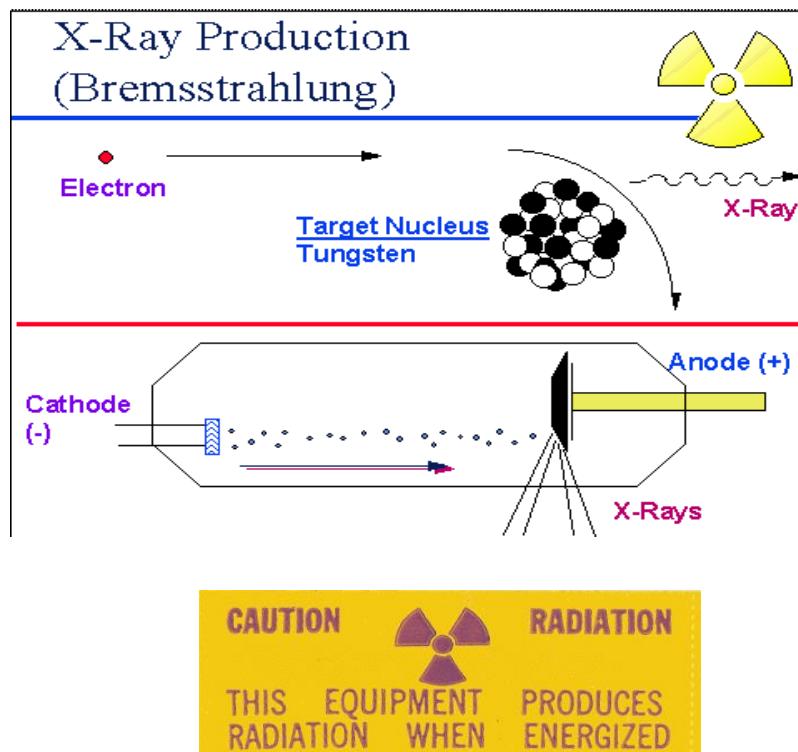


NIU Radiation Safety

Research X-ray Safety Manual



This Manual will:

- Provide the basic fundamentals of X-ray devices.
- Explain the hazards of X-ray devices used in NIU research.
- Provide THREE ways to reduce x-ray exposure.
- Explain NIU requirements and responsibilities for the safe use of X-ray devices.
- Help X-ray users recognize and respond to unsafe conditions.

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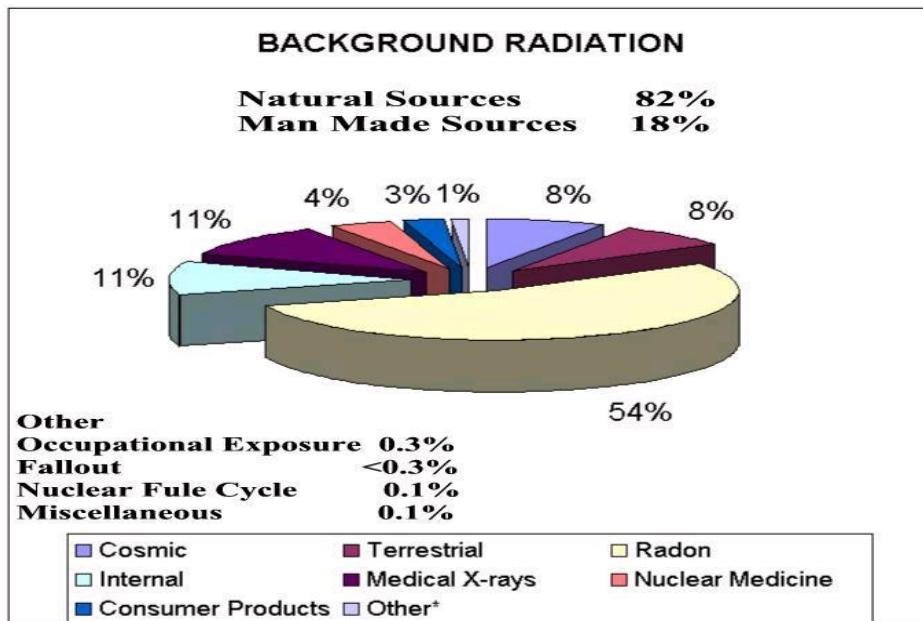
Introduction

NIU research operations require the use of X-ray equipment. X-rays are used for analysis of samples, non-destructive testing, or diagnostic imaging. X-ray devices at NIU can be and have been operated safely for years. X-ray users must understand hazard(s) of device and follow operating procedure and/or owner manual instructions for device. If you have any questions or concerns about X-ray devices at NIU, contact NIU Radiation Safety Officer – Michele Crase.

Radiation is energy in the form of waves or particles. Radiation high enough in energy to cause ionization is called **ionizing radiation**. It includes particles and rays given off by radioactive material, stars, and high-voltage equipment. Ionizing radiation includes x-rays, gamma rays, beta particles, alpha particles, and neutrons.

Without the use of monitoring equipment, humans are not able to "find" ionizing radiation. In contrast to heat, light, food, and noise, humans are not able to see, feel, taste, smell, or hear ionizing radiation.

The background radiation we are all exposed to has two sources Natural Background and Man- Made Radiation. The NCRP Report No. 93 states that the average background dose in the US is 360 mrem/year.



X-rays in general

X rays are a form of electromagnetic radiation, which arises as electrons are deflected from their original paths, or inner orbital electrons change their orbital levels around the atomic nucleus. X- rays, like gamma rays, are capable of traveling long distances through air and most other materials. Like gamma rays, X-rays require more shielding to reduce their intensity than do beta or alpha particles. X and gamma rays differ primarily in their origin: X-rays originate in the electronic shell, gamma rays originate in the nucleus.

X-rays were discovered in 1895 when **Wilhelm Conrad Roentgen** observed that a screen coated with a barium salt fluoresced when placed near a cathode ray tube. Roentgen concluded that a form of penetrating radiation was being emitted by the cathode ray tube and called the unknown rays, **X- rays**.

Like radio waves, light, and gamma rays, X-rays are a form of electromagnetic radiation. All electromagnetic radiation is characterized by the movement of massless waves of energy called photons. Photons travel at the speed of light and move with a characteristic wavelength and frequency that defines the specific type of electromagnetic radiation. The amount of energy carried by a photon is directly proportional to the frequency of the radiation and inversely proportional to the wavelength. Thus, X-rays which have a relatively short wavelength and high frequency possess a great deal of energy. X-rays are termed ionizing radiation because they contain sufficient energy to remove orbital electrons from atoms, creating ions.

X-rays have several interesting properties. Because of their short wavelength X-rays can penetrate materials that absorb or reflect visible light. Like light, x-rays can produce a visible image on photographic film. X-rays can produce biological changes in tissue that can be beneficial when used in radiation therapy. However, X-rays can also be harmful to biological organisms because of their ability to damage chromosomes. X-rays can also cause certain substances to fluoresce or emit radiations of longer wavelengths.

Because of these properties the use of X-rays has found wide applications in the fields of medicine, industry, and research. Physicians were using X-rays as a diagnostic tool within months of Roentgen's discovery. Industrial applications include the location of internal defects in materials, such as weld joints, and inspection of the internal parts of machinery. Principal applications of X-rays in research are X-ray diffraction and X-ray fluorescence analysis. These procedures are used to analyze both the chemical composition and crystalline structure of substances.

Tubes

X-rays are produced by two different mechanisms when high-speed electrons collide with a metal target in a high vacuum.

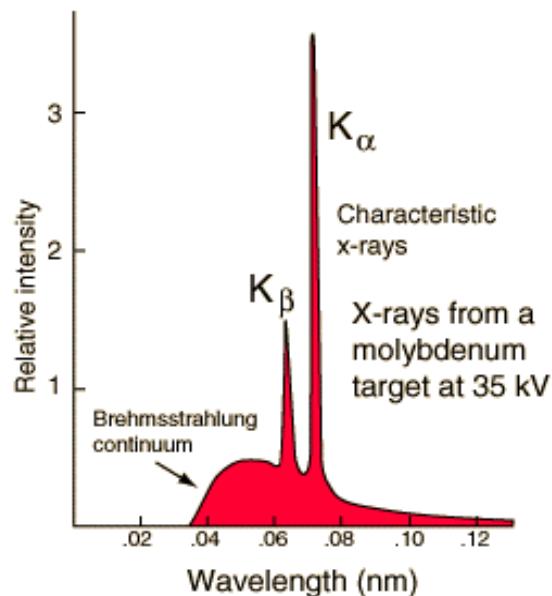
The resultant X-rays consist of a continuous spectrum known as Bremsstrahlung (German for braking radiation), and radiation with specific energies characteristic of the target material.

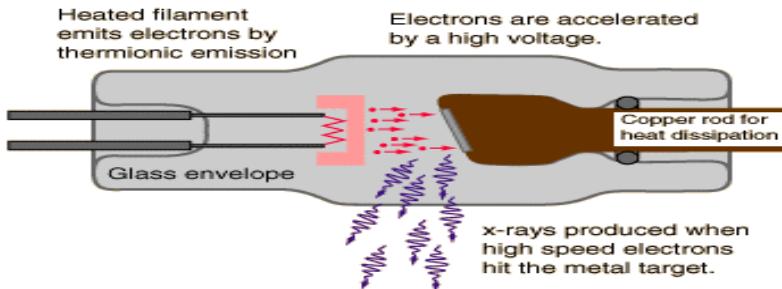
The second method X-rays are produced is termed the characteristic radiation effect. This results in the production of very specific radiations characteristic of the target material. Characteristic radiation is produced when an incident high-speed electron collides with an orbital electron of the target material.

Characteristic radiation is important in research because each element produces a characteristic spectrum that can be used to identify unknown samples.

An X-ray generating system requires a source of electrons, a means to accelerate the electrons, and a target to stop the high-speed electrons. In 1913, Coolidge developed the basic type of X-ray tube that is still in use today. A typical tube, called a hot cathode X-ray tube, consists of a cathode with a tungsten filament for generating electrons, and a tungsten target embedded in a copper anode that stops the electrons. The filament is located in a concave cup that focuses the electron beam onto a small area of the target called the focal spot.

Electrons are produced at the cathode by heating the tungsten filament to incandescence. Adjusting the temperature of the filament controls the number of electrons. The amount of charge flowing per second to the cathode is termed the current, expressed in milliamperage (mA). Electrons are accelerated towards the positive anode by a high voltage potential. This potential difference is expressed in kilovoltage (kV). Since the voltage across the tube may fluctuate it is usually expressed as peak kilovoltage (kVp).





An electron drawn across a voltage of one volt has energy of one electron volt (eV). The peak kilovoltage therefore defines the upper limit of

the most energetic photon. From a practical standpoint, however, the energy of the average photon in the beam is approximately one-third the peak kilovoltage. Adjusting the kVp to 60 for example, will produce an X-ray beam having a maximum energy of 60 keV with an average energy of approximately 20 keV. Superimposed on this continuous spectrum will be the characteristic radiation of the target material.

Only a small percentage of the energy carried by the electrons are converted to X-rays upon striking the anode. Typically greater than 99 percent of the energy will be converted to heat and absorbed by the target. The target is usually cooled with water or oil to prevent it from melting.

Each X-ray Tube has the following Components

Cathode: The cathode acts to excite electrons to the point where they become free from their parent atom and are then able to become part of the electron beam. The cathode acts as a negative electrode and propels the free electrons, in the form of an electron beam, towards the positive electrode (the anode).

Anode: The anode acts as a positive electrode, attracting the free electrons and accelerating the electrons through the electromagnetic field that exists between the anode and cathode. This acts to increase the velocity of the electrons, building potential energy. The higher the kV rating, the greater the speed at which the electrons are propelled through the gap between the cathode and anode. The electrons then impact a target (most commonly made of tungsten, but this target can also be molybdenum, palladium, silver or other metal). This causes the release of the potential energy built up by the acceleration of the electrons comprising the electron beam. Most of this energy is converted to heat and is radiated by the copper portions of the anode. The remainder is refracted off of the target in the form of high energy photons, or X-rays, forming the X-ray beam.

Glass envelope: The above components are sealed into a glass envelope. This allows for gases and other impurities to be pumped out of the tube, creating the vacuum necessary for proper performance. The X-ray creation process must occur in a vacuum so as not to disrupt the electron beam, and also to allow for proper filament performance and durability.

This is an X-ray tube with a fixed anode target from a Faxitron X-ray device. This X-ray tube was in service for many years. When in use the X-ray tube was submersed in oil – which helped to displace the heat.



The spinning anode tube design is used in many diagnostic X-ray systems. The anode spins or rotates at high speed during X-ray exposure. This design permits the produced heat to be distributed over a much larger area, allowing a corresponding increase in X-ray production and reduction in exposure times.



Interactions

In passing through matter, energy is transferred from the incident X-ray photon to electrons and nuclei in the target material. An electron can be ejected from the atom with the subsequent creation of an ion. The amount of energy lost to the electron is dependent on the energy of the incident photon and the type of material through which it travels. There are three basic methods in which x-rays interact with matter: photoelectric effect, Compton scattering, and pair production.

Photoelectric Effect - In the photoelectric effect, an incident X-ray photon strikes an orbital electron and is totally absorbed by the electron. The electron is then ejected from the atom creating a vacancy in the shell. The ejected electron interacts with other atoms creating ionizations until it loses its kinetic energy. Electrons in the atom drop from the outer shells to fill the vacancy in the inner shell forming characteristic photons. Photoelectric absorption occurs predominantly in X-ray photons with energies below 10 keV.

Compton Scattering occurs when an X-ray photon scatters from an orbital or free electron. Unlike the photoelectric process, only part of the photon's energy is transferred to the electron. The electron is ejected from the atom and the incident X-ray photon is scattered with a reduction in energy. This scattered photon continues to interact with orbital electrons by additional Compton or photoelectric processes. The probability of Compton scattering increases as the energy of the x-ray photon increases. At approximately 35 keV the probability of interactions through photoelectric and Compton collisions are about equal.

Pair Production- The third mechanism, pair production, is not encountered in analytical systems because the incident photon must possess a minimum energy of 1.02 MeV. In pair production, a photon interacts with the electric field around the nucleus and undergoes transformation into matter, with the creation of an electron and positron (positive electron). The

positron is annihilated in microseconds by interacting with an electron, creating two 0.511 MeV gamma photons (annihilation radiation). These photons then interact with matter by Compton and photoelectric collisions.

Types

A) Analytical X-rays is the most common type of research X-ray device at NIU and there are two main uses: Diffraction [XRD] and Fluorescence [XRF].

Typical acceleration voltages are 25-50 kilovolts for diffraction tubes and 25-100 kilovolts for fluorescence tubes. Tube currents are approximately 20 millamps. The maximum energies of the X-rays produced are therefore 50 keV for diffraction tubes and 100 keV for fluorescence tubes. The Bremsstrahlung effect produces a continuous energy spectrum extending from approximately 5 keV to 100 keV. The maximum intensity is in the range of 20 to 30 keV. Although energies below 5 keV are produced, these X-rays are readily attenuated. These radiations are usually called "soft" X-rays because they are readily absorbed in matter. Fluorescence tubes typically use tungsten targets which have characteristic lines around 60 keV.

Analytical X-ray equipment produces beams that are very narrow (1 mm^2) and highly intense. Exposure rates at the X-ray tube port where the primary beam exits the housing may be as high as 400,000 R/min. As the beam exits the collimator exposure rates may still be several thousand R/min. Diffracted beams from the sample may be several R/min. and scattered radiation from objects in the beam path can deliver exposure rates of several hundred mR/hr.

Fortunately, because of the low energy of these radiations, only relatively thin layers of shielding are required to attenuate the X-rays. It is this property, however, that make these X-rays so dangerous to the skin. Low energy X-rays are highly absorbed in soft tissue and severe and permanent local injury can result from exposure to the primary or diffracted beams.

XRD X-ray diffraction is an analytical technique used to look at X-ray scattering from crystalline materials. Each material produces a unique X-ray "fingerprint" of X-ray intensity versus scattering angle that is characteristic of its crystalline atomic structure. Qualitative analysis is possible by comparing the X-ray diffraction pattern of an unknown material to a library of known patterns.

XRD systems can be operated safely, with virtually no radiation dose to the operator provided commonsense safeguards are followed. The primary X-ray beam is typically very small, and is confined to areas that are not accessible to the operator. Localized radiation effects, such as burns, are only possible if safety devices are disabled and parts of the body are placed in the direct X-ray beam. This is why it is important to be familiar with the safety devices, warning systems, and procedures that are in place for your X-ray diffraction equipment.

When a beam of monochromatic X-rays strikes matter, X-rays are scattered in all directions. In crystalline materials atoms are organized in an orderly manner with sets of parallel planes arranged in a lattice structure. Irradiating a crystal with monochromatic X-rays will result in

X-rays emanating from the sample in an orderly pattern that is dependent on the position and intensity of each reflected beam. This directional dependence of the diffracted beam is called a diffraction pattern. It can be used to identify compounds, study phase transformations, determine crystalline size, measure stress or strain, and other similar structure related properties of materials. Since X-ray diffraction is applicable to the study of most solid materials, it has found wide use in a variety of fields including geology, archeology, materials science, chemistry, physics, mineralogy, ceramics, metallurgy, biology, forensics, and medicine, to name a few.

XRD results provide direct evidence for the atomic-level spacing within the crystal lattice of the specimen. This information can tell us details of the crystal structure for the substance ("phase") which is formed from the chemical components in the specimen. Where different phases with identical compositions occur, these can be distinguished by XRD. In addition, finer details of the crystal structure, such as the state of atomic "order", also can be derived.

X-ray Fluorescence or **XRF** is an analytical method for determining the elemental composition of a substance. The sample is irradiated with high intensity X-rays generated from a tungsten target.

Characteristic X-rays are emitted and the spectrum is analyzed in an X-ray spectrometer. The elements present in the sample can be identified by their characteristic wavelengths. The relative proportion of the elements can be estimated by the respective intensities of the lines.

High intensity beams of fairly penetrating radiation are utilized in this method. The instruments are usually completely enclosed to minimize scattered radiation and to prevent access to the primary beam. To prevent accidental exposure to the X-ray beam, sample chamber doors are provided with safety interlocks. The sample is usually placed very close to the X-ray port. Serious burns have been received as a result of insertion of the finger into the sample chamber while the unit was operating.

The XRF method is widely used to measure the elemental composition of materials. Since this method is fast and non-destructive to the sample, it is the method of choice for field applications and industrial production for control of materials.

When a primary X-ray excitation source from an X-ray tube or a radioactive source strikes a sample, the X-ray can either be absorbed by the atom or scattered through the material. The process in which an X-ray is absorbed by the atom by transferring all of its energy to an innermost electron is called the "photoelectric effect." During this process, if the primary X-ray had sufficient energy, electrons are ejected from the inner shells, creating vacancies. These vacancies present an unstable condition for the atom. As the atom returns to its stable condition, electrons from the outer shells are transferred to the inner shells and in the process give off a characteristic X-ray whose energy is the difference between the two binding energies of the corresponding shells. Because each **element** has a unique set of energy levels, each element produces X-rays at a unique set of energies, allowing one to non-destructively measure the elemental composition of a sample. The process of emissions of characteristic X-rays is called "X-ray Fluorescence," or XRF. Analysis using X-ray fluorescence is called "X-ray Fluorescence Spectroscopy."

B) There are two main types of diagnostic X-ray devices: Radiograph – a picture with film or image is sent direct to computer screen and Fluoroscopic – a real time “moving” inspection on internal functions

Diagnostic radiology is the branch of medicine that has traditionally been known for taking and reading X-rays. Like every other field of medicine, technology has radically changed this specialty forever. Diagnostic radiology is the nucleus of almost every physician's diagnosis. Being able to detect disease sooner and pinpoint its location more accurately is a huge factor in stopping disease in its tracks.

C) Industrial X-rays are used for non-destructive testing and has applications in a wide range of industries. Non-destructive testing (NDT) by means of the X-ray beam inspects the integrity of industrial products or processes without damaging the items under observation. Industrial radiography is a form of NDT that uses ionizing radiation. Industrial X-ray machines are used primarily to find defects in castings, structures, and welds. These units help to find foreign material in food products. X-ray machines are used for the inspection of luggage at airports and buildings.

HAZARDS

1.The primary beam: The primary beam is most hazardous because of the extremely high exposure rates. Exposure rates of 4×10^5 R/min at the port have been reported for ordinary diffraction tubes.

2.Leakage or scatter of the primary beam through cracks in ill-fitting or defective equipment: The leakage or scatter of the primary beam through apertures in ill-fitting or defective equipment can produce very high intensity beams of possibly small and irregular cross section.

3.Penetration of the primary beam through the tube housing, shutters or diffraction apparatus: The hazard resulting from penetration of the useful beam through shutters or the X-ray tube housing is slight in well-designed equipment. Adequate shielding is easily attained at the energies commonly used for diffraction and fluorescence analysis.

4.Diffracted rays: Diffracted beams also tend to be small and irregular in shape. They may be directed at almost any angle with respect to the main beam, and occasionally involve exposure rates of the order of 80 R/h for short periods.

The main causes of accidental exposure using **ANALYTICAL** X-ray devices are:

- Putting fingers in X-ray beam to change sample
- Aligning X-ray beam visually
- Modification of shielding
- Failure to realize X-rays are emitted from several ports
- Failure to read & follow manufacturers X-ray operating instructions

X-ray Safety Components

Shielding must be adequate to ensure that stray radiation escaping into the room does not exceed permissible dose limits and is as low as reasonably achievable. **Contact NIU RSO with any concerns about X-ray shielding.**

Diffraction equipment the housing may contain up to four **ports** to allow the primary beam to exit from the tube. Unused ports must be effectively closed to prevent the beam from emerging and accidentally exposing a worker. Ports must be secured in such a manner that tools are required to open the ports.

The **shutter** is located immediately in front of the port of the tube and behind the collimator coupling. The purpose of the shutter is to place a piece of highly absorbent material such as lead in front of the port to block the emergence of the primary beam.

Collimators are connected to the shutter to limit the size of the X-ray beam and reduce the amount of background scatter.

Interlocks are used to prevent access to the primary beam by either cutting off the high voltage supply or closing the shutter.

Effects

The effects of X-ray exposure depend upon the duration of exposure, how fast the dose is delivered, Energy - How much energy was in the X-ray, and total Dose - The magnitude of the dose.

Low Energy (<50 KeV) X-rays can cause damage only to skin or outer part of body while high energy X-rays can penetrate the body to internal organs.

Acute Effects of Radiation Exposure

Appears quickly (days or weeks) and a minimum dose of 100 rads is needed.

Radiation sickness, known as acute radiation sickness (ARS), is a serious illness that occurs when the entire body (or most of it) receives a high dose of radiation, usually over a short period of time. People exposed to radiation will get ARS only if: The radiation dose was high (doses from medical procedures such as chest X-rays are too low to cause ARS; however, doses from radiation therapy to treat cancer may be high enough to cause some ARS symptoms), the radiation was penetrating (that is, able to reach internal organs), the person's entire body, or most of it, received the dose, and the radiation was received in a short time, usually within minutes.

Chronic Effects of Radiation Exposure

Ionizing radiation affects people by depositing energy in body tissue, which can cause cell damage or cell death. In some cases there may be no effect. In other cases, the cell may survive but become abnormal, either temporarily or permanently, or an abnormal cell may become malignant.

Chronic exposure is continuous or intermittent exposure to low levels of radiation over a long period of time. Chronic exposure may produce only effects that can be observed some time following initial exposure. These may include genetic effects and other effects such as cancer, precancerous lesions, benign tumors, cataracts, skin changes, and congenital defects.

Unsafe conditions

You may have an unsafe condition if access interlocks are not working, shielding has been damaged, new X-ray tube was installed, viewing glass is cracked, or a fixed X-ray device has been moved.

If at any time – you feel that the X-ray device is not safe!

Stop work!

Turn power OFF to X-ray (An X-ray requires power to produce radiation) Notify your Principal Investigator and NIU Radiation Safety at 815-753-9251

Time, Distance and Shielding

Time, Distance and Shielding are three fundamental strategies to protect you from unnecessary exposure to X-rays. Using these strategies will help maintain your exposure As Low As Reasonably Achievable (**ALARA**).

- Minimize the time spent near X-ray device (a linear reduction).
- Maximize the distance from X-ray (an inverse square reduction).
- Use shielding of appropriate type (an exponential reduction).

TIME: The dose of radiation a worker receives is directly proportional to the amount of time spent in a radiation field. Thus, reducing the time by one-half will reduce the radiation dose received by one-half. Operators should always work quickly and spend as little time as possible around the equipment while it is operating.

DISTANCE: Radiation exposure decreases rapidly as the distance between the worker and the x-ray source increases. The decrease in exposure from a point source, such as an 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. For example, doubling the distance from an X-ray tube will reduce the dose to one-fourth of its original value, and increasing the distance by a factor of three will reduce the dose to one-ninth of its original value.

Although the inverse square law does not accurately describe scattered radiation, distance will still dramatically reduce the intensity from this source of radiation. Maintaining a safe distance, therefore, represents one the simplest and most effective methods for reducing radiation exposure to workers. Using the principle of distance is especially important when working around open beam analytical X-ray equipment.

SHIELDING: Placing an attenuating material between a worker and the X-ray tube can also reduce Radiation exposure to personnel. Compton and photoelectric interactions in the shielding material reduce the energy of the incident X-ray photon. Thus, substances such as **lead**, that are very dense and have a high atomic number, are very practical shielding materials because of the abundance of atoms and electrons that can interact with the X-ray photon. Shielding is often incorporated into the equipment, such as the metal lining surrounding the X-ray tube. It may also consist of permanent barriers such as concrete and lead walls, leaded glass, and plastic movable screens in the case of analytical X-ray equipment.

Dose Limits

The State of Illinois has set the following limits for maximum permissible external & internal radiation exposures for occupationally exposed individuals ("radiation workers"):

Area of body	Annual Limit
Whole Body	5 rem (5000 mrem)
Lens of the eye	15 rem
Skin or Exremity	50 rem

Dose limitations to an embryo/fetus are 0.5 rem/gestation period, pregnant woman are encouraged to voluntarily inform NIU Radiation Safety, in writing, of her pregnancy and the estimated date of conception.

The permissible limits for persons under 18 years of age are 10% of the above limits. The total effective dose equivalent to individual members of the "general public," from operations at the NIU, must not exceed 0.1 rem per year.

State of Illinois Regulations

X-ray devices must be registered with the Illinois Emergency Management Agency, Department of Nuclear Safety.

Each X-ray system MUST meet State of Illinois requirements.

The State of Illinois routinely inspects X-rays devices per 32 Illinois Administrative Code: Chapt. II, Part 380.

NIU requirements for X-ray devices

If you acquire any X-ray devices YOU MUST **Notify NIU** radiation safety office!

NIU Radiation Safety inspects X-ray devices annually using, at a minimum, the Radiation Protection Plan on page 12 of this document.

X-ray users must be approved by device Principal Investigator (PI).

Responsibilities of X-ray owners & users

Operate X-ray device only as specified in manufacturers operating instructions.

Notify NIU Radiation Safety Office of any repairs, modifications, disposal, or relocation of X-ray device.

X-ray owners & users are required to read NIU Radiation Protection Plan (RPP); page 12 of this document.

At NIU personnel monitoring is required if there is a possibility that an X-ray user might receive greater than 10% of the State of Illinois maximum permissible dose limit.

Most analytical X-ray devices at NIU **do not require** users to be issued personnel monitoring devices.

X-ray users should address any radiation safety concerns to NIU Radiation Safety Officer at: 815-753-9251.

SURVEYING ANALYTICAL X-RAY EQUIPMENT

The Radiation Safety Office conducts an annual radiation survey of X-ray devices in use at NIU using a thin window ($1\text{-}2 \text{ mg/cm}^2$) Geiger Muller (GM) counter. With its fast

response and sensitivity, the GM is ideal for detecting leaks in the shielding and around couplings. If a leak has been detected, the “True” exposure rate can be accurately determined with a low energy ionization chamber. Appropriate actions, such as adding shielding, will then be taken to correct the problem.

Northern Illinois University Radiation Protection Plan

All personnel involved in using a Northern Illinois University (NIU) radiation- generating device must review this program and will be held accountable for violations.



- Any PI that may have a research need to purchase, borrow, or build a radiation generating device shall notify NIU's Radiation Safety Officer (RSO).
- NIU Radiation Safety will inspect X-ray devices and facilities annually.
- Any changes to an X-ray device (new tube, design modifications, etc.) MUST be approved by NIU RSO. *Call 815-753-9251*

1. This X-ray machine will be used as it is currently configured and approved for operation by NIU RSO.
2. This machine will be operated in accordance with the manufacturers operating and safety procedures.
3. A restricted area will be designated as needed by the NIU RSO to protect personnel against undue risks from exposure to radiation.
4. X-ray device users will be persons authorized by the Principal Investigator and/or NIU RSO.
5. Minors (age less than 18) or members of the general public are not allowed to operate X-ray device without **prior** approval of NIU RSO.
6. Members of the public will be considered to be all persons other than those involved in the authorized use, surveillance, or inspection of this machine.
7. Declared pregnant workers may use X-ray after a dosimeter is obtained from NIU RSO. The dosimeter device shall be worn at all times while using X-ray device in compliance with 32 Ill. Admin. Code 340.
8. Radiation dosimeter badges are required for operation of these X-ray devices as directed by NIU RSO.
9. The NIU Radiation Protection Plan will be evaluated and laboratories inspected annually by NIU Radiation Safety
10. Ensure the device is registered with the State of Illinois under Radioactive Materials License

IL-01773-01.

Emergency Contacts:

**Radiation Safety Officer, 815-753-9251 (office),
815-751-4294 (cell)**