another risk that must be balanced with the benefit of a source of power, the ability to do research, or to receive medical diagnosis or treatment.

What is a safe level of radiation exposure? Unfortunately, there is no answer to this question. Rather the question that should be asked is: “What is the risk associated with a given exposure?” This is what we do more or less unconsciously with everyday risks. For example, the question “What is a safe driving speed?” has no answer; all driving entails some risk of an accident occurring with anything from a minor to a major injury. The appropriate question to ask is: “What is the risk of injury for this situation and speed?” Driving on a narrow, curving road in a residential neighborhood at 20 mph is a risk most people take but they would find driving at freeway speeds in this situation unacceptably dangerous. Similar to the everyday risk evaluations we make, a risk evaluation should be part of each individual’s decision on radiation exposure. It is difficult to estimate risks from radiation because most of the exposures that we receive are very close to background levels and the effects are small. The main radiation risk is a small increase in the chance of getting cancer. Approximately 25% of all adults will develop cancer at some time. If a radiation worker receives an occupational radiation dose of 1000 millirem, the risk of obtaining cancer is estimated to increase to 25.03%. Using a conservative estimate, the risk of developing cancer from a lifetime dose of 10,000 millirems is 25.3% and from a lifetime dose of 100,000 millirems is 28%. The risk table (Table 4) compares the risk of

radiation with other health risks and shows that radiation is a small risk compared to the risks we take every day. Radiation is not a mysterious source of disease. After nearly 100 years of study, it is a well understood phenomenon and better understood than almost any other cancer causing agent.

How can we reduce our radiation dose from radioactive materials and thus reduce our risk? When working with a radioactive material there are three basic ways an individual can reduce their radiation dose. These protective measures are known as time, distance, and shielding. A radiation dose is cumulative (like exposure to the sun); decreasing the amount of time spent near the source will reduce your dose. The amount of radiation received also decreases as the distance from the source increases (like light from a light bulb); so increasing the distance from the source will decrease the received dose. Since radiation is reduced or attenuated as it passes through materials, placing a shielding material between the source and the body is the third way to reduce the dose. For instance, the dose to the patient from a dental x-ray is minimized by having a very short exposure time and wearing a lead apron, while the dose to the x-ray technician is minimized by moving away from the x-ray machine or moving behind a shielding wall.



Remember, there is nothing unique about radiation. There are no detrimental health effects caused by radiation that are not also caused by one or more physical, chemical, or biological agents. Keep in mind that giant spiders, mutant crabs, and other fearsome creatures are created in the Special Effects Department of Hollywood — not by radiation.

**Table 1
Radiation Doses**

Acute Radiation Dose Effects in Millirem	
450,000.0	Acute dose, LD 50/60 (a lethal dose to 50% of a population within 60 days if no medical treatment)
100,000.0	Acute dose, radiation sickness, reduced blood count, recovery
25,000.0	Acute dose, reduced fertility, and temporary sterility
10,000.0	Minimum acute dose for which prompt effects are detectable

(**Prompt** effects occur within a matter of hours or days after an **acute** dose — a dose received within a few hours.)

**Radiation Doses in Millirem from Various Exposures
(Annual Dose Unless Otherwise Stated)**

10,000.0	Dose to Chernobyl evacuees
5,000.0	U.S. Occupational Dose limit
2,000.0	Tobacco smoking
1,500.0	Underground uranium mines
400 – 800.0	St. Peters Square, Rome
600.0*	Pelvic x-ray exam
500.0*	Barium enema x-ray exam
500.0	U.S. Occupational Dose limit for pregnant women per 9 months
500.0	N.Y. Grand Central Station entrance
480.0	Denver, Colorado
360.0	Average U.S. dose
170.0*	Gall bladder x-ray exam
140.0*	Rib cage x-ray exam
100.0	Airplane flight crew yearly dose
100.0	Dental x-ray dose to center of cheek
20.0	1 Chernobyl per year
15.0*	Chest x-ray
7.0	Nuclear testing (peak year)
4.0	Fallout
2.0	Airplane trip coast to coast
1.0	Nuclear power
0.5	TV at surface
0.1	Sleeping with another human

*Variations by a factor of 2 (above and below) are not unusual.

**Table 2
Comparing Radiation Risk to Other Risks**

Estimated Loss of Life Expectancy from Health Risks	
Health Risk	Average Days Lost
Unmarried male	3500 (9.6 yr)
Smoking 20 cigarettes/day	2370 (6.5 yr)
Unmarried female	1600 (4.4 yr)
Overweight (by 20%)	985 (2.7 yr)
All accidents combined	435 (1.2 yr)
Auto accidents	200
Alcohol consumption (U.S. avg.)	130
Home accidents	95
Drowning	41
1000 millirem per year for 30 years*	30
Natural background radiation*	8
Medical diagnostic x-rays*	6
All catastrophes (earthquake, etc.)	3.5
1000 millirem occupational	1

*Calculated.

Explanatory Note on Health Risk Table

Note that these are statistics describing a large population and cannot be used to make a simple statement concerning a particular individual. However, they can indicate how different lifestyles affect your life expectancy. For example, being overweight does not necessarily reduce your life expectancy by 2.7 years, but since the average life expectancy is reduced by 2.7 years, your chances of dying prematurely are increased. Another example: the average days of life expectancy lost due to drowning (41) does not represent what an individual with a life expectancy of 70 years might lose off his own life due to drowning but rather, for example, could correspond to a total of 23 people out of a population of 10,000 dying at age 20 in a drowning accident (23 people × 50 years lost × 365 days/year/10,000 people ~41 average days lost). The risk to the total group is low because the average loss of life expectancy for the whole group due to drowning is only 41 days. However, the consequences to the 23 people who drown is significant because they will have lost 50 years of life. Similarly, if 5000 people received a dose of 1000 millirem, all but one might live to age 70 while the one person would die at age 56 [1 person × (70–56) years × 365 days/year/5000 people ~1 day lost].

Table 3
Radioactivity of Some Natural and Man-Made Materials

Material	Amount	Becquerels
Source for radiotherapy	1	100,000,000,000,000 (100 trillion)
50-year old high level nuclear waste	1 kg	10,000,000,000,000 (10 trillion)
Uranium	1 ton	10,000,000,000 (10 billion)
Medical isotope for diagnosis	1	70,000,000 (70 million)
Coal ash	1 ton	2,000,000 (2 million)
Low level nuclear waste	1 kg	1,000,000 (1 million)
Fertilizer — super phosphate	25 kg	125,000
Human adult	1	3,000
Coffee	1 kg	1,000
Bread	1 loaf	70
Hamburger	4 oz.	29
Red kidney beans	1/2 cup	29
Sunflower seeds	3.5 oz	28
French fries	3.5 oz	20
2% Milk	1 cup	11
Banana	Small	9
Hot chocolate	1 packet	6
Oatmeal	1 cup	4

Table 4
Half-lives of Some Radioactive Isotopes and Their Uses

Isotope	Half-life	Use
Carbon 11	20 min	Agriculture
Iodine-131	8 day	Medical therapy
Krypton-85	11 year	Industry
Cesium-137	30 year	— Treat cancers
		— Calibrate equipment
		— Irradiate blood for transfusions
Carbon-14	5730 year	— Test new drugs for harmful by-products
		— Carbon-dating ancient artifacts
Iodine-129	15.7 million year	Check radioactivity counters in in-vitro diagnostic labs
Uranium-238	4.5 billion year	Color brightness in dental fixtures

Table 5
Units of Radiation and Radioactivity

Common Units USA	Abbreviation	Used to Measure
Roentgen	R	<ul style="list-style-type: none"> — Exposure (obsolete) — Measure of the amount of ionizations in a mass of air, gamma and x-rays only, only in air — $1 R = 2.58 \times 10^{-4}$ coulombs per kg of dry air
Rad (radiation absorbed dose)	rad	<ul style="list-style-type: none"> — Absorbed dose, measure of amount of energy absorbed in a material, any type radiation, any type material — $1 \text{ rad} = 100$ ergs per gram of material
Rem (roentgen equivalent man)	rem	<ul style="list-style-type: none"> — Equivalent dose, relates absorbed dose in human tissue to the effective biological damage; "rem" doses which are equal but from different types of radiation produce the same amount of biological damage — $\text{rem} = \text{rad} \times Q$ (the quality factor) — $Q = 1$ for x-rays, up to 20 for neutron or alpha
Curie	Ci	<ul style="list-style-type: none"> — Radioactivity — $1 \text{ Ci} =$ quantity of material that has 3.7×10^{10} disintegrations/second

SI Units International Standard	Abbreviation	Used to Measure
Gray	Gy	<ul style="list-style-type: none"> — Absorbed dose (equivalent to rad) — $1 \text{ Gy} = 1$ joule per kg of material — $1 \text{ Gy} = 100$ rads
Sievert	Sv	<ul style="list-style-type: none"> — Equivalent dose (equivalent to rem) — $1 \text{ Sv} = \text{Gy} \times Q$ — $1 \text{ Sv} = 100$ rem
Becquerel	Bq	<ul style="list-style-type: none"> — Radioactivity (equivalent to Ci) — $1 \text{ Bq} = 1$ disintegration/second — $3.7 \times 10^{10} \text{ Bq} = 37$ billion Bq = 1 Ci

Note: frequently units are prefixed with milli (m) (one thousandth) or micro (μ) (one millionth), i.e., 1 millirem = 1 mrem = 0.001 rem, 1 microCi = $1 \mu\text{Ci} = 0.000001 \text{ Ci}$.



INSTRUCTOR'S GUIDE

This separate discussion parallels the reading material in the beginning of this section and provides some additional details for the teacher's use. Brief discussions of activities and experiments associated with the main concepts are included.

What Is Radiation?

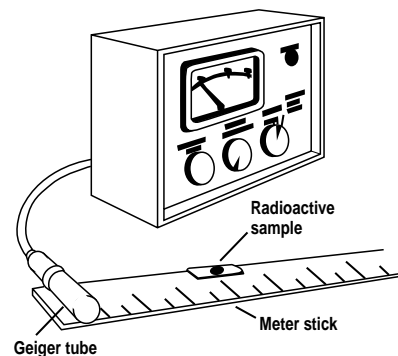
Radiation is energy of two types: **energetic particles** and **electromagnetic waves**. **Particles** have mass, may have an electric charge, and transfer energy to matter by their motion. The particles of most interest when discussing ionizing radiation include: **alpha** (positively charged particle with 2 neutrons and 2 protons), **beta** (negatively charged electrons), and **neutrons** (neutral charge).

Electromagnetic waves exhibit both a particle nature with energy bundles called photons but without any mass and a wave nature which can be described by wavelength or frequency. The electromagnetic spectrum is examined in great detail in a separate unit of this notebook. It consists of waves from the longer wavelengths (low frequency) like radio and microwaves, through infrared, visible and ultraviolet light, to shorter waves like x-rays and gamma rays. Since the energy of these waves is proportional to their frequency, only the shortest waves (highest frequency) like **x-rays** and **gamma rays** are energetic enough to be ionizing radiation.

How Is Radiation Measured?

One of the most biologically important considerations related to ionizing radiation is the **amount of energy deposited** in the living matter. This is referred to as the "**dose**." Common units used in measuring doses are found in Table 5 **Units of Radiation and Radioactivity**.

The **Quality Factor** (sometimes called **Relative Biological Effect**) accounts for the penetrating and ionizing characteristics of the various types of radiation. It seems obvious that the massive **alpha particle** with its 2+ charge would be the most damaging. What might not be obvious is that it is the **least penetrating** particle due to its charge and relatively large size. Since the amount of alpha radiation penetrating the skin is small, its largest effect is due to ingestion (breathed or swallowed). In that case, the alpha radiation will ionize atoms in surrounding cells.



Neutrons carry no charge, have about the same mass as a proton, and are **relatively penetrating**. Neutron shielding uses water and other hydrogen containing materials with which the neutrons have the largest interaction.

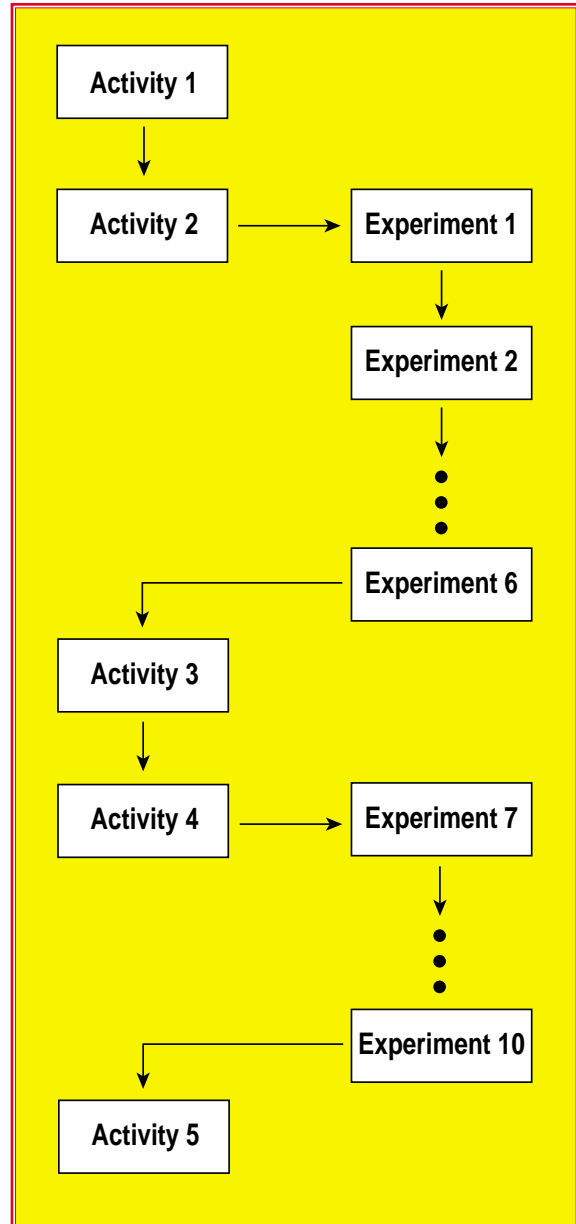
Beta particles have a single negative charge, are much less massive than a neutron, and are **not very penetrating**; they can be shielded by a thin sheet of aluminum.

Gamma rays and **x-rays** are the **most penetrating** forms of radiation but will pass through living tissue without transferring much energy. They can only be effectively shielded by thick lead or other dense material.

Several types of devices are used to measure and record radiation. The **accumulated dose** received by individuals is measured by a **dosimeter** or by a “**film badge**.” A dosimeter records the ionizations occurring in a small tube or chamber by measuring the electrostatic discharges they cause. Modern digital dosimeters electronically count and display the dose. A “film badge” contains a number of different elements, usually chips of thermoluminescent dosimeters (TLD) made of lithium fluoride (LiF) and film. The TLDs are processed by heating causing radiation-induced transitions to decay and light to be emitted, which is proportional to the received dose. The film displays the radiation exposure after it is developed. Both types of devices only record how much **accumulated radiation** has been received and **not the dose rate**.

A useful way to avoid exposure is the use of **survey meters**, which measure **dose rate** usually in millirem per hour. These instruments include the common **Geiger counter**, **scintillation counter**, and **ionization chamber**. These instruments use a very high voltage between electrodes in a vacuum to create an “avalanche” or discharge when ions are formed in their detector tubes by radiation. These discharges are recorded as **counts per minute** and displayed on meters.

Activity 1 is a short set of questions to help review some of the main concepts in the reading material, and **Activity 2** is a timeline exercise which lends historical perspective to the discussion. **Experiment 1** is an electroscope demonstration of the ionizing effect of radiation, and **Experiment 2** (somewhat challenging) is a “visible” look at radiation using a cloud chamber. (It will require practice and patience, but can be very rewarding.)



What Is Radioactivity?

All elements are made up of atoms. Each atom contains a nucleus of positively charged protons and neutral neutrons which provide the “strong force” attractions to hold the protons in the nucleus. (A reasonable analogy would be that the neutrons are like Velcro covered balls which can overcome the repulsive forces of the positively charged protons.) The smaller negatively charged electrons are found in “orbits” around the outside of the atom. The number of protons (and equal number of electrons in neutral atoms) are unique for atoms of each element. Hydrogen has one proton (and is usually the exception with no neutrons), carbon has six, and uranium has 92. The number of neutrons, however may vary in atoms. Atoms with just enough neutrons to hold its protons in the nucleus are considered to be **stable**. If the nucleus contains too many or too few neutrons, it will be **unstable** and will correct this instability by casting off energy in the form of energetic **particles** or **electromagnetic waves** which we identify as **ionizing radiation**. This disintegration process is called **radioactivity**. It may occur in elements found naturally in the earth or as the result of splitting of heavy atoms in fission reactions — producing lighter but unstable fission products. Atoms of the same element which contain different numbers of neutrons are called **isotopes**.



Experiment 3 is a familiarization with the use of Geiger counters or survey meters for detecting some common radioactive materials. **Experiment 4** uses an assortment of beans to develop the isotope concept. **Experiments 5 and 6** provide visual demonstrations of a fissioning atom and chain reactions using a suspended oil drop and dominos.

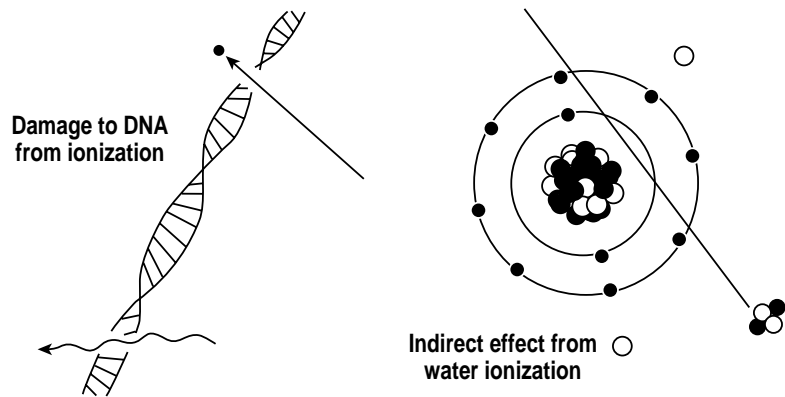
When atoms undergo **radioactive decay**, they form atoms of a different element. This may occur several times until stability is achieved. For example, radioactive **uranium** isotopes undergo a series of decay steps, emitting alpha and beta particles and gamma rays, until they finally produce stable **lead** atoms. Some isotopes decay rapidly while others may take a very long time. A convenient way to compare decay rates is by the **half-life** of each isotope. The half-life is defined as the time required for half of an isotope present in a sample to decay away. (Note: a graph of the isotope concentration versus time will produce a nonlinear decreasing curve which can only asymptotically approach zero.) For example, if an isotope has a half-life of 2 hours, half will remain after 2 hours of decay, and a quarter (1/4) of the original amount will remain at the end of 4 hours, an eighth (1/8) at the end of 6 hours, etc. Half-lives of radioactive isotopes vary from small fractions of a second to billions of years. Each isotope has its own unique half-life. Table 4 contains **Half-lives of Some Isotopes and Their Uses**.

The rates at which these radioactive decays occur have units of measurement named after some of the pioneers in this field, Marie and Pierre Curie, Becquerel, and others. These are defined in Table 5 **Units of Radiation and Radioactivity**.

Activities 3 and 4 show some practical applications of radioactivity involving a mathematical calculation that may be more advanced. **Experiments 7 and 8** offer a variety of approaches to demonstrate the half-life concept.

How Does Radiation Affect Us?

Whatever the source and amount of ionizing radiation, it will have some **biological effect** on living organisms. **Atoms** will be **ionized** as described earlier by having electrons displaced. These altered atoms will affect the **molecules** to which they belong and, therefore, the cells which contain these molecules. Since cells make up **organ tissue**, there may be an effect on the organ, and as a result, the **whole body** may be affected.



The biological effect on a cell may be **direct** or **indirect**. If radiation interacts with atoms of a **DNA molecule**, or some other molecule critical to the survival of the cell, the cell is considered **directly affected**.

A more likely interaction would be with atoms in a **water molecule** since cells contain primarily water. Such an interaction may break apart the water molecule, producing fragments such as hydrogen (H^+) or hydroxyl (OH^-) **radicals**, which have the capability to form toxic substances such as hydrogen peroxide (H_2O_2). These compounds can contribute to cell damage. This is called an **indirect effect**.

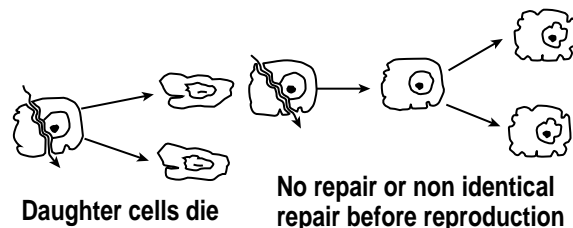
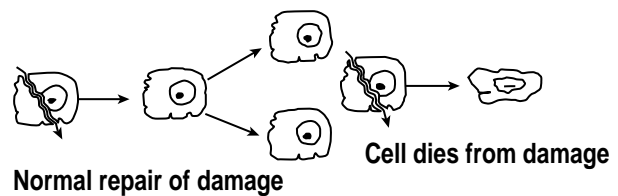
The results of these interactions depend on the **sensitivity** of the cell to ionizing radiation and on the **amount** and **type** of radiation the cell receives.

Cellular Sensitivity To Radiation

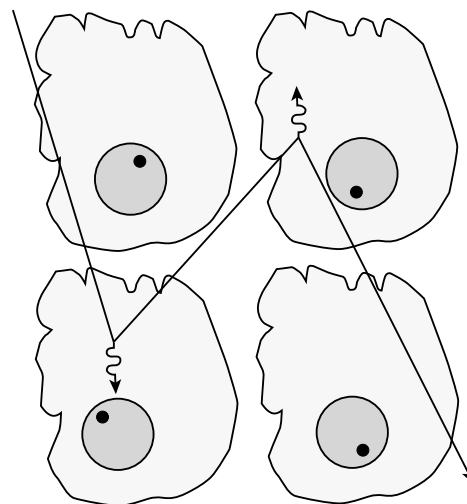
Living cells are not all equally sensitive to radiation damage. Rapidly reproducing cells are more sensitive than those cells which have longer to repair ionization damage since dividing cells require correct DNA information for the survival and normal functioning of daughter cells.

Cells damaged by radiation can respond in one of four ways:

1. Less active cells receiving small amounts of radiation are able to accomplish normal repair of the damage before reproduction, so there is no lasting effect.
2. Large amounts of radiation may cause the death of the cell.
3. More active cells may reproduce before repair, resulting in death of the daughter cell.
4. Incomplete or nonidentical repair of damage before reproduction — resulting in mutant daughter cells.



As a result of these cellular sensitivity differences, organs with rapid cell reproduction are more sensitive to damage than slower growing organs. Actively dividing white blood cells are more likely to be damaged than cells in muscles, nerves, the brain, and the skin. A **beneficial** use of this knowledge is the radiation treatment of **malignant tumors**. These tumors grow faster than surrounding tissue if they have adequate blood and oxygen supply and are, therefore, more prone to destruction if the amount of radiation can be carefully controlled to permit surrounding cells to repair damage. Also, side effects of radiation treatment such as hair loss and nausea or intestinal upset, again occur in areas where the cells are more rapidly dividing (hair growth cells and cells in the stomach lining). A **developing fetus** is very sensitive to radiation damage due to its rapidly reproducing cells and is most sensitive in the first three months, when the cell reproduction is largest.



Health Effects of Exposure

Low dose exposures are not clinically detectable. That means that the long term effects can only be **estimated** in **statistical studies** of whole populations. In this way, the estimated effects are compared to other common societal health risks (driving, flying, sports, alcohol, etc.) to look for the smallest discernible increased risk. This might mean that an increase of one additional case of cancer in a population of a million would be noted.

The biological effects of low doses can be divided into three categories:

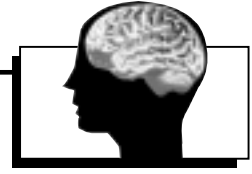
1. **Genetic Effects.** Observed in offspring of exposed individuals resulting from egg or sperm cell mutations. As in the case of chemically (drugs) or biologically (viruses) related mutations, these effects usually result in nonviable organisms, but never in the “monsters” portrayed in movies or comics.
2. **Somatic Effects.** Observed in the exposed individuals. These might take the form of cancers similar to the effects of chemical agents (smoking or drinking alcohol) or biological agents (viruses).
3. **In-Utero Effects.** Observed after birth due to exposure of the embryo. This is a sub-set of somatic effects, more serious in earlier stages of development, probably resulting in death, with diminishing consequences later in fetal development.

In contrast to the low doses over long time, there have been occasions in which humans have received large doses in a matter of hours. These are called **acute doses**. In the cases of the atomic bombing of Hiroshima and Nagasaki and the catastrophic release of radioactive material from the Chernobyl power plant in the former Soviet Union, the clinical effects were detectable. Cells were killed with resulting organ and whole body damage. Table 1 briefly describes the expected effects from acute doses.

Even in circumstances involving high doses of radiation, treatment can be given if the specific isotopes are known since body organs exhibit differing sensitivities to various isotopes. For example, Iodine-131 will be absorbed preferentially by the thyroid while Strontium-90 (chemically like Calcium) will find its way to the bones.

Because of the inability to observe definite effects of low exposure levels in living tissue, the most conservative approach is used when evaluating risks from radiation exposure. This approach is called the **Linear No-Threshold Risk Model** which assumes some minimal biological effect from **any** exposure even though it would only apply statistically to large populations — not to individuals.

Experiment 9 is an extensive investigation of the **Time, Distance, and Shielding** concepts necessary to minimize radiation exposure of **workers**. **Experiment 10** is a very instructive demonstration of the difficulties in limiting the spread of radioactive contamination. Finally, **Activity 5** contains three crossword exercises for use in review or for initiating further library research.

Activity*Radiation, Radioactivity, and Risk Assessment*

ACTIVITY 1 LET'S INVESTIGATE

Purpose

To reinforce the major concepts of radiation, radioactivity, and risk assessment.

Discussion

Read the Overview on “Radiation, Radioactivity, and Risk Assessment” and answer the following questions.

Questions

1. Identify each type of radiation as ionizing (mark with I) or nonionizing (mark with NI).

- | | | | |
|--------------------------------|-------|----------------|-------|
| A. sound | _____ | G. infrared | _____ |
| B. light | _____ | H. radio waves | _____ |
| C. alpha | _____ | I. microwaves | _____ |
| D. neutron | _____ | J. x-ray | _____ |
| E. gamma | _____ | K. beta | _____ |
| F. low frequency
power line | _____ | | |

2. True or False:

The average American is exposed to about 360 millirem of ionizing radiation per year. More than 80% of this dose comes from natural sources.

3. True or False:

Ionizing radiation refers to the ability of higher energy radiation to create electrically charged particles called ions in the material it penetrates including human tissue.

Let's Investigate

4. Radioactive atoms
- give off surplus energy by emitting radiation.
 - are unstable.
 - change or decay until they become stable.
 - all of the above.
5. Sources of ionizing radiation that contribute to the dose received each year by the average American are: (enter True or False next to each entry)
- medical x-rays _____
 - cosmic rays from the sky above _____
 - the earth below us _____
 - food we eat _____
 - our own bones _____
 - modern luminous watch dials _____
6. Which of the following consumer items can contribute to radiation exposure?
- cigarettes
 - camping lantern mantles
 - fertilizer
 - natural gas cooking
 - dental ware (crowns, dentures)
 - All of the above
7. Caution should be used by workers handling highly radioactive materials. Choose the method(s) workers can minimize their exposure to radiation dosage.
- Minimize the time spent near the radioactive material.
 - Maximize the distance between the radioactive material and the worker.
 - Use shielding between the radioactive material and the worker whenever possible.
 - All of the above.
 - None of the above.
8. Radon, the radioactive gas that contributes more than half the yearly dose to the average American, has a half-life of approximately four days. How long does it take a sample containing radon to decay to one-eighth ($1/8$) of its original level of radioactivity?
- 2 days
 - 4 days
 - 8 days
 - 12 days
 - 16 days
9. True or False:
- Giant spiders, mutant crabs, and other fearsome creatures are the product of the special effects department of Hollywood — not radiation. In other words, the effects of radiation are not unique. There are no detrimental health effects caused by radiation that cannot also be caused by one or more physical, chemical, or biological agents.

10. What is a safe radiation dose?

- A. Depends on the age of the individual.
- B. Depends on the time over which the dose exposure was received.
- C. A poorly phrased question that has no answer.
- D. Depends on the frequency of the radiation.

11. The following table ranks the risks of a number of activities. The risk is ranked from high to low on the basis of the estimated number of days of life expectancy lost for that activity. Compared to the activities listed in the table, where does the risk associated with receiving a radiation dose of 1000 millirem every year for 30 years fit?

Higher Risk	Smoking 20 cigarettes per day
	Overweight by 20%
	All accidents combined
↑ increasing risk	Auto accidents
	Drowning
	Medical diagnostic x-rays
Lower Risk	All catastrophes (earthquake, etc.)

- A. Greater than the risk of being overweight by 20%.
- B. Greater than the risk due to auto accidents.
- C. Slightly less than the risk of drowning.
- D. Less than the risk associated with x-rays used in medical diagnostics.

Activity

Radiation, Radioactivity, and Risk Assessment



ACTIVITY 2 TIME LINE

Purpose

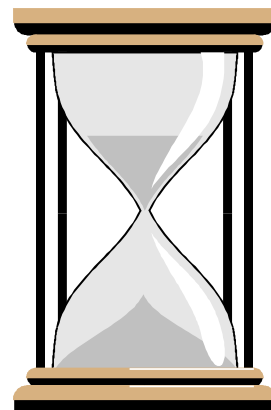
To gain a perspective of both the events related to the development of atomic theory and our understanding of radiation and radioactivity and the people involved.

Discussion

Read through the time line of atomic events then use the atomic events time line to fill in the items in the historical time line.

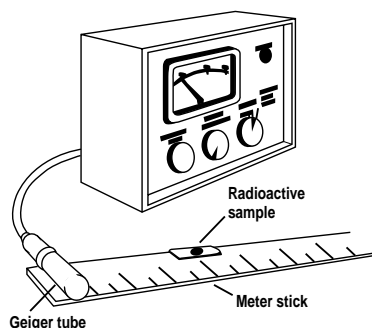
Atomic Time Line

- 400 B.C. In Greece, Democritus proclaims all material things are made of tiny particles, which he called atoms — the Greek word meaning “not divisible.”
- 1789 The element uranium is discovered (Martin Klaproth).
- 1869 Dmitri Mendeleev develops the periodic law of elements, which later evolves into the Periodic Table of Elements.
- 1890 Radioactive thorium is first used in mantles for camping lanterns because of its bright, light-producing properties when burning.
- 1895 X-rays discovered (Wilhelm Roentgen).
- 1896 French scientist Henri Becquerel discovers some atoms give off energy in the form of rays. Uranium gives off radiation.
- 1898 Radium discovered (Marie and Pierre Curie). Radioactivity is named (Marie Curie).
- 1899 Ernest Rutherford concludes that radiation can be divided into two types — alpha and beta rays.
- 1900 Pierre Curie observes another type of radiation — the gamma ray.
- 1905 Theory of relativity ($E = mc^2$). Mass can be changed into energy (Albert Einstein).



Time Line

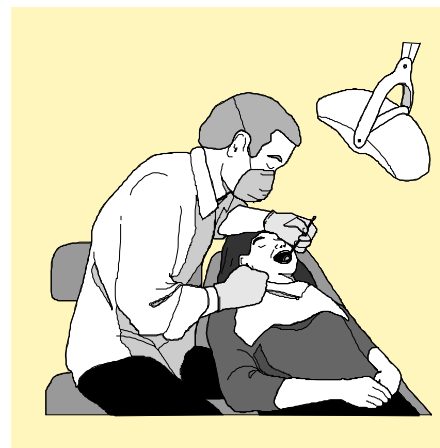
- 1911 Ernest Rutherford discovers that most of an atom is empty space and identifies the atomic nucleus.
- 1911 George de Hevesy is the first person credited with using radioisotope tracers. As a young researcher living in a cheap boarding house, he suspected that his landlady was saving leftovers and serving them to the boarders the next day. He added a tracer to his uneaten food. The next day he used a radiation detector to prove he was right. She evicted him, but later he won a Nobel Prize in biology for the use of radioisotopes as tracers.
- 1913 Theory of atomic structure is developed, dividing the atom into two parts — a nucleus and electrons which orbit the nucleus (Niels Bohr).



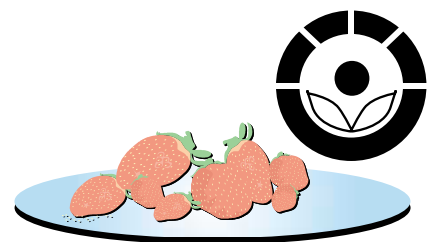
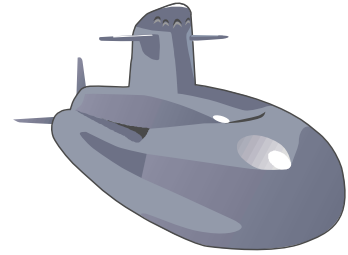
- 1913 Hans Geiger invents the Geiger counter for measuring radioactivity.
- 1919 The NC-4, a Navy flyboat, crosses the Atlantic Ocean guided by radium-powered instrument lights.
- 1920 The proton is discovered and named (Ernest Rutherford).
- 1927 Herman Blumgart, a physician at Thorndike Laboratory, Boston City Hospital, first uses radioactive tracers to diagnose heart disease.

Early 1930s Elements are bombarded with neutrons in an attempt to produce new isotopes or elements.

- 1930s Dental laboratories begin blending trace amounts of uranium oxide with porcelain materials to give crowns, bridges, and dentures the fluorescent color of natural teeth.
- 1932 The neutron is discovered (James Chadwick).
- 1934 When Uranium-235 is bombarded with neutrons, it does NOT produce a heavier element as expected, but instead several lighter ones (Enrico Fermi).
- 1935 Irene Joliot-Curie (daughter of Marie and Pierre Curie) and her husband Frédéric receive the Nobel Prize for creating the first artificial radioactive isotope.
- 1935 Nuclear medicine comes into existence when cyclotron-produced radioisotopes and nuclear radiations become available in the U.S.
- 1938 Otto Hahn and Fritz Strassman produce lighter elements by bombarding uranium with neutrons. Later that year, this is recognized as the splitting of the atom by Lise Meitner and Otto Frisch. The term “fission” is first used for this event in early 1939.
- 1939 The principle of nuclear reactors is first recorded and sealed in an envelope where it remains secret during the war years (Irene and Frédéric Joliot-Curie).



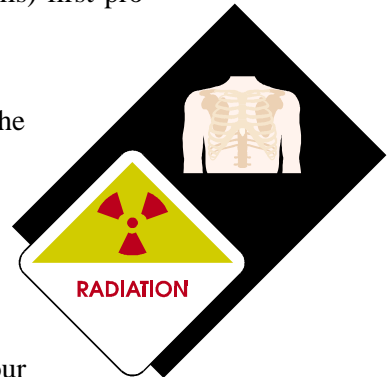
- 1939 U.S. Advisory Committee on Uranium recommends a program to develop an atomic bomb. (This is later named the Manhattan Project).
- 1942 First self-sustaining nuclear chain reaction produced in the first reactor at the University of Chicago on December 2 (Enrico Fermi).
- 1945 First atomic weapon is exploded at Alamogordo, New Mexico. Atomic bombs dropped on Hiroshima and Nagasaki, Japan.
- 1946 First civilian use of reactor produced radioisotopes shipped to Barnard Cancer Hospital, St. Louis, Missouri.
- 1954 First nuclear submarine, U.S.S. Nautilus, launched.
- 1957 First U.S. large-scale nuclear power plant begins operating in Shippingport, Pennsylvania (retired 1982).
- 1965 Polyester-cotton fabric (for permanent press uniforms and coveralls) first produced using radiation-induced grafting method.
- 1965 World's first commercial irradiation plant for food processing commissioned in Canada.
- Late 1960s Since the late 1960s, American astronauts and Russian cosmonauts have eaten radiation-sterilized foods in space.
- 1973 X-ray scanners first mandated at U.S. airports.
- 1979 Three Mile Island nuclear plant accident in Pennsylvania.
- 1983 Eleven years after launch, Pioneer 10, using a nuclear generator, passes beyond Pluto to become first man-made object to leave our solar system.
- 1984 Nuclear medicine procedures performed yearly on one of three people entering U.S. Hospitals.
- 1986 Chernobyl nuclear plant accident in Russia.
- 1986 100th U.S. commercial nuclear power plant begins operating — Perry-1 in Ohio.
- 1988 Carbon-14 dating determines the Shroud of Turin could not be the burial cloth of Jesus.
- 1989 Nuclear weapons production facilities at Rocky Flats Plant in Colorado and Fernald Feed Materials Production Center in Ohio cease production and change their missions to cleaning up their facilities.
- 1992 First U.S. commercial food irradiation plant in Florida ships its first irradiated strawberries to Miami, Seattle, Spokane, Pittsburgh, Rhode Island, Italy, and France.
- 1992 110 commercial reactors are operating in the U.S.



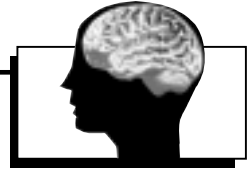
Activity

Using the Atomic time line, write the following items in the historical time line below at the appropriate spot.

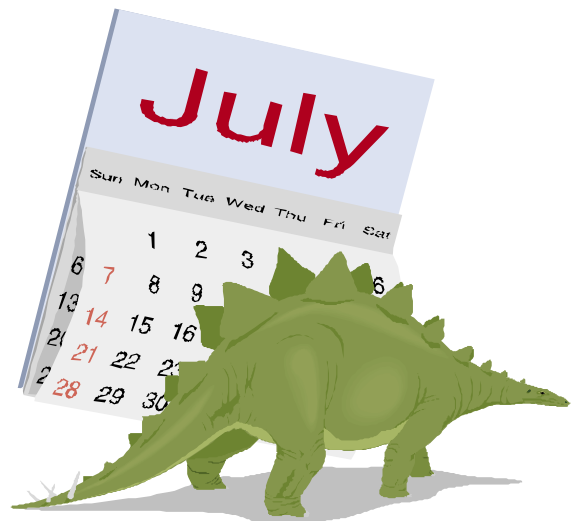
- a. Rutherford discovers that most of an atom is empty space.
- b. Becquerel discovers uranium naturally gives off some kind of radiation.
- c. Enrico Fermi achieves the first sustained nuclear chain reaction.
- d. Marie Curie names radioactivity.
- e. Lise Meitner and Otto Hahn understand experiments with uranium in which the atom splits.
- f. Marie and Pierre Curie discover radium.
- g. Nuclear plant accident at Chernobyl, Russia.
- h. Neils Bohr develops the theory of atomic structure.
- i. Albert Einstein develops an equation stating that matter and energy are the same thing.
- j. First civilian use of reactor produced radioisotopes shipped to Barnard Cancer Hospital, St. Louis, Missouri.
- k. Polyester-cotton fabric (for permanent press uniforms and coveralls) first produced using radiation-induced grafting method.
- l. X-ray scanners first mandated at U.S. airports.
- m. Carbon-14 dating determines the Shroud of Turin could not be the burial cloth of Jesus.
- n. Three Mile Island nuclear plant accident in Pennsylvania.
- o. World's first commercial irradiation plant for food processing commissioned in Canada.
- p. Eleven years after launch, Pioneer 10, using a nuclear generator, passes beyond Pluto to become first man-made object to leave our solar system.
- q. First U.S. commercial food irradiation plant in Florida ships its first irradiated strawberries to Miami, Seattle, Spokane, Pittsburgh, Rhode Island, Italy, and France.
- r. Nuclear medicine procedures performed yearly on one of three people entering U.S. Hospitals.



- 1891 Sport of basketball invented by James Naismith.
- 1896 _____
- 1898 _____
- 1903 Wright Brothers make first flight at Kitty Hawk.
- 1905 _____
- 1910 Boy Scouts and Camp Fire begin.
- 1911 _____
- 1913 _____
- 1915 First telephone talk from N.Y. To San Francisco is made by Alexander Graham Bell and Thomas A. Watson.
- 1920 Women's Voting Rights Amendment passes.
- 1926 Robert Goddard invents first rocket using liquid fuel.
- 1929 Martin Luther King is born.
- 1931 First NFL Championship — Chicago Bears 23, New York Giants 21.
- 1934 _____
- 1935 Elvis Presley is born.
- 1938 _____
- 1941 Pearl Harbor is bombed.
- 1945 World War II ends.
- 1946 _____
- 1953 Salk vaccine for Polio developed by Jonas Salk.
- 1958 First domestic jet airline passenger service.
- 1962 John Glenn is first American to orbit the Earth in Friendship 7 capsule.
- 1963 President John F. Kennedy assassinated.
- 1965 _____
- 1965 _____
- 1969 Neil Armstrong is first person to walk on the moon.
- 1973 _____
- 1974 President Richard Nixon resigns.
- 1979 _____
- 1983 _____
- 1984 _____
- 1986 _____
- 1988 _____
- 1989 "Fall" of the Berlin wall.
- 1991 U.S. and its allies begin Gulf ground war and liberate Kuwait from Iraq four days later.
- 1992 _____
- 1995 Cal Ripken breaks Lou Gehrig's record with 2130 consecutive baseball games played.

Activity*Radiation, Radioactivity, and Risk Assessment***ACTIVITY 3
FINDING THE AGE OF A FOSSIL****Discussion**

Carbon-14 (C-14) is a radioactive isotope of Carbon-12 (C-12) that is found in small amounts in living or once living matter and is used to estimate the age of fossils and prehistoric items. This isotope is believed to arise from nitrogen in the upper atmosphere that is bombarded by cosmic-ray neutrons and is continually being produced. Thus, a small fraction of the CO₂ molecules in the air will contain radioactive C-14 instead of C-12. The C-14 enters living organisms by exchange processes. The concentration of C-14 reaches an equilibrium value in the organism; the radioactive C-14 in the organism is decaying, but new C-14 is continually being added. Once the organism dies, no new isotope is absorbed and the C-14 remaining continues to decay with its 5730 year half-life. By comparing the amount of C-14 in the dead material with that in the atmosphere, the time since death can be computed assuming the atmospheric concentration has not changed. This method of measuring the age of organic items was first proposed by W.F. Libby in 1952 and is known as radio-carbon dating. Other radioactive elements can also be used to date different objects. Uranium can be used to date rocks which can be as old as 4.5 billion years (the approximate age of the Earth).



Finding the Age of a Fossil

Activity

The amount of Carbon-14 in a fossil sample is measured to be 1% of the atmospheric concentration. What is the age of the fossil?

I. Method 1: Start by filling in the following table:

Number of Half Lives	Fraction of C ¹⁴ Remaining from Initial Amount	Elapsed Time (Years)
0	1.0	0
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

1. Using the table above, find the amount of half-lives and elapsed time (years) for C-14 to decay to 0.01 (or 1%).

0.01 falls between _____ **(a)** and _____ **(b)** half-lives or
between _____ and _____ years.

2. Use a ratio to estimate the fractional part of a half-life between answers **(a)** and **(b)**:

$$\begin{aligned} x \text{ half-lives} / 1 \text{ half-life} &= (\text{amount decaying in } x \text{ half-lives}) / (\text{amount decaying in } 1 \text{ half-life}) \\ &= [\text{fraction remaining from } \mathbf{(a)} \text{ above} - 0.01] / [\text{fraction remaining from } \mathbf{(a)} \text{ above} - \text{fraction remaining from } \mathbf{(b)} \text{ above}] \end{aligned}$$

Now add the fractional half-life **x** to obtain the total number of elapsed half-lives and total years:

- total half-lives = answer **(a)** + **x** = _____ half-lives **(c)**
- total years = **(c)** × 5730 = _____ × 5730 = _____ years

II. Method 2: Exact method using logarithms.

Write an equation and solve for the number of half-lives. After each half-life, the fraction remaining is one-half ($1/2$) the previous amount.

- amount remaining after 1 half-life = $1/2$
- amount remaining after 2 half-lives = $1/2 \times 1/2 = (1/2)^2 = 1/4$
- amount remaining after 3 half-lives = $1/2 \times 1/2 \times 1/2 = (1/2)^3 = 1/8$
- amount remaining after 4 half-lives = $1/2 \times 1/2 \times 1/2 \times 1/2 = (1/2)^4 = 1/16$
- amount remaining after n half-lives = $(1/2)^n$

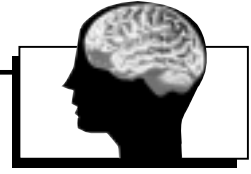
So solve $A = (1/2)^n = (0.5)^n$ with $A = 0.01$ by use of logarithms.

Questions

1. An individual claims to be the oldest living person with an age of 120 years. Can this method be used to verify this claim after they die? (How accurate a measurement would be needed to be able to make the measurement?)

Activity

Radiation, Radioactivity, and Risk Assessment



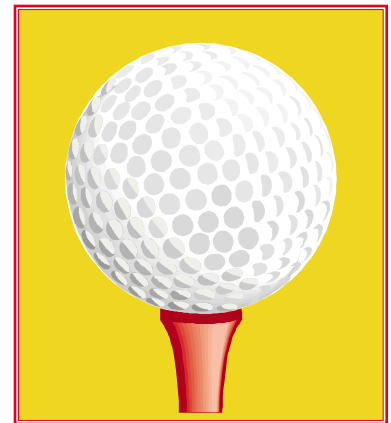
ACTIVITY 4 RADIOACTIVE GOLF BALL FINDER

Discussion

Henry (a.k.a. young Einstein) has an idea to find lost golf balls. He suggests including some radioactive material in the golf balls and searching for the lost balls by using a Geiger counter to detect the radioactivity in the ball. Evaluate the feasibility of Henry's idea.

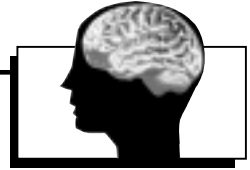
Activity

First calculate the strength (in curies) that would be required of a radioactive source in the golf ball to double the background reading on a Geiger counter at a distance of 25 feet from the ball. A typical Geiger counter would measure the background radioactivity as 50 to 100 counts per minute — assume this corresponds to approximately 12 microrem (0.012 millirem) per hour. To calculate the amount of radioactive material producing a given dose, we can use the “6CE” rule. The “6CE” rule is a handy and approximate estimate of the dose from gamma-producing sources. The rule states that the dose rate in rem per hour at 1 foot is $6 \times C \times E$ where C is the amount of radioactive material in curies and E is the energy of the gamma radiation in million electron volts (MeV). Assume the source material chosen is Cobalt-60 (Co^{60}), which emits gamma radiation at an energy of 1.3 MeV. Also, remember that radiation from a point source decreases proportional to the distance from the source squared. In effect, if you increase the distance from a source by a factor of 2, the dose will be a factor of 4 less. Calculate the strength in curies of the required source.



Assume you carry a basket of these radioactive golf balls 1 foot from your body for an hour. How many golf balls would be required to produce a total dose equal to your total yearly average dose of 360 millirem?

Is this project a good idea? Why? (Note that federal and state government regulations set the maximum amount of radioactivity in a material above which there are requirements on controlling the material. For Cobalt-60, amounts greater than 1 microcurie (0.001 millicurie) are to be controlled.)

Activity*Radiation, Radioactivity, and
Risk Assessment***ACTIVITY 5
NUCLEAR CROSSWORD PUZZLES****Purpose**

To reinforce concepts, vocabulary, and knowledge of scientists in the field.

Discussion

Crossword puzzles can serve as vocabulary reviews and are convenient as group or individual assignments in class or as makeup or extra credit. This activity contains three crossword puzzles.

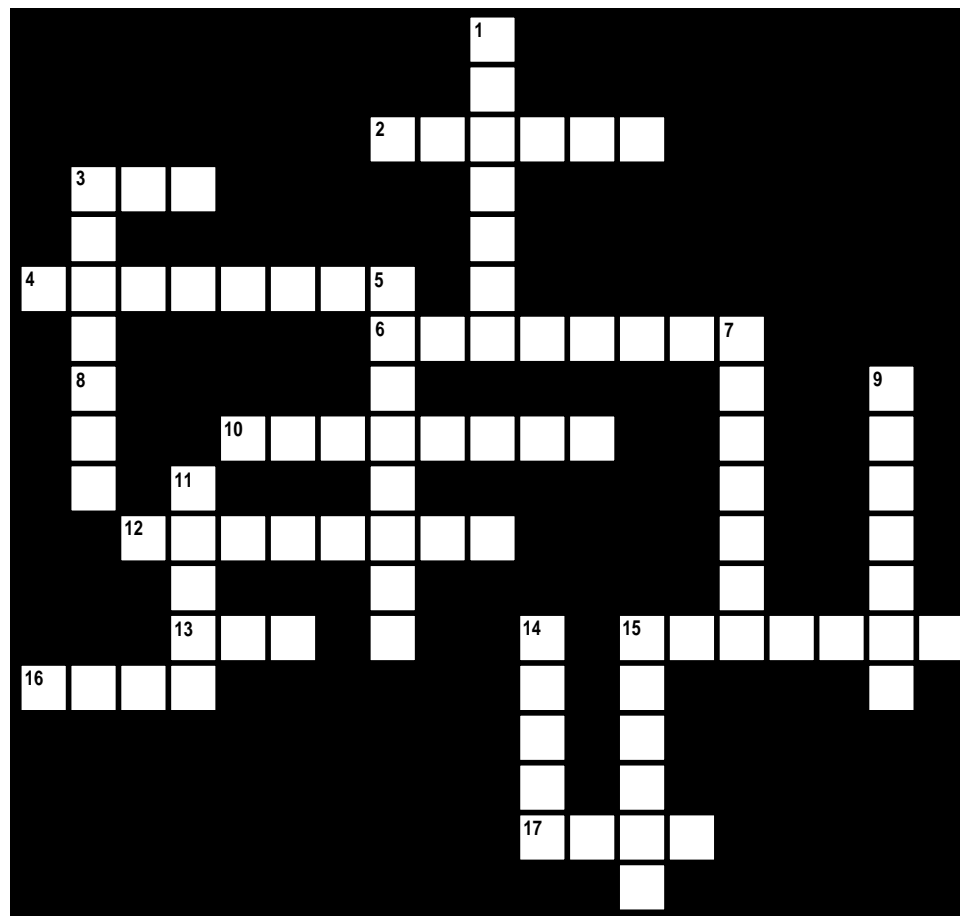
The first two puzzles review terms used in the discussion of radiation from radioactive decay and from fission. They might be used to review a reading assignment or before a quiz on the subject.

The third puzzle deals with the historical aspects and the scientists who pioneered the field of nuclear energy and other uses. This puzzle could introduce a research project involving biographical reports or a detailed timeline.

(Note: The following crossword puzzles were adapted from the Teacher Activity Booklet, Radiation Science and Engineering Center, Breazeale Nuclear Reactor, Pennsylvania State University, University Park, Pennsylvania 16802.)

Nuclear Crossword Puzzles

NUCLEAR
TERMS
NO. 1

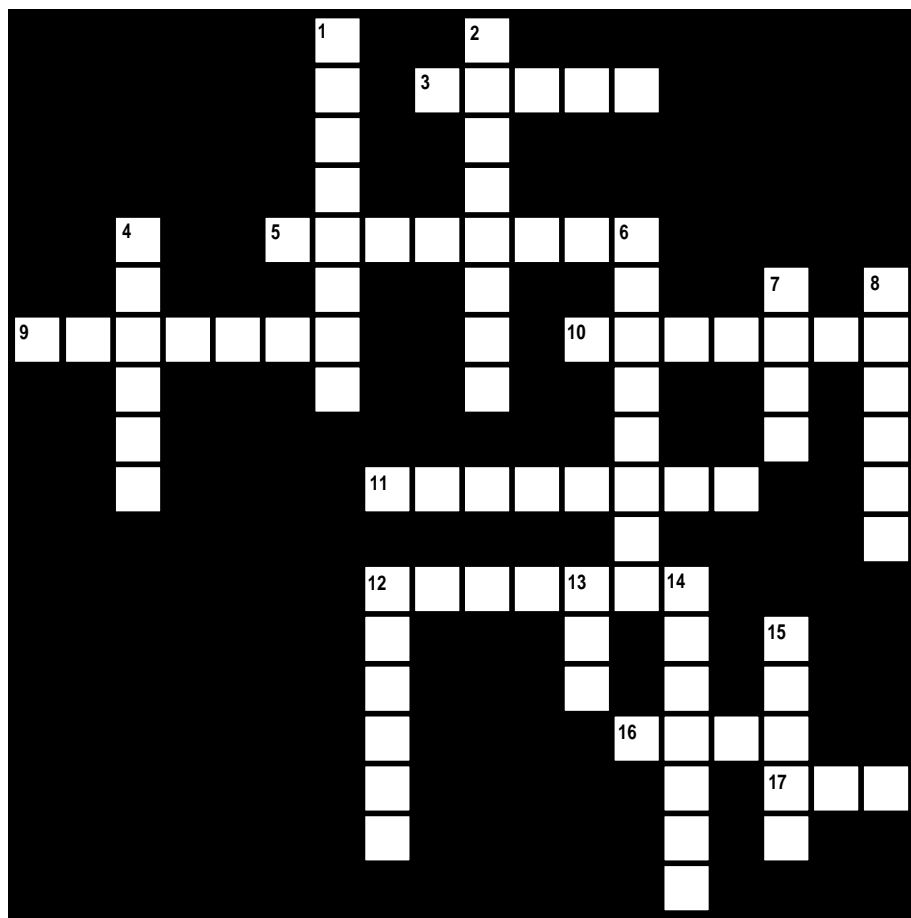
**ACROSS**

2. A positive subatomic particle.
3. An atom with an unbalanced electrical charge.
4. A positive beta particle.
6. The subatomic particle that holds a negative electrical charge.
8. The letter which represents the atomic mass.
10. Atoms of different elements that have the same "n" number.
12. The amount of time required for one-half of the atoms of a radioactive isotope to decay.
13. Abbreviation for million electron volts.
15. The splitting of an atom.
16. Radiation which is similar to an electron.
17. The smallest particle of an element that still has the properties of the element.

DOWN

1. Atoms with the same "z" number but with different number of neutrons.
3. Atoms of different elements that have the same "a" number.
5. A chargeless, massless particle given off in positron decay.
7. The center portion of an atom consisting of protons and neutrons.
9. A neutral subatomic particle.
11. Radiation from the nucleus which is in the form of electromagnetic radiation.
14. Subatomic particle similar to a helium nucleus.
15. The joining of light nuclei to form a heavier nucleus.

NUCLEAR
TERMS
NO. 2



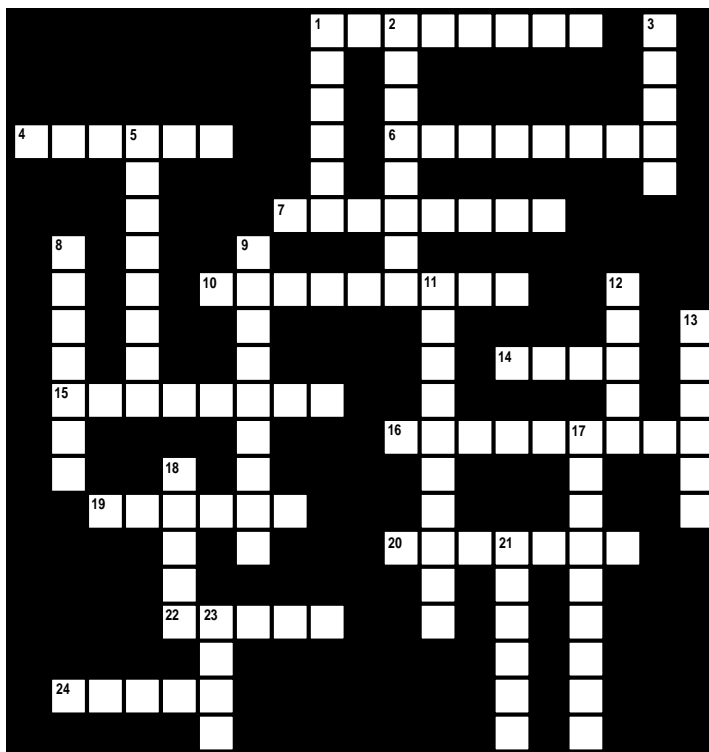
ACROSS

3. A particle identical to a helium nucleus.
5. A positive beta particle.
9. Atoms with the same "z" number but with different number of neutrons.
10. The center portion of an atom consisting of protons and neutrons.
11. The amount of time required for one-half of the atoms of a radioactive isotope decay.
12. The splitting of an atom.
16. The smallest particle of an element that still has the properties of the element.
17. Abbreviation for million electron volts.

DOWN

1. Atoms of different elements that have the same "n" number.
2. The subatomic particle that holds a negative electrical charge.
3. The letter which represents the atomic mass.
4. A positive subatomic particle.
6. A chargeless, massless particle given off in positron decay.
7. Radiation which is similar to an electron.
8. Atoms of different elements that have the same "a" number.
12. The combination of two light elements to form a heavier element.
13. An atom with an unbalanced electrical charge.
14. A neutral particle within the nucleus.
15. Very high energy electromagnetic radiation.

Nuclear Crossword Puzzles

NUCLEAR
HISTORY

ACROSS

1. 1863–1953 American physicist who determined the charge on the electron (oil drop experiment).
4. 1766–1844 Considered the Father of Modern Atomic Theory.
6. 1845–1923 Discovered x-rays in Germany in 1895.
7. 1706–1790 Defined positive and negative character of electricity (kite experiment).
10. 1852–1908 French physicist who discovered radiation from uranium on a photo plate.
14. 1885–1962 Danish physicist who defined the structure of the atom.
15. 1879–1955 Developed special and general theory of relativity.
16. 1779–1848 Swedish chemist who determined atomic weights from known elements.
19. 1882–1945 Developed the GM tube.
20. 1892–1962 Worked with the scattering effect of x-rays and electrons.
22. 1867–1934 The only person to win 2 Nobel Prizes and named the element polonium.
24. 1627–1691 Defined what an element is.

DOWN

1. 1878–1969 Female Austrian physicist who discovered fission.
2. 1901–1958 Invented the cyclotron.
3. 1858–1947 German physicist who developed quantum mechanics.
5. 1856–1940 British physicist who discovered the negative electron.
8. 1831–1879 Scottish physicist who developed the electromagnetic theory.
9. 1834–1907 Formed the first periodic table from the 63 known elements of that time period.
11. 1871–1937 The Father of Nuclear Science; named alpha, beta, and gamma radiation.
12. 1901–1954 Discovered slow neutrons and helped build the first nuclear reactor.
13. 1869–1959 Scottish physicist who developed the cloud chamber.
17. 1743–1794 Stated the law of conservation of mass.
18. 1902–1984 Predicted the existence of anti-particles.
21. 1751–1826 Law of definite proportions.
23. 1893–1981 Discovered deuterium — an isotope of hydrogen.

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 1
ELECTROSCOPE RADIATION DETECTOR****Purpose**

To demonstrate that ionizing radiation produces electric charges by showing the effect radiation has on the electrostatic charge stored in an electroscope.

Objective

The students will be able to charge an electroscope and demonstrate that a radioactive source causes the instrument to discharge.

Required Equipment and Supplies

1. A low-level alpha radiation source. (A Coleman lantern mantle can be used for this purpose.)
2. A laboratory electroscope. (If a commercial electroscope is not available, one can be constructed as described below.)
 - 2 water glasses — one about 1 inch taller than the other.
 - An old phonograph record and a wool cloth to “charge” it up.
 - A small wood dowel about 4 inches long.
 - A 6-inch stripped stiff copper wire.
 - Aluminum foil.
 - Thin foil from a chewing gum wrapper (separate with hot water to remove wax).

(**Note:** The following phonograph record electroscope art was adapted from Nuclear Experiments You Can Do, Thomas Alva Edison Foundation, Cambridge Office Plaza, Suite 141, 18280 W. Ten Mile Road, Southfield, Michigan 48075.)

Electroscope Radiation Detector

Set Up

Note: This experiment is only likely to be effective when the relative humidity is low — the kind of conditions which result in a strong door knob shock following a “carpet shuffle.”

1. If constructing the electroscope shown in the diagram, twist one end of the wire around the dowel and bend an L-shaped hook on the other end. Wrap and crumble a small aluminum foil ball around the dowel to make good contact with the wire.
2. Remove the thin foil from the gum wrapper and cut a 2-inch by 1/2-inch strip. Fold the strip in half and hang it over the wire hook. Then position the assembled device in the short glass as shown.



Procedure

1. If using a commercial electroscope, charge it with a vinyl strip and the wool cloth. If using the constructed device, place the tall glass about 4 or 5 inches from the device and charge the record with the wool cloth; then place it, charged side down on the tall glass so the rim hangs over the aluminum foil ball.
2. As the “charging device” is brought near the electroscope, the leaves of thin foil will separate due to the repulsive force of their similar charges.
3. Hold the radiation source close to the electroscope ball (without touching it). The leaves should begin to drop to their closed position only when the source is near.
4. Repeat the charging and discharging action by rotating the record to a charged position or using the wool cloth, etc., as necessary.
5. Hold a small sheet of paper between the source and the electroscope ball to determine any change in discharging action.

Questions

1. Explain why the “ionizing radiation” from the radioactive source causes the electroscope leaves to lose their charge and drop back together.
2. Why does this discharging effect speed up as the source is held closer to the electroscope?
3. Why would a sheet of paper between source and electroscope affect the outcome?

Experiment

Radiation, Radioactivity, and Risk Assessment



EXPERIMENT 2 CLOUD CHAMBER

Purpose

To make radiation “visible” by displaying tracks caused by the interaction of ionizing radiation with a supercooled vapor.

Objective

Students will be able to construct and utilize a cloud chamber to obtain vapor trail evidence of the paths of various forms of ionizing radiation.

Required Equipment and Supplies

1. Cloud chamber kit, such as the plastic kit available from The Science Source or other vendors. (If a kit is not available, a simple chamber can be constructed as described below.)
 - A clear glass or plastic jar with a tight lid (a peanut butter jar will do).
 - A piece of blotter paper cut and glued to the bottom of the jar.
 - Some black velvet cloth or flat black paint glued or applied inside the lid.
2. A high intensity flashlight or lamp.
3. Low level sources. (An alpha source comes with the commercial kit, or a Coleman lantern mantle may be used.)
4. A plastic dish and insulating foam material.
5. Dry ice or liquid nitrogen. **Note:** *thick protective gloves, a face shield for liquid nitrogen, and caution should be used when handling these substances to prevent frostbite burns.* Dry ice is available from commercial manufactures and may also be purchased from ice-cream stores.
6. Ethyl or isopropyl alcohol (pure, not diluted, rubbing alcohol).

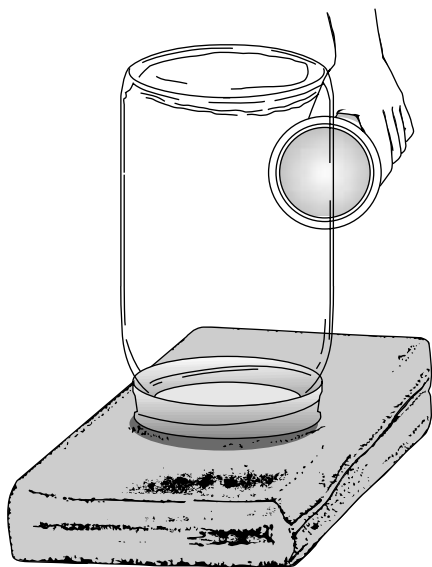
Discussion

The cloud chamber, invented in 1907 by C.T.R. Wilson, was one of the first and most useful radiation detectors. Since we cannot detect radiation with our senses, the ability of this simple detector to see and photograph the trail of ions produced by charged particles makes it a very useful instrument for studying nuclear

reactions. The cloud chamber performs with the same principle that allows cooled water vapor to form rain droplets on dust particles in the upper atmosphere. This demonstration chamber is filled with alcohol vapor and cooled below its condensation temperature. Ions are then produced by the passage of high energy particles from the radioactive decay of the source resulting in very small condensation or “vapor trails” which indicate the presence of radiation.

Procedure

1. Saturate the blotter material with alcohol.
2. Lay a block of dry ice on an insulating foam pad, or pour a small amount of liquid nitrogen into a plastic dish. Wear heavy gloves and handle these substances carefully to avoid injury.
3. Place the radioactive source in the kit as directed, or lay it in the jar lid and screw the lid on the inverted jar as shown in the diagram.
4. Place the chamber on the dry ice block or in the dish of liquid nitrogen. (Liquid nitrogen will require replenishing periodically.) The chamber may have to be temporarily removed if wisps of fog develop around the bottom.
5. Dim the room lights and shine the bright light horizontally through the chamber.
6. Wait patiently for the appearance of the barely detectable vapor trails. It may take 30 minutes or more for the chamber to achieve the necessary conditions.



Questions

1. Compare your results with expected results from different types of sources. (If possible, repeat the experiment using other sources.)
2. Explain the term “ionizing radiation,” based on your observations in this experiment.
3. Why did you use alcohol rather than water for this experiment?

(**Note:** The cloud chamber art above was adapted from Nuclear Experiments You Can Do, Thomas Alva Edison Foundation, Cambridge Office Plaza, Suite 141, 18280 W. Ten Mile Road, Southfield, Michigan 48075.)

Experiment*Radiation, Radioactivity, and Risk Assessment*

EXPERIMENT 3

RADIOACTIVITY HUNT

Purpose

To learn how to identify radioactive material and its effects on other material.

Objectives

Students will be able to:

1. Use a radiation detector.
2. Differentiate between radioactive and nonradioactive materials.
3. Describe the effects of radiation on matter.

Required Equipment and Supplies

1. Geiger counters. (Several types are available; most will detect only beta and gamma radiation. An alpha detector probe would contain a very fragile thin mica window and could be easily damaged.)
2. Sealed low-level commercial alpha, beta, and gamma sources.
3. Old Fiestaware dishes (the deep orange color contains uranium compounds — available at swap meets and antique stores).
4. Coleman lantern mantles (several brands contain thorium).
5. Ionization model smoke detectors (contain americium); older models have larger, more detectable amounts of americium.
6. Uranium ore and other radioactive rock samples.
7. Older glow-in-the-dark radium dial clocks or watches.
8. Weighted cellophane tape dispensers (fill sand often contains thorium).
9. “Lite” salt (containing potassium chloride) and super-phosphate fertilizer.



10. Materials that have been processed by ionizing radiation such as nonstick pans, shrink-wrap, exposed x-ray film, sterilized surgical gloves, etc.
11. Various lamps and flashlights (sources of nonionizing radiation).
12. Assorted nonradioactive rocks, dishes, watches, etc., similar to the radioactive samples above.

Procedure

1. Use the operating procedure for the Geiger counter to turn it on and perform an operability check. Select the appropriate scale for counts/minute or mrem/hour midscale readings with a check source, if installed. Use a headset, if provided, or turn the audible speaker up to hear the “clicks” clearly.
2. Measure background level with detector well away from any sample.
3. Starting with the sealed sources, test all of the assembled sample materials slowly and carefully. Record the results of each surveyed item in a data table similar to the one below. Use the beta window, if installed, or a thin sheet of aluminum to determine which type of energy is being detected.
4. Compare results with other teams. Discuss and resolve any differences.

Radioactivity Worksheet

Check the appropriate column and indicate type of energy for each item.

Item	Background	Slightly R/A	Very R/A	Type

Questions

1. What is the difference between radiation and radioactivity? Which does the survey instrument detect?
2. What is the difference between ionizing and nonionizing radiation? Give examples of each from your observations.
3. What causes background radiation (clicks heard with no sample being tested)?
4. How does a Geiger counter work?
5. If nonradioactive items are exposed to radiation, do they become radioactive? What would be the purpose of such exposure?

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 4
ATOMIC MASS OF "BEANIUM"****Purpose**

To demonstrate the concepts of isotopes and of average atomic mass (i.e., why atomic mass is not an even number).

Objectives

Students will be able to:

1. Use the balances to find the masses of objects.
2. Calculate weighted average masses of mixed samples.
3. Use these results to explain the concept of average atomic mass of an element.

Required Equipment and Supplies

1. Beam or electronic balance.
2. Several hundred beans (at least three different types: pinto, navy, kidney, lima, black-eyed peas, etc. Whatever is easiest to acquire.)
3. Paper cups or Zip-lock bags.

**Set Up**

Obtain a sample of "Beanium" from the teacher, containing a mixture of different "isotopes." For simplicity, the sample should contain an even multiple of 100 total beans (100, 200, 300, etc.).

Atomic Mass of "Beanium"

Procedure

1. Measure and record the total mass of the sample in the cup or Zip-lock bag container. _____
Total Mass

2. Carefully empty the contents onto a large flat surface. Measure the mass of the empty container. Subtract this empty (tare) mass from the total mass to give the mass of the sample alone. _____
Empty Mass

(Total mass) minus (Empty container mass) equals (Sample mass) _____
Sample Mass

3. Sort and record the "atoms" by type. Check the total number of "atoms."

4. Find the mass of an "atom" of each type. (Suggestion: determine the average by measuring the mass of 10 atoms of each type and dividing by 10.)

Average mass of each type:	Type Atom	Mass
	_____	_____
	_____	_____
	_____	_____

5. Calculate the percentage of each isotope in the sample.

Percentage of each isotope:	Type Atom	Percentage
	_____	_____
	_____	_____
	_____	_____

6. Determine the "weighted average mass" for Beanium.

$$\frac{[\text{mass}_a \times (\%)_a] + [\text{mass}_b \times (\%)_b] + [\text{mass}_c \times (\%)_c]}{100} = \text{weighted average mass}$$

Questions

1. Is your weighted average mass consistent with the total sample mass?
2. Define isotope. Explain the difference between Neon-19, Neon-20, and Neon-22.
3. The following are natural isotopes of magnesium. Calculate the average atomic mass of magnesium.

Mg — 24	78.99%
Mg — 25	10.00%
Mg — 26	11.01%

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 5
OIL-DROP MODEL OF FISSION****Purpose**

To simulate the fissioning of a nucleus of an atom.

Objectives

Students will be able to:

1. Adjust the density of a fluid, suspending an oil drop to form a sphere.
2. Simulate the effect of an energetic neutron to cause the spherical drop “nucleus” to split into smaller drops.

Required Equipment and Supplies

1. Small water glass.
2. Isopropyl alcohol (pure — not a diluted rubbing alcohol solution).
3. Cooking oil.
4. Water.
5. Teaspoon and butter knife.
6. Paper towels.

Oil-Drop Model of Fission

Procedure

1. Pour the alcohol into the glass — about half full. Then add water until the glass is two-thirds full. Mix the solution.
2. Use the dry teaspoon to carefully add a spoonful of cooking oil at the surface of the solution. Slowly tip the spoon so the oil slides into the glass in a single blob.
3. Adjust the solution to suspend the oil blob in the middle of the glass. If it initially floats on the surface, carefully add a little more alcohol. If the oil sinks to the bottom, carefully add water. The drop should be spherical — simulating a stable nucleus.
4. Use the butter knife as an “energetic neutron” to carefully prod the “nucleus” apart. At first it will bulge and stretch. Then it will tear apart into two smaller (but not necessarily equal) spherical drops.

**Questions**

1. What is the significance of the spherical shape of the suspended oil drop?
2. How does action of the butter knife simulate a bombarding neutron?
3. Does it matter whether the “fission product nuclei” are equal in size?

(Note: The oil drop art above was adapted from Nuclear Experiments You Can Do, Thomas Alva Edison Foundation, Cambridge Office Plaza, Suite 141, 18280 W. Ten Mile Road, Southfield, Michigan 48075.)

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 6
DOMINO CHAIN REACTION MODEL****Purpose**

To demonstrate the concept of chain reactions.

Objectives

The students will be able to:

1. Simulate an uncontrolled (bomb) chain reaction, and a controlled (reactor) chain reaction.
2. Explain the difference between the two types and why a reactor cannot be a bomb.

Required Equipment and Supplies

One or two sets of dominos.

Discussion

In the oil-drop fission model, the splitting of a uranium nucleus is simulated to produce two smaller nuclei and produce energy. This fission process also produces two or three energetic neutrons, which have the ability to strike other nuclei and cause subsequent fissions. If most of these neutrons are permitted to bombard additional nuclei, a rapidly multiplying **chain reaction** would occur producing enormous energy in a fraction of a second. This is the basic process involved in an atomic bomb.

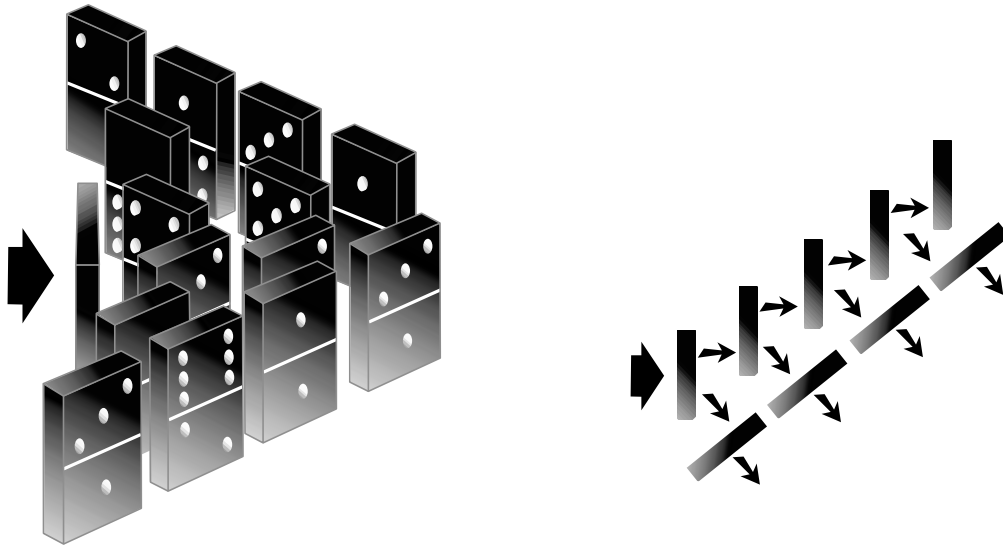
The nuclear reactor in a nuclear power plant is designed and built with materials to prevent such an uncontrolled reaction. The uranium fuel is arranged in modules, which are surrounded with water to act as a moderator and coolant, and with control rods containing a neutron-absorbing material (“poison”). When control rods are inserted, no neutrons are available for fission. As the rods are slowly withdrawn, the reactor reaches **criticality** — the point at which each fission reaction leads to exactly one more fission reaction and a steady-state chain reaction is maintained. The heat energy produced by fission is removed by the coolant for use in electric power generation or propulsion.

Domino Chain Reaction Model

Procedure

1. In the first trial, arrange the dominos in a phalanx as shown in the first diagram below. They will be on end about 1/2 inch apart, positioned so that each falling domino strikes two dominos in the next row.

Push the first domino to initiate a “bomb” chain reaction.



2. In the second trial, arrange the dominos in the in-line pattern of the second diagram below.

When the first domino is pushed to initiate the “controlled” chain reaction, only one neutron from each fission is permitted to continue to fall or advance to cause the next generation fission. The second neutron falls away to simulate “capture” by control rod poisons.

Questions

1. What determines the amount of energy released in the uncontrolled chain reaction of an atomic bomb?
2. Why can't the controlled reaction in a nuclear reactor produce the same kind of results as an atomic bomb?
3. If more neutrons are “lost” from a chain reaction when the core expands from higher temperatures, what would result from raising the control rods in an already critical reactor?

(**Note:** The domino art above was adapted from Nuclear Experiments You Can Do, Thomas Alva Edison Foundation, Cambridge Office Plaza, Suite 141, 18280 W. Ten Mile Road, Southfield, Michigan 48075.)

Experiment

Radiation, Radioactivity, and Risk Assessment



EXPERIMENT 7 DEMONSTRATING HALF-LIFE WITH PENNIES

Purpose

To demonstrate the concept of the half-life of a radioactive material.

Objective

Students will be able to calculate and graphically determine the half-life of a radioactive isotope.

Required Equipment and Supplies

1. One hundred pennies. (A tastier option might be to substitute M&Ms for the pennies.)
2. Shallow box with a tight-fitting lid.
3. Graph paper and a data table to record results.

Set Up

1. Place the 100 pennies (or M&Ms) all “heads up” in the box. (**Note:** For the sake of realism, you might consider using forceps or tongs to handle the “radioactive” objects in the box.)
2. Place the lid securely on the box.



Determining Half-Life with Pennies

Procedure

1. Before proceeding, consider how many landing options a flipped penny has and predict how many “heads” will remain after the box is thoroughly shaken.
2. Enter the starting number of pennies (100) in Time Period 0.

Number of Heads Remaining

	Time Period								
	0	1	2	3	4	5	6	7	8
Trial 1	100								
Trial 2	100								
Trial 3	100								

3. Make sure the lid is securely held closed and shake the box vigorously.
4. Set the box down, remove the lid, and carefully extract all “tails” counting them as they are removed. Record the number of “heads” remaining in the box. This represents the first Period.
5. Close the lid securely and repeat the process recording remaining “heads” in each subsequent Period. Continue until only 1 or 2 pennies remain.
6. Plot the number of remaining “heads” for each Period, starting with 100 for Period 0. Use regular linear graph paper, then plot the same data on a semi-log graph (if available). Plot number of pennies on the y-axis.
7. Repeat the experiment or compare results with other teams. Average the results from multiple experiments for each time period.

Questions

1. If each period represents a half-life, approximately what fraction of the previous number of “heads” remain after each shaking?
2. What is the significance of removing all the “tails” after each period?
3. About how many half-lives would be required to have fewer than 5 “heads” remaining in the box.
4. Why do results from multiple experiments vary, particularly when the number of pennies remaining is small?

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 8
HALF-LIFE DEMONSTRATION WITH WATER****Purpose**

To demonstrate the concept of the half-life of a radioactive material.

Objectives

The student will be able to:

1. Use measurements of time and distance to determine flow characteristics of a column of water.
2. Use the flow analogy to explain the concept of radioactive half-life.

Discussion

This simple demonstration uses the flow resulting from the gravitational force on a column of water to approximate the diminishing decay rate of a radioactive isotope as it disappears as a result of transmutation.

Required Equipment and Supplies

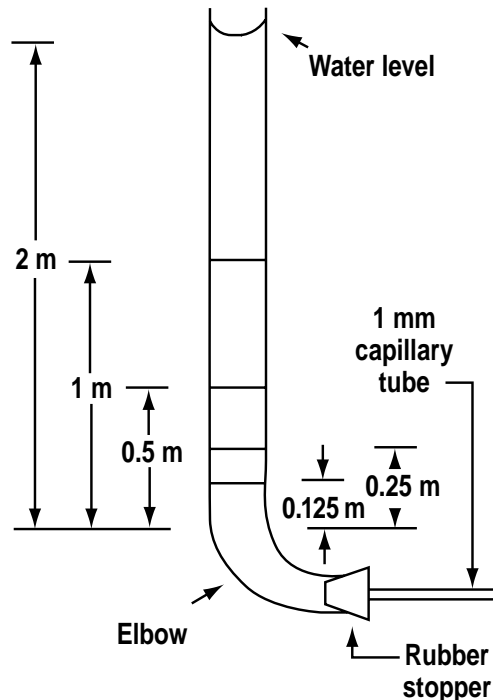
1. Transparent plastic pipe and 90° elbow or clear plastic tubing — 2 meters long.
2. Small one-hole rubber stopper sized to fit into elbow or tubing.
3. Short piece of 1 mm capillary tube to fit into rubber stopper.
4. Bucket to catch water.
5. Stopwatch or other timing device.
6. Small funnel.
7. Phenolphthalein pH indicator and ammonia or other weak base (optional).



Half-Life Demonstration with Water

Set Up

1. Tape the pipe or tube to a door or the wall. Leave room at the bottom for the bucket to catch water. Use small pieces of tape to mark the following heights above the bottom: 2 m, 1 m, 0.5 m, 0.25 m, 0.125 m.
2. Insert capillary tube into rubber stopper (use dish soap or glycerin for safety). Put the stopper snugly into the attached elbow or bottom of the tube.
3. Position the bucket to catch water as it drains from the pipe or tube. (Optional: pour a few milliliters of the ammonia or other weak base into the bucket and drop several drops of phenolphthalein indicator into a beaker of water which will be used to fill the pipe or tube.)
4. Zero or set the timer.



Procedure

1. With one team member holding a finger over the end of the capillary, use the funnel to fill the pipe or tube to above the 2 m mark.
2. Release the finger to initiate flow, starting the timer as the level passes the 2 m mark. Record the time to reach the 1 m mark. Depending on flow rate and practice, either stop for each segment or permit continuous flow, timing each decreasing segment — 0.5 m, 0.25 m, 0.125 m.
3. Record and compare the elapsed time for each segment.
4. Repeat the test several times. (Use fresh indicator solution each time if that procedure is being used.)

Questions

1. How do the times compare for each segment?
2. How do these times compare to the half-life of a radioactive isotope?
3. If the pH indicator was used, how does the color change as the water enters the bucket simulate radioactive decay?

(**Note:** The water pipe art above was adapted from the Teacher Activity Booklet, Radiation Science and Engineering Center, Breazeale Nuclear Reactor, Pennsylvania State University, University Park, Pennsylvania 16802.)

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 9
TIME, DISTANCE, AND SHIELDING****Purpose**

To demonstrate techniques used to minimize radiation exposure of laborers.

Objectives

Students will be able to:

1. Compare exposure doses depending on length of exposure.
2. Measure and calculate the strength of radiation from a source based on the distance from the source.
3. Compare and explain the effects of shielding materials on various kinds of radiation.

Required Equipment and Supplies

1. Geiger counter (reading in counts/min) or survey meter (reading in mrem/hour).
2. Low energy beta and gamma sources.
3. Meter stick.
4. Paper or thin cardboard sheets, aluminum sheets or foil, lead sheets.
5. Concrete brick or block.

Note: If a battery-powered survey meter is used, ensure the batteries are removed when the experiment is complete. This prevents damage to the instrument.

Part III — Shielding Effects

1. Place a beta source a few centimeters from the detector probe to obtain a nearly full-scale reading. Fix the source and detector in place with the source centered on the detector. Adjust meter scales if necessary. Leave room to insert several sheets of shielding material. Record the initial reading.
2. Place 1 or 2 sheets of paper between the source and probe and record the reading. Repeat the process with additional sheets, recording readings until the background level is reached. Maintain a constant distance between source and probe.
3. Repeat Step 2 using sheets of cardboard and record readings. Then repeat using aluminum sheet(s).
4. Next, replace the beta source with a gamma source. Repeat Steps 1 and 2, this time comparing the cardboard, aluminum, lead, and (if room) concrete.

Shielding Data Table

Number of sheets	Beta			Gamma			
	Paper	Cardboard	Aluminum	Cardboard	Aluminum	Lead	Concrete
0							
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							

5. Using graph paper, plot the beta readings versus shielding results. Plot the gamma results on a second graph. Plot detector readings on the y-axis and number of sheets of shielding on the x-axis.
6. **Extra** — Plot the same data on semilog paper using the log scale as y-axis. (This can also be done on a regular graph by plotting the logarithm of radiation readings on the y-axis and shielding on the x-axis.)

Questions

1. What causes the background counts?
2. Explain how time of exposure affects total radiation dose received.
3. From your data and graph in Part 2, describe the relationship between radiation levels and distance from the source. (Hint: Is the relationship linear or otherwise?)
4. Which materials provided the most effective shielding against beta radiation; against gamma radiation? Describe the relationship between radiation levels and shielding thickness. Can you give an explanation for these results?
5. Find the “half-thickness” for several of the shielding materials. (The amount of shielding which reduces the radiation by a factor of 2.)

Experiment*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 10
RADIOACTIVE CONTAMINATION SIMULATION****Purpose**

To demonstrate the practical procedures and problems involved in containing radioactive material.

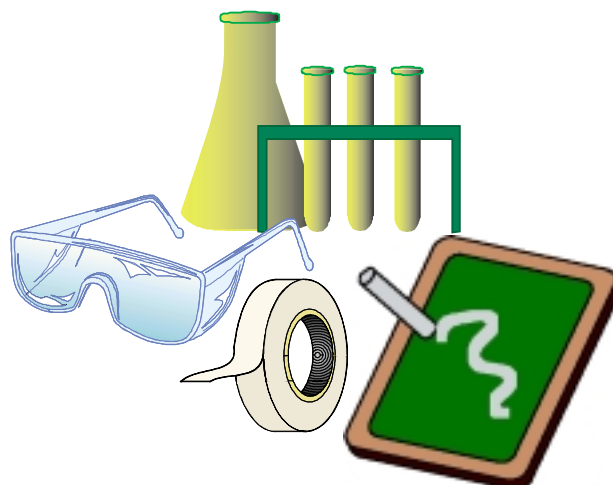
Objectives

Students will be able to:

1. Describe procedures required to prevent the spread of radioactive contamination.
2. Discuss problems and limitations of various approaches to decontamination.

Required Equipment and Supplies

1. Fluorescent chalk.
2. Ultraviolet (UV) lamp and UV protective goggles.
3. Mortar and pestle.
4. Test tubes.
5. Soap, water, and paper towels.
6. Large beakers or plastic buckets for waste.
7. Latex or other waterproof gloves.
8. A dirt-filled ant farm apparatus or a thin wall plastic cup full of dirt (container walls should permit UV light penetration; UV will not pass through plastic).
9. Cellophane or masking tape and Zip-lock bags.



*Radioactive Contamination Simulation***Discussion**

This activity is designed to simulate the practical aspects of managing low-level radioactive waste associated with the production, cleanup, storage, and disposal of nuclear material. Students are encouraged to suggest procedures for containment and to utilize any means available to minimize the spread of “invisible” contamination.

Before beginning, the instructor should briefly demonstrate the “black light” effect of the UV lamp with a piece of fluorescent chalk. This should take place in a “clean” area, with no residual chalk residue from any previous classes. **Note:** It is important that students understand that fluorescence (an electron excitation phenomenon) and radioactivity (nuclear disintegration) are entirely different and should not be confused. No radioactive material is being used in this simulation.

Set Up

1. Place a small piece of fluorescent chalk at each station with a mortar and pestle. Have towels, soap, and water available.
2. Provide labeled containers for “radioactive” waste.

Procedure

1. Direct each laboratory team to devise a procedure to crush the small piece of chalk using the mortar and pestle. Remind them that an important objective is to avoid any “contamination” from the spread of the “radioactive” chalk.
2. Evenly divide the resulting powder. Place one-half (1/2) of the powder onto a paper towel. Place the remaining powder into a test tube filled half way with water.
3. Pour the test tube of water and chalk onto the dirt in the jar or ant farm.
4. Now ask the teams to carefully fold the towel holding the chalk powder and to “package” it for safe shipping — using tape or other means they consider effective.
5. When the packaging is complete, direct the teams to thoroughly clean up all traces of chalk “contamination” at their station. Remind them that all materials, solid or liquid, used in this clean-up must be properly disposed into appropriate waste containers.
6. When the clean-up is complete, “survey” the work areas and waste containers using the UV lamp “radiation monitor.” (Ensure anyone using the UV lamp is wearing the UV protective goggles.) Include the “workers” hands and clothes and the surrounding bench and floor in the survey. The results should be very enlightening.
7. Examine the dirt-filled jar or ant farm with the UV lamp. Add a little water to demonstrate the movement of materials and potential effect on the water table.

Questions

1. How would you recommend disposing of the “contaminated” waste generated in this experiment to avoid spreading it any further?
2. What was the most effective means of cleanup? What problems or limitations might be associated with that approach?
3. Could you recommend any other ways to “decontaminate?”
4. What will eventually happen to most stored radioactive material? How is this different from chemical contamination in the environment?

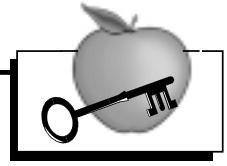
Name:

Class:

Date:

INSTRUCTOR'S KEY

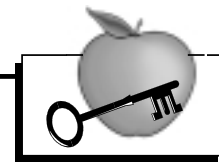
*Radiation, Radioactivity, and
Risk Assessment*



ACTIVITY 1 LET'S INVESTIGATE

Answers:

1. A,B,F,G,H,I are NI ;
C,D,E,J,K are I
2. T
3. T
4. D
5. A,B,C,D,E are T ;
F is F
6. F
7. D
8. D
9. T
10. C
11. C

**ACTIVITY 2
TIME LINE**

- 1891 Sport of basketball invented by James Naismith.
- 1896 **b**
- 1898 **d, f**
- 1903 Wright Brothers make first flight at Kitty Hawk.
- 1905 **i**
- 1910 Boy Scouts and Camp Fire begin.
- 1911 **a**
- 1913 **h**
- 1915 First telephone talk from N.Y. To San Francisco is made by Alexander Graham Bell and Thomas A. Watson.
- 1920 Women's Voting Rights Amendment passes.
- 1926 Robert Goddard invents first rocket using liquid fuel.
- 1929 Martin Luther King is born.
- 1931 First NFL Championship — Chicago Bears 23, New York Giants 21.
- 1934 **c**
- 1935 Elvis Presley is born.
- 1938 **e**
- 1941 Pearl Harbor is bombed.
- 1945 World War II ends.
- 1946 **j**
- 1953 Salk vaccine for Polio developed by Jonas Salk.
- 1958 First domestic jet airline passenger service.
- 1962 John Glenn is first American to orbit the Earth in Friendship 7 capsule.
- 1963 President John F. Kennedy assassinated.
- 1965 **k**
- 1965 **o**
- 1969 Neil Armstrong is first person to walk on the moon.
- 1973 **l**
- 1974 President Richard Nixon resigns.
- 1979 **n**

Activity 2 – Time Line

1983 **p**

1984 **r**

1986 **g**

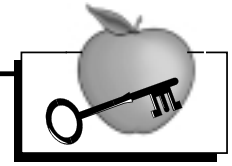
1988 **m**

1989 “Fall” of the Berlin wall.

1991 U.S. and its allies begin Gulf ground war and liberate Kuwait from Iraq four days later.

1992 **q**

1995 Cal Ripken breaks Lou Gehrig’s record with 2130 consecutive baseball games played.



ACTIVITY 3

FINDING THE AGE OF A FOSSIL

I. Method 1 — Solution:

Number of Half Lives	Fraction of C ¹⁴ Remaining from Initial Amount	Elapsed Time (Years)
0	1.0	0
1	0.5	5,730
2	0.25	11,460
3	0.125	17,190
4	0.0625	22,920
5	0.03125	28,650
6	0.015625	34,380
7	0.0078125	40,110
8	0.0039063	45,840
9	0.0019531	51,570
10	0.0009765	57,300

1. Using the table above, find the amount of half-lives and elapsed time (years) for C-14 to decay to 0.01 (or 1%).

0.01 falls between 6 (a) and 7 (b) half-lives or
between 34,380 and 40,110 years.

2. Use a ratio to estimate the fractional part of a half-life between answers (a) and (b):

- $$\begin{aligned} x \text{ half-lives} / 1 \text{ half-life} &= (\text{amount decaying in } x \text{ half-lives}) / (\text{amount decaying in } 1 \text{ half-life}) \\ &= [\text{fraction remaining from (a) above} - 0.01] / [\text{fraction remaining from (a) above} - \text{fraction remaining from (b) above}] \\ &= \underline{(0.015625 - 0.01) / (0.015625 - 0.0078125)} \\ x &= \underline{0.72} \end{aligned}$$

Now add the fractional half-life x to obtain the total number of elapsed half-lives and total years:

- total half-lives = answer (a) + x = $6 + 0.72 = \underline{6.72 \text{ half-lives}}$ (c)
- total years = (c) \times 5730 = $6.72 \times 5730 = \underline{38,500}$ years.

Activity 3 – Finding the Age of a Fossil

II. Method 2 — Solution: Exact method using logarithms.

Write an equation and solve for the number of half-lives. After each half-life, the fraction remaining is (one-half) $1/2$ the previous amount.

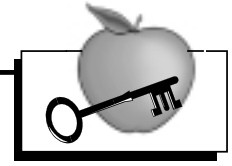
- amount remaining after 1 half-life = $1/2$
- amount remaining after 2 half-lives = $1/2 \times 1/2 = (1/2)^2 = 1/4$
- amount remaining after 3 half-lives = $1/2 \times 1/2 \times 1/2 = (1/2)^3 = 1/8$
- amount remaining after 4 half-lives = $1/2 \times 1/2 \times 1/2 \times 1/2 = (1/2)^4 = 1/16$
- amount remaining after n half-lives = $(1/2)^n$

So solve $A = (1/2)^n = (0.5)^n$ with $A = 0.01$ by use of logarithms.

- **$0.01 = (0.5)^n$**
- **$\log(0.01) = n \times \log(0.5)$**
- **$n = \log(0.01) / \log(0.5) = -2 / (-0.301) = 6.6445$ half-lives**
and total years elapsed = $6.6445 \times 5730 = 38,072$ years

Question 1:

1. Solving $A = (0.5)^n$ where for 120 years, $n = 120/5730 = 0.02094$ gives $A = 0.986$. Thus, less than 1.4% of the Carbon-14 has decayed. You would have to be able to make measurements of changes this small and have error bars less than this value. A difficult task.



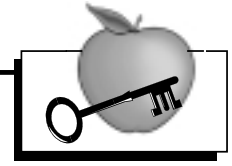
ACTIVITY 4 RADIOACTIVE GOLF BALL FINDER

Solution:

- To detect at twice the background requires a dose rate at the detector of 2×0.012 millirem/hour = 0.024 millirem/hour.
- If this is the dose at the detector 25 feet away from the ball. Then the dose at 1 foot from the ball is 25^2 times greater.
 - dose $\sim 1 / \text{distance}^2$ so form a ratio
 - (dose at 1 ft) / (dose at 25 ft) = $(25 \text{ ft})^2 / (1 \text{ ft})^2$
 - (dose at 1 ft) = (dose at 25 ft) $\times (25 \text{ ft})^2$
 - dose at 1 ft = $25^2 \times 0.024 = 15$ millirem /hour.
- Using the “6CE” rule, the amount of material in curies is found:
 - dose rate at 1 ft in millirem/hour = $6 \times C \times E$
 - solving for C gives

$$C = (\text{dose rate at 1 ft in millirem/hour}) / (6 \times E) = (0.015 \text{ rem/hour}) / (6 \times 1.3)$$

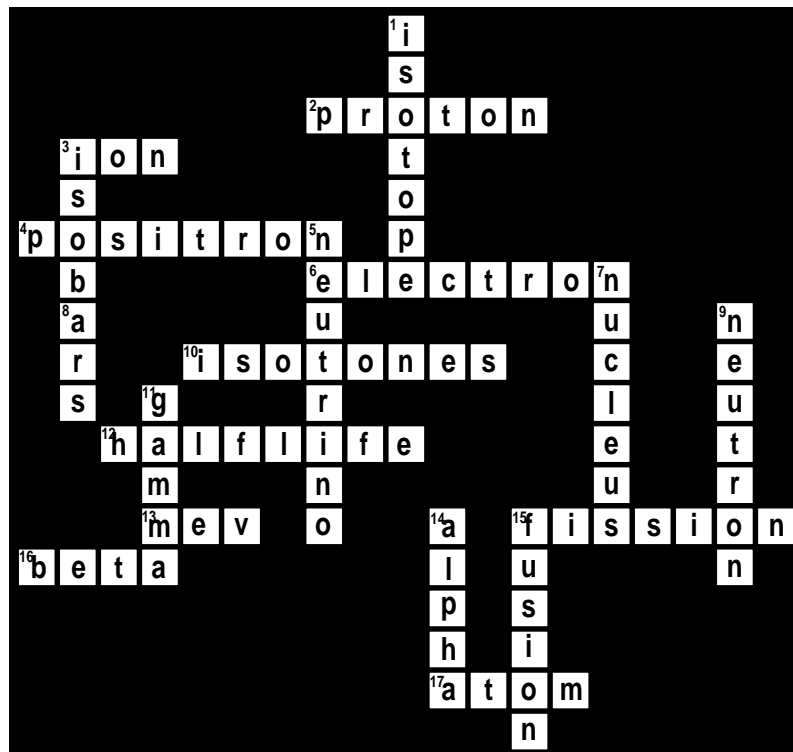
$$= 0.0019 \text{ Ci or } 1.9 \text{ mCi (millicurie).}$$
- One golf ball produces a dose rate of 15 millirem/hour at 1 foot. So in 1 hour, the dose from a golf ball is:
 - dose = dose rate \times time
 - dose = 15 millirem/hour \times 1 hour = 15 millirem in one hour
- The number of balls required to produce a dose of 360 millirem in an hour would be:
 - $360 \text{ millirem} / (15 \text{ millirem} / \text{ball}) = 24 \text{ balls} .$
- Not a good idea because it would only take 1 hour to double your yearly background dose with only a few golf balls. The amount in 1 golf ball is 1900 times the amount requiring controls.



ACTIVITY 5 NUCLEAR CROSSWORD PUZZLES

Answer Key to Nuclear Terms No. 1

NUCLEAR
TERMS
NO. 1



ACROSS

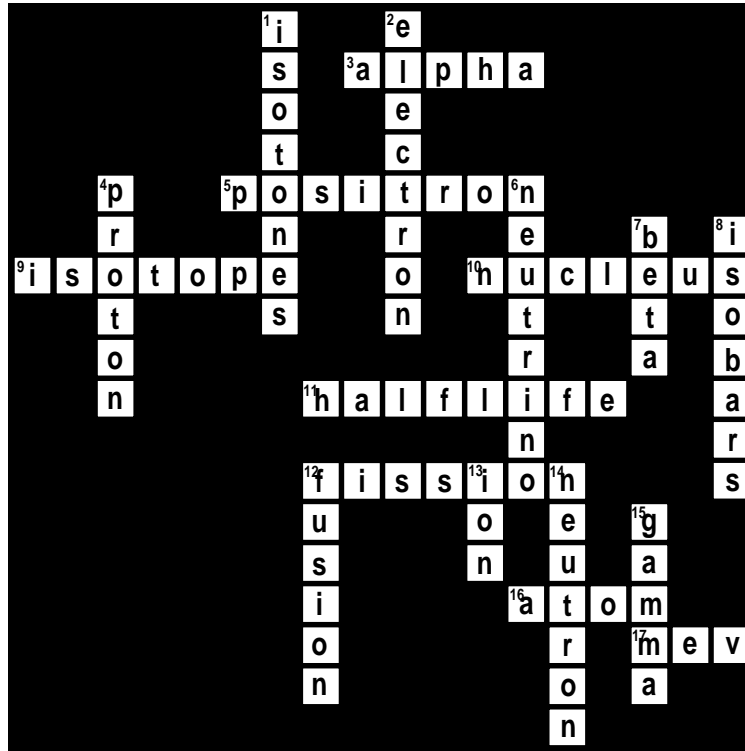
2. proton
3. ion
4. positron
6. electron
8. A
10. isotones
12. half-life
13. MeV
15. fission
16. beta
17. atom

DOWN

1. isotope
3. isobars
5. neutrino
7. nucleus
9. neutron
11. gamma
14. alpha
15. fusion

Answer Key to Nuclear Terms No. 2

NUCLEAR
TERMS
NO. 2



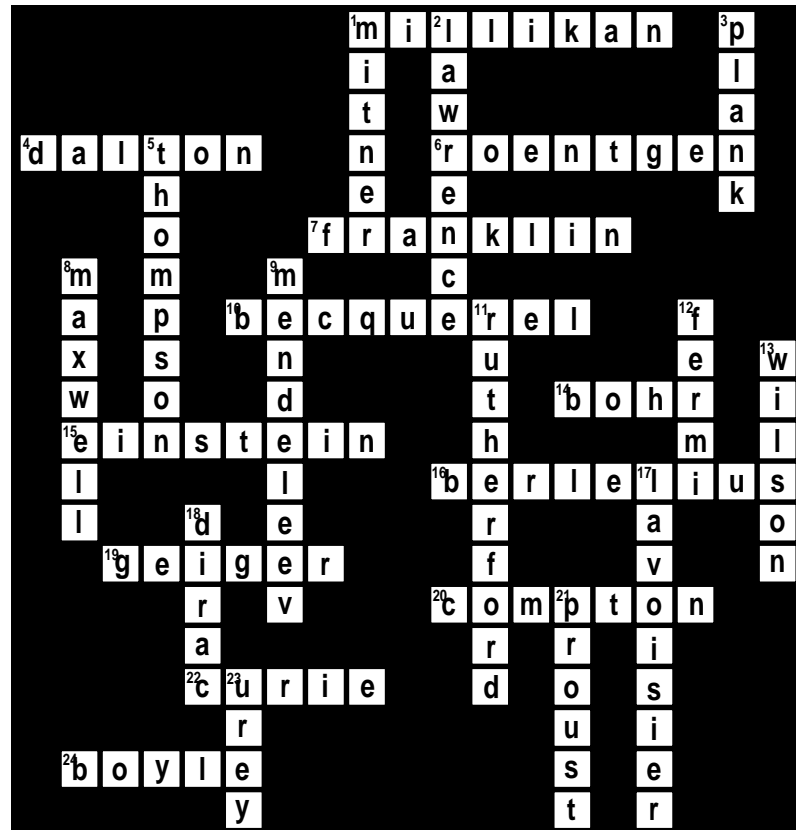
ACROSS

- 3. alpha
- 5. positron
- 9. isotope
- 10. nucleus
- 11. half-life
- 12. fission
- 16. atom
- 17. MeV

DOWN

- 1. isotones
- 2. electron
- 3. A
- 4. proton
- 6. neutrino
- 7. beta
- 8. isobars
- 12. fusion
- 13. ion
- 14. neutron
- 15. gamma

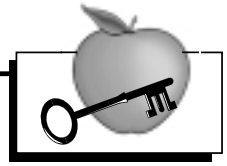
Answer Key to Nuclear History

NUCLEAR
HISTORY**ACROSS**

1. MILLIKAN
4. DALTON
6. ROENTGEN
7. FRANKLIN
10. BECQUEREL
14. BOHR
15. EINSTEIN
16. BERZELIUS
19. GEIGER
20. COMPTON
22. CURIE
24. BOYLE

DOWN

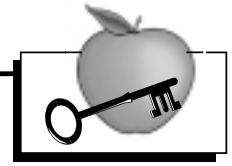
1. MITNER
2. LAWRENCE
3. PLANK
5. THOMPSON
8. MAXWELL
9. MENDELEEV
11. RUTHERFORD
12. FERMI
13. WILSON
17. LAVOISIER
18. DIRAC
21. PROUST
23. UREY



EXPERIMENT 1

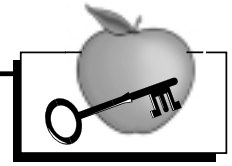
ELECTROSCOPE RADIATION DETECTOR

1. The leaves repel each other because their electrostatic charges are the same. The alpha source produces charged particles, which collide with atoms in the electroscope and neutralize its charges. The decreased charge results in less repulsion.
2. As the source is brought closer, more of the radiation from the source hits the electroscope. This is the same idea as a lighthouse, which is seen only dimly at a distance but seems very bright when viewed from close range.
3. The alpha particle is relatively heavy, but it is greatly attenuated by just a sheet of paper. This explains why ingesting alpha radioactivity (swallowing or breathing) is considered more of a hazard than an external alpha exposure.



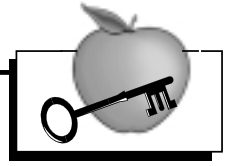
EXPERIMENT 2 CLOUD CHAMBER

1. An alpha source would produce short trails due to the low penetrating power of the heavy alpha particle (helium nucleus). A beta source would give longer, thinner trails because the lighter beta particles (electrons) have more penetration. A gamma source produces only high energy rays, which are very penetrating but interact with fewer atoms in their path, so the vapor trails might be much longer but very difficult to see.
2. The rays and particles produced by radioactive decay interact with atoms in their path removing an electron to produce charged particles called ions.
3. Alcohol has a higher vapor pressure and lower condensation and freezing temperature than water. The water vapor in the chamber would form ice and be ineffective in showing vapor trails. The more plentiful alcohol vapor can be supercooled below its condensation temperature so that it will readily condense on any charged particles formed by ionization.



EXPERIMENT 3 RADIOACTIVITY HUNT

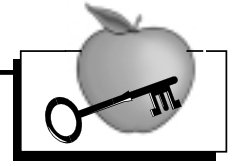
1. Radioactivity is the disintegration of the unstable nucleus of an atom. The energetic neutrons, alpha particles, beta particles, gamma rays, or x-rays released by these disintegrations are called radiation. The instrument detects radiation.
2. Ionizing radiation (described in Question 1) is produced from radioactive material like uranium. It transfers energy to atoms in the matter it penetrates, producing ions by removing electrons from the atom. Nonionizing radiation, such as the flashlight beam, does not have enough energy when it interacts with matter to create ions.
3. Background radiation comes from outer space (cosmic radiation), from rocks and soil, and building materials.
4. A Geiger counter uses a tube filled with gas which ionizes as radiation passes through it. The charged ions are attracted to electrodes operating with a potential of around 1000 volts. The electron motion toward the electrodes results in an “avalanche,” discharging the tube momentarily until the potential can build back up. Each of these events produces a “click” which can be amplified and heard on earphones or speakers, or stored and displayed as a meter reading.
5. In general, materials exposed to radiation do not become radioactive. People receiving x-rays are not made radioactive; food and instruments sterilized by very high gamma doses are not made radioactive. Certain types of radiation, generally neutron radiation, can cause certain elements to change to radioactive isotopes. This is one way that radioactive isotopes for medical diagnosis and treatment are created. Exposure of living cells to high enough levels of ionizing radiation can kill the cells, which in the case of harmful bacteria, etc., can be helpful in sterilizing surgical instruments or preventing spoilage of food.



EXPERIMENT 4

ATOMIC MASS OF "BEANIUM"

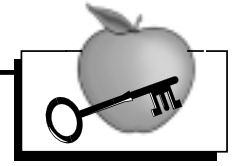
1. The average atomic mass times the total number of beans in the sample should equal the total sample mass.
2. An isotope is an atom of an element containing a different number of neutrons. Neon-20 has 10 protons (Atomic number 10) and 10 neutrons; Neon-19 has 10 protons but only 9 neutrons; Neon-22 has 10 protons and 12 neutrons.
3. Magnesium has an average atomic mass of 24.32.



EXPERIMENT 5

OIL-DROP MODEL OF PLASMA

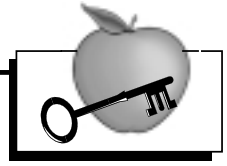
1. The spherical shape of the initial and final “nuclei” represent the most stable energy condition of a nucleus with its protons and neutrons tightly held by the strong force.
2. The bombarding neutron carries energy into the nucleus, upsetting its stable condition, resulting in distortion of the sphere and weakening of the strong force attractions. If parts of the nucleus move far enough apart, their attractions are overcome by the weaker but longer range repulsive forces between positively charged protons. The nucleus separates into two smaller nuclei, which attempt to achieve stability usually by the release of alpha, beta, or gamma radiation energy.
3. Fission products are rarely identical in size, given the randomness and violence of the splitting action. What matters is that all the particles and resulting neutrons produced by the fission total almost the same as the initial mass. The very slight amount of mass lost in the process (mass defect) is converted into energy. *Remember $E = mc^2$?*



EXPERIMENT 6

DOMINO CHAIN REACTION MODEL

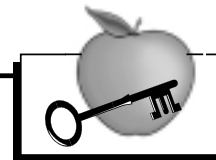
1. Once initiated, the uncontrolled chain reaction proceeds until either all the fuel is used up or the rapidly expanding fissionable material is blown apart so neutrons cannot reach more nuclei. This depends on mass and geometry.
2. Neutron absorbing poisons limit the available neutrons for the next generation's bombardment.
3. If control rods are raised from a critical reactor, more heat energy will be produced, raising the temperature and expanding the core to "lose" more neutrons. The power level will decrease until the reactor is once more just critical. Essentially raising control rods raises the operating temperature.



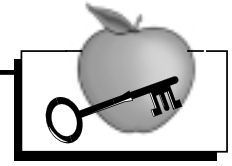
EXPERIMENT 7

DETERMINING HALF-LIFE WITH PENNIES

1. Approximately 50% of the “heads” remain after each shaking. This is because there are only two possible results for each flip of a coin. Therefore, half of the “atoms” in the sample will decay in this time period.
2. Once an atom has “decayed” to its nonradioactive daughter product, it can no longer contribute to further decays. This is an artificiality, since daughter products do remain mixed with the original atoms and contribute their mass, but they cannot revert to become a parent atom and repeat their decay pattern as a coin could do if left in the box.
3. After 1 period, about 50 “heads” would be left; 25 after the second period; 12 or 13 after the third period; 6 after the fourth period; and about 3 after the fifth period. So it should take 5 half-lives to drop below 5 remaining “heads.”
4. This shows the statistics or randomness of the event. Just as radioactive decay is random, so is flipping a penny. Only for samples with a large number of pennies or a large number of radioactive atoms will the measured decay be close to the theoretical value of 50% for penny flipping or the half-life of the radioactive isotope.

INSTRUCTOR'S KEY*Radiation, Radioactivity, and
Risk Assessment***EXPERIMENT 8
HALF-LIFE DEMONSTRATION WITH WATER**

1. The times should be approximately equal for each segment; it may be easier to see with average values of several trials.
2. The decreasing flow rate simulates diminishing decay rate as the parent isotope transmutes to the daughter. In each segment, half of the remaining quantity disappears.
3. The indicator solution should turn pink as it enters the ammonia in the bucket, simulating the formation of a new substance.



EXPERIMENT 9

TIME, DISTANCE, AND SHIELDING

1. Background counts or background dose rates result from the radiation that is always present around us such as cosmic radiation from the sun and outer space, building materials, and even our classmates (very small level).
2. Since the instrument reading represents a dose rate (in mrem/hour), the total dose received is simply the dose rate times the time spent at that rate. For example: if a worker spent a half hour in a 100 mrem/hour area, the total dose would be

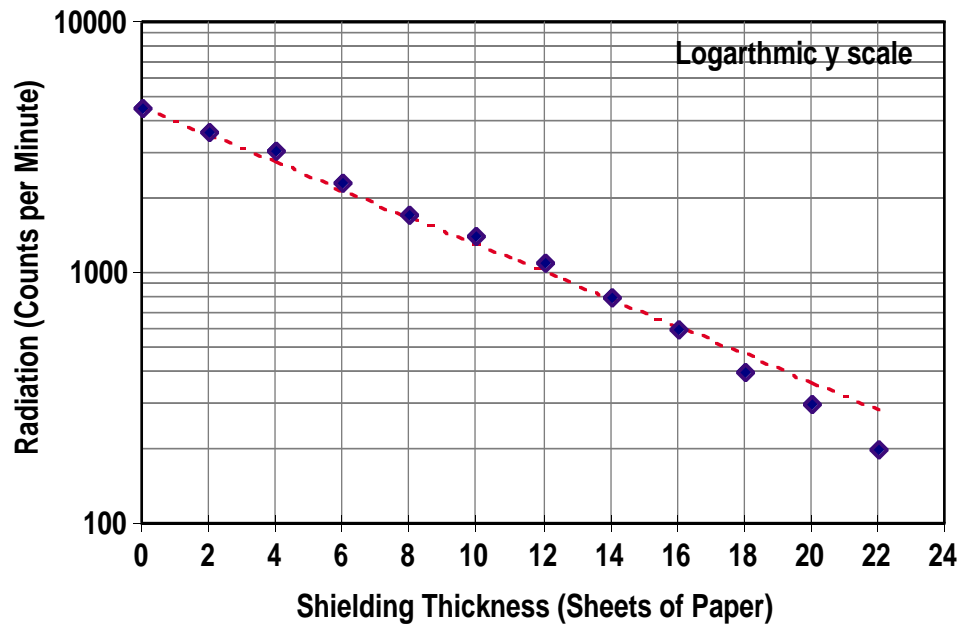
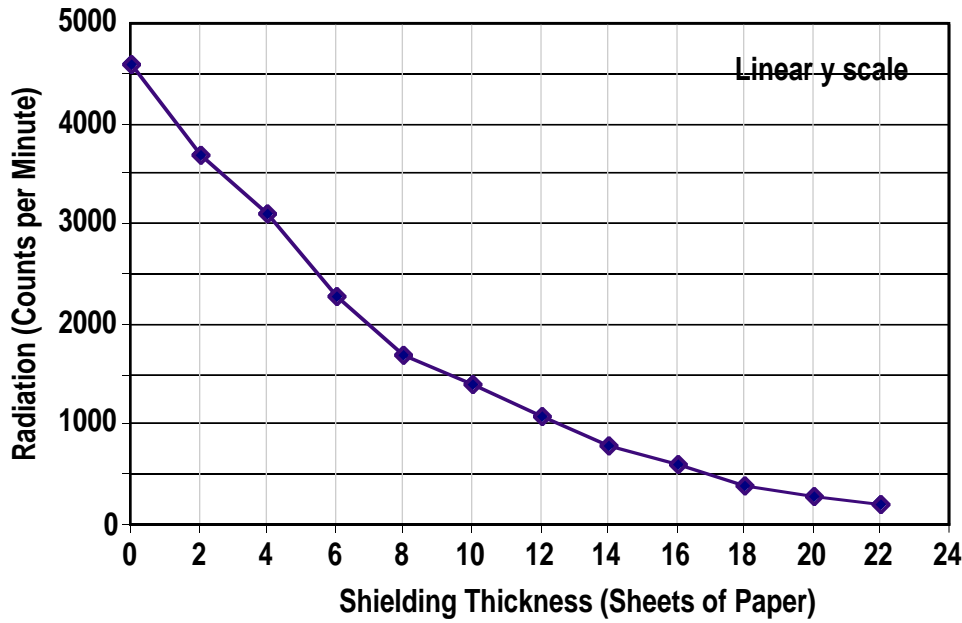
$$100 \text{ mrem/hour} \times 1/2 \text{ hour} = 50 \text{ mrem.}$$

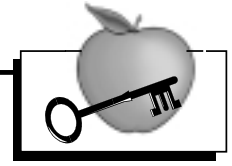
Radiation workers plan their work to minimize the amount of time they spend in high radiation areas.

3. The relationship between radiation levels and distance from the source is nonlinear, specifically, the level is inversely proportional to the square of the distance ($1/d^2$) due to the spherical spreading characteristics of radiation (similar to light from a light bulb).
4. The beta particles can be greatly attenuated by a single aluminum sheet while the more energetic gamma rays require much denser material such as lead to be attenuated. The relationship between radiation levels and shielding thickness is also a nonlinear inverse function; not a square function but rather an exponential function. Quantities which decrease by the same factor for each additional sheet of shielding will plot as an exponential decay curve on a linear graph and as a straight line on a semilog graph. See the attached sample graphs. It is convenient to refer to “half-thickness” or “tenth-thickness” (the thickness that reduces the radiation by one-half or one-tenth) when comparing shielding effectiveness. A half-thickness of aluminum would be much less than a half-thickness of paper for example.
5. These results would vary, but should be comparable between participating teams.

Measuring Radiation Shielding

Sample Graphs





EXPERIMENT 10

RADIOACTIVE CONTAMINATION SIMULATION

1. Discussion could include compacting dry waste and sealing in drums or concrete for burial. Liquids could be evaporated to leave dry residue for packaging.
2. Open-ended question. The more cleanup material used, the more contaminated waste generated.
3. Possibilities might include high efficiency vacuums or chemical treatment with chelating compounds such as EDTA. EDTA chemically binds metals that may be radioactive and in a solution makes their extraction easier.
4. It will decay to nonradioactive material. In the case of isotopes with long half-lives, this may take quite a while. Chemical contamination, on the other hand, does not decay but remains forever.