

**RADIATION SAFETY GUIDE
FOR USERS OF ANALYTICAL X-RAY SYSTEMS
Radiation Safety Office
Indiana University – Bloomington (IUB)**

1.0 INTRODUCTION

Analytical x-ray devices are important tools in research and teaching. However, the x-rays produced by such devices can pose a hazard to human health. For this reason, special precautions must be observed when these devices are used.

1.1 Authorization Requirements

Each Principal Investigator whose research involves the use of an analytical x-ray device at IUB shall:

- Register each device with the Radiation Safety Officer by completing and submitting Form XS-1.
- Restrict access to the device to those personnel who have completed training requirements as documented in Form XS-2.
- Ensure that the device is operated safely and in accordance with all university requirements as detailed in the *Radiation Safety Guide for Users of Analytical X-Ray Systems*.
- Develop, for each x-ray device, a written standard operating procedure that incorporates “specific” safety considerations and provide training to each user on these procedures.

1.2 Training Requirements

Any individual who wishes to use an analytical x-ray device must first receive sufficient training to ensure that he or she is aware of both the potential hazards associated with the use of such devices and the proper precautions that must be employed to minimize these hazards. The required training is to:

- Complete online IUB Radiation Safety Training for Analytical X-Ray Users.
- Read the *Radiation Safety Guide for Users of Analytical X-Ray Systems*.
- Review safe operating procedures with the Principal Investigator (or Lab Manager).
- Complete an X-Ray Safety Exam and Form XS-2; forward both to the Radiation Safety Office.
- Complete an onsite review of safety procedures with the Radiation Safety Officer (for users of non-enclosed “open beam” systems).

2.0 FUNDAMENTALS OF X-RAY PHYSICS

In 1895, the German physicist, Wilhelm Roentgen was studying the fluorescence produced by cathode rays (electrons) when he discovered a form of highly penetrating radiation which he termed "x-rays". Through subsequent experiments, he and other researchers demonstrated that these x-rays possessed the ability to penetrate matter differentially, as a function of density and elemental composition. This led promptly to the widespread application of x-rays for observing the internal structure of various objects, including the human body. Progressive improvements in x-ray technology over the past century have greatly expanded the uses and capabilities of x-ray devices as analytical tools.

2.1 Nature of X-rays

X-rays consist of photons of electromagnetic radiation and are distinguished from gamma rays only by their origin. Whereas gamma rays arise from transitions in the nuclei of radioactive atoms, x-rays are produced from extranuclear processes involving electrons.

2.2 Production of X-Rays

There are two principal mechanisms by which x-rays are produced. The first mechanism involves the rapid deceleration of a high-speed electron as it enters the electrical field of a nucleus. During this process the electron is deflected and emits a photon of x-radiation. This type of x-ray is often referred to as bremsstrahlung or "braking radiation". For a given source of electrons, a continuous spectrum of bremsstrahlung will be produced up to the maximum energy of the electrons.

The second mechanism by which x-rays are produced is through transitions of electrons between atomic orbits. Such transitions involve the movement of electrons from outer orbits to vacancies within inner orbits. In making such transitions, electrons emit photons of x-radiation with discrete energies given by the differences in energy states at the beginning and the end of the transition. Because such x-rays are distinctive for the particular element and transition, they are called characteristic x-rays.

Both of these basic mechanisms are involved in the production of x-rays in an x-ray tube. Figure 1 is a schematic diagram of a standard x-ray tube. A tungsten filament is heated to 2000⁰C to emit electrons. These electrons are accelerated in an electric field toward a target, which could be tungsten also (or more likely copper or molybdenum for analytical systems). The interaction of electrons in the target results in the emission of a continuous bremsstrahlung spectrum along with characteristic x-rays from the particular target material. Unlike diagnostic x-ray equipment, which primarily utilize the bremsstrahlung x-rays, analytical x-ray systems make use of the characteristic x-rays.

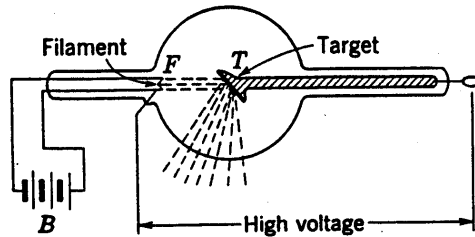


Figure 1. Diagram of a standard x-ray tube

2.3 Interaction of X-Rays with Matter

X-rays transfer their energy to matter through chance encounters with bound electrons or atomic nuclei. These chance encounters result in the ejection of energetic electrons from the atom. Each of the electrons liberated goes on to transfer its energy to matter through thousands of direct ionization events (i.e. events involving collisions between charged particles). Since x-rays and gamma rays transfer energy in this "indirect" manner, they are referred to as "indirectly ionizing radiation".

Because the encounters of photons with atoms are by chance, a given x-ray has a finite probability of passing completely through the medium it is traversing. The probability that an x-ray will pass through a medium without interaction depends upon numerous factors including the energy of the x-ray and the medium's composition and thickness.

3.0 OPERATIONAL MODES OF ANALYTICAL X-RAY SYSTEMS

Analytical x-ray systems generally consist of three basic components: an x-ray source, a specimen support or holder, and a detector. In a given experimental setup, these three components may be enclosed in one integral, commercially available unit or they may be three distinct systems assembled by the user. The way in which the basic components of the x-ray system are assembled depends largely upon the mode of operation. Analytical x-ray systems have two principal modes of operation: diffraction and fluorescence.

3.1 X-Ray Diffraction

X-ray diffraction is used extensively for analyzing the structure and properties of solid materials. Typical acceleration potentials for devices operating in this mode are from 25-50 kVp. This method may be applied in a number of ways depending upon the thickness and form of the sample and the specific results desired. Figure 2 illustrates a typical configuration of a diffraction system. In this example, the primary beam from the target of the x-ray tube emerges from the machine through a collimator and strikes the sample, which diffracts it in a characteristic manner. The diffraction pattern is measured with photographic film or a radiation detector.

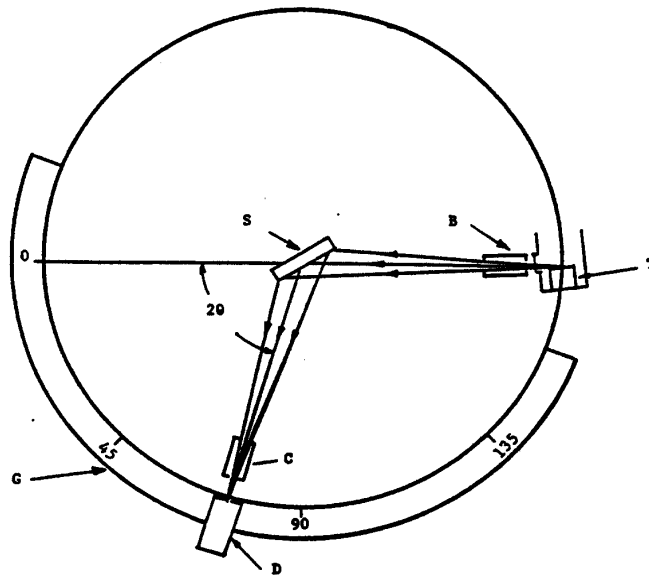


Figure 2. Schematic diagram of x-ray diffractometer.
 T, x-ray tube target; B & C, slit and collimator assemblies;
 S, sample holder; D, x-ray detector; G, goniometer scale graduated in degrees.

3.2 X-Ray Fluorescence

X-ray fluorescence spectroscopy is an analytical method for determining the elemental composition of a sample. Typical acceleration potentials for devices operating in this mode are in the range of 25-100 kVp. Figure 3 illustrates the configuration of a fluorescence system's components. As shown, the primary radiation beam strikes the sample inside a shielded enclosure, and only scattered radiation and secondary radiation produced in the sample emerges from the machine for analysis.

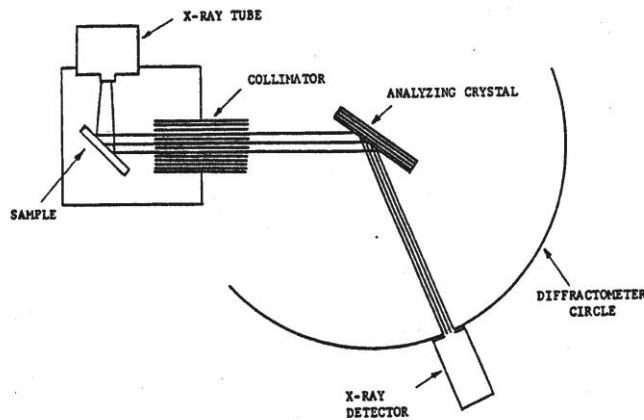


Figure 3. Schematic diagram of x-ray fluorescence spectrometer

4.0 ENCLOSED AND OPEN SYSTEMS

Many modern analytical x-ray systems are designed with interlocked barriers that enclose all system components in a manner that prevents radiation levels in excess of 0.25 mR/hr at any operator position. Such “enclosed” systems dramatically reduce potential risks to personnel that are inherent in the operation of “open beam” systems. For enclosed systems, standard operating procedures should include references to the various interlocks present in the system and the means for recognizing any failures of these interlocks.

5.0 RADIATION HAZARDS OF ANALYTICAL X-RAY SYSTEMS

Analytical x-ray systems produce highly intense beams of x-rays that are predominantly low in energy relative to those utilized in medical diagnosis and therapy. Such x-rays are often described as being "soft" because of the ease by which they are absorbed in matter. While this characteristic enables soft x-rays to be readily shielded (generally requiring only a few millimeters of lead), it also makes them particularly hazardous since they are highly absorbed even by soft tissue. For example, 10 KeV x-rays will deposit 50 percent of their energy in the first 0.25 millimeters of tissue.

Radiation emitted from an analytical x-ray device consists of the primary beam, diffracted beam, scattered x-rays, and secondary x-rays. The degree to which these various radiation components pose a potential hazard to the equipment operator is determined largely by whether the x-ray system is “enclosed” or “open”.

5.1 Primary Beam

The primary beams from analytical x-ray systems are generally well collimated with beam diameters of less than one centimeter. Because of their intensity and their high degree of absorption in tissue, they can produce severe and permanent local injury from exposures of only a fraction of a second. The greatest risk of acute accidental exposure from an analytical system occurs in manipulation of the sample to be irradiated by the direct beam in diffraction studies. Exposure rates on the order of 10,000 R/sec can exist at the tube housing port. At these levels, erythema would be produced from exposures of only 0.03 second and permanent injury could be inflicted in only 0.1 second. The hands, of course, are the part of the body most at risk from such high exposures.

Potential exposure to the primary x-ray beam is generally not a major concern for analytical systems operating in the fluorescence mode since these are generally closed systems (i.e., the primary beam is contained within a shielded enclosure). The possibility of leakage of the primary beam through the shield, however, cannot be discounted.

5.2 Diffracted X-Ray Beam

For x-ray diffraction systems, the diffracted beam is also small and often well collimated with an intensity of up to 80 R/hr. Prolonged or repeated exposures to a beam of this intensity could result in an individual exceeding the annual dose limit for the particular tissue irradiated.

5.3 Scattered and Secondary X-Rays

Through interactions with the sample and shielding material, the primary beam in diffraction systems often produces diffuse patterns of scattered and secondary x-rays in the environment around the equipment. Exposure rates of 100 mR/hr near the shielded sample are possible. In contrast, scattered and secondary radiation levels in the vicinity of a fluorescence system (where only secondary radiation emerges from the shielded target-sample assembly) are generally an order of magnitude less.

6.0 BIOLOGICAL EFFECTS OF X-RAY EXPOSURE

The energy deposited by x-rays as they interact with matter results in the breaking of chemical bonds. If the irradiated matter is living tissue, such chemical changes may result in altered structure or function of constituent cells. If sufficient numbers and types of cells are killed, various "prompt" effects will be manifested. Delayed effects, such as cancer, may also occur ultimately as a result of DNA damage produced by the radiation in surviving cells.

One of the earliest visual indications of a high radiation dose from an analytical x-ray system is erythema or skin reddening. The threshold dose for this effect is approximately 300 rads (3.0 Gray). Generally, this effect occurs within a day of the exposure and then disappears. The effect may recur 8-14 days later with accompanying pain in the affected tissue. After a few days, the skin may return to its normal appearance but remain highly sensitive to future x-ray or ultraviolet radiation exposures. Chronic dermatitis or skin cancer may develop months to years later as a result of the exposure.

For doses in excess of 5000 rads (50 Gray), the affected tissues will likely develop blood flow problems leading to atrophy and ulcerations. Such effects may eventually require the amputation of fingers or major portions of the hand.

7.0 OCCUPATIONAL DOSE LIMITS

Current dose limits for occupational radiation exposure have been established at levels which, in light of present knowledge, should: (1) prevent all acute radiation effects (e.g., erythema, epilation); and (2) limit the risks of late effects such as cancer or genetic damage to very low, "acceptable" levels. The limits are based upon the conservative assumption that there is no safe level of exposure. In other words, even the smallest radiation dose has some probability of causing a late effect such as cancer or genetic damage. This assumption has led to the general philosophy of not only keeping personnel doses below recommended levels or regulatory limits but of also maintaining all doses "**as low as is reasonably achievable**" (ALARA). This is a fundamental tenet of current radiation safety practice. The Indiana Administrative Code (Section 410 IAC 5-4-2) specifies dose limits for x-ray users. These are listed in Table 1 below.

Table 1. Occupational Dose Limits for External Exposures to Ionizing Radiation.

	Quarterly	Annual
Whole body; head and trunk; lens of eye; gonads	1.25 rems	5 rems
Hands and forearms; feet and ankles	18.75 rems	75 rems
Skin of the whole body	7.5 rems	30 rems

8.0 HAZARD CONTROL MEASURES FOR ANALYTICAL X-RAY SYSTEMS

The requirements for controlling potential hazards associated with analytical x-ray systems are specified in Rule 8, Article 5, Title 410 of the Indiana Administrative Code. Use of analytical x-ray equipment at Indiana University – Bloomington must comply fully with these regulatory requirements, which are summarized below.

8.1 Equipment Requirements

8.1.1 Beam Entry Shut-off Device

A device which prevents the entry of any portion of an individual's body into the primary beam path or which causes the beam to be shut off upon entry into its path shall be provided on all open-beam configurations.

8.1.2 Warning Devices

Open-beam configurations shall be provided with a readily discernible indication of x-ray tube status (ON-OFF) and/or shutter status (OPEN-CLOSED).

8.1.3 Ports

Unused ports on radiation source housings shall be secured in the closed position in a manner that will prevent casual opening.

8.1.4 Labeling

All analytical x-ray equipment shall be labeled with a readily discernible sign bearing the radiation symbol and the words:

- (1) "CAUTION - HIGH INTENSITY X-RAY BEAM" on the x-ray source housing;

and

- (2) "CAUTION RADIATION - THIS EQUIPMENT PRODUCES RADIATION WHEN ENERGIZED" near any switch that energizes the x-ray tube.

8.1.5 Shutters

On open-beam configurations, each port on the source housing shall be equipped with a shutter that cannot be opened unless a collimator or coupling has been connected to the port.

8.1.6 Warning Lights

An easily visible warning light with the words "X-RAY ON" shall be located near any switch that energizes an x-ray tube and shall be illuminated only when the tube is energized.

8.1.7 Housing Interlock

Each x-ray tube housing shall be equipped with an interlock that shuts off the tube if the tube is removed from the housing or if the housing is disassembled.

8.1.8 Shielding Provided by Housing

Each x-ray tube housing shall be constructed so that, with all shutters closed, the radiation, measured at a distance of five centimeters from its surface, is not capable of producing a dose in excess of 2.5 millirems in one hour.

8.2 Area Requirements

8.2.1 Radiation Levels

The components of an analytical x-ray system shall be arranged and shall be sufficiently shielded to ensure that radiation levels near the components cannot result in an individual receiving a dose in excess of 2 millirem in any one hour.

8.2.2 Surveys

Radiation surveys of all analytical x-ray systems sufficient to show compliance with the radiation levels established in 8.2.1 must be performed:

- (1) Upon installation of the equipment and at least every twelve months thereafter.
- (2) Following any change in the number, type, or arrangement of components in the system.
- (3) Following any maintenance requiring the disassembly or removal of a system component.

8.2.3 Posting

Each area containing analytical x-ray equipment shall be conspicuously posted with a sign bearing the radiation symbol and the words "CAUTION - X-RAY EQUIPMENT."

8.3 Operating Requirements

8.3.1 Procedures

Normal operating procedures shall be written and available to all users of analytical x-ray equipment.

8.3.2 Bypassing Safety Devices

No individual shall bypass a safety device or interlock unless the individual has obtained written approval from the Radiation Safety Officer.

8.3.3 Altering System Components

No operation involving the removal or alteration of shielding materials, tube housing, shutter, collimators, or beam stops shall be performed until it has been determined that the beam is off and will remain off until conditions have been restored.

8.4 Personnel Monitoring Requirements

Finger or wrist dosimeters shall be provided to and shall be used by all analytical x-ray equipment workers using systems having open-beam configurations and not equipped with a beam shut-off device. At Indiana University, the Radiation Safety Officer (RSO) issues ring dosimeters to all users of x-ray diffraction devices. The results of personnel monitoring performed for individuals working with x-rays at Indiana University - Bloomington are maintained on file by the RSO. Each individual's exposure records are available to him or her upon request. An individual is notified immediately by the RSO should his or her reported exposure for a particular monitoring period appear to be excessive.

9.0 RADIATION QUANTITIES AND TERMS

The following quantities and terms are essential to the description and measurement of x-rays and other forms of ionizing radiation.

9.1 Exposure

Exposure is a measure of the strength of a radiation field at some point. It is usually defined as the amount of charge (i.e., sum of all ions of one sign) produced in a unit mass of air when the interacting photons are completely absorbed in that mass. The most commonly used unit of exposure is the "roentgen" (R) which is defined as that amount of X or gamma radiation which produces 2.58×10^{-4} coulombs of charge per kilogram of dry air. In cases where exposure is to be expressed as a rate, the unit would be R/hr or, more commonly, milliroentgen per hour (mR/hr).

9.2 Absorbed Dose

Whereas exposure is defined for air, the absorbed dose is the amount of energy imparted by radiation to a given mass of any material. The special unit of absorbed dose is the "rad" which is defined as a dose of 100 ergs of energy per gram of the matter. The S.I. unit for absorbed dose is the gray where 1 gray equals 100 rads. Absorbed dose may also be expressed as a rate with units of rad/hr, millirad/hr, gray/hr, etc.

9.3 Dose Equivalent

Although the biological effects of radiation are dependent upon the absorbed dose, some types of radiation produce greater effects than others for the same absorbed dose. In order to account for these variations when describing human health risk from radiation exposure, the quantity "dose equivalent" is used. This is the absorbed dose multiplied by certain "quality" and "modifying" factors indicative of the relative biological-damage potential of the particular type of radiation. The special unit of dose equivalent is the rem or mrem. The S.I. unit for dose equivalent is the sievert where 1 sievert equals 100 rem. Dose equivalent may likewise be expressed as a rate with units of rem/hr millirem/hr, sieverts/hr, etc. For gamma or x-ray exposures, the numerical value of the rem is essentially equal to that of the rad.

9.4 Shielding

Shielding is any material, which is placed around or adjacent to a source of penetrating radiation for the purpose of attenuating the exposure rate from the source. For shielding x-rays, materials composed of high atomic number elements such as lead are highly effective.

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