UNIVERSITY OF OREGON
Environmental Health & Safety

Analytical X-ray Machine Safety Tutorial

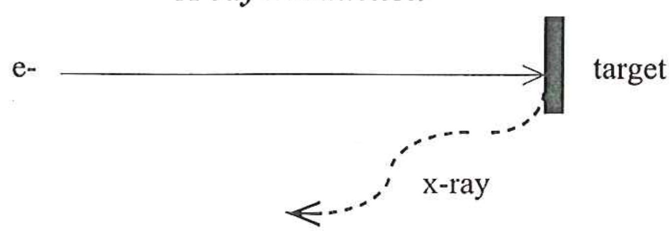
Introduction

This tutorial is intended to cover the aspects of radiation safety in regards to the use of analytical x-ray machines. In addition, instruction covering the proper operating procedures of the equipment is required and must be documented.

What are x-rays

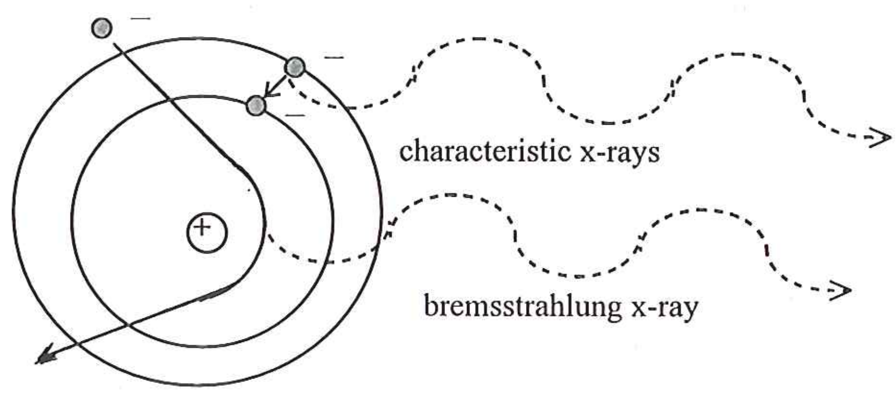
X-rays are photons (electromagnetic radiation) which originate in the energy shells of an atom, as opposed to gamma rays, which are produced in the nucleus of an atom.

X-ray Production



Electrons bombarding target with resulting x-ray

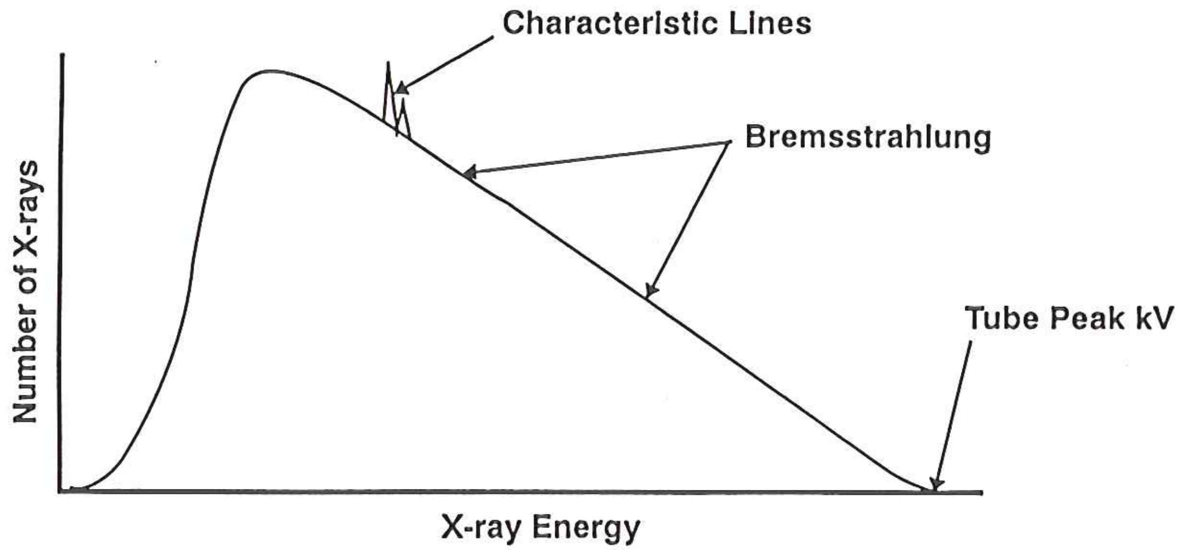
X-rays are produced when accelerated electrons interact with a target, usually a metal absorber, or with a crystalline structure. The method of x-ray production is known as bremsstrahlung.



Bremsstrahlung and characteristic x-rays.

Bremsstrahlung means "braking radiation" in German. Bremsstrahlung occurs when high energy electrons are slowed down in the presence of the field of the atom. The deceleration of the electron causes the release of energy in the form of x-rays.

The bremsstrahlung produced is proportional to the square of the energy of the accelerated electrons used to produce it, and is also proportional to the atomic number (Z) of the target (absorber).



Spectrum of x-rays. Note characteristic peaks.

The x-rays from bombardment of a target with electrons are emitted as a continuous spectrum of different x-ray energies. However, depending on the target, the spectrum will have characteristic photon peaks which result from displacement of electrons in the shell of the target atom.

Many different types of machines produce x-rays, either intentionally or inadvertently. Some devices that can produce x-rays are x-ray diffractometers, electron microscopes, x-ray photoelectron spectrometers, and Van de Graaf accelerators. X-rays can also be produced by the attenuation of beta particles emitted from radionuclides.

What are the commonly-used units of radiation

With the use of Analytical x-rays, we are concerned with the possibility of receiving an unnecessary dose of radiation. The units used to describe the radiation have been the **roentgen**(R), the **rad**, and the **rem**. Dose is currently reported in millirem although the preferred unit is the *System Internationale (SI)* unit, the **sievert** (Sv). A sievert is equal to 100 rem.

The **roentgen**(R) is a unit of exposure in air. It is defined as the amount of x-ray or gamma radiation that will generate 2.58E-4 coulombs per kilogram of air at standard temperature and pressure. The roentgen is limited to photons only, applies only to air and is defined only for energy less than 3 MeV. The unit is being phased out of use in radiation safety because of these limitations but is still often used as reference.

The **rad** stands for *R*adiation *A*bsorbed *D*ose. The rad is the amount of radiation that will deposit 0.01 Joules of energy in a kilogram of material. The *System Internationale* unit of absorbed dose is the Gray (Gy), which is also measured in Joules per kilogram. A gray is equal to 100 rad.

The **rem** stands for *R*oentgen *E*quivalent *M*an. The rem is a unit of absorbed dose and is equal to the rad multiplied by a quality factor that varies according to the type of radiation. The quality factor for x-rays, gammas, and betas is equal to 1. For fast neutrons the quality factor is 10, for alpha particles it is 20.

As a matter of historical record, before the roentgen was adopted officially in 1928 to replace a quantity that had been unofficially in wide use to measure the output of an x-ray machine. The "erythema dose" was measured by timing the irradiation period necessary to just produce reddening on the skin of the hand or arm placed in the beam. This method resulted in much unwarranted tissue damage. This type of unnecessary damage is what we are now trying to prevent.

What are the sources of "background" radiation

The human body is exposed to radiation from a variety of "background' sources - some natural, some manmade.

In 1987 the National Council of Radiation Protection (NCRP) issued Report 93, which summarized the data on all sources of radiation exposure to individuals in the United States. A summary of the total average Effective Dose Equivalent is shown in the table:

Average Annual Effective Dose Equivalent to the Entire U.S. Population

Source of Radiation	mrem	mSv
Natural Sources		
Radon	200	2.0
Other	100	1.0
Occupational	0.9	0.009
Nuclear Fuel Cycle	0.05	0.0005
Consumer Products	5-13	0.05-0.13
Misc. Environmental	0.06	0.0006
Medical		
Diagnostic	39	0.39
Nuclear Medicine	14	0.14
ROUNDED TOTAL	**360**	**3.6**

Natural Sources

"Natural" background radiation is composed of cosmic radiation, external terrestrial radiation and internal terrestrial radiation. Cosmic radiation originates outside our atmosphere and the dose received varies with altitude. The external terrestrial radiation contribution is that from the radionuclides deposited in the earth's crust. The internal terrestrial radiation is from the radionuclides that are consumed with food or water or inhaled as radioactive gases.

Occupational Sources

This source of exposure is for individuals who actually work with radiation. According to NCRP Report 93, the average dose for workers that were actually exposed to radiation (in

1980) was approximately 230 mrem. The average annual occupational dose for all workers was 0.9 mrem (0.009 mSv).

The Nuclear Fuel Cycle

Each step in the nuclear fuel cycle can produce radioactive effluents in the air or water. Release of radioactivity can occur during the mining, milling conversion, fuel enrichment, fabrication, operation and storage phases of the cycle.

Consumer Products

The estimated annual dose from some commonly used consumer products:

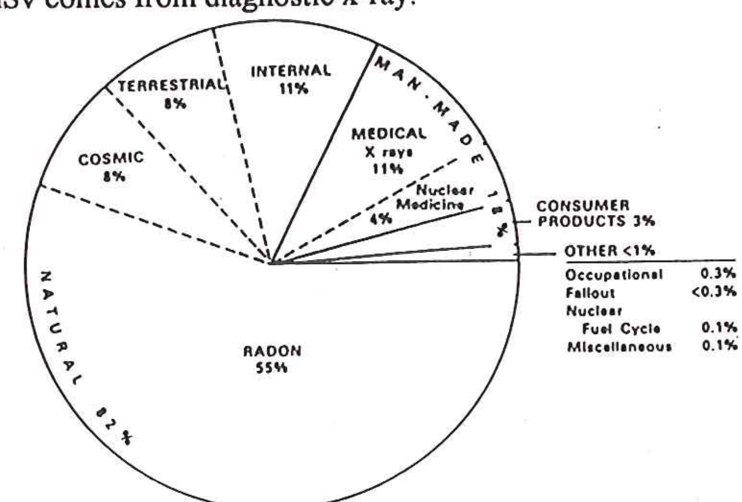
- Cigarettes, 1.5 pack / day
  - 80 mSv (8,000 mrem)
- Natural gas cook stove
  - 0.06-0.09 mSv (6-9 mrem)
- Smoke detector
  - 0.1 mSv (1 mrem)
- Building masonry
  - 0.07 mSv (7 mrem)
- Coal fired power plant, to lungs
  - 0.01-0.04 mSv (1-4 mrem)

Miscellaneous Environmental Sources

A few environmental sources of background radiation are not included in the above categories. Radiation dose may also be received form the fallout of nuclear weapons testing, some Department of Energy facilities, some Nuclear Regulatory Commission-licensed facilities, some mineral extraction facilities and transportation of radioactive materials.

Medical Sources

The two contributors to the radiation dose from medical sources are diagnostic x-rays and nuclear medicine procedures. Of the estimated 0.53 mSv dose received annually, approximately 0.39 mSv comes from diagnostic x-ray.



Contributions to US population background radiation

What's so special about analytical x-ray machines

"Analytical x-ray machine" is a general term which refers to instruments that produce x-rays for the purpose of analyzing materials or structures such as x-ray diffractometers (XRDs) and certain spectrometers (such as x-ray photoelectron spectrometers).

For the purposes of complying with State and Federal law, instruments not normally considered to be analytical x-ray machines, such as electron microscopes and particle accelerators, are also classified as such. These instruments are capable of producing x-rays as a by-product of their function.

The specific hazards of analytical x-ray equipment can include:

Exposure to an intense, localized x-ray beam

Exposure to diffracted and/or scattered portions of the primary x-ray beam (includes x-ray leakage)

Some Sources of Radiation from Analytical X-ray machines

Source	Exposure Rate
Primary beam - open, unshielded port	50,000 - 500,000 R / min.
Primary beam - between collimator / slit assemblies and sample	5,000 - 50,000 R / min.
Leakage of primary beam (@5 cm.)	0.5 - 5 R / hr.
Scatter (@ 5 cm.)	< 10 - 30 mR/ hr.

Note: The table is in Roentgen since it is exposure in air

A very high dose rate to the skin can occur. In the direct beam, a significant x-ray burn can occur in a few seconds. Skin layers are destroyed right down to the underlying bone. These injuries are quite painful and slow healing due to destruction of the underlying skin regenerative tissue.

What are the biological effects of radiation?

There are two general types of biological effects of radiation. They are somatic or whole body effects which may be 'prompt' or 'delayed' and genetic effects of radiation.
In order to produce "prompt" effects attributed to radiation exposure, the whole body acute exposure must be quite large. The following table describes the prompt effects of an exposure.

"Prompt" Effects

Dose			
Sv	rem	Syndrome	Problem
1 - 10	100 - 1000	Hematopoietic	maintaining a minimum level of circulating blood cells
10 - 50	1000 - 5000	Gastrointestinal	breakdown of the small intestine, bacterial invasion of the blood stream
50 - 100	5000 - 10000	Central Nervous System	loss of muscular coordination and death results within hours

It is important to note that whole body radiation exposures of magnitudes shown above are extremely rare. As a comparison, the maximum allowable whole body dose permitted for a radiation worker in one year is 0.05 Sv (5.0 rem). The maximum allowable extremity (e.g. hands) dose permitted for a radiation worker in one year is 0.5 Sv (50 rem).

The long-term or delayed effects of an acute whole body exposure to radiation are often classified as life shortening, leukemia, and other cancers.

The life shortening aspect appears to be a result of accelerated aging. This is well documented in animal experiments. The estimate is an estimated loss of life expectancy of a few days per rem of radiation.

For leukemia and other cancers, one of the best summaries of human data is the 1990 report by the **U.S. National Academy of Sciences Biological Effects of Ionizing Radiation Committee (BIER V)** Their estimate of the risk of contracting leukemia following an acute, one-time radiation exposure of 0.1 Sv (10 rem) is approximately 95 excess deaths from leukemia per 100,000 persons over the rest of the exposed person's lifetime. *Without* the extra radiation, the **Vital Statistics of the US 1980**, states about 685 individuals per 100,000 residents will die of leukemia.

The effects mentioned above relate to the effects of an acute one-time exposure to radiation, not low dose, low dose rate radiation exposure. A person might display clinical symptoms of radiation exposure after receiving a single, whole body exposure of 0.05 Sv (5 rem); however, if the same total 0.05 Sv (5 rem) were delivered in low doses over 20 years, the same clinical symptoms would not be manifested.

Genetic effects are those that would show up in the offspring of the exposed person. From animal studies it was concluded that it took about 0.4 Sv (40 rem) to produce a mutation.

The effects of low dose, low dose rate irradiation is still debated. Since the effects of low dose radiation are not easily documented the regulatory community has adopted a policy of **ALARA, As Low As Reasonably Achievable.** The objective is to keep all radiation exposure to a minimum.

What can I do about protecting myself?

There are three general principles of radiation protection: time, distance and shielding.

Time: Decreasing the amount of time spent in the vicinity of the source of radiation will decrease the amount of radiation exposure. Radiation doses are approximately directly proportional to the time spent in a radiation field.

Distance: Increasing the distance from a source of radiation will decrease the amount of radiation exposure. Radiation doses will decrease approximately as the inverse square of the distance from the radiation source.

Shielding: Increasing the amount of shielding around a source of radiation will decrease the amount of radiation exposure.

Shielding for analytical x-ray units can range from the use of leaded glass to enclosures constructed of tin-impregnated polycarbonate.

What about radiation detection equipment?

An x-ray unit should be surveyed before resuming routine operations any time that the unit or procedures for use of the unit are changed such that radiation output may be increased in intensity, penetration or distribution.

A ratemeter with a scintillation detector, such as a sodium-iodide crystal, can be used to detect leakage from an x-ray unit. However, a ratemeter can exhibit a large variation in response with x-ray energy, and is not appropriate for quantitative assessment of radiation leakage levels.

In order to assess the levels of leakage, a survey instrument calibrated to the x-ray energies that might be encountered should be used. The instrument preferred by the Radiation Safety office is a hand-held ionization chamber.

What are the main causes of accidents?

There are four main causes of accidents:

1. Poor equipment configurations; e.g., unused beam ports not covered.
2. Manipulation of equipment when energized; e.g., adjustment of samples or alignment of cameras when x-ray beam is on.
3. Equipment failure; e.g., failure of shutter, warning lights
4. Inadequate training or violation of procedure; e.g. incorrect use of equipment

Suggestion for preventing accidents:

1. Make sure that any unused ports are capped off.
2. Perform alignments / adjustments and maintenance only when the beam is not energized.
3. Test all safety devices periodically
4. Have written procedures and FOLLOW them!

What are the requirements and regulations governing the use of x-ray sources?

The following requirements are condensed form the Oregon Administrative Rules: Chapter 333, Division 108.

- A device which prevents personnel exposure to the primary beam. If a device is not present, procedures must be submitted that would assure the operators and others will be informed of the absence of the safety device.
- There must be a readily discernible indication of an energized x-ray beam. This is usually a light.
- Unused ports shall be secured in the closed position.
- A label saying "CAUTION - HIGH INTENSITY X-RAY BEAM". on the source housing.
- A label saying "CAUTION RADIATION - THIS EQUIPMENT PRODUCES RADIATION WHEN ENERGIZED" near any switch which energizes an X-ray tube.
- A visible light labeled X-RAY ON, near any switch that energizes the X-ray tube.

- Radiation surveys shall be conducted upon installation, following any change in the initial arrangement, following any maintenance requiring disassembly or removal of a component, and at least every 12 months thereafter.
- Normal operating procedures must be written and available to all analytical X-ray equipment workers.
- No individual shall bypass a safety device without approval of the Radiation Safety Officer.
- Operators shall be informed of the radiation hazards, safe working conditions, proper procedures for operating the equipment and the significance of the various warning devices.
- Operators must know how to report an actual or suspected radiation exposure.
  At the University of Oregon any suspected exposure should be reported to the supervisor of the unit and the Radiation Safety Officer as soon as possible.
- Dosimeters must be worn by workers using analytical X-ray equipment having an open-beam configuration and not equipped with a safety device.

In addition, notify the Office of Environmental Health and Safety:

◊ if any X-ray machine is modified or moved to a new location.

◊ if any X-ray unit is rendered inoperable and will not be repaired or is moved to long term storage.

◊ prior to receipt and installation of any new X-ray producing equipment.

References

Woo, Melissa, UIUC Analytical X-ray Machine Safety Tutorial, 1997

Gollnick, Daniel, Basic Radiation Protection Technology, 1994

NCRP Report No. 93, Ionizing Radiation Exposure of the Population of the United States, 1987