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University of Arizona
Radiation Generating Machine Protection Reference Guide

Research Laboratory & Safety Services
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Research Laboratory & Safety Services (RLSS) is the primary coordinating unit responsible for the radiation safety program at the University of Arizona. The Radiation Generating Machine Protection Reference Guide is maintained at RLSS at 1717 E Speedway Blvd, Suite 1201, Tucson, AZ, and is readily available to anyone via the RLSS website (rlss.arizona.edu).

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Tables and Figures

I. Introduction

The Radiation Generating Machines Reference Guide serves to describe the Radiation Generating Machines program at The University of Arizona (UA) and to provide information regarding the safe use of radiation generating machines and ionizing radiation. The term “radiation generating machine” includes, but is not limited to, x-ray fluorescence, x-ray diffraction, cabinet radiography, accelerators, x-ray spectrometers, and medical radiography units used in non-human research. Other machines may qualify depending on the planned use of the radiation that is produced. The responsibilities of the UA Research Laboratory & Safety Services (RLSS), Approval Holders, Radiation Safety Coordinators and Radiation Workers are also described.

The program is intended to:

- Provide a basic introduction to radioactive materials and the hazards associated with their use;
- Provide guidance to Approval Holders and workers authorized under their approvals;
- Provide instruction on the safe use, transfer, and disposal of radiation generating machines and ionizing radiation;
- Maintain regulatory compliance with applicable state and federal regulations, and
- Inform Approval Holders of the resources available to them through the Research Laboratory & Safety Services (RLSS).

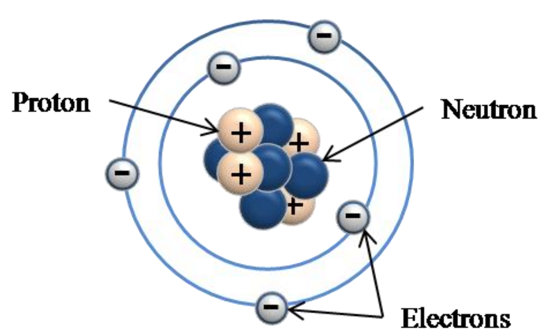
All personnel working with radiation generating machines must complete the Radiation Generating Machines Protection Course prior to use of these machines. Course materials and schedules are available on the RLSS website. Approval Holders and Radiation Safety Coordinators must also complete an Approval Holder Orientation (provided by RLSS personnel).

II. Physics

A. Atomic Structure

The basic unit of matter is the atom. The basic atomic model, as described by Ernest Rutherford and Niels Bohr in 1913, consists of a positively charged core surrounded by negatively-charged shells (see Figure 1). The central core, called the nucleus, is held together by nuclear forces.

Figure 1: Atomic Structure



Protons (p+) are positively charged particles and neutrons (n) are uncharged particles; both are located in the nucleus of the atom. Electrons (e-) are negatively charged particles that travel in structured orbits, or energy shells, around the nucleus.

An atom is electrically neutral if the total electron charge equals the total proton charge. The term ion is used to define atoms or groups of atoms that have either a positive or negative electrical charge. Isotopes are forms of an element that have the same number of protons, but different numbers of neutrons.

B. Ionizing Radiation

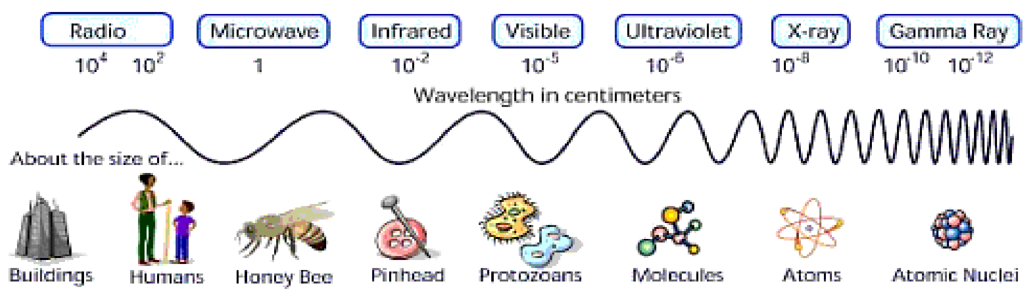
Radiation is the transfer of energy, in the form of particles or waves, through open space. Radiation with sufficient energy to create ions by physically removing electrons from neutral atoms is referred to as ionizing radiation. Ionizing radiation includes alpha particles, beta particles, electromagnetic waves, and neutrons. Radiation that lacks the energy to cause ionization is referred to as non-ionizing radiation. Examples of non-ionizing radiation include radio waves, lasers, microwaves, and visible light. The following are four main categories of ionizing radiation.

1. **Alpha Particles**
The alpha particle is similar to a helium nucleus, comprised of two protons and two neutrons (without surrounding electrons). Alpha particles are heavier and generally more energetic compared to other common types of radiation; however, typical alpha particles travel less than a few inches in air and are stopped by a sheet of paper or the outermost layer of dead cells which protect the skin.

2. **Beta Particles**
Beta particles are charged particles that come in positive and negative forms. When an unstable atom converts a surplus neutron in the nucleus to a proton, it emits an electron. When an unstable atom converts a surplus proton in the nucleus to a neutron, it emits a positive electron (or positron). Positrons, such as those emitted by ^{18}F, interact with electrons, destroying both and yielding energy (annihilation radiation). That interaction represents a conversion of mass to radiant electromagnetic energy, which can be harmful if not properly controlled. A beta particle has less mass and less charge than an alpha particle, which allows it to travel farther in air, deeper into skin, and through thin shielding and clothing.

3. **Electromagnetic Waves: Gamma Rays (Gammas) and X-Rays**
Gamma and x-rays differ only in their origin. Gammas originate from an unstable atomic nucleus and x-rays originate from accelerated electrons interacting with matter. Unlike alpha and beta particles, gammas and x-rays penetrate deeply into objects because they do not interact as readily with matter. This is due to their extremely small mass and lack of charge. Both are electromagnetic radiation and differ from radio waves and visible light in that they have a much shorter wavelength, higher frequency and higher energy (see Figure 2).

Figure 2: Comparison of Wavelengths



Radiation generating machines produce x-rays through two processes, bremsstrahlung and the production of characteristic x-rays.

a. Bremsstrahlung X-Rays
When negatively charged electrons come into proximity to positively charged atoms, some of the electrons are rapidly deflected from their original trajectory (path) because of electromagnetic attraction to each other. This deflection causes the energy of the electron to rapidly decrease; this sudden decrease in energy emits bremsstrahlung (meaning, 'braking radiation' in German). The energy of a bremsstrahlung x-ray depends on how great the electrons' original trajectory was changed, with a greater change in the acceleration resulting in a higher energy x-ray.

b. Characteristic X-Rays

Characteristic x-rays can be produced when an accelerated electron interacts with an inner shell electron instead of an outer shell electron. The interaction must be strong enough to ionize the atom by the total removal of the inner shell electron. The atom is then in an unstable state due to the temporary electron hole in the K-shell (the shell closest to the nucleus); this is corrected when an outer shell electron falls into the hole in the K-shell. The energy of the resulting x-ray photon is characteristic to the target material used to produce the x-rays and equals the difference between the binding energy of the K-shell electron and the binding energy of the electron that falls into the K-shell.

4. Neutrons

Neutrons are nuclear particles that have an exceptional ability to penetrate other materials. Of the types of ionizing radiation discussed here, neutrons are the only ones that can make objects radioactive. This process, called neutron activation, produces many of the radioactive sources that are used in medical, academic, and industrial applications (including oil exploration).

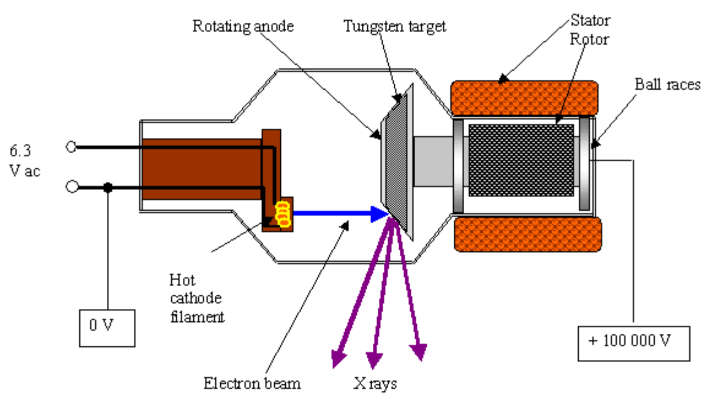
Because of their exceptional ability to penetrate other materials, neutrons can travel great distances in air and require very thick hydrogen-containing materials (such as paraffin or water) to absorb them. Neutron radiation primarily occurs inside a nuclear reactor, where many feet of water provide effective shielding.

C. Radiation Generating Machines

1. Production of X-Rays

X-rays are penetrating electromagnetic radiations that occur when accelerated electrons interact with matter. X-rays are produced when charged particles, usually electrons, are accelerated by an

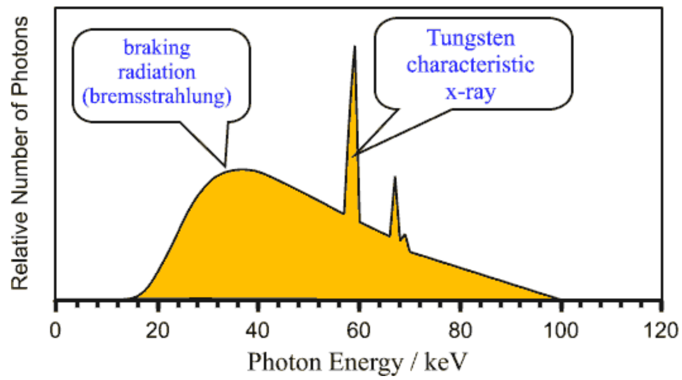
Figure 3: X-Ray Tube



electrical voltage (potential difference). Whenever a high voltage potential, a vacuum, and a source of electrons are present in any scientific device, x-rays can be produced by accelerating electrons through an electric voltage potential and stopping them with a target (such as a heavy metal target called an anode). X-ray tubes may differ in configuration, but the method of producing x-rays is the same. A typical X-ray tube consists of an evacuated envelope, an anode, and a cathode (see Figure 3).

A typical x-ray spectrum generated with a tungsten target and consisting of the bremmstrahlung and characteristic x-rays is shown below (see Figure 4).

Figure 4: Composite X-Ray Spectrum



a. The Cathode
The cathode (filament) is the negative terminal of the x-ray tube. Electrons are produced at the cathode when a high current flows through it and heats it. Adjusting the amount of current through the filament controls the number of electrons produced. Tube current is the number of electrons traveling from the cathode to the anode per second, is measured in amperes, and is expressed in milliamps (mA) or microamps (μA). The product of the tube current and the number of seconds that the current flows is expressed in milliampere-second (mAs). The mAs value determines the total amount of x-rays that are generated during an exposure.

b. The Anode
The anode is the positive terminal of the x-ray tube. The anode material determines the x-ray energy that will be produced; clinical diagnostic units utilize a thin layer of tungsten embedded in copper, while analytical units typically use copper, chromium or cobalt. To produce x-rays, electrons are accelerated from the cathode to the anode by a high voltage potential. The potential difference is measured in kilovolts (kV) and, since the voltage may fluctuate across the tube, it is usually expressed as peak voltage (kVp). The peak voltage limits the maximum energy of the photons produced. Most of the kinetic energy of the accelerated electrons is converted to thermal energy (heat), leaving less than 1% available for the production of x-rays.

c. The Envelope
The envelope is the container in which the cathode and anode are sealed. Since x-ray production occurs in a vacuum, the sealed container allows for gases and other impurities to be removed, creating the necessary vacuum.

2. Power

The power of a radiation generating machine is measured in watts (W) and equals voltage (V) times current (I), thus P = V*I. For example a 10 kVp device with a current of 1 mA emits 10 W of power.

3. Safety Devices and Other Protective Measures

Most modern enclosed radiation-producing machines are equipped with safety devices to prevent accidental exposure to ionizing radiation. Safety devices include warning lights and interlocks. Bypassing of, or modifications to, these safety devices may not be made without prior approval from RLSS.

a. Warning Lights

The warning lights must be labeled so that their purpose is easily identified. The following warning lights are required when applicable to the individual device:

- X-ray tube status (On-Off) indicator;
- Shutter status (Open-Closed) indicators; and
- X-RAY ON" warning light or a similar warning located near any switch that energizes an x-ray tube, which lights up only when the tube is energized.

b. Interlocks

Interlocks are defined as mechanical devices that prevent a component from functioning when another component is functioning or in a certain position. In the context of radiation machine use, this means that an enclosure switch must be closed or a warning light operating before the machine can begin to produce x-rays or continue to produce x-rays.

Shutter mechanisms and interlocks must not be tampered with or defeated unless prior authorization from the Approval Holder and RLSS has been granted for maintenance purposes (such as, alignment of a diffraction x-ray beam). Personnel who intend to override interlocks must be listed on an interlock override memo maintained for review by RLSS and BRC, and must be assigned and wear both a whole body dosimeter and at least one ring badge (used to measure radiation exposure to the hand). Interlocks must not be used to turn the unit off; the main switch should be used to turn the unit off.

c. Safety Device Tests

Safety device tests must be performed monthly and test documentation must be available for RLSS and BRC inspection. These safety device tests include, as applicable:

- "X-RAY ON" light on control panel
- "X-RAY ON" light on or near source housing
- "SHUTTER OPEN" light
- Door interlocks

d. Operating Procedures

Written operating procedures must be available near the machine; a current user manual meets this requirement. In the absence of a user manual, the Approval Holder must ensure that written operating procedures are developed and available.

e. Dedicated Room

To reduce potential exposure of non-radiation workers, the machine should be placed in a room that is separated from other work areas or in low traffic areas, if practical.

D. Units of Radiation Measurement

The energy of ionizing radiation is usually measured in electron volts (eV). The electron volt is defined as the kinetic energy gained by an electron when it accelerates through an electric potential difference 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 ionizing radiation produced by radiation generating machines.

1. **Exposure**
   Radiation exposure refers to absorption of ionizing radiation or ingestion of a radionuclide. Electromagnetic waves (gammas and x-rays) can produce ionization of air. The unit of measure for ionization of air by electromagnetic waves is the Roentgen (R), where:

   1 R = 2.58 x 10^{-4} Coulombs/kg of air

2. **Absorbed Dose**
   When predicting biological effects, it is important to determine the energy deposited in human tissue rather than in air or other matter. The total ionizing radiation energy deposited per unit mass of material is the absorbed dose. The rad is the traditional unit of radiation absorbed dose.

   1 rad = 100 ergs/gram
   1 R = ~0.87 rad (in air); up to 0.96 rad (in tissue)

   The SI unit of radiation absorbed dose is the gray (Gy).

   1 gray = 1 joule/kg

   The relationship between the gray and the rad is:

   1 gray = 100 rad

3. **Dose Equivalent**
   The dose equivalent is used to measure the biological effects of ionizing radiation on the human body. It is a function of the absorbed dose and the type of radiation absorbed. The weighting factor used according to the type of radiation absorbed is called the quality factor (QF). The rem is the product of the absorbed dose in tissue (the biological dose), calculated by multiplying the rad by a quality factor (see Table 1). This quality factor is used to address the fact that, for the same absorbed dose, different types of ionizing radiation have differing biological effects in the scope of exposure to low levels of radiation.

Table 1: Quality Factors for Different Radiations

Radiation	Quality Factor
X, gamma, or beta radiation and high-speed electrons	1
Neutrons of unknown energy	10
High-energy protons	10
Alpha particles, multiple-charged particles, fission fragments, and heavy particles of unknown charge	20

Because the quality factor for commonly used ionizing radiation (x-rays, gammas and betas) is one, for radiation safety purposes it may be assumed that:

1 R = 1 rad = 1 rem

The SI unit for dose equivalent is the sievert (Sv). As it was between the gray and the rad, the relationship between rem and sievert is:

1 Sv = 100 rem

III. Biological Effects of Radiation

A. Origins of Biological Damage from Radiation Exposure

Biological effects can be categorized as direct or indirect based on how cellular damage occurs. An indirect effect occurs when free radicals produced by the ionization of water molecules in the body, interact with other molecules or intracellular structures. Most of the time, free radicals interact with molecules that cells can easily survive without.

Radiation that deposits energy directly into intracellular structures (including DNA) results in a direct effect. Changes to DNA can produce cell death, the inability to reproduce, the inability to function, or a change in the function of the cell (mutation), which could lead to cancer. DNA has the ability to repair itself, reverting to its original state or mutating, depending on the type and extent of the damage.

B. Exposure Risks

1. Acute Radiation Dose Exposure

Acute radiation dose is exposure to a large radiation dose over a short time (the period of exposure is considered short when the dose is delivered so quickly that damaged DNA cannot repair itself). At low levels of radiation exposure, the amount of cell death or mutation that results is usually irrelevant and does not impact the function of an entire organ. With an acute radiation dose, large numbers of cells may die and impact the ability of organs to function. Acute radiation dose results in a specific and prompt effect called acute radiation syndrome (or radiation sickness). The dose at which symptoms occur depends on the sensitivity of various cells to radiation. In general, the faster a cell divides and the less specialized it is (e.g. an immature blood cell is less specialized then a mature one), the more sensitive it is to radiation. Immature blood cells are the most radiation-sensitive cells. Effects and outcomes of the three acute radiation syndromes are shown in Table 2. Radiation levels when using radiation generating machines at The University of Arizona are too low to result in acute radiation syndrome.

Table 2: Acute Radiation Syndromes

	Hematopoietic Syndrome (affects blood cell formation)	Gastrointestinal Syndrome	Central Nervous System Syndrome
Dose (rad)	200-1000	> 1000	> 2000
Time to Death (if fatal)	3-8 weeks	3-10 days	< 3 days
Organ/System Damaged	Bone Marrow	Small Intestine	Brain
Signs & Symptoms	• Decreased number of stem cells in bone marrow • Increased amount of fat in bone marrow • Pancytopenia (reduction in red/white blood cells and platelets) • Anemia (reduction in red blood cells) • Hemorrhage (bleeding) • Infection	• Denudation of villi in small intestine • Neutropenia (reduction in white blood cells) • Infection • Bone marrow depression • Electrolyte imbalance • Watery diarrhea	• Vasculitis (inflammation of the blood vessels) • Edema (water-retention) • Meningitis (inflammation of the brain/spinal cord membranes)
Recovery Time	Dose dependent, 3 weeks to 6 months; some individuals do not survive.	None; fatal	None; fatal

2. Recognizing Acute X-Ray Exposure

X-rays do not harm the outer, mature layers of skin. Instead, x-ray burns occur in the basal skin layer and damage or kill rapidly dividing germinal cells which would normally replace the outer layers of skin as they slough off. Lack of a fully viable basal layer of cells means that x-ray burns are slow to heal and may never heal in some cases. Burns may require skin grafts and may be severe enough to result in gangrene and amputation of one or more digits.

An acute dose of greater than 300 rad (3 Gy) to a body part causes a radiation burn equivalent to a first-degree thermal burn or mild sunburn. There typically is no immediate pain, but a sensation of warmth or itching occurs within about a day of exposure, followed by a reddening or inflammation of the affected area that fades after a few more days. The reddening may reappear as late as two to three weeks after the exposure along with a dry scaling or peeling of the irradiated portion of the skin. A typical x-ray unit can produce this level of radiation dose in just a few seconds if the exposure occurs very close to the x-ray tube or the beam is collimated (focused).

An acute dose greater than 1,000 rad (10 Gy) to a body part causes serious tissue damage similar to a second-degree thermal burn. First reddening and inflammation occurs, followed by swelling and tenderness. Blisters form within one to three weeks and break open, leaving raw, painful wounds that can become infected. An even larger acute dose causes severe tissue damage similar to a scald or chemical burn; intense pain and swelling occurs, sometimes within hours.

If acute x-ray exposure is suspected, medical care to avoid infection should be sought (if open wounds or blisters occur) and the Approval Holder, Radiation Safety Coordinator and RLSS should be notified as soon as possible.

3. **Chronic Low Level Radiation Exposure**

Chronic low level radiation exposure is exposure to low levels of radiation over long periods of time. The dose effects from chronic low level radiation exposure are delayed effects and include an increased risk of cancer and hereditary effects.

Some other effects, such as skin reddening, cataract formation and temporary sterility in males, occur after receiving a threshold dose (the minimum dose that will produce a detectable degree of any given effect); however, none of these effects have been seen at occupational levels. It is important to realize that the potential risks associated with occupational radiation exposure are similar to, and sometimes less than, risks encountered in daily life (accidental death and the impact of lifestyle choices).

IV. Radiation Exposure and Protections

Individuals are exposed to radiation in the normal course of everyday life. Sources of radiation exposure can be classified as natural, man-made, and occupational.

A. Natural Radiation

Natural radiation is the background radiation that is always present in the environment. The main sources of natural radiation are: cosmic radiation which comes from the sun and stars, terrestrial radiation which comes from the earth, and internal radiation which exists within all living things.

B. Man-Made Radiation

Man-made ionizing radiation includes medical exposures (such as diagnostic x-rays, fluoroscopy, and other types of imaging, and nuclear medicine diagnostic and treatment procedures), building materials, combustible fuels (including gas and coal), X-ray security systems, smoke detectors, luminous watches, and tobacco.

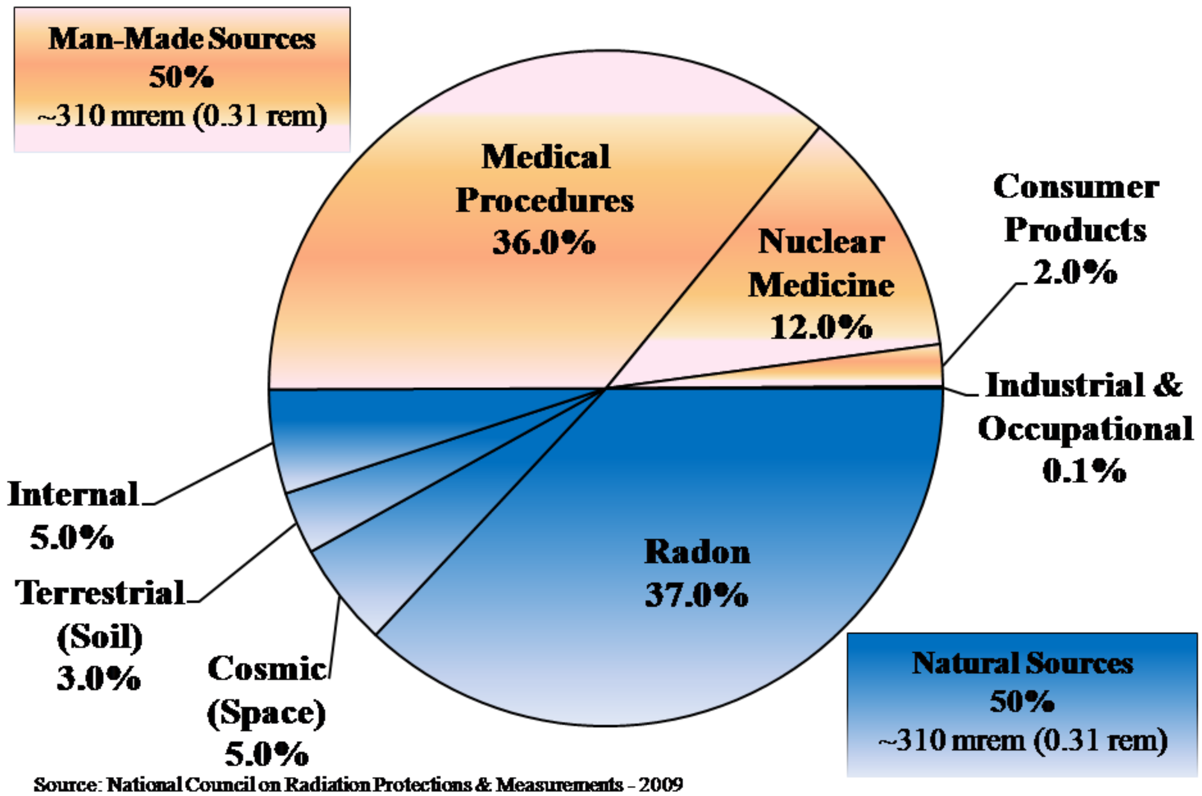
C. Occupational Dose

Occupational dose is the total dose received by radiation workers in the course of their work. It is important to note that industrial and occupational exposure accounts for only about 0.1% (0.62 mrem) of the average total radiation exposure experienced by an individual annually.

The average radiation dose received by individuals in the U.S. is about 620 mrem/yr (310 mrem/yr from natural sources and about 310 mrem/yr from human-generated sources, including occupational dose). Previously, the total annual dose was estimated at 360 mrem and the change in the current estimate is mainly the result of increased exposure from medical diagnostic and treatment procedures.

Figure 5 illustrates sources of radiation exposure experienced in the U.S and the percentage each represents of an individual's total annual dose. These are only average doses and an individual's dose can vary depending on geographic location, the amount of medical exposures experienced, and various lifestyle choices. For example, smoking (30 cigarettes/day) will expose the lungs to the equivalent of 1.5 rem to the whole body.

Figure 5: Sources of Radiation Exposure in the United States



D. Occupational Dose Limits

The State of Arizona is a regulatory Agreement State and as such, the U.S. Nuclear Regulatory Commission (NRC) has given the Bureau of Radiation Control (BRC) jurisdiction in regulating work with radioactive materials within the State of Arizona. Limits on occupational doses are based on data regarding known biological effects of ionizing radiation. The International Commission on Radiological Protection and the National Council on Radiation Protection and Measurements publish guidance for setting radiation protection standards. Federal Regulations set regulatory requirements related to radiation exposure and BRC sets regulatory requirements related to radiation protection in the State of Arizona. These limits are set to ensure that the probability of detrimental biological effects from occupational exposure to ionizing radiation is equivalent to what has been observed in other safe industries.

A radiation worker is an individual who has received both general and specific radiation safety training and is authorized to use radioactive materials and/or radiation-producing machines. A non-radiation worker is an individual who is not trained or authorized in the use of radioactive materials and/or radiation-producing machines. The radiation dose received by radiation workers in the course of their work is defined as occupational dose.

Occupational radiation dose limits set by the State of Arizona for different parts of the body and for minors range from 0.5 rem to 50 rem per year (see Table 3). Occupational radiation dose limits are set well below the exposures that cause acute radiation syndrome.

Table 3: Occupational Radiation Dose Limits	
Whole Body	5 rem (5000 mrem)
Lens of Eye	15 rem (15,000 mrem)
Skin of Any Extremity	50 rem (50,000 mrem)
Skin of Whole Body	50 rem (50,000 mrem)
Non-Radiation Worker	0.1 rem (100 mrem)
Minors (personnel under 18 years of age)	10% of adult dose limits
Fetus (total for entire gestation period)	0.5 rem (500 mrem)

1. **Pregnant Women: Dose Limits**
   If a radiation worker is planning to become pregnant or is pregnant, it is recommended that she request information from the Research Laboratory & Safety Services (RLSS) concerning radiation exposure to a fetus. A pregnant woman may choose to declare her pregnancy to RLSS. A declared pregnant woman is a woman who has voluntarily informed RLSS in writing of her pregnancy and the estimated date of conception. It is a regulatory requirement that a declared pregnant woman be provided information about the potential risks of radiation exposure to a fetus.

   As part of counseling, RLSS will conduct a review of the work situation and previous exposure history of a declared pregnant woman (or a woman planning to become pregnant) and will provide her with information about her potential for fetal exposure. Based on the work situation review, an additional dosimeter to be worn at the waist and monthly urine bioassay samples may be required for a declared pregnant woman. The dose limit to an embryo/fetus is 500 mrem over the entire pregnancy. It is also required that every effort be made to avoid substantial variation above a uniform monthly dose rate of 50 mrem/month.

   It is a woman's right to “undeclare" her pregnancy at any time. This decision terminates RLSS’s involvement with her pregnancy even though she may still be pregnant and had previously declared the pregnancy.

2. **Minors: Dose Limits**
   Occupational dose limits for minors are 10% of the adult limits. The University of Arizona only allows a minor to become a radiation worker as part of an educational experience, not solely for employment.

E. Protection Against External Radiation Exposure

The concept of ALARA (<u>A</u>s <u>L</u>ow <u>A</u>s <u>R</u>easonably <u>A</u>chievable) is mandated by both Federal and State of Arizona regulations. The ALARA principle is to maintain radiation dose as far below the occupational limits as is reasonably achievable. This regulatory requirement is based on the following:

- No practice shall be adopted unless its introduction produces a net positive benefit;
- All exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account; and

- The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the regulatory authority.

The ALARA policy is based on the linear, non-threshold (LNT) dose-effect hypothesis. The LNT hypothesis assumes that the known effects of high doses of ionizing radiation may be used to predict the possible effects of long-term, low-dose radiation exposure. According to the LNT hypothesis, there is a relationship between radiation dose and the occurrence of cancer such that any increase in dose, results in an incremental increase in risk. Even though there is disagreement as to whether the LNT hypothesis overestimates or underestimates this risk, Federal and BRC regulations require that The University of Arizona demonstrate that the ALARA principles are being applied.

1. Keeping Exposures As Low As Reasonably Achievable (ALARA)

When working with radiation generating machines, it is essential to keep the radiation exposure to a minimum. Three of the ALARA principles intended to minimize occupational exposure due to use of radiation generating machines are time, distance, and shielding.

a. Time

The dose of radiation a worker receives is directly proportional to the amount of time spent in a radiation field. Reducing the amount of time spent in a radiation field by one-half will reduce the radiation dose received by one-half. Workers should always spend as little time as possible around radioactivity. The following actions may be used to minimize time of exposure:

- plan work carefully
  - read and understand the experiment protocol prior to performing tasks with radiation
  - read and understand equipment manuals, if applicable
- have all necessary equipment in one place
- ensure all equipment is in good working condition before work begins
- repeat experiments only when absolutely necessary

b. Distance: The Inverse Square Law

Radiation exposure decreases rapidly as the distance between the worker and the x-ray source increases. The decrease in exposure from a point source (e.g., the x-ray tube) can be calculated by using the inverse square law. This law states that the amount of radiation at a given distance from a point source varies inversely with the square of the distance. Therefore, if the distance to the source is doubled, the exposure decreases by a factor of 4 and if the distance is tripled, the exposure decreases by a factor of 9. The change in percentage of intensity resulting from an increase or decrease in distance from a radiation source is shown

Inverse Square Law

$$I_2 = I_1 (D_1/D_2)^2$$

I_1	=	original tensity
D_1	=	original distance
I_2	=	new intensity
D_2	=	new distance

Table 4: Effect of Inverse Square Law

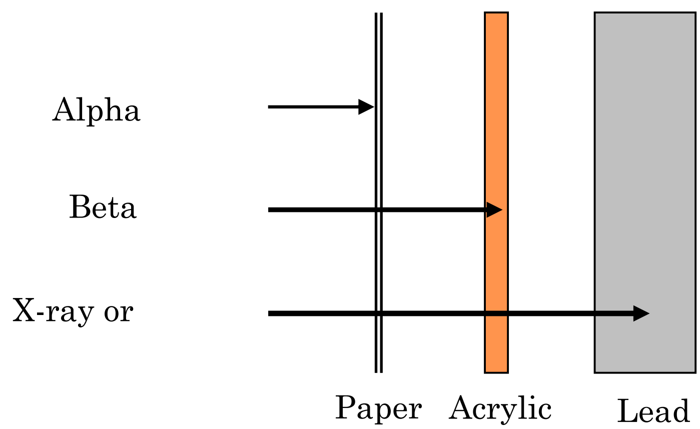
Distance	Intensity
1 foot	**100%**
2 feet	**25%**
4 feet	**6.25%**
10 feet	**1%**
6 inches	**400%**

in Table 4. Although the inverse square law does not accurately describe scattered radiation and does not apply to exposure to a collimated beam (such as the primary beam of an x-ray diffraction unit), distance will still dramatically reduce the intensity from this source of radiation. Maintaining a safe distance, therefore, represents one of the simplest and most effective methods for reducing radiation exposure to workers and non-workers.

c. Shielding

Shielding is the use of a material or obstruction to absorb radiation and thus protect personnel or materials from the effects of ionizing radiation. The thickness of the required shielding material is dependent on the energy level of the emitted radiation (higher energy requires thicker shielding). The appropriate type and thickness of shielding material must be used in order to reduce the dose rate of different types of ionizing radiation (see Figure 6). Efficacy of shielding is determined by contamination surveys.

Figure 6: Shielding Materials



Alpha particles can be completely stopped by almost anything (such as a sheet of paper). Beta particles can be shielded by a sheet of acrylic. Use of lead for shielding high-energy beta emitters is discouraged because the resulting bremsstrahlung x-rays can produce significant additional exposures.

Gamma and x-ray radiation is diminished in intensity by any given absorber but not completely stopped. In order to reduce radiation dose, shielding should be placed to separate radiation workers and non-radiation workers from radiation generating machines. Lead is an appropriate shield for gamma and x-ray radiation, and for photons. Concrete can also be used as a shield for gamma and x-rays; however, RLSS should be contacted prior to shielding gammas with anything other than lead. Stainless steel or lead- or tin-loaded acrylic viewing windows can also be effective barriers. For x-ray enclosures or outside local components, shielding must be of an adequate thickness to reduce the radiation level to below regulatory limits.

Neutrons differ from the ionizing radiation of photons or charged particles in that they are repeatedly bounced and absorbed by light nuclei. Effective shielding material therefore must contain high concentrations of hydrogen, such as is found in water, acrylic, sheets of paraffin, or concrete.

F. Measurement of External Exposure to Radiation

Various types of radiation dosimeters (including badge, extremity or ring, and supplemental/secondary dosimeters) are used to measure an individual's external exposure to radiation. Individuals who are likely to receive at least 10% of the occupational dose limit will be assigned a dosimeter. The need for personal dosimeters is dependent on the machine type and its proposed use.

Users of enclosed x-ray units are not issued radiation dosimeters because the potential for exposure is limited by the machine’s configuration. If an open beam radiation generating machine is not equipped with a safety device, users are required to wear a dosimeter whenever they work with the machine; this also applies to individuals who are authorized to perform maintenance (e.g., alignment) involving access to open beams. RLSS sets investigation exposure levels for radiation dose recorded during each period that a dosimeter is worn. If a worker exceeds the investigation level in one of the periods, RLSS will review the worker’s practices to ensure that radiation doses are ALARA.

Badge, extremity and supplemental/secondary dosimeters are issued free of charge by RLSS. Whether or not a dosimeter is assigned, or whether bioassays are required (for monitoring internal exposure), is determined by a health physicist.

1. Badge Dosimeters

Badge dosimeters (see Figure 7) are the primary type of whole body personal dosimeter provided by RLSS. These dosimeters are typically collected by RLSS on a bimonthly basis and sent to their manufacturers to be analyzed. The dosimeter should not be exposed to temperatures above 150^{o} F, as this may affect the exposure measurements that are obtained.

2. Extremity (Ring) Dosimeters

Extremity (ring) dosimeters are used to measure exposure to the hands when whole body exposure and hand exposure could differ significantly (see Figure 8). The “chip side” of the finger ring must be aimed towards the palm and must be worn on the designated hand.

Figure 7: Badge Dosimeter
(showing front of unit and front/back of holder)

Figure 8: Extremity (Ring) Dosimeter

3. Supplemental/Secondary Dosimeters

Pocket ion chambers and electronic personal dosimeters are two types of supplemental/secondary dosimeters. An ion chamber is an instrument designed to measure the quantity of ionizing radiation in terms of the charge of electricity associated with ions produced within a defined volume. A pocket ion chamber is an ion chamber the size of a fountain pen and is used to detect gamma or neutron ionizing radiation exposure. It provides the user with an immediate measurement of exposure.

Figure 9: Electronic Personal Dosimeter

An electronic personal dosimeter is an electronic unit capable of measuring gamma, beta and x-radiation exposure. It provides the user with immediate feedback as to the current rate of exposure as well as exposure over a specified period of time (see Figure 9).

Pocket ion chambers and electronic personal dosimeters are only issued on an as needed basis and proper use requires additional training and documentation. The number of available units is limited due to high cost.

V. Laboratory Practices

All individuals working with radiation generating machines should be aware of the location of the necessary documents, records, and guidelines that pertain to machine use approvals. A visiting RLSS or state inspector may ask to view this information at any time.

A. Education and Training

Individuals may not work with radiation generating machines until they have received appropriate training. In conjunction with RLSS, this is a two-part process that includes laboratory or machine-specific training and completion of the Radiation Generating Machines Protection Course. Machine-specific training should include:

- Description of the system
- Safety device identification and safety device check procedure
- Review of written operating and safety procedures
- Selection and use of personal protective equipment, if required
- Completion of machine use log
- Review of emergency procedures
- Identification of ancillary hazards

Course schedules and registration information for the Radiation Generating Machines Protection Course are located on the RLSS website. Depending on a prospective Approval Holder’s prior experience with radiation generating machines, the Approval Holder may be required to complete the Radiation Generating Machines Protection Course in addition to the Approval Holder Orientation (provided by RLSS personnel). A radiation worker must complete RLSS training before an individual begins working in a new laboratory or under an additional approval.

B. Approval to Use Radioactive Materials

A ‘Radiation Machines Approval’ is granted to an individual after the University Radiation Safety Committee or the Medical Radiation Safety Committee reviews and approves an Application for Radiation Machines Approval. The intended use of the machine, the protocols, and the rooms where the machine will be used and stored must be specified in the application. The approval issued by the Radiation Safety Committee may include special conditions regarding possession and use of a radiation generating machine. To change machine locations or configurations, contact RLSS.

1. Exemptions

Users of electronic products which produce x-rays that are incidental to operation may be exempted from the requirements contained in this manual depending on the product and/or the results of radiation survey measurements. Such products may include electron microscopes (scanning electron microscopes), ion-implanters, and cathode ray tubes. RLSS must be contacted to request an ionizing radiation survey of this type of electronic equipment in order to determine exempt status.

2. Machine Registration

All x-ray generating machines must be registered with RLSS prior to operation. The registrant must provide the specifications of the unit and a description of its proposed use. An evaluation of the unit and its use will be made to determine if any operation restrictions or additional safety devices are necessary. An initial radiation survey and safety device check will also be performed by RLSS personnel.

In addition to RLSS approval, proposed experiments may require additional regulatory approvals from the Institutional Animal Care Use Committee (IACUC), the Institutional Review Board (IRB) at the Human Subjects Protection Program office, or the Institutional Biosafety Committee (IBC).

C. Posting and Labeling for Radiation Generating Machines

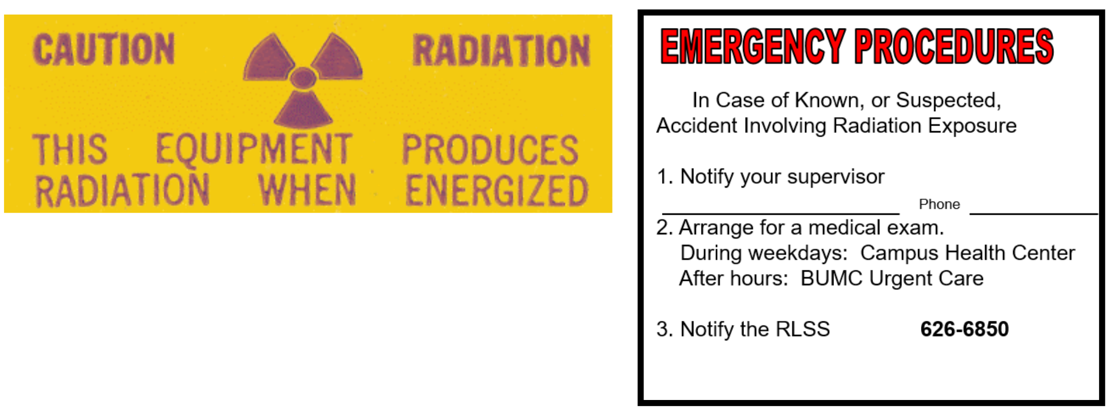
Once a room is approved for radiation generating machine use or storage, RLSS will post the required signs. No work involving radiation generating machines may be initiated until the signs have been posted.

1. Room and Area Entrances
   "Caution Radiation Generating Equipment in this Area" (see Figure 10).

Figure 10: Sample Entrance Signs

2. **Machine and Control Panel Labels**
   These labels must be displayed on or near the control panel of Radiation Generating Machines. The **"Caution Radiation – This Equipment Produces Radiation When Energized"** label must be displayed on or near the control panel and the **"Emergency Procedures" Label** must be displayed on the Radiation Generating Machine (see Figure 11)

Figure 11: Sample Labels



3. **Notice to Employees (Form ARRA-6)**
   This document summarizes the rights and responsibilities of State radiation workers, and radiation exposure protections required by the BRC.

D. Dosimetry Use

The measurements obtained by a dosimeter are a legal record of a person's individual radiation exposure and RLSS maintains these records for personnel using RLSS-issued dosimeters. Personal dosimeters issued by RLSS may not be shared or exposed to any source of radiation outside of the specific work assignment for which they were issued. If a dosimeter is issued, it must be worn whenever working with radioactivity or radiation generating machines in the work assignment.

A lost or damaged badge should be reported immediately to RLSS. A worker may not perform any work with radioactive materials or radiation generating machines until a new badge has been obtained.

RLSS will immediately replace any damaged or lost dosimeter; however, a replacement fee may be charged to the department for lost dosimeters; the department may pass the charge on to the responsible individual. Current information pertaining to the use of dosimeters, monitoring and documentation of exposure is located on the RLSS web site.

E. Activation, Recordkeeping & Security of Radiation Generating Machines

The registration, possession and use of radiation generating machines in Arizona is regulated by BRC and the possession and use of machines registered to the UA is administered by RLSS. Approvals for possession and use of radiation generating machines granted to an Approval Holder are documented as sub-registrations under the UA registrations.

1. Activation

Radiation generating machines may not be activated until an approval has been issued, required education of workers has been documented, RLSS has inspected the machine and its required safety components, and the Approval Holder Orientation has been conducted.

2. Recordkeeping

Once a radiation generating machine is cleared for activation, the Approval Holder is required to maintain a separate use log for each machine; the use log must, at a minimum, contain the name of the user and the date of the use. The required safety device checks may also be documented in the use log.

Transfer (whether internally to another Approval Holder, or externally to another institution) or de-activation of radiation generating machines must be arranged through RLSS.

3. Security

When not in use, radiation generating machines must be secured in such a manner that they cannot be used by untrained, unauthorized personnel or members of the public. If the unit requires a key for activation, the key must be stored away from the machine in a locked drawer or cabinet when not in use. For machines that do not have a locking mechanism, unauthorized use must be prevented by controlling access to the machine location (e.g., locking the laboratory or room where the machine is located when authorized personnel are not present) or by an alternate method approved by RLSS.

The physical securing of the machine must be combined with preventing unauthorized entry into the laboratory. Visitors must be questioned as to their purpose for being in a radiation laboratory. Visitors and outside contractors shall be under constant supervision by a radiation worker when in radiation use areas unless machines have been secured. UA Facilities Management personnel and custodial staff have been trained to work safely around radioactive materials and radiation generating machines, so supervision is not required.

Any known or suspected loss or theft of a radiation generating machine must be reported immediately to RLSS.

F. Monitoring of Radiation Generating Machines

1. Radiation Surveys

Portable radiation survey instruments are used to verify the efficacy of the radiation shielding placed around radiation generating machines to protect personnel from unnecessary exposure. Surveys also measure radiation dose rates (identifying current levels and any changes from prior levels), determine appropriate dosimetry requirements, confirm effectiveness of shielding and ensure that radiation levels are below regulatory limits during machine operation. Machine users are not required to perform radiation surveys unless it is specified by RLSS in the machine approval. Radiation surveys of local components and x-ray enclosures are performed by RLSS.

Radiation surveys are performed by RLSS under the following circumstances:

- Upon installation and prior to initial use of the machine
- Every twelve months (usually during the annual approval audit)
- Following any change in the arrangement of local components
- Following maintenance or service that requires the removal or disassembly of a local component
- Any time a visual inspection by a user reveals an abnormal condition
- When personnel monitoring devices show a significant increase over the previous monitoring period

An Approval Holder, Radiation Safety Coordinator or radiation worker may request that a radiation survey be performed by RLSS at other times as needed.

2. Area Radiation Monitors

Depending on the condition or use of an x-ray system, RLSS may mount area radiation monitors to measure radiation dose to members of the public in unrestricted areas. The Approval Holder should be aware of the location of these dosimeters and inform RLSS if any are missing or damaged.

G. Disposal of Radiation Generating Machines

Disposal or transfer of all radiation generating machines must be coordinated with and conducted by RLSS.

VI. Emergency Procedures

Emergency procedures are stated on the Radiation Emergency Procedures sticker. Radiation workers should familiarize themselves with the information on the sticker. The Radiation Safety Coordinator is the designated person, other than the Approval Holder, who can provide information about radiation generating machine use in the laboratory in case of an emergency.

A. Common Causes of Accidental Exposures

- Poor equipment design or configuration (e.g., unused ports not covered or inadequate shielding)
- Equipment failure (e.g., shutter failure, interlock failure)
- Manipulation of equipment when the x-ray tube is energized (moving samples or aligning cameras while unit is in operation)
- Inadequate training and awareness of exposure potential
- Improvising and ignoring established procedures (e.g., overriding interlocks)

B. Actions and Notifications

- Access to the accident area should be restricted until the area is determined to be safe.
- If the beam cannot be turned off, the machine should be turned off (a master emergency “STOP” button is usually present).
- If an individual has been exposed to the primary beam, contact RLSS immediately.

- The machine configuration must not be changed (except for turning the beam or machine off) in order for RLSS to evaluate the accident and any exposure.
- If oil is leaking from the tube area, it may be very hot and should not be touched until it has cooled. It can then be treated as any other oil spill, including contacting UA Risk Management.

C. Fire Emergencies Involving Radiation Generating Machines

- In case of fire, call '911' from a University telephone, notify dispatcher that a radiation generating machine is involved, pull the nearest fire alarm, and vacate the building.
- Call RLSS (if after business hours or if no answer at the RLSS telephone number, call University Police).

D. Loss or Theft of Radiation Generating Machines

Suspected loss or theft of a radiation generating machine must be reported immediately to the Radiation Safety Coordinator and/or Approval Holder, and RLSS. If after business hours or if no answer at the RLSS telephone number, call University Police.

VII. Responsibilities By Roles

The responsibility for maintaining radiation doses to workers and the public under the ALARA principles and for the safe use of radiation generating machines is shared by RLSS, the Approval Holder, the Radiation Safety Coordinator, and each radiation worker.

A. Approval Holder Responsibilities

Approval Holders are the individuals ultimately responsible for the safe use of the radiation generating machines under their control and listed on their approval. Approval Holder Orientation is provided by RLSS at the time of approval, during audits, or at a minimum of every three years. Approval Holders have the responsibility to:

- Comply with the rules and regulations administered by the University Radiation Safety Committee or the Medical Radiation Safety Committee, RLSS, and the BRC;
- Properly train radiation workers to use, document use, secure, and dispose of radiation generating machines under their approval in accordance with the Radiation Training Policy;
- Provide in-house, system-specific training;
- Ensure that RLSS is notified of new proposed radiation workers;
- Provide adequate supervision of authorized radiation workers;
- Maintain a written inventory of machine use;
- Ensure that monthly checks of machine safety features are performed and documented, as stipulated in approval;
- Respond to information requests by RLSS in a timely manner;
- Notify RLSS immediately if an exposure has occurred or is suspected;
- Maintain all required postings and labeling for radiation generating machine use areas, for the machines, and for tools associated with the machines;
- Provide and ensure proper use of personal protective equipment, if required;
- Notify RLSS prior to relocation or transfer of radiation generating machines (to internal or external sites);
- Notify RLSS of intent to override interlocks or safety devices (for purposes of maintenance, etc.);
- Notify RLSS if the Approval Holder will be absent from the institution for an extended time that will reduce the effective oversight of laboratory operations. If an extended absence is planned,

an agreement must be reached with an appropriate substitute to oversee the use of radiation generating machine while the Approval Holder is away.

B. Radiation Safety Coordinator Responsibilities

Some Approval Holders may not have the time or resources to personally monitor the day-to-day operation of a laboratory. Therefore, Approval Holders may appoint a Radiation Safety Coordinator to operate under their approval, but the ultimate responsibility for use of the radiation generating machine remains with the Approval Holder. The Radiation Safety Coordinator, in addition to attending the Radiation Generating Machines Protection Course will receive an Approval Holder Orientation from RLSS personnel (initially, during audits, or at a minimum of every three years). At the direction of the Approval Holder, the Radiation Safety Coordinator may be assigned extra responsibilities such as those in the above list.

C. Radiation Worker Responsibilities

Radiation Workers have the responsibility to:

- Complete the Radiation Generating Machines Course and any other required training prior to beginning work;
- Notify RLSS if transferring to a new Approval Holder's group or laboratory;
- Comply with the requirements for the safe use and security of machines under the approval;
- Perform and document contamination surveys/safety device checks, as required;
- Report all accidents and exposures (known or suspected) to the Radiation Safety Coordinator and/or Approval Holder, and to RLSS.

D. Research Laboratory & Safety Services (RLSS) Responsibilities

RLSS has responsibility to:

- Provide training (e.g., Radiation Generating Machines Protection Course, Approval Holder's Orientation);
- Evaluate new installations of research radiation generating machines;
- Review and approve modifications to x-ray equipment in relation to effect on radiation protection, tube housings, cameras, shielding, enclosures and safety devices;
- Maintain a current inventory of radiation generating machines;
- Register radiation generating machines with the BRC;
- Calibrate survey instruments;
- Provide signs for entrances to radiation generating machine use areas;
- Provide personnel dosimeters and area monitors, if necessary;
- Maintain exposure records for Radiation Workers;
- Perform audits and laboratory inspections (at least annually);
- Investigate exposures to personnel and provide assistance in corrective actions, as needed.

VIII. Obtaining Radiation Generating Machines

It is recommended that RLSS be notified of the intent to obtain (purchase, fabricate, or receive through transfer or donation) a radiation generating machine. It is required that RLSS be notified prior to initial use of a radiation generating machine.