Analytical X-Ray Safety Workbook

University of California, Santa Cruz
Environmental Health & Safety

Acknowledgements

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This information is being provided in accordance with the state requirements outlined in the CALIFORNIA RADIATION CONTROL REGULATIONS, which in essence state, “Each user shall: Inform all individuals working in or frequenting any portion of a controlled area of the storage, transfer, or use of radioactive materials or of radiation in such portions of the controlled area; instruct such individuals in the health protection problems associated with exposure to such radioactive materials or radiation, in precautions or procedures to minimize exposure, and in the purposes and functions of protective devices employed; instruct such individuals in, and instruct them to observe, to the extent within their control, the applicable provisions of Department regulations and license conditions for the protection of personnel from exposures to radiation or radioactive materials occurring in such areas; instruct such individuals of their responsibility to report promptly to the licensee or registrant any condition which may lead to or cause a violation of department regulations or license conditions or unnecessary exposure to radiation or radioactive material, and of the inspection provisions of Section 30254; instruct such individuals in the appropriate response to warnings made in the event of any unusual occurrence or malfunction that may involve exposure to radiation or radioactive materials; and advise such individuals as to the radiation exposure reports which they may request pursuant to this section. The extent of these instructions shall be commensurate with potential radiological health protection problems in the controlled area. [17, CCR, 30255(b) (1)]

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Analytical X-Ray Safety Workbook

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1 Introduction

Here at UCSC you may, in the course of your education or employment, work with radioactive isotopes or radiation producing machines. We use radioactivity in experimental and diagnostic situations at UCSC because there is no better way to obtain the information we seek. However, working with radiation has unavoidable risks. Compared with other environmental hazards in the laboratory, we know a great deal about these risks and, unlike other hazardous material, radiation is relatively easy to measure and protect ourselves against.

One of the means by which the safe use and handling of radioactive isotopes or radiation producing machines may be accomplished is for you to become familiar with some of the technical and practical aspects associated with safe use of the more common sources of radiation found at UCSC.

The purpose of this workbook is to increase your knowledge in order to enable you to perform your job safely by adhering to proper radiation protection practices while working with or around x-ray-generating devices. This course will inform you about the policies and procedures you should follow to reduce the risk of exposure to the ionizing radiation produced by x-ray-generating devices.

Other hazards associated with the use of some x-ray machines such as electrical, mechanical, laser light, and explosives are not addressed in this course because they are specific to particular machines and procedures. This workbook does not address operating procedures for specific installations. You will receive training on the specific operating procedures in your laboratory.

UCSC is licensed to possess various amounts of radioactive material and radiation producing machines that may be used in a variety of procedures. A broad scope license confers authority upon the University to approve, manage, and control the receipt, use, and disposal of radioactive materials and radiation producing machines. In fact, the University must act to “police” itself under the authority given in its broad scope license.

As you review this guide, please keep in mind that each worker at UCSC must be responsible for his or her own safety. Knowledge of the following guidelines and procedures will help to ensure that you can continue to conduct your research safely and without incident. Here at UCSC, as at other educational institutions, working with radioactive material is a *privilege*, not a right. A serious violation or accident could result in the cancellation of the State Radioactive Materials License for the whole University. Therefore, the Radiation Safety Committee and the EH&S Radiation Safety Department take violations of UCSC policies regarding radiation safety very seriously.

2 Objectives

This manual is a companion to the Radiation Safety Manual (RSM). The RSM describes the radiation protection program at UCSC. The policies and procedures contained in the RSM have been approved by the Radiation Safety Committee (RSC), and are submitted to the California Department of Health Services as part of our radioactive materials license.

Upon completion of this course, you will be able to understand

- what x-rays are and how they are generated,
- the biological effects of x-rays,
- how x-rays are detected,
- the measures that protect you from x-rays,
- the regulations and requirements governing x-ray devices,
- the responsibilities of EH&S Radiation Safety, operating groups, x-ray-device custodians, and x-ray-device operators.

Radiation Safety staff are available for your consultation on the safe use of radioactive materials and radioactive machines. Feel free to call us at extension x9-2553 with any questions.

2.1 Radiation Safety Fundamentals

This Analytical X-Ray Safety Workbook presents the information necessary for users of radiation producing machines to properly understand and follow the procedures in the RSM.

After studying this workbook you will need to pass a written examination administered by the EH&S Radiation Safety Department. To use a radiation producing machine at UCSC, you must first obtain authorization from the EH&S Radiation Safety Department.

All new radiation users will need to complete the following steps:

☐ Read this *Analytical X-Ray Safety Workbook*. You will be responsible for knowing all the information in this document. A closed book test will be administered and must be passed before radiation work begins. The questions will be similar to those included in this workbook.

☐ Have several important documents on file with Radiation Safety. You will need to complete a Training and Experience Form to provide information about you and your radiation use experience. Your Principal Investigator must sign this form to add your name to their permit, indicating that they will be responsible for your supervision. If you have previously worked with radioactive materials or radiation producing equipment, complete the Exposure History Request Form for the last institution where you were a radiation worker. If you are female, read through the Prenatal Packet carefully. Sign and return Form 1 Prenatal Radiation Exposure Risks and Precautions indicating that you have received information on UCSC's prenatal radiation exposure policy. If you are now pregnant or attempting to become pregnant and **want** to declare yourself pregnant, complete Form 2 Notification of Status as a Declared Pregnant Woman.

☐ Call EH&S Radiation Safety (x9-2553) to schedule a time to watch a thirty minute video and take the written exam. This may be scheduled at your convenience (Monday through Friday, 8 a.m. - 4 p.m.) Please bring the documents described above when you come in to take your test.

If you successfully pass the exam you will be issued dosimetry (if needed) and authorized to begin working with radiation under the supervision of a more experienced user in the lab. You will be required to attend a specialized training class offered by Radiation Safety within four months of receiving initial authorization.

2.2 On-the-Job Training

This written guide does not replace the requirement that a laboratory supervisor or an appropriate alternate provide practical, hands-on training in the correct storage, use, disposal, and transportation of radioactive materials.

After receiving authorization from EH&S Radiation Safety you may begin using radioisotopes under the supervision of the Principal Investigator (PI) or the appropriate alternate. Hands-on training for each user is also provided in the laboratory by the Principal Investigator or an experienced user designated by the PI. Topics covered during this training include, as appropriate:

- safe operating procedures for radiation producing machines,
- methods to control and measure radiation levels,
- proper maintenance of required records, and
- emergency procedures.

2.3 Annual Refresher Training

You will also be required to attend annual refresher training, usually presented at a meeting of each research group, to keep up-to-date with the latest regulations and university policies. EH&S Radiation Safety will assist you in meeting this requirement.

2.4 Regulations and Guidance

The prime compliance document for occupational radiation protection at UC Santa Cruz is Title 10 of the Code of Federal Regulations, 10 CFR 20. The UCSC Radiation Safety Manual provides detailed guidance on the best practices currently available in the area of radiological control.

The American National Standards Institute (ANSI) details safety guidelines for x-ray devices in two standards, one on analytical (x-ray diffraction and fluorescence) x-ray equipment and the other on industrial (non-medical) x-ray installations. Guidance for x-ray training is also provided by the Department of Health Services in 17 CCR 30255.

At UCSC, the protection program for individuals working with or around x-ray devices is implemented through the following documents:

- UCSC Radiation Safety Manual (RSM),
- ANSI N43.2 (1989), Radiation Safety for X-Ray Diffraction and Fluorescence Analysis Equipment, and
- ANSI N43.3 (1993), American National Standard for General Radiation Safety—Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV.

Most of the information presented in this course is based on the radiation safety guidelines for x-ray devices contained in ANSI N43.2 and N43.3 and Section 8 of the RSM, which outlines the safety requirements for x-ray producing equipment.

2.5 UCSC Radiation Safety Program

The main objectives of the UCSC Radiation Safety Program are to keep worker exposure to ionizing radiation at levels that are *as low as reasonably achievable* (ALARA) and to ensure that no worker receives greater than the maximum permissible dose equivalent. These objectives may be achieved through the following methods:

- using firm management controls,
- following the radiation use authorization (RUA) and standard operating protocol (SOP),
- maintaining equipment appropriately,
- employing a comprehensive maintenance and surveillance program,
- using adequate shielding,
- maximizing distance from the source, and
- minimizing the time duration of x-ray production.

3 Radiation Protection Principles

Upon completion of this chapter, you will understand basic radiation protection principles essential to the safe operation of x-ray devices.

Using the self-assessment, you will be able to identify

- the structure of atoms and ions,
- the definition of ionizing radiation,
- sources of natural and manmade background radiation,
- UC and UCSC dose limits,
- the ALARA policy, and
- three basic methods for reducing external exposure.

3.1 Atomic Structure

The basic unit of matter is the atom. The basic atomic model, as described by Ernest Rutherford and Neils Bohr in 1911, consists of a positively charged core surrounded by negatively-charged shells. The central core, called the nucleus, contains protons and neutrons. Nuclear forces hold the nucleus together. The shells are formed by electrons which exist in structured orbits around the nucleus.

What are the three basic parts of an atom?

Protons

Protons (p^+) are positively charged and located in the nucleus of the atom. The number of protons determines the element.

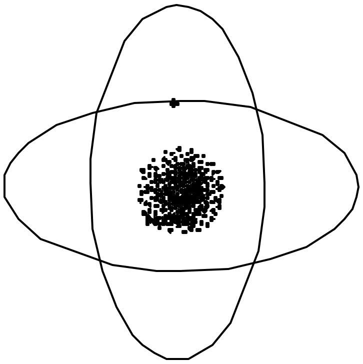

Figure 1 Atomic Model

Neutrons

Neutrons (n) are uncharged and located in the nucleus of the atom. Atoms of the same element have the same number of protons, but can have a different number of neutrons.

Atoms which have the same number of protons but different numbers of neutrons are called isotopes. Isotopes have the same chemical properties; however, the nuclear properties can be quite different.

Electrons

Electrons (e^-) are negatively charged and travel in specific orbits or energy levels about the nucleus. Each electron has energy which enables it to resist the positive charge of the nucleus. An atom is electrically neutral if the total electron charge equals the total proton charge. Electrons are bound to the positively charged nucleus by electrostatic attraction.

The number of electrons and protons determines the overall electrical charge of the atom. The term ion is used to define atoms or groups of atoms that have a net positive or negative electrical charge.

The energy of ionizing radiation is usually given in electron volts (eV). The electron volt is defined as the energy of an electron that has been accelerated through an electron potential of one volt. The eV is a very small amount of energy and therefore KeV (thousand electron volts) and MeV (million electron volts) are used as the units of measurement for the energies associated with the emissions from radioactive materials or machines. The energy of visible light is about two or three eV.

3.2 Ionizing and Non-ionizing Radiation

Radiation is the transfer of energy in the form of particles or waves through open space.

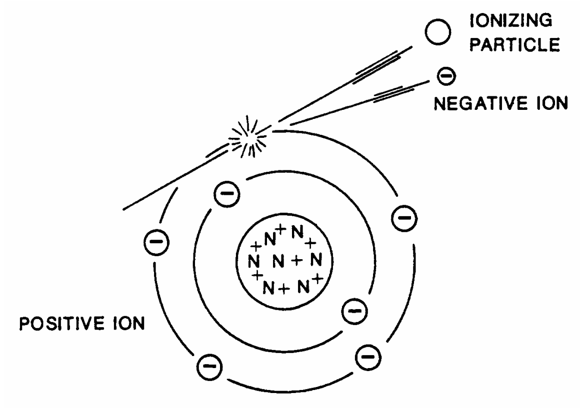

Figure 2 Ionization

Radiation commonly encountered in campus laboratories falls into two broad categories depending on its ability to form charged species (ions) during interactions with matter. Radiation that has single particles or quanta with enough energy to eject electrons from atoms is known as ionizing radiation. From the standpoint of human health and safety, ionizing radiation is of greater concern since it can create many energetic ionized atoms which in living cells engage in chemical reactions that interfere with the normal processes of cells.

Energy (particles or rays) emitted from radioactive atoms can cause ionization. Ionizing radiation includes alpha particles, beta particles, gamma or x-rays, and neutron particles.

Non-ionizing radiation does not have enough energy to eject electrons from electrically neutral atoms. Examples of non-ionizing radiation are ultraviolet (could ionize), visible light, infrared, microwaves, radio waves, and heat.

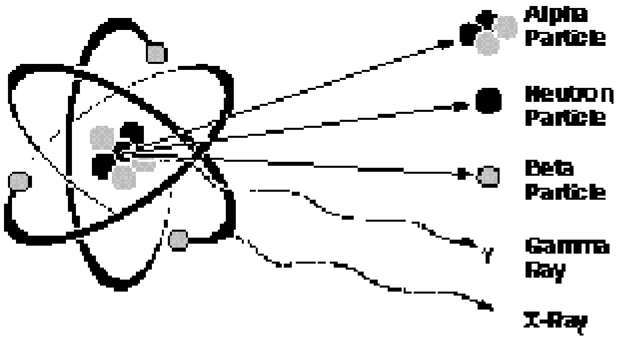

Figure 3
Ionizing Radiation

X-rays are a form of electromagnetic radiation and are very similar to gamma rays. They differ in their point of origin. Gamma rays originate from within the atomic nucleus, whereas x-rays originate outside the nucleus. From a radiation safety standpoint, however, both gamma rays and x-rays produce the same biological effects; hence, gamma rays and x-rays are commonly grouped together as one type of radiation. This course will discuss in detail how x-rays are produced in Section 2.

3.3 Units of Measure

Ionizing radiation is measured in the following units:

- roentgen (R), the measure of *exposure* to radiation, defined by the ionization caused by x-rays in air,
- rad, the *radiation absorbed dose* or energy absorbed per unit mass of a specified absorber, and
- rem, the *roentgen equivalent man* or dose equivalent.

Since 1 R of exposure delivers approximately 0.95 rads of absorbed dose to muscle tissue, for radiation safety purposes the approximation is often made that 1 R = 1 rad = 1 rem.

Note: For a more detailed discussion of R, rad, and rem, refer to Unit 4 in *Radiation Safety Fundamentals Workbook*.

3.4 Background Radiation

Background radiation, to which everyone is exposed, comes from both natural and manmade sources. The most common sources of natural background radiation are cosmic, terrestrial, internal, and radon. The most common sources of manmade background radiation are medical procedures and consumer products.

The average background dose to the general population from both natural and manmade sources is about 360 mrem per year.

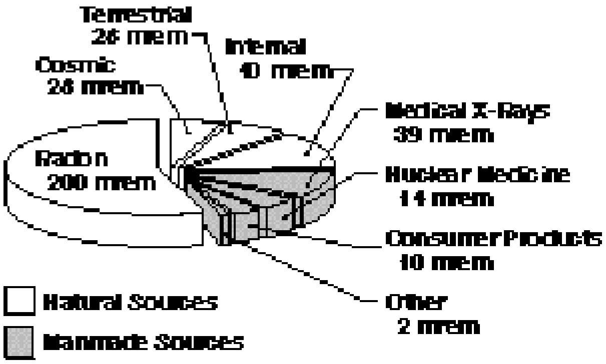

Figure 4
Average Annual Background Dose

Naturally occurring sources include an average of about 200 mrem per year from radon and its decay products, about 40 mrem per year from internal emitters such as potassium-40, about 28 mrem per year from cosmic rays, and about 28 mrem per year from terrestrial sources such as naturally occurring uranium and thorium.

Manmade sources of ionizing radiation exposure include an average of about 10 mrem per year from consumer products such as building materials and about 53 mrem per year from medical procedures such as diagnostic x-ray and nuclear machine procedures. Note that the dose from a chest x-ray procedure (two views) is approximately 20-26 mrem. The average dose from a mammographic procedure (two views per breast) is 1.4 mrem, which totals 2.8 mrem for both breasts. The average dose for a dental x-ray (one bitewing) is 1.5 mrem per bitewing. However, a full-mouth dental x-ray exam may include 21 views, which totals approximately 32 mrem for the full mouth exam. Because these doses are only to portions of the body, the effective dose equivalent to the whole body is a fraction of these values.

3.5 Dose Limits and Control Levels

Limits on occupational doses are based on data on the biological effects of exposure to ionizing radiation and guidance from the International Commission on Radiological Protection, the National Council on Radiation Protection, and the Environmental Protection Agency. The limits are well below the doses at which any symptoms of biological effects appear.

Table 1 Dose Limits

	Radiation Worker		Declared Pregnant Worker	General Public
	Federal Limit[1]	UCSC Limit		
Whole Body	5,000 mrem/yr	**500** mrem/yr		**100** mrem/yr[2]
Extremities	50,000 mrem/yr	**5,000** mrem/yr		
Skin/Organ	50,000 mrem/yr	**5,000** mrem/yr		
Lens (Eye)	15,000 mrem/yr	**1,500** mrem/yr		
Embyro/Fetus			**500** mrem/gestation	

[1] Occupational dose limits for minors are 10% of the adult limit.
[2] Exposure rates must also not exceed 2 mrem in any one hour.

UC facilities are designed and operated to reduce workers' dose equivalents as far below the occupational limits as reasonable. The average exposure for x-ray workers is typically between 0 and 100 mrem per year above natural background exposure.

3.6 Causes of Accidental Exposures

Although most x-ray workers do not receive any measurable radiation above background, accidents related to x-ray devices have occurred when proper work procedures have not been followed. Failure to follow proper procedures has been the result of

- rushing to complete a job,
- fatigue,
- illness,
- personal problems,
- lack of communication, or
- complacency.

Every year about one x-ray incident per hundred x-ray units occurs nationwide. Approximately one-third of these incidents result in injury to a person. The accident rate at UC laboratories is lower than the national average.

3.7 ALARA

Because the effects of chronic exposure to low levels of ionizing radiation are not precisely known, there is an assumed long-term risk of developing some forms of cancer associated with any radiation dose. ALARA policy is to keep radiation dose *as low as reasonably achievable,* considering economic and social constraints.

The goal of the ALARA program is to keep radiation dose ALARA, that is, as far below the occupational dose limits and administrative control levels as is reasonably achievable so that there is no radiation exposure without commensurate benefit based on sound economic principles. The success of the ALARA program is directly linked to a clear understanding and following of the policies and procedures for the protection of workers. Keeping radiation dose equivalent ALARA is the responsibility of each worker.

Linear Nonthreshold (LNT) Hypothesis

The ALARA policy is based philosophically on the linear, nonthreshold (LNT) dose-effect hypothesis, which predicts the risk of developing cancer associated with long-term radiation exposure in the workplace. The LNT hypothesis assumes that the high doses of ionizing radiation associated with observed injurious effects in humans may be used to predict the effects of low doses.

According to the LNT hypothesis, any dose of ionizing radiation, no matter how small, has some sort of injurious effect. Furthermore, it regards each increment of dose as having the same biological damage-producing potential regardless of dose rate, and it regards every increment of dose as irreversible, permanent, and cumulative.

However, there is some controversy associated with the LNT hypothesis. Many safety professionals maintain that no injurious effects of low-dose and low-dose rate ionizing radiation have ever been documented to occur in human populations, which is counter to the hypothesis.

Furthermore, they maintain that scientific evidence confirms that there are probably no injurious effects from low-dose and low-dose rate ionizing radiation at even many times the dose and dose rates of natural background radiation. They suggest that the doses and dose rates from natural background radiation are comparable to the doses and dose rates experienced by most radiological workers in the workplace and by members of the public.

Despite the controversy in the safety professional community, the UC has endorsed the LNT hypothesis as a prudent and conservative approach for the protection of workers and the public. The ALARA policy is mandated by law and requires that exposure be kept as low as possible.

Reducing External Exposure

Three basic ways to reduce external exposure to radiation are to

- minimize time,
- maximize distance, and
- use shielding.

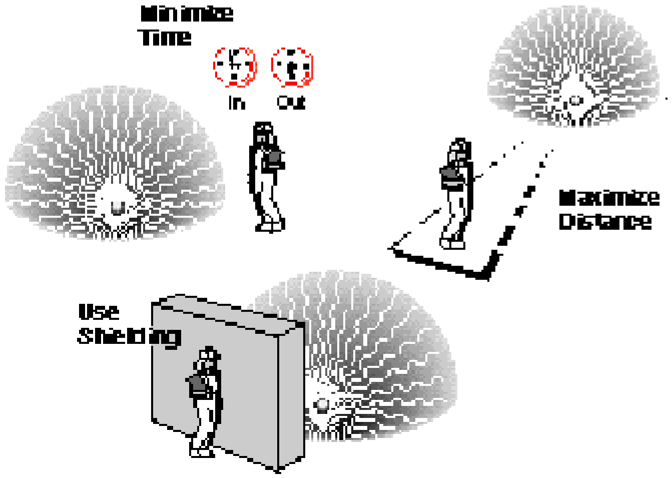

Figure 5
Methods for Reducing External Exposure

Minimize time near a source of radiation by planning ahead. Maximize distance by moving away from the source of radiation whenever possible. Exposure from x-ray sources is inversely proportional to the square of the distance (inverse-square law), that is, when the distance is doubled, the exposure is reduced by one-fourth. Use shielding appropriate for the type of radiation. Lead, concrete, and steel are effective in shielding against x-rays and gamma ray sources.

Self-Assessment

1. Ionizing radiation can remove electrons from a neutral atom to form
    a. neutrons
    b. protons
    c. electrons
    d. ions

2. All of the following are examples of ionizing radiation, *except*
    a. alpha
    b. beta
    c. atom
    d. x-ray

3. Radiation to which everyone is exposed is called
    a. alpha
    b. background
    c. cathode ray
    d. occupational

4. Background radiation averages about
    a. 360 mrem per hour
    b. 360 mrem per year
    c. 360 rem per hour
    d. 360 rem per year

5. The UC dose guideline for the whole body is
    a. 5 mrem per hour
    b. 5 rem per hour
    c. 5 mrem per year
    d. 5 rem per year

6. One of the methods of reducing exposure to radiation is to minimize
    a. distance
    b. time
    c. shielding
    d. speed

7. If you move away from a point source of x-rays until you are four times as far away, your exposure will be
    a. the same
    b. one-half
    c. one-fourth
    d. one-sixteenth

4 Production of X-Rays

Upon completion of this chapter, you will understand what x-rays are and how they are produced so that you will be able to work around them safely.

Using the self-assessment, you will be able to identify:

- the types of electromagnetic radiation,
- the difference between x-rays and gamma rays,
- how x-rays are produced,
- Bremsstrahlung and characteristic x-rays,
- the difference between photon energy and total power,
- the effects of voltage, current, and filtration on x-rays,
- how x-rays interact with matter, and
- how energy relates to radiation dose.

4.1 Electromagnetic Radiation

X-rays are a type of electromagnetic radiation. Other types of electromagnetic radiation include radio waves, microwaves, infrared, visible light, ultraviolet, and gamma rays. The types of radiation are distinguished by the amount of energy carried by the individual photons.

All electromagnetic radiation consists of photons, which are individual packets of energy. One is not usually aware of these individual packets because they are so numerous. For example, a household light bulb emits about 10^{21} photons per second.

The energy carried by individual photons, which is measured in electron volts (eV), is related to the frequency of the radiation. Different types of electromagnetic radiation and their typical photon energy are listed in the following table.

Table 2 Electromagnetic Radiation

Type of Radiation	Typical Photon Energy
radio wave	1 µeV
microwave	1 meV
infrared	1 eV
red light	2 eV
violet light	3 eV
ultraviolet	4 eV
x-ray	100 KeV
gamma ray	1 MeV

X-Rays and Gamma Rays

X-rays are similar to gamma rays in their ability to ionize atoms. Other types of electromagnetic radiation are non-ionizing. It takes 5 eV of photon energy to ionize a carbon atom, so one x-ray photon (typically 100 KeV) can ionize thousands of atoms.

As discussed in Chapter 3, the distinction between x-rays and gamma rays is their origin and method of production. Gamma rays originate from within the nucleus; x-rays originate outside the nucleus.

In addition, gamma photons often have more energy than x-ray photons. For example, diagnostic x-rays are about 40 KeV, whereas gammas from cobalt-60 are about 1 MeV. However, there are many exceptions. For example, gammas from plutonium are less than 60 KeV, whereas x-rays from the pulsed high-energy radiographic machine emitting x-rays (PHERMEX) are about 10 MeV.

4.2 X-Ray Production

X-rays are produced when charged particles, usually electrons, are accelerated by an electrical voltage (potential difference). Whenever a high voltage, a vacuum, and a source of electrons are present in any scientific device, x-rays can be produced. This is why many devices that use high voltages produce *incidental* x-rays, i.e., x-rays produced during normal operation of the device that are an unwanted byproduct of the device's normal function. Televisions, computer monitors, scanning electron microscopes, and many other devices at UCSC produce incidental x-rays.

Most x-ray devices emit electrons from a cathode, accelerate them with a voltage within a vacuum, and allow them to hit an anode, which emits x-ray photons.

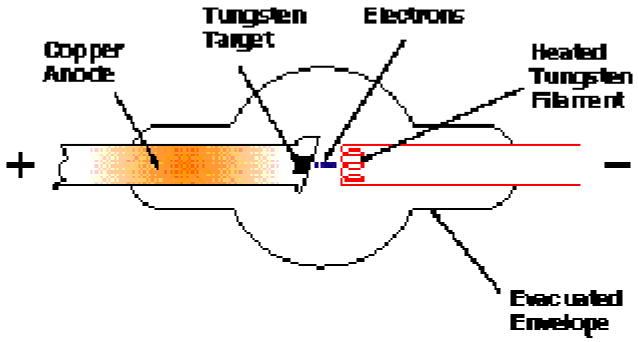

Figure 6
X-Ray Tube

While x-rays are extremely useful in areas ranging from basic research to trace element analysis to radiography, the actual production of x-rays is rather difficult and very inefficient. More than 99% of the kinetic energy of electrons bombarding a particular target material results only in the production of heat. Indeed, heat buildup in the x-ray production target is the key limiting factor in the design of intentional x-ray producing devices.

Bremsstrahlung

When high-speed electrons from a cathode bombard an anode target material, some of the negatively charged electrons are able to get through the target atom's electron cloud due to their high velocity and interact with the positively charged nucleus. This proximity causes the electrons to undergo a change in momentum due to the strongly attractive force of the target nuclei. The electrons that are able to penetrate near the target material nuclei are "braked," or decelerated, to varying degrees depending on how closely they approach the target nuclei. The Coulomb force field of the target nuclei causes up to 100% of the kinetic energy of the bombarding electrons to be converted to x-ray photon energy. X-ray photons are thus produced by many individual energies over a wide energy spectrum depending upon the degree of braking that the original bombarding electrons experienced in the Coulomb force field of the target nuclei. The process of producing x-rays in this manner is called Bremsstrahlung x-ray production after the German word for “braking radiation.” Bremsstrahlung production in a given target material varies directly as the square of the target material’s atomic number (Z) and inversely as its atomic weight (A). Thus,

$$Bremsstrahlung = \frac{Z^2}{A}$$

Bremsstrahlung is most effectively produced when small charged particles bombard atoms of high Z number such as tungsten. In theory, however, Bremsstrahlung can be produced by bombarding targets of low Z number, e.g., hydrogen with high-velocity electrons.

Characteristic X-Rays

High-speed electrons traveling in a vacuum may impinge upon a target material such that the negatively charged high-velocity electrons liberate electrons from the target atom. The target atom electron vacancy thus created is filled by other electrons within the atom moving to fill the vacancy. The transition of electrons between energy states results in the emission of x-rays that are “characteristic” of the target atom identity and whose energy corresponds to the difference between the initial and final electron energy state. For example, when bombarded by high-velocity electrons in a vacuum, copper emits characteristic x-rays of 9.04 KeV. In contrast, tungsten emits characteristic x-rays of 58.87 KeV; molybdenum, 17.44 KeV; cobalt, 6.93 KeV; iron, 6.40 KeV; and chromium, 5.41 KeV.

In summary, x-rays can be produced by either radiative interaction as the bombarding electrons are braked by the Coulomb force field of the target nuclei (Bremsstrahlung x-ray production) or by collision interactions with atomic electrons of the target material (characteristic x-ray emission).

4.3 Photon Energy and Total Power

For radiation protection purposes, it is important to distinguish between the energy of individual photons in an x-ray beam and the total energy of all the photons in the beam. It is also important to distinguish between average power and peak power in a pulsed x-ray device.

Typically, the individual photon energy is given in electron volts (eV), whereas the total power of a beam is given in watts (W). Consider an analogous example from visible light: a 100-W red light emits more total power than a 10-W blue light; however, blue light photons have more energy than red light photons.

The photon energy may be varied either by changing the voltage or by using filters that are analogous to the colored filters used in photography. Changing the current may vary the number of photons emitted.

Voltage

The photon energy produced by an x-ray device depends on the voltage, which is measured in volts (V). A voltage of 10 kV will produce up to 10-KeV x-ray photons. Most of the x-ray photons produced by a given maximum electron acceleration potential will be approximately one-third of the maximum electron acceleration potential. For example, a 120-kV-peak (kVp) diagnostic x-ray device produces x-ray photons most of which will have energies around 40 KeV. Many x-ray devices have meters to measure voltage. Whenever the voltage is on, a device can produce x-rays, even if the current is too low to read.

Current

The total number of photons produced by an x-ray device depends on the current, which is measured in amperes, or amps (A). The higher the electron current, the more x-ray photons are emitted from the anode. Many x-ray devices have meters to measure the x-ray current produced. The x-ray current from many intentional x-ray producing devices is on the order of milliamps (mA).

Determining Total Power

Total power equals voltage multiplied by current (W = V x A). For example, a 10-kV device with a current of 1 mA produces 10 W of power.

4.4 Interaction with Matter

Scattering

When x-rays pass through any material, some will be transmitted, some will be absorbed, and some will scatter. The proportions depend on the photon energy and the type of material.

X-rays can scatter off a target to the surrounding area, off a wall and into an adjacent room, and over and around shielding. A common mistake is to install thick shielding walls around an x-ray source but ignore the need for a roof, based on the assumption that x-rays travel in a straight line. The x-rays that scatter over and around shielding walls are known as *skyshine.*

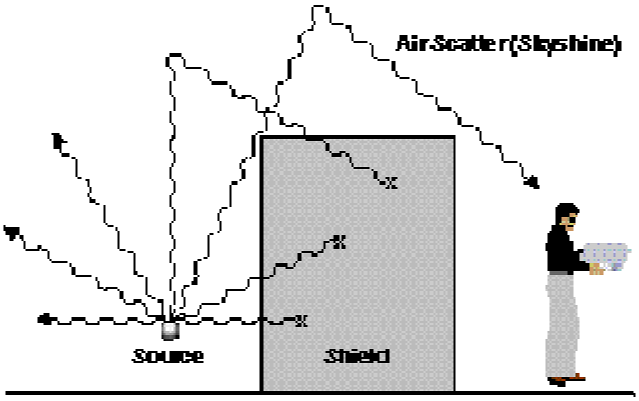

Figure 7
Skyshine

Shielding

High-energy x-ray photons are more penetrating than low-energy photons. This makes high-energy photons more difficult to shield. Thicker shielding may be required or, if the shielding thickness is fixed, high-energy photons will penetrate more often than low-energy photons. Varying thickness of lead, concrete, and steel are most effective in shielding against x-rays.

Filtration

High- and low-energy photons are sometimes referred to as *hard* and *soft* x-rays, respectively. Because hard x-rays are more penetrating, they are more desirable for radiography (producing a photograph of the interior of the body or a piece of apparatus). Soft x-rays are less useful for radiography because they are absorbed near the surface. Filters typically of aluminum, copper, or lead are used to "harden" the x-ray beams from low, medium, and high-energy x-ray machines, respectively.

Implications of Photon Energy and Total Power

High-energy photons penetrate deeply into and through the body, resulting in the deposition of dose to internal organs. Low-energy photons are absorbed in the top layers of tissue, resulting in the deposition of dose mostly to the skin.

The greater the number of photons, and therefore the greater the total energy, the more damage is caused to whatever part of the body in which the photons deposit energy. This is measured in units of *rad* or *rem*, defined as the result of 0.01 W for 1 second in 1 kilogram of human tissue (0.01 W-sec/kg = 1 rad = 1 rem, for x-rays). Note that a concentrated beam of x-rays could deposit all of its energy in much less than 1 kilogram of tissue. For example, 0.01 W for 1 second in1 gram would result in 1,000 rem of damage.

A 100-KeV photon is more hazardous than a 10-KeV photon, and 10 W are more hazardous than 1 W, but the precise hazards depend on what part of the body is exposed, how far the x-ray photon penetrates, and other factors discussed in Chapter 5.

Self-Assessment

8. X-rays are different from some other types of electromagnetic radiation because x-rays are
   - a. electrons
   - b. ionizing
   - c. nonionizing
   - d. atoms

9. Which of the following types of radiation is the most similar to x-rays?
   - a. microwaves
   - b. infrared
   - c. ultraviolet
   - d. gamma rays

10. In an x-ray device, x-rays are emitted from the
    - a. anode
    - b. vacuum
    - c. cathode
    - d. diode

11. Production of x-rays by bremsstrahlung is generally increased when charged particles with _____ mass hit an anode with _____ atomic weight.
    - a. small, low
    - b. large, low
    - c. small, high
    - d. large, high

12. When filtration is used in an x-ray device to *harden* the beam, the remaining photons are
    - a. low-energy, more penetrating
    - b. low-energy, less penetrating
    - c. high-energy, more penetrating
    - d. high-energy, less penetrating

13. Scattering of x-rays by air may result in increased
    - a. skyshine
    - b. power
    - c. current
    - d. voltage

5 Biological Effects

Upon completion of this chapter, you will understand the biological effects of x-rays and the importance of protective measures for working with or around x-rays.

Using the self-assessment, you will be able to identify

- the early history of x-rays and the consequences of working with or around x-rays without protective measures,
- factors that determine the biological effects of x-ray exposure,
- the differences between thermal and x-ray burns,
- the signs and symptoms of an acute exposure to x-rays,
- the effects of chronic exposure to x-rays, and
- the difference between somatic and heritable effects.

5.1 Early History of X-Rays

Discovery of X-Rays

X-rays were discovered by German scientist Wilhelm Roentgen. In early November 1895, Roentgen was investigating high-voltage electricity and noticed that a nearby phosphor glowed in the dark whenever he switched on his apparatus. He quickly demonstrated that these unknown "x" rays, as he called them, traveled in straight lines, penetrated some materials, and were stopped by denser materials. He continued experiments with these "x" rays and eventually produced an x-ray picture of his wife's hand showing the bones and her wedding ring. In early January 1896, Roentgen mailed copies of this picture along with his report to fellow scientists.

Figure 8
Roentgen's First X-Ray

By February 1896, the first diagnostic x-ray in the United States was taken, followed quickly by the first x-ray picture of a fetus in utero.

Discovery of Harmful Effects

Because virtually no protective measures were used in those early days, people soon learned about the harmful effects of x-rays. X-ray workers were exposed to very large doses of radiation, and skin damage from that exposure was observed and documented early in 1896. In March of that year, Thomas Edison reported eye injuries from working with x-rays. By June, experimenters were being cautioned not to get too close to x-ray tubes. By the end of that year, reports were being circulated about cases of hair loss, reddened skin, skin sloughing off, and lesions. Some x-ray workers lost fingers, and some eventually contracted cancer. By the early 1900s, the potential carcinogenic effect of x-ray exposure in humans had been reported.

Since that time, more than a billion dollars have been spent in this country alone on radiation effects research. The biological effects of exposures to radiation have been investigated. National and international agencies have been formed to aid in the standardization of x-ray use to ensure safer practices.

5.2 Biological Effects of Radiation

X-rays can penetrate deeply into the human body, strip electrons from orbit, and thereby break or modify chemical bonds within critical biological molecules that make up the cells. This process can cause cell injury and even cell death, depending on the dose and dose rate of the exposure.

In some cases, altered cells are able to repair the damage. In other cases, the effects are passed to daughter cells through cell division and after several divisions can result in a group of cells with altered characteristics. The division of these cells may be the first step in tumor or cancer development. If enough cells in a body organ are injured or altered, the functioning of the organ can be impaired.

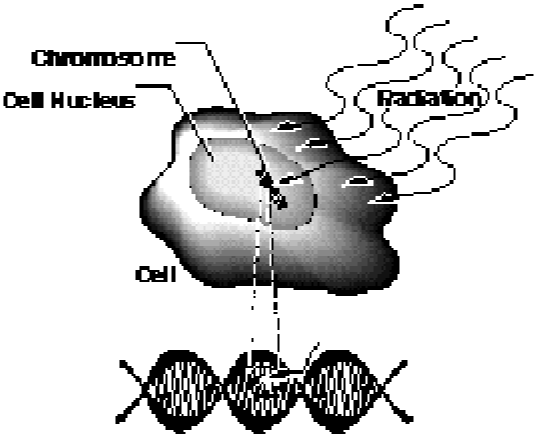

Figure 9
Effects of Radiation on a Cell

5.3 Factors that Determine Biological Effects

Several factors contribute to the biological effects of x-ray exposure, including

- dose rate,
- total dose received,
- energy of the radiation,
- area of the body exposed,
- individual sensitivity, and
- cell sensitivity.

Dose Rate

Depending on the period of time over which it is received, a dose is commonly categorized as acute or chronic. An *acute* dose is received in a short period (seconds to days); a *chronic* dose is received over a long period (months to years).

For the same total dose, an acute dose is more damaging than a chronic dose because the cell does not have adequate time to repair all the damage between “hits,” thus resulting in residual enduring cell damage.

Total Dose Received

The higher the total amount of radiation received, the greater the effects observed. The effects of an acute dose of more than 100 rem are easily observed. However, the signs and symptoms of an acute dose of amounts less than 10 to 25 rem are not easily observed. Currently effects below 10 rem exposure cannot be reliably quantified.

The effects of a chronic dose are also difficult to observe. Although chronic effects have not been observed directly, it is assumed under the ALARA philosophy that the higher the total dose, the greater the risk of contracting cancer or other long-term effects.

Energy of the Radiation

The energy of x-rays can range from less than 1 KeV up to more than 10 MeV, but are typically 40 to 100 KeV. The higher the energy of the x-ray, the greater the penetration into body tissue (deep dose) and the higher the probability of damage to internal organs, bone, or bone marrow, the site of blood-forming tissue. Lower energy x-rays are absorbed in the first few millimeters of tissue (shallow dose) and can cause damage to the skin but less damage to the internal organs of the body.

Area of the Body Exposed

Just as a burn to the majority of the body is more damaging than a burn confined to a small area, similarly a radiation dose to the whole body, which contains the vital organs and blood-forming tissue, is much more damaging than a dose delivered only to a hand. In addition, the larger the area exposed, the more difficult it is for the body to repair the damage.

Individual Sensitivity

Some individuals are more sensitive to radiation than others are. Age, gender, lifestyle, and overall health can have an effect on how the body responds to radiation dose.

Cell Sensitivity

Some cells are more sensitive to radiation than others. Cells that are more sensitive to radiation are *radiosensitive;* cells that are less sensitive to radiation are *radioresistant.*

Cells that are non-specialized, such as sperm and ovum cells, or cells that are actively dividing, such as hair follicle and gastrointestinal cells, are the most radiosensitive. Cells that are specialized (mature) or cells that are less-actively dividing, such as bone, muscle, or brain cells, are more radioresistant.

5.4 Somatic Effects

Somatic effects are biological effects that occur in the individual exposed to radiation. Somatic effects may result from acute or chronic doses of radiation.

Early Effects

The most common injury associated with the operation of analytical x-ray equipment occurs when a part of the body, usually a hand or finger, is exposed to the primary x-ray beam. Both x-ray diffraction and fluorescence analysis equipment generate high-intensity x-rays that can cause severe and permanent injury if any part of the body is exposed to the primary beam.

The most common injury associated with the operation of industrial x-ray equipment occurs when an operator is exposed to the intense primary x-ray beam for even a short time. UCSC has some intentional x-ray devices that produce more than 1000 rem/minute one meter away from the x-ray production target. Thus, strict engineered access controls must be emplaced to prevent the operator from ever placing himself/herself in the primary x-ray beam area when the machine is energized.

These types of injuries are sometimes referred to as *radiation burns*.

X-Ray Burns versus Thermal Burns

Most nerve endings are near the surface of the skin, so they give immediate warning of a surface burn such as you might receive from touching a high-temperature object. In contrast, high-energy x-rays readily penetrate the outer layer of skin that contains most of the nerve endings, so you may not feel an x-ray burn until the damage has been done.

X-ray burns do not harm the outer, mature, non-dividing skin layers. Rather, the x-rays penetrate to the deeper, basal skin layer, damaging or killing the rapidly dividing germinal cells that were destined to replace the outer layers that slough off. Following this damage, the outer cells that are naturally sloughed off are not replaced. Lack of a fully viable basal layer of cells means that x-ray burns are slow to heal, and in some cases, may never heal. Frequently, such burns require skin grafts. In some cases, severe x-ray burns have resulted in gangrene and amputation of a finger.

The important variable is the energy of the radiation. Heat radiation is infrared, typically 1 eV; sunburn is caused by ultraviolet radiation, typically 4 eV; x-rays are typically 10 to 100 KeV.

Signs and Symptoms of Exposure to X-Rays

500 rem. An acute dose of about 500 rem to a part of the body causes a radiation burn equivalent to a first-degree thermal burn or mild sunburn. Typically, there is no immediate pain, but a sensation of warmth or itching occurs within about a day after exposure. A reddening or inflammation of the affected area usually appears within a day and fades after a few more days. The reddening may reappear as late as two to three weeks after the exposure. A dry scaling or peeling of the irradiated portion of the skin is likely to follow.

If you have been working with or around an x-ray device and you notice an unexplained reddening of your skin, notify your supervisor and the Radiation Safety Officer. Aside from avoiding further injury and guarding against infection, further medical treatment will probably not be required and recovery should be fairly complete.

Figure 10
Mihran Kassabian (1870-1910) meticulously noted and photographed his hands during progressive necroses and serial amputations, hoping the data collected might prove useful after his death.

An acute dose of about 600-900 rem to the lens of the eye causes a cataract to begin to form.

>1,000 rem. An acute dose of greater than 1,000 rem to a part of the body causes serious tissue damage similar to a second-degree thermal burn. First reddening and inflammation occurs, followed by swelling and tenderness. Blisters will form within one to three weeks and will break open leaving raw, painful wounds that can become infected. Hands exposed to such a dose become stiff and finger motion is often painful. If you develop symptoms such as these, seek immediate medical attention to avoid infection and relieve pain.

An even larger acute dose causes severe tissue damage similar to a scalding or chemical burn. Intense pain and swelling occurs, sometimes within hours. For this type of radiation burn, seek immediate medical treatment to reduce pain. The injury may not heal without surgical removal of exposed tissue and skin grafting to cover the wound. Damage to blood vessels also occurs, which can lead to gangrene and amputation.

A typical x-ray device can produce such a dose in about 3 seconds. For example, the dose rate from an x-ray device with a tungsten anode and a beryllium window operating at 50 KeV and 20 mA produces about 900 rem per second at 7.5 cm. The dose rate can be estimated from the formula

$$rem / \sec = \frac{50VI}{R^2}$$

where V is the potential in volts, I is the current in amperes, and R is the distance in centimeters.

Latent Effects

The probability of a latent effect appearing several years after an acute exposure to radiation depends on the amount of the dose. The higher the dose, the greater the risk of developing a long-term effect. When an individual receives a large accidental dose, and the prompt effects of that exposure have been dealt with, there still remains a concern about latent effects years after the exposure. Although there is no unique disease associated with exposure to radiation, the concern usually centers around the possibility of developing cancer. If the exposure is directly to the lens of the eye, the development of cataracts is the expected latent effect.

Chronic Effects

Chronic somatic effects may not appear until several years after exposure to radiation. Chronic effects result from doses of radiation received over a long period. The higher the cumulative dose, the greater the risk of developing a chronic effect. One chronic effect is cataracts. Chronic dose to the lens of the eye can result in cataracts and other optical problems if the total dose exceeds about 600 rem.

Risk of Developing Cancer from Chronic Exposure

The risk of cancer from chronic low doses of radiation cannot be estimated precisely because the risk is so low that it cannot be distinguished from natural causes. Thus, estimates of the risk from low doses must be inferred from those developed for the effects observed at acute high doses.

The Fifth Committee on the Biological Effects of Ionizing Radiation (BEIR V) estimates the risk to be 0.8% for an acute dose of 10 rem. This risk estimate for high doses was developed through studies of Japanese atomic bomb survivors, uranium miners, radium watch-dial painters, and radiotherapy patients.

Below 10 rem, the effects of chronic, low doses have not been observed. Therefore, using the ALARA philosophy, risk estimates for low doses have been inferred from high-dose data to provide probably ultraconservative protection guidelines for worker/public radiation exposure.

Effects of Prenatal Exposure (Teratogenic Effects)

The embryo/fetus is most sensitive to the effects of ionizing radiation during the first trimester of pregnancy when cells are rapidly dividing and the major organs are forming. If you are planning a pregnancy, you should seek advice from the Radiation Safety Officer and keep your radiation dose ALARA.

If you become pregnant, you are strongly encouraged to declare your pregnancy in writing to the RSO and to keep your total accumulated dose ALARA during the nine months of pregnancy. The dose limit for a declared pregnant worker is 500 mrem during the term of pregnancy, with no more than 50 mrem per month.

5.5 Heritable Effects

Heritable effects are biological effects that are inherited by children from their parents at conception. Irradiation of the reproductive organs can damage and alter cells that are involved in conception and can potentially alter heritable information passed on to offspring.

Heritable effects have been observed in large-scale experiments with fruit flies and mice irradiated with large doses of radiation. However, heritable effects from radiation exposure have not been observed in humans. The probability of heritable effects in humans is prudently inferred from the animal data, under the ALARA philosophy, but no heritable radiation effects have ever been observed in human populations.

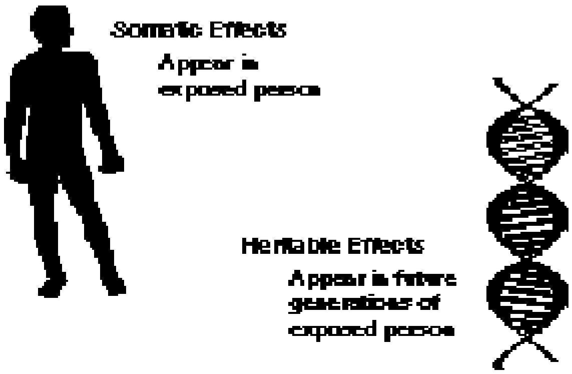

Figure 11
Somatic vs. Heritable Effects

The heritable effects of ionizing radiation do not result in biological conditions in the offspring that are uniquely different from the effects that occur naturally. Extensive observations of the children of Japanese atomic bomb survivors have not revealed any statistically significant heritable effects.

Note: *Teratogenic (congenital) effects are not heritable effects. Teratogenic effects are not inherited; they are caused by the action of agents such as drugs, alcohol, radiation, or infection to an unborn child in utero. Teratogenic effects occurred in children who were irradiated in utero by the atomic bombs at Hiroshima or Nagasaki.*

Self-Assessment

15. X-rays were discovered by Wilhelm Roentgen in 1895 while he was
    - a. x-raying his wife’s hand
    - b. investigating fluorescence of uranium
    - c. experimenting with high-voltage vacuum tubes
    - d. visiting Thomas Edison

16. Which of the following types of cells is most radiosensitive?
    - a. skin
    - b. bone
    - c. muscle
    - d. gastrointestinal

17. Which of the following types of cells is most radioresistant?
    - a. gastrointestinal
    - b. brain
    - c. sperm
    - d. ovum

18. One of the first signs of an x-ray burn to the extremities is
    - a. loss of hair
    - b. cancer
    - c. nausea
    - e. reddening of the skin

19. Acute effects occur in a _____ period; chronic effects occur over a _____ period.
    - a. long, longer
    - b. long, short
    - c. short, long
    - d. short, short

20. Somatic effects occur in the ______, heritable effects occur in the ______
    - a. children, exposed person
    - b. children, body
    - c. exposed person, children
    - d. skin, hair

6 Radiation Detection

Upon completion of this chapter, you will understand which radiation monitoring instruments and which personnel monitoring devices are appropriate for detecting x-rays.

Using the self-assessment, you will be able to identify

- the requirements for surveying x-ray devices,
- the instruments used for x-ray detection and measurement, and
- the devices used for personnel monitoring.

6.1 Radiation Surveys

Radiation protection surveys are conducted on all new or newly installed intentional x-ray devices by EHS Radiation Safety and resurveyed annually as specified in the RSM. A UCSC x-ray compliance label certifies that the device has been surveyed and that safe operating requirements have been met.

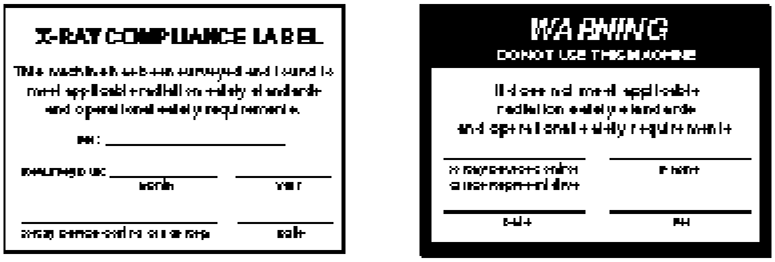

Figure 12
Compliance and Warning Labels

6.2 Radiation Monitoring Instruments

External exposure controls used to minimize the dose equivalent to workers are based on the data taken with portable radiation monitoring instruments during a radiation survey. An understanding of these instruments is important to ensure that the data obtained are accurate and appropriate for the source of radiation.

Many factors can affect how well the survey measurement reflects the actual conditions, including

- selection of the appropriate instrument based on the type and energy of radiation and the radiation intensity,
- correct operation of the instrument based on the instrument operating characteristics and limitations, and
- calibration of the instrument to a known radiation field similar in type, energy, and intensity to the radiation field to be measured.

Instruments Used for X-Ray Detection and Measurement

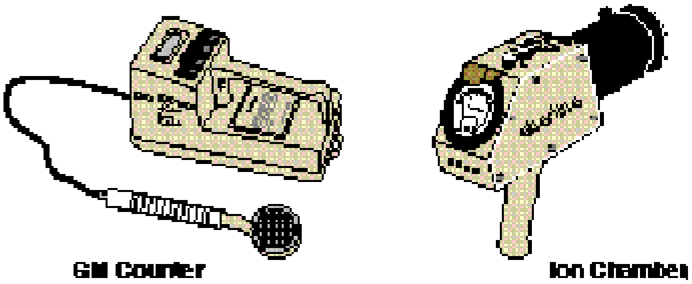

Figure 13
Detection and Measurement Instruments

X-ray device operators often use a radiation monitoring instrument for the *detection* of x-rays, for example, to verify that the device is off before entry into the area. The *measurement* of x-rays is normally the job of EHS Radiation Safety staff.

Instruments such as Geiger-Mueller (GM) counters, which count individual photons in counts per minute (cpm), are sensitive to x-rays. However, because a low-energy and a high-energy photon are both assigned one count, the GM counters tend to over respond to the low-energy photons.

Measurement of radiation dose rates and surveys of record require an instrument that reads in roentgen or rem per time (R/hour, mR/hour, rem/hour, mrem/hour). Ion chambers, which detect current instead of counting pulses, have the flattest energy response.

6.3 Personnel Monitoring Devices

Whole-Body Dosimeters

Operators of intentional x-ray devices wear whole-body and finger dosimeters such as thermoluminescent dosimeters (TLDs). TLDs can accurately measure radiation doses as low as 10 mrem and are used to assess the legal dose of record. Hazardous situations or practices that otherwise may go unnoticed can be spotted by higher-than-usual dosimeter readings.

Whole-body dosimeters should be worn so that they represent the dose to the trunk of the body. Standard practice is to wear a dosimeter between the neck and the waist, but in specific situations such as non-uniform radiation fields, special considerations may apply. Some dosimeters have a required orientation with a specific side facing out. TLD badges must be worn with the label facing outward.

Figure 14
Personnel Monitoring Device

Finger Ring Dosimeters

To monitor hand exposure to radioactive materials, TLDs in the form of finger rings are worn. Ring dosimeters should be worn on the dominant hand with the chip facing the most likely source of radiation, usually towards the inside of the hand. Finger rings should always be worn on the same finger. Always remember to wear the ring inside your glove. It is important to ensure that the chip is in place, in the dosimeter, prior to each use.

6.4 Precautions on Use of Dosimetry

The radiation dosimeter issued to you is your responsibility. The radiation doses recorded by your dosimeter become part of your occupational radiation dose record. Make sure that this record is valid and accurate by observing the following precautions:

- Always wear your dosimeter when using radioactive materials or radiation producing machines. Primary dosimeters are worn on the chest area, between the waist and the neck in a manner directed by radiological control personnel.
- The dosimeter must be stored in a safe location away from radiation sources when not in use. In each lab there is a special rack on which you can store your dosimeter.
- Do not take your dosimeter home. Excessive heat from leaving the dosimeter on the dashboard of a car will cause an erroneous reading, as will washing it with personal clothing.
- Do not wear your dosimeter at other institutions.
- Never wear someone else’s dosimeter or let someone else wear yours.
- Do not deliberately expose a dosimeter to radiation or wear your badge when receiving medical or dental x-rays.
- Do not tamper with the TLD chip or remove it from the holder.
- Avoid subjecting the badge to high temperatures or getting it wet.
- Return dosimeters for processing periodically.
- The loss of a dosimeter should be reported to EH&S as soon as the loss is noticed. Working in a radiation area without a dosimeter is a violation of federal, state, and campus regulations.

Distribution and Use of Badges

Dosimetry badges are issued by EH&S Radiation Safety based on the experimental protocols used and the type and amount of radioactivity used in the lab. Please call EH&S at x9-2553 for dosimetry needs.

Badges are exchanged quarterly. Return all radiation dosimeters promptly at the end of the quarterly rotation period so they may be processed. When you terminate your work assignment involving radiation at UCSC, please return your dosimeter(s) to the “dosimeter contact person” for your group or to EH&S on the last day of your employment.

6.5 Dosimetry Records

The radiation dosimeter is UCSC’s guide to your occupational radiation exposure. The dosimetry reporting company, an independent contractor, will report exposures per individual. Should your quarterly body dosimeter reading exceed 125 mrem or your ring exceed 1,250 mrem you will be notified and an investigation into the cause will be initiated.

All dosimetry records are on file at the Radiation Safety Office. Upon your request, we will supply you with your dosimetry history. Each year, you will receive an annual written summary of your radiation exposure even if your exposure has been zero for the entire year. Terminating personnel can request a report of the radiation dose received at UCSC. Notify the RSO of any radiation dose received at another facility so that dose records can be updated.

6.6 State Notification

The dosimeter vendor and UCSC are required by law to report to the California Department of Health Services (DHS) any personal dosimeter which shows a dose higher than the federal occupational dose limits. It is a violation of the California Radiation Control Regulations and the conditions of our Radioactive Material License to deliberately expose a personnel dosimeter to a radiation source (except when being used as intended). The dose recorded by the dosimeter will become part of the dose record of the individual to whom it was issued unless it can be proven to DHS that the individual did not actually receive the dose.

Self-Assessment

21. An x-ray device must be surveyed
    a. annually
    b. semiannually
    c. quarterly
    d. weekly

22. The sensitive instrument of choice to *detect* x-rays, in cpm, is a (an)
    a. personnel contamination monitor
    b. thin layer of ZnS scintillator
    c. thin-windowed GM counter
    d. ion chamber

23. The best instrument to *measure* the dose rate for x-rays, in mR/hour, is a (an)
    a. personnel contamination monitor
    b. thin layer of ZnS scintillator
    c. thin-windowed GM counter
    d. ion chamber

24. A TLD can measure doses as low as
    a. 0.5 mR per hour
    b. 10 mrem
    c. 10 rem
    d. 5 R per hour

7 Protective Measures

Upon completion of this chapter, you will understand about protective measures that restrict or control access to x-ray areas and devices or warn of x-ray hazards, and about work documents that provide specific procedures to ensure safe operation of x-ray devices.

Using the self-assessment, you will be able to identify

- the purpose of posting,
- the defining conditions and entry requirements for areas controlled for radiological purposes,
- the requirements for labels and warning signals,
- the requirements for fail-safe interlocks,
- the criteria for determining appropriate shielding, and
- the purpose of an RUA and SOP and when each is used.

7.1 Radiological Posting

Purpose of Posting

The two primary reasons for radiological posting are

- to inform workers of the area's radiological conditions, and
- to inform workers of the entry requirements for the area.

In order to maintain exposure to radiation ALARA, access to areas or devices in which one can receive more than 100 mrem per year is restricted.

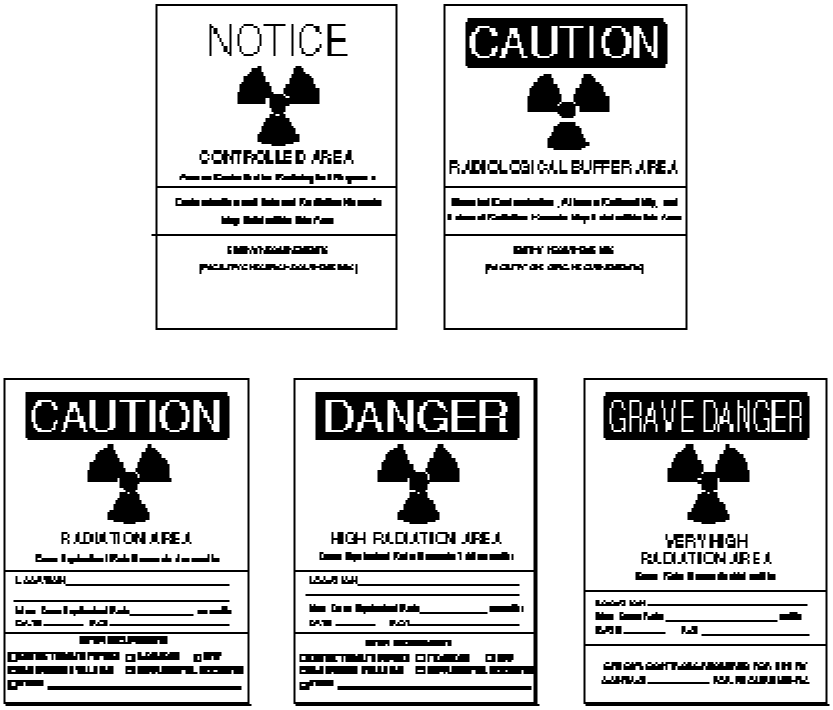

Figure 15
Radiological Postings

Posting Requirements

Areas controlled for radiological purposes must be posted with a black or magenta standard three-bladed radiological warning symbol or trefoil on a yellow background. Additionally, yellow and magenta ropes, tapes, chains, or other barriers can be used to mark the boundaries of radiological areas.

Postings and barriers must be clearly visible from all accessible directions. Postings on doors should remain visible when doors are open or closed. Postings should state the radiation dose rate and the entry requirements. If more than one radiological hazard exists in an area, the posting should identify each hazard. Postings that indicate an intermittent radiological condition should include a statement specifying when the condition exists such as; for example, when a red light is "on." The same posting requirements apply for x-ray or gamma radiation as for any other type of radiation.

7.2 Labels

The control panel of an intentional x-ray device must be labeled with the words "CAUTION—THIS EQUIPMENT PRODUCES X-RAYS WHEN ENERGIZED."

An x-ray device that has been surveyed by EH&S Radiation Safety and meets safe operating requirements displays a UCSC x-ray compliance label. A device that fails to meet all appropriate safety requirements displays a warning label indicating that the device must not be used.

An x-ray device must also display a label stating that EHS Radiation Safety (459-2553) must be notified if the machine is moved, transferred, or altered.

7.3 Warning Devices

Figure 16
Labels and Indicator Lights

Warning signals are used to alert workers to the status of the x-ray tube. Visible indicators that are activated automatically when power is available for x-ray production include

- a current meter on the x-ray device control panel,
- a warning light labeled "X-RAYS ON" near or on the x-ray device control panel,
- a warning light or rotating beacon near the x-ray device or the x-ray room door, and
- a "SHUTTER OPEN" indicator on or near the x-ray device.

Interlocks

Fail-safe interlocks are provided on doors and access panels of x-ray facilities so that x-ray production is not possible when they are open. A fail-safe interlock is designed so that any failure that can reasonably be anticipated will result in a condition in which personnel are safe.

Interlocks must be tested annually by the x-ray-device custodian for proper operation. The interlock test procedure may be locally specified, but typically is as follows:

1. Energize the x-ray tube.
2. Open each door or access panel, one at a time.
3. Observe the x-ray warning light or the meter that measures current at the control panel.
4. Record the results in a log book.

7.4 Shielding

Analytical Systems

For analytical x-ray machines such as x-ray fluorescence and diffraction systems, the manufacturer provides shielding in accordance with ANSI N43.2. However, prudent practice requires that any device or source that involves radiation should be surveyed to determine the adequacy of the shielding.

Enclosed-beam systems have sufficient shielding so that the dose rate does not exceed 0.25 mrem per hour under normal operating conditions. The dose rate may be difficult to evaluate. According to ANSI N43.2, this requirement is met if the shielding is equal to the thickness of lead specified in the table below for the maximum rated anode current and voltage.

Table 3 Shielding Requirements

Anode Current	Millimeters of Lead		
(mA)	50 kVp	70 kVp	100 kVp
20	1.5	5.6	7.7
40	1.6	5.8	7.9
80	1.6	5.9	—
160	1.7	—	—

Industrial Systems

Some industrial x-ray systems such as the cabinet x-ray systems used for airport security are completely enclosed in an interlocked and shielded cabinet. Larger systems are enclosed in a shielded room to which access is restricted. Shielding for x-ray rooms is designed to handle the most severe operating conditions of the x-ray machine. EHS Radiation Safety periodically verifies that the shielding integrity has not deteriorated or has not been compromised.

The RSO office personnel develops recommendations for shielding based on the following information:

- type of source,

- voltage or energy,
- amperage or current,
- contemplated use,
- expected workload,
- structural details of the building, and
- type of occupancy for all affected areas.

7.5 Radiation Use Authorization (RUA)

In general, RUAs are used to establish radiological controls for the conduct of radiological operations. RUAs serve to

- inform workers of area radiological conditions,
- inform workers of entry requirements for the areas, and
- provide a means to relate radiation doses to specific work activities.

Standard Operating Procedures

Each intentional x-ray device must have an SOP to ensure that the x-ray device will be operated safely and efficiently. As specified in the RSM, SOPs should include the following:

- description of the x-ray device and its intended use,
- normal x-ray parameters (peak power, current, exposure time, x-ray source-to-film distance, etc,),
- procedures for proper sample preparation, alignment, or handling of object to be radiographed,
- description of all safety hazards (electrical, mechanical, explosive, and radiation) associated with the operation of the x-ray device,
- description of the safety features (interlocks, warning signals, etc.) and any other safety precautions,
- procedures for performing interlock tests and the recommended frequency of such tests,
- required operator training and dosimetry,
- posting of signs and labels,
- x-ray-device safety checklist (items to be checked before use),
- actions to take in the event of an abnormal occurrence or emergency, and
- use of a radiation monitoring instrument upon entry into the area, as specified in ANSI N43.3 for some x-ray devices.

EHS Radiation Safety personnel review each SOP to verify that is establishes appropriate safety practices and can assist the operating groups in preparing or modifying an SOP. The current SOP must be kept near the x-ray device.

Self-Assessment

25. A primary purpose of posting radiological areas is to
    a. prevent workers from entering radiological areas
    b. inform workers of the radiological conditions
    c. allow EHS Radiation Safety personnel to measure the dose
    d. eliminate all occupational doses at UCSC

26. Whenever x-rays are on, which of the following is required?
    a. a bell must ring continuously
    b. a warning light must read “X-RAYS ON”
    c. a line manager must be in the room
    d. a EPO switch must be pressed

27. All of the following are true for x-ray interlocks, *except*
    a. they must be fail-safe
    b. they must be tested every twelve months
    c. tests must be documented
    d. they must be computer controlled

28. According to ANSI 43.2, approximately how much lead shielding is required for 70-kVp x-rays?
    a. 2 mm
    b. 6 mm
    c. 8 mm
    d. 12 mm

8 X-Ray-Generating Devices

Upon completion of this chapter, you will understand the categories of x-ray devices and the risks associated with each.

Using the self-assessment, you will be able to identify

- the difference between incidental and intentional x-ray devices,
- the types of analytical and industrial x-ray devices,
- the safety features essential for operation of analytical enclosed- and open-beam systems, and
- the safety features essential for operation of industrial cabinet, exempt shielded, shielded, unattended, and open installations.

8.1 Intentional and Incidental Devices

X-ray systems are divided into two broad categories: intentional and incidental.

An *incidental* x-ray device produces x-rays that are not wanted or used as a part of the designed purpose of the machine. Examples of incidental systems are computer monitors, televisions, electron microscopes, high-voltage electron guns, electron-beam welding machines, and electrostatic separators.

An *intentional* x-ray device is designed to generate an x-ray beam for a particular use. Intentional x-rays are typically housed within a fixed, interlocked and/or shielded enclosure or room. Examples include x-ray diffraction and fluorescence analysis systems, flash x-ray systems, medical x-ray machines, and industrial cabinet and noncabinet x-ray installations.

X-ray generating devices/facilities may also be divided into two subcategories, analytical and industrial, based upon increasing operator radiation safety hazard.

8.2 Incidental X-Ray Devices

In a research environment such as UCSC laboratories, many devices produce incidental x-rays. Any device that combines high voltage, a vacuum, and a source of electrons could, in principle, produce x-rays. For example, a television or computer monitor generates incidental x-rays, but in modern designs the intensity is low, much less than 0.5 mR per hour.

Occasionally, the hazard associated with the production of incidental x-rays is recognized only after the device has operated for some time. If you suspect an x-ray hazard, contact EHS Radiation Safety to survey the device.

Electron Microscopes

The exposure rate during any phase of operation of an electron microscope at the maximum rated continuous beam current for the maximum rated accelerating potential should not exceed 0.5 mR per hour at 2 inches (5 cm) from any accessible external surface.

8.3 Intentional Analytical X-Ray Devices

Analytical X-Ray Devices

Analytical x-ray devices use x-rays for diffraction or fluorescence experiments as research tools, especially in materials science. ANSI N43.2 defines two types of analytical x-ray systems: enclosed beam and open beam.

Safety requirements and features for analytical systems include the following:

- control panel labels with the words "CAUTION—THIS EQUIPMENT PRODUCES X-RAYS WHEN ENERGIZED,"
- fail-safe lights with the words "X-RAYS ON" near x-ray tube housings,
- fail-safe indicators with the words "SHUTTER OPEN" for beam shutters,
- fail-safe interlocks on access doors and panels,
- beam stops or other barriers, and
- appropriate shielding.

Enclosed-Beam System

In an enclosed-beam system, all possible x-ray paths (primary and diffracted) are completely enclosed so that no part of a human body can be exposed to the beam during normal operation. Because it is safer, the enclosed-beam system should be selected over the open-beam system whenever possible.

The x-ray tube, sample, detector, and analyzing crystal (if used) must be enclosed in a chamber or coupled chambers. The sample chamber must have a shutter or a fail-safe interlock so that no part of the body can enter the chamber during normal operation.

The dose rate measured at 2 inches (5 cm) from the outer surface of the sample chamber must not exceed 0.25 mrem per hour during normal operation.

Open-Beam System

In an open-beam system, one or more x-ray beams are not enclosed, making exposure of human body parts possible during normal operation. The open-beam system is acceptable for use only if an enclosed-beam system is impractical for any of the following reasons:

- a need for making adjustments with the x-ray beam energized,
- a need for frequent changes of attachments and configurations,
- motion of specimen and detector over wide angular limits, or
- the examination of large or bulky samples.

An open-beam x-ray system must have a guard or interlock to prevent entry of any part of the body into the primary beam. Each port of the x-ray tube housing must have a beam shutter with a conspicuous shutter-open indicator of fail-safe design.

The dose rate at 2 inches (5 cm) from the surface of the source housing must not exceed 2.5 mrem per hour during normal operation.

8.4 Intentional Industrial X-Ray Devices

Industrial X-Ray Devices

Industrial x-ray devices are used for radiography; for example, to take pictures of the inside of an object as in a medical chest x-ray or to measure the thickness of material. ANSI N43.3 defines three classes of industrial x-ray installations: cabinet, exempt shielded, and shielded.

Safety requirements and features for industrial installations depend on the magnitude of the hazard. Safety features include some or all of the following:

- area postings,
- control panel caution labels,
- surveillance,
- barriers or enclosures,
- appropriate shielding,
- fail-safe interlocks,
- visible warning signals such as a rotating beacon,
- audible warning signals, 20 seconds before the x-rays are energized and if an interlock is broken, and
- EPO switches to de-energize x-rays in an emergency.

Cabinet X-Ray Installation

A cabinet x-ray installation is similar in principle to the analytical enclosed-beam system. The x-ray tube is installed in an enclosure (cabinet) that contains the object being irradiated, provides shielding, and excludes individuals from its interior during x-ray production. An example is the x-ray device used to inspect carry-on baggage at airline terminals. Certified cabinet x-ray systems comply with the requirements of 21 CFR 1020.40.

The low allowable dose rate of 0.5 mrem per hour at 2 inches (5 cm) from the outside surface of the enclosure for this class of installation necessitates a higher degree of inherent shielding.

The inherent safety of the cabinet x-ray system makes installation possible in a non-controlled area.

Exempt Shielded Installation

An exempt shielded installation is similar to the cabinet x-ray installation. In an exempt shielded installation the source of radiation and all objects exposed to that source are within an enclosure that excludes individuals from its interior.

The low allowable dose rate of 0.5 mrem per hour at 2 inches (5 cm) from the outside surface of the enclosure for this class of installation necessitates a higher degree of inherent shielding.

An exempt shielded installation does not require occupancy restrictions because inherent shielding is sufficient.

Shielded Installation

A shielded installation, in which the source of radiation and all objects exposed to that source are within an enclosure, has less shielding than an exempt shielded installation. This is a cost advantage for fixed installations, particularly for high-energy sources where the reduction in shielding may result in significant savings. However, there is more reliance on protective measures such as warning lights, posting, and procedures.

If the enclosure is large enough to permit entry and exit of workers, visible and audible warning signals are required. Interlocks are required to prevent access to the enclosure during x-ray production. An EPO switch and a suitable means of exit are required so that any worker who inadvertently remains in the enclosure may leave immediately.

The entrance to an exposure room must be posted to alert workers that they are entering an exposure room. The inside of an exposure room must be posted according to the radiation level in the enclosure. Occupancy restrictions may be required.

8.5 Summary of X-Ray Devices

The following table summarizes the types of x-ray devices recognized by ANSI and UCSC. For enclosed beam, exempt shielded, and cabinet systems, the access is controlled by enclosing the device within a shielded room, enclosure, or cabinet. The other systems can have potentially hazardous dose rates outside the system housing, so access must be controlled by a combination of interlocked doors, posting, warning lights, and procedures.

Table 4 Summary of X-Ray Device

Category of Installation	Type of X-Ray Device	Maximum Dose Rate	Access Control
analytical	enclosed beam	0.25 mrem/hour	chamber
	open beam	2.5 mrem/hour	beam guard
industrial	Cabinet	0.5 mrem/hour	cabinet
	exempt shielded	0.5 mrem/hour	cabinet
	Shielded	as posted	interlock

Self-Assessment

29. An x-ray beam that is purposely generated for a particular use is a (an) ______ system.

    a. intentional
    b. incidental
    c. open
    d. closed

30. Which of the following is classified as an analytical x-ray system?

    a. x-ray diffraction unit
    b. cabinet x-ray unit
    c. industrial x-ray unit
    d. hot covered

31. An analytical x-ray system in which all possible x-ray paths are confined within a shielded chamber with interlocks is called a (an) ______ beam.

    a. shielded
    b. enclosed
    c. collimated
    d. controlled

32. The external radiation from a cabinet or an exempt-shielded x-ray installation must not exceed

    a. 0.5 mrem per hour at 1 ft
    b. 0.5 mrem per hour at 2 in.
    c. 5 mrem per hour at 1 ft
    d. 5 mrem per hour at 2 in.

33. Generally, x-ray systems require all of the following, *except*

    a. warning lights
    b. shielding
    c. weekly surveys
    d. interlocks

9 Responsibility for X-Ray Safety

Upon completion of this chapter, you will understand who is responsible for implementing x-ray safety policies and procedures and what their specific responsibilities are.

Using the self-assessment, you will be able to identify:

- the responsibilities of EH&S Radiation Safety,
- the responsibilities of the Radiation Principal Investigator regarding x-ray safety, and
- the responsibilities of x-ray-device operators.

9.1 Responsibilities

The responsibility for maintaining exposures from x-rays ALARA is shared among EH&S Radiation Safety, the x-ray-device PI, and x-ray-device operators.

EHS Radiation Safety

The EHS Radiation Safety Department is responsible for:

- establishing requirements and standards,
- offering consulting services and training,
- approving all purchases, moves, transfers, and alterations of x-ray equipment,
- surveying x-ray equipment, verifying that the appropriate safety program requirements have been met, and affixing UCSC compliance labels to the devices, and
- issuing variances for devices that do not meet one or more of the requirements specified in the radiation safety manual, if safety is achieved through alternative means or if the function could not be performed if the device met the requirements.

Radiation Principal Investigator (RPI)

The RPI is responsible for specific x-ray-generating machines. Their duties include:

- preparing SOPs for their x-ray devices,
- ensuring that operators know and follow the SOPs,
- registering new electron microscopes, intentional x-ray devices, and new x-ray tube assemblies or source housings with EHS Radiation Safety,
- making arrangements for operator training,
- maintaining a list of qualified operators authorized for particular machines,
- documenting that operators have read the appropriate SOPs,
- posting an authorized operator list near the control panel of each x-ray device,
- checking enclosure door safety interlocks every six months to ensure proper functioning and recording results on an interlock test log posted on or near the control panel,

- contacting EHS Radiation Safety when a device is due for resurveying and before performing any repair, maintenance, and/or non-routine work that could cause exposure of any portion of the body to the primary beam, and
- meeting all requirements of the UCSC Radiation Safety Manual and Laboratory Safety Guide.

X-Ray-Generating Device Operators

Authorized x-ray-device operators are responsible for:

- wearing a TLD and other appropriate dosimetry,
- knowing and following the SOP for each machine operated,
- knowing and following the operator safety checklist,
- notifying their supervisors of any unsafe or hazardous work situations, and
- before reaching into the primary beam, verifying that the beam shutter is closed or that machine power is off.

Self-Assessment

34. Who is responsible for surveying x-ray devices at UCSC?
    a. EHS Radiation Safety
    b. x-ray device PI
    c. x-ray device operator
    d. none of the above

35. Who is responsible for ensuring that SOPs are prepared for x-ray devices?
    a. EHS Radiation Safety
    b. x-ray device PI
    c. x-ray operator
    d. x-ray-device operator

36. Who is responsible for checking x-ray-device interlocks?
    a. The x-ray device manufacturer
    b. EHS Radiation Safety
    c. x-ray device PI
    d. x-ray device operator

37. Who should be most familiar with the SOP for a particular x-ray device?
    a. Department Chair
    b. EHS Radiation Safety
    c. x-ray device PI
    d. x-ray-device operator

A Acronyms and Abbreviations

ANSI	American National Standards Institute
ALARA	As Low As Reasonably Achievable. The operational radiation protection philosophy of keeping radiation dose as far below the occupational dose limits and administrative control levels as is reasonably achievable so that there is no radiation exposure without commensurate benefit based on sound economic principles.
CFR	Code of Federal Regulations
DHS	Department of Health Services
EHS	Environmental Health and Safety (Department)
EPO	Emergency Panic Off switch
GM	Geiger-Mueller (counter)
LNT	Linear, NonThreshold (hypothesis)
NRC	Nuclear Regulatory Commission
RSM	Radiation Safety Manual
RUA	Radiation Use Authorization. A document that at a minimum defines the work, identifies the hazards associated with the work, and describes the controls needed to reduce the risk posed by the work to an acceptable level.
SOP	Standard Operating Procedure
TLD	Thermoluminescent Dosimeter
XGF	X-ray Generating Facility
UCSC	University of California, Santa Cruz

B Glossary

absorbed dose. The energy imparted to matter by ionizing radiation per unit mass of irradiated material. The unit of absorbed dose is the rad.

accelerator. A device employing an electrostatic or electromagnetic field to impart kinetic energy to charged molecular, atomic, or subatomic particles. It discharges the resultant particulate or other radiation into another medium and creates a radiological area, due to direct, prompt (beam on) particles or beam radiation *and* indirect, induced (beam off) radioactivity from beam interactions with targets and device components. Significant portions of the whole body (as opposed to the extremities) could be exposed.

Examples include linear accelerators (LINACs), cyclotrons, synchrotrons, synchrocyclotrons, free-electron lasers (FELs), and ion LINACs. Single and tandem Van de Graaff generators, when used to accelerate charged particles *other than electrons*, are also considered accelerators.

Specifically *excluded* from this definition are devices that accelerate electrons for the sole purpose of producing x-rays, miscellaneous electronic devices that produce ionizing radiation as an incidental byproduct of their primary function; machines that are incapable of extracting the beam to a target other than to an x-ray production target and/or that do not produce enough neutrons to cause target activation sufficient to create a radiological area in areas normally occupied by operating personnel.

analytical x-ray device. A type of intentional x-ray device consisting of local and remote components that use intentionally produced x-rays to evaluate, typically through x-ray diffraction or fluorescence, the phase state, surface characteristics, and/or elemental composition of various materials. Local components include those that are struck by x-rays, such as the x-ray source housing, beam ports, shutter assemblies, collimators, sample holders, cameras, goniometers, detectors, and shielding. Remote components include power supplies, transformers, amplifiers, readout devices, and control panels.

as low as reasonably achievable (ALARA). The operational radiation protection philosophy of keeping radiation dose as far below the occupational dose limits and administrative control levels as is reasonably achievable so that there is no radiation exposure without commensurate benefit based on sound economic principles.

bremsstrahlung. The electromagnetic radiation emitted when an electrically charged subatomic particle such as an electron loses energy upon being decelerated and deflected by the electric field surrounding an atomic nucleus. In German, the term means *braking radiation.*

cabinet x-ray device. A type of intentional x-ray device where the x-ray tube is installed in an enclosure (cabinet) which, independent of existing architectural structures except the floor upon which it may be placed, is intended to contain at least that portion of a material being irradiated, provide radiation attenuation, and exclude individuals from its interior during x-ray generation. Included are all x-ray devices designed primarily for the inspection of carry-on baggage at airline, railroad, and bus terminals or similar x-ray devices used to radiologically inspect items prior to entry into a nuclear facility. X-ray devices using a building wall for shielding and those using portable shields on a temporary basis are excluded from this definition.

Cabinet x-ray devices are certified as such by the Food and Drug Administration under 21 CFR 1020.40.

compliance label. A UCSC label affixed to an intentional x-ray device certifying that the device has been surveyed and that safe operating requirements have been met.

control panel. A device containing the means for regulating and activating x-ray equipment or for preselecting and indicating operating factors.

controlled area. Any area to which access is managed to protect individuals from exposure to radiation and/or radioactive material and which is under the supervision of a person who has knowledge of the appropriate radiation protection practices, including pertinent regulations, and who has responsibility for applying them. Individuals who enter only the Controlled Area, without entering radiological areas, are not expected to receive a total dose equivalent of more than 100 mrem (0.001 sievert) in a year.

door. In this context, any barrier that is designed to be moved or opened for routine operation purposes, does not generally require tools to open, and permits access to the interior of the cabinet.

dose equivalent. The product of absorbed dose, the quality factor, and any other modifying factors necessary to express, on a common scale for all ionizing radiations, the dose incurred by exposed persons. The unit of dose equivalent is the rem. (In tissue and for radiation protection purposes, the dose equivalent in rem may be considered numerically equivalent to the absorbed dose in rad or the exposure in roentgen.)

dosimeter. A device that measures and indicates radiation dose.

EHS Radiation Safety. An EHS program area that establishes x-ray-device program requirements and standards, provides x-ray-device radiation protection consultation, and serves as the central UCSC point of contact for the management/control of x-ray devices as mandated by the UC.

electron volt (eV). A unit of energy equal to the energy gained by an electron passing through a potential difference of 1 volt.

emergency off switch. See “EPO button,” below

Emergency Panic Off (EPO) button. An electromechanical device, installed within an x-ray facility exposure room/enclosure in and out of which workers enter in the course of x-ray operations, that when manually depressed/activated, prevents or interrupts the production of x-rays from the x-ray device. EPO buttons are wired to the x-ray device control panel in such a manner that x-ray production cannot be resumed unless the EPO button is reset, e.g., depressed EPO button manually pulled back out to the “on” position, and x-ray exposure procedures reinitiated at the x-ray device control panel. The safety function of a EPO button is to prevent the x-ray device from producing x-rays in order to permit the rapid egress of workers located inside the x-ray exposure room/enclosure to a safe location outside of the room/enclosure, basically the opposite safety function of an interlock.

enclosed-beam analytical x-ray device. An analytical x-ray device in which all possible x-ray paths (primary as well as diffracted beams) are fully enclosed and which meets the radiation safety requirements specified in ANSI N43.2.

exempt shielded intentional XGF installation. An intentional XGF that meets the radiation safety requirements specified in ANSI N42.3. Such installations provide such a high degree of protective shielding to the operator that individual dosimetry is generally not necessary.

exposure. A measure of the ionization produced in air by x-ray or gamma radiation. It is the sum of the electrical charges of all of the ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in the air, divided by the mass of the air in the volume element. The unit of exposure is the roentgen (R).

external surface. An outside surface of a cabinet x-ray system, including the high-voltage generator, doors, access panels, latches, control knobs, and other permanently mounted hardware and including the plane across any aperture or port.

fail-safe design. A device design in which all credible failure modes of x-ray system indicator or radiation safety components results in a condition in which individuals are intrinsically safe from exposure to x-rays. Such a design may cause beam port shutters to close, primary transformer electrical power to be interrupted, or otherwise prevent the production of x-rays upon failure of the safety or warning device.

flash x-ray unit. A radiation-producing device that can produce nanosecond bursts of high-intensity x-rays.

fluorescence analysis. Analysis of characteristic x-rays and the x-ray emission process.

half-value layer (HVL). The thickness of a specified substance that, when introduced into a beam of radiation, reduces the exposure rate by one-half.

high radiation area. Any area, accessible to individuals, in which radiation levels could result in a deep dose equivalent in excess of 0.1 rem in one hour at 30 cm from the source or from any surface that the radiation penetrates.

incidental x-ray device. An x-ray device that emits or produces x-rays during its normal operation where the x-rays are an unwanted byproduct of the device's intended purpose. The x-rays are produced only when electrons are accelerated under vacuum, are not put to any constructive use in a particular application, and are not intentionally conveyed beyond the contiguous vacuum in which they are produced.

installation. A radiation source, with its associated equipment, and the space in which it is located.

installation enclosure. The portion of an x-ray installation that clearly defines the transition from a non-controlled to a controlled area and provides such shielding as may be required to limit the dose rate in the non-controlled area during normal operations.

intentional x-ray device. A category of x-ray device, typically housed within a fixed, interlocked, and/or shielded enclosure/room, specifically designed to intentionally produce and convey beyond the vacuum surrounding the electron acceleration chamber ionizing bremsstrahlung and/or characteristic x-ray radiation that is then used for purposes of imaging, analysis, or research for which such radiation is essential to the process.

interlock. A device for precluding access to a radiation hazard area either by preventing entry or by automatically removing the hazard when the device is actuated. The safety function of an interlock is to prevent personnel access from outside to the inside of a radiation exposure room/enclosure when x-rays are being generated.

ion. An atomic particle, atom, or chemical radical bearing an electric charge, either negative or positive.

ionizing radiation. Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter, including gamma and x-rays and alpha, beta, and neutron particles.

UCSC-owned x-ray device. X-ray devices owned by UCSC that do *not* have to be licensed/authorized by the state of New Mexico Office of Radiological Control.

lead equivalent. The thickness of lead affording the same attenuation, under specific conditions, as the material in use.

leakage radiation. Any radiation, except the useful beam, coming from the x-ray assembly or sealed source housing.

maximum permissible dose equivalent (MPDE). The maximum dose equivalent that the body of a person or specific parts thereof shall be permitted to receive in a stated period of time.

medical x-ray system. An x-ray system for medical use, generally categorized as either diagnostic or therapeutic. Diagnostic x-ray procedures are used to obtain images of body parts; therapeutic x-ray procedures are used to treat malignancies.

normal operation. Operation under conditions suitable for collecting data as recommended by the manufacturer of an x-ray system. Recommended shielding and interlocks shall be in place and operable.

open-beam intentional x-ray device. An analytical x-ray device that has one or more x-ray paths (primary or diffracted beams) not fully enclosed and which meets the radiation safety requirements specified in ANSI N43.2.

primary beam. The x-radiation emitted directly from the target and passing through the window of the x-ray tube.

primary radiation. Radiation coming directly from the target of the x-ray tube or from the sealed source.

rad (radiation absorbed dose). The unit of absorbed dose. A rad is 100 ergs of absorbed energy per gram of absorbing material. It is a measure of the energy imparted to matter (i.e., retained by matter) by ionizing radiation per unit mass of irradiated material at the place of interest.

radiation area. Any area, accessible to individuals, in which radiation levels could result in a deep dose equivalent in excess of 0.005 rem in one hour at 30 cm from the source or from any surface that the radiation penetrates.

radiation-producing device. A device with a reasonable potential to expose an individual to significantly hazardous levels of ionizing radiation. Specifically excluded are exempt-shielded devices, as defined by ANSI N43.3, and devices that do not have a reasonable potential to expose an individual to more than 100 mrem per year of whole-body dose, or 1 rem per year extremity dose.

radiation protection survey. An evaluation of the radiation hazard potential in and around an x-ray installation. It customarily includes a physical survey of the arrangement and use of the equipment and measurements of the exposure rates under expected or routine equipment operating conditions.

radiation source. A device or a material that is capable of emitting ionizing radiation.

radiation area. Any area within a controlled area which must be posted as a "radiation area," "high radiation area," "very high radiation area," "contamination area," "high contamination area," or "airborne radioactivity area" in accordance with 10 CFR 20.

radiological worker. A general employee whose job assignment involves operating radiation-producing devices or working with radioactive materials, or who is likely to be routinely occupationally exposed above 0.1 rem per year total effective dose equivalent.

rem (roentgen equivalent man). The unit of dose equivalence used to measure human exposures, which considers the biological effects of different types of radiation. The dose equivalent in rem is numerically equal to the absorbed dose in rad multiplied by the quality factor and any other necessary modifying factors.

roentgen (R). The unit of exposure that applies only to electromagnetic radiation (x-rays and gamma radiation). An exposure of 1R corresponds to an absorption of 87.7 ergs per gram of air or to a dose to the air of 0.877 rads. One roentgen equals 2.58 x 10^{-4} coulomb per kilogram of air.

scattered radiation. Radiation that has been deviated in direction as a result of interaction with matter and has usually been reduced in energy.

secondary radiation. Radiation (electrons, x-rays, gamma rays, or neutrons) produced by the interaction of primary radiation with matter.

shield or shielding. Attenuating material used to reduce exposure of personnel to radiation.

shielded intentional installation. An intentional installation that meets the radiation safety requirements specified in ANSI N43.3. Such installations typically provide a moderate degree of protective shielding to the operator, but the operator typically sustains sufficient annual dose to require individual dosimetry.

skyshine. Radiation emerging from a shielded enclosure which then scatters off air molecules to increase radiation levels at some distance from the outside of the shield.

subcontractor-owned x-ray device. X-ray devices owned and possessed under an authorization issued to the subcontractor by an NRC Agreement State, such as New Mexico, or by the Office of Radiological Control of a non-agreement state.

system barrier. The portion of an x-ray installation that clearly defines the transition from a Controlled Area to a Radiation Area and provides such shielding as may be required to limit the dose rate in the Controlled Area during normal operation.

tenth-value layer (TVL). The thickness of a specified substance that, when introduced into a beam of radiation, reduces the exposure rate to one-tenth of the original value. One TVL is equivalent to 3.3 HVLs.

units. Systeme Internationale (SI) units used for quantities that are not unique to ionizing radiation measurements such as energy per unit mass, that is, joules/kilogram; 1 J/kg = 1 gray. Conventional special radiation units are units used for quantities unique to ionizing radiation measurement such as the rad, rem, and roentgen. To convert conventional radiation units to SI units, the following factors are used:

1 rad = 0.01 gray (Gy)

1 rem = 0.01 sievert (Sv)

1 roentgen (R) = 2.58×10^{-4} coulomb per kilogram of air

warning label. A UCSC label affixed to the x-ray device warning that the device must not be used.

workload. A measure, in suitable units, of the amount of use of radiation equipment. For the purpose of this document, the workload is expressed in milliampere-minutes per week for x-ray sources, and roentgens per week at 1 meter from the source for gamma-ray sources and high-energy equipment (such as linear accelerators, betatrons, etc.).

X-Ray Device custodian. A person trained and authorized by the operating group PI responsible for the safe use and control of the x-ray devices owned by that group. An x-ray device custodian may also be an x-ray device operator.

X-ray device operator. An individual authorized by the custodian and qualified by training and experience to operate specific x-ray devices.

x-ray diffraction. The scattering of x-rays by matter with accompanying variation in intensity in different directions due to interference effects.

x-ray installation. One or more x-ray systems, the surrounding room or controlled area, and the installation enclosure.

x-ray power supply. The portion of an x-ray device that generates the accelerating voltage and current for the x-ray tube.

x-ray system. An assemblage of components for the controlled generation of x-rays.

x-ray tube. An electron tube that is designed for the conversion of electrical energy to x-ray energy.

C Incidents and Lessons Learned

On April 4, 1974, a worker (worker A) who had been repairing an x-ray spectrometer noticed redness, thickening, and blisters on both hands. At the medical center, the doctors tried nonspecific anti-inflammatory measures, without effect. Later that month, two coworkers (workers B and C) noticed similar skin changes, and the true nature of the problem became evident.

On March 21, March 29, April 2, and April 4, the three workers had been working to repair a 40-kV, 30-mA x-ray spectrometer. In the absence of the usual repair people, the three workers were not aware that the warning light was not operating and that the device was generating x-rays estimated at 100 R/min. During the work, all three had received doses of >1,000 R to their hands.

By May 9, the acute reactions had largely subsided, but worker A developed a shallow necrotic ulcer on the right index finger and another on the left ring finger. Over the next few weeks, the ulcer on the left ring finger gradually healed, but the right index finger became increasingly painful. In June, three months after the x-ray exposure, the ulcer began to spread, extending up the finger toward the knuckle. On July 19, the finger was amputated. In August, a painful ulcer developed on the left middle finger. Surgery was performed to sever some nerves, and the finger healed satisfactorily after a few weeks.

Worker B received a much smaller dose than worker A. Blisters formed during April and completely healed during May. When last seen, four years after the x-ray exposure, some abnormalities were still apparent but without any long-term disability.

Worker C was exposed only on April 4. On April 17, he felt a burning pain and noticed redness on the fingers of both hands. By May 20, these injuries appeared to heal, leaving no apparent disability. However, in November, a minor injury to his left hand developed into an ulcer that appeared to be like the ulcers on patient A. Worker C's ulcer healed in December without requiring surgery.

In a separate accident on July 26, 1994, a 23-year-old engineer was repairing a 40-kV, 70-mA x-ray spectrometer. He removed several panels and inserted his hand for 5–6 seconds at a distance 6-8 cm from the x-ray tube, before realizing that he had failed to de-energize the device.

The engineer recalled having a sensation of tingling and itching in his fingers the day after the accident. A pinching sensation, swelling, and redness were present between days four and seven. By day seven, a large blister was developing, in addition to increased swelling and redness. One month after the accident, the entire hand was discolored, painful, and extremely sensitive to the slightest touch. Blood circulation to the entire hand was low, especially to the index and middle fingers. Surgery was performed to sever the sympathetic nerve to allow the constricted blood vessels to dilate, and a skin graft was sutured in place. One month later, the hand had returned to a normal color and the skin graft was adherent.

In July 1995, one year after the accident, his index finger started to itch and turn black with necrosis or gangrene. As a result, his finger was amputated.

Lessons Learned

- No pain was felt at the time of the x-ray exposure, but considerable pain was felt later. The injuries took months to heal. In two cases, the injuries resulted in permanent disability.
- The warning light was not fail-safe. Warning lights must be designed in such a manner that light failure results in cessation of x-ray production.
- The workers were not authorized or trained to repair the equipment. They did not analyze the hazards or develop controls before doing the work. There was no procedure and no SOP.
- The workers did not unplug or lockout and tagout the equipment.

D

Answers to Study Questions

1. d
2. c
3. b
4. b
5. c
6. b
7. d
8. b
9. d
10. a
11. c
12. c
13. a
14. a
15. c
16. d
17. b
18. e
19. c
20. c
21. a
22. c
23. d
24. b
25. b
26. b
27. d
28. b
29. a
30. a
31. b
32. b
33. c
34. a
35. b
36. b
37. d