X-ray Safety for Analytical Instrumentation: It's what you cannot see or feel that will hurt you!

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X-rays are high-energy electromagnetic radiation that will ionize material that it illuminates and as such can be very hazardous to unprotected skin, organs and tissue. For scientific instrumentation, the X-rays are restricted to short linear paths between the X-ray source, the specimen and the detector. These paths have a high degree of directionality and are the most dangerous areas of the X-ray instrument that the ordinary user can access. It is thus wise to educate oneself on where the X-ray beam path is and how to avoid exposure (Cook and Oosterkamp, 1962; Martin, 1983).

X-rays are invisible and if they come into contact with your skin they cannot be seen or felt directly. In some instances the X-rays will ionize the air and a tingling sensation will be felt when one comes near the X-ray beam path, however this indicator is unreliable and cannot be trusted as a warning sign before exposure. It is therefore necessary to take every precaution to avoid accidental exposure, rather then rely on some outside stimulation. It is what you cannot see or feel that will hurt you!

The goal of the X-ray safety program is to keep the radiation exposure of any individual occupational worker to be **A**s **L**ow **A**s **R**easonably **P**ossible or **ALARA.** For X-ray instrumentation workers, in general, this is achieved by reducing the time you can be exposed to the radiation source, increasing the distance between you and the radiation source and increasing the shielding between you and the radiation source. Instrumentation design and *Operational Safety Procedures* (OSP) specifically written for each instrument and laboratory can help accomplish these goals.

Modern analytical X-ray instruments are very safe but are still considered to be ultra hazardous equipment. The manufacture and use of these instruments is regulated by federal and state agencies and require the incorporation of a variety of "fail safe" devices that will prevent accidental exposure. Even with the high degree of built in safety features; it is still wise for the occasional user to limit their access to the X-ray beam path and specimen area of the instrument. The less time spent in harm's way the lower the probability of exposure and if exposed the less time spent in direct contact with the X-ray radiation.

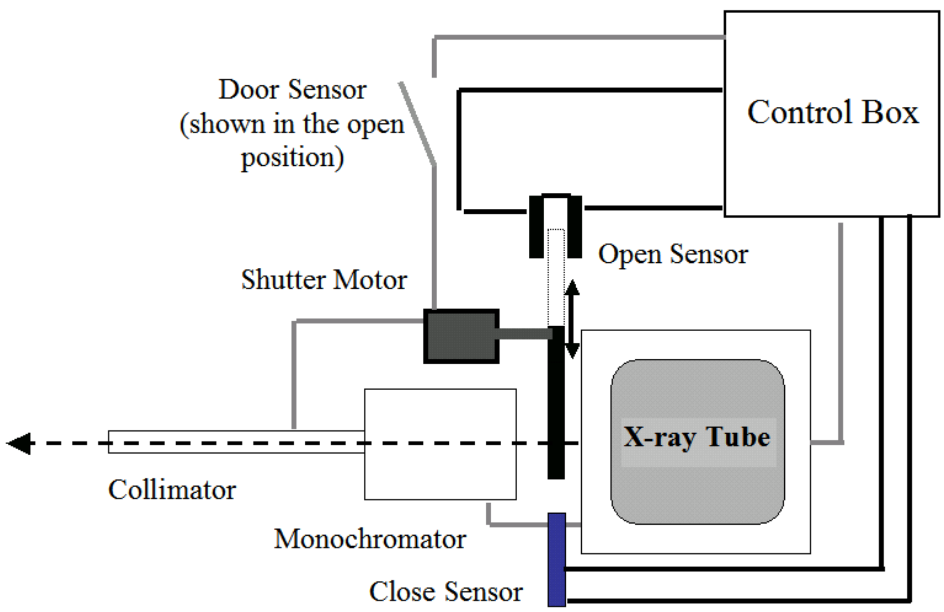
The units used when discussing radiation exposure are the Roentgen (**R**), radiation absorbed dose (**rad**) and the radiation equivalent dose (**rem**). The Roentgen is the amount of radiation that produces one unit of ions/cm^3 where 1m**R**/hr is considered a low rate and 100m**R**/hr is considered high. The **rad** is the energy imparted to matter in volume (V) divided by the mass and the **rem** is the product of the absorbed dose and the relative biological effect (RBE) necessary to express on a common scale (in SI units : 100 **rad** = 1 gray, **Gy,** and 100 **rem =** 1 sievert, **Sv**). For X-ray radiation the RBE = 1 and 1 **rad** x (RBE) = 1 **rem**. In fact, for X-ray radiation of 10-20Kev one **R**/hr = one **rad** = one **rem**.

The Maximum Permissible Dose (radiation) for occupational users has been defined by the Department of Energy (10 CFR Part 835 : http://www.hss.energy.gov/healthsafety/) as 5 **rem**/yr for the whole body, 15 **rem**/yr for the eyes and 50 **rem**/yr for the hands. Minors and non-occupational workers (custodians, plumbers etc) are allowed only 0.1 **rem**/yr, while a declared pregnant occupational worker is allowed less than 0.5 **rem**/9-month. The highest background radiation in the world is 5 **rem**/yr located at Kerala, India, while in the USA the highest background radiation of 0.2 **rem**/yr is located around Leadville, Colorado. The lowest background radiation (0.07 **rem**/yr) is located along the Atlantic and Gulf coast while the average background radiation is 0.09 **rem**/yr. For comparison it should be noted that a single dental X-ray would deliver about 0.3 **rem** of radiation, which means that two exams per year will accumulate about 1.2 **rem**/yr.

The radiation sources for most analytical X-ray instruments are the sealed tube, the normal focus rotating anode and the micro-focus rotating anode tube. The X-rays are generated by the deacceleration of high velocity electrons by a metallic target in the tube. In practice thousands of watts of electricity are required to accelerate the electrons and circulating water is required to cool the target. From a safety standpoint, the radiation produced by these tubes (measured at the window of the tube where the X-rays exit) is approximately 10^7 **R**/hr for the sealed tube, 10^8 **R**/hr for the normal focus rotating anode and about $3x10^8$ **R**/hr for the micro-focus rotating anode (Honkimski et al., 1990; Lubenau, 1971). For safety reasons, it is important for the user to know which tube the X-ray instrument employs and what the tube's power consumption is.

The three most important X-ray safety features for modern analytical X-ray instruments are the primary (safety) shutter, the instrument enclosure and the beam stop. The primary shutter is a mechanical device that can be inserted in the X-ray path to completely attenuate the X-ray beam. The primary shutter is actuated by an electronic solenoid and an open and closed sensor will determine its position. Normally if the command to open the shutter is made and the open shutter sensor does not register a physically open shutter than the X-ray generator will deactivate. The same is true when a close command will not result in the closure of the shutter. This safety feature cannot be overridden.

The instrument enclosure keeps stray X-ray radiation from leaking out and keeps the user from accidentally coming into contact with the X-ray beam. Sensors normally monitor the doors and the panels to the enclosure. If the door or panel is open the shutter will immediately close and cannot be opened unless the door or panel is secured (See figure below). For some instruments the doors and panels are directly linked to the X-ray generator so that opening them while the shutter is open, will result in deactivation. Expert users can override the door sensors by activating a keyed switch, which is necessary for routine instrument alignment but is not intended for everyday instrument use.



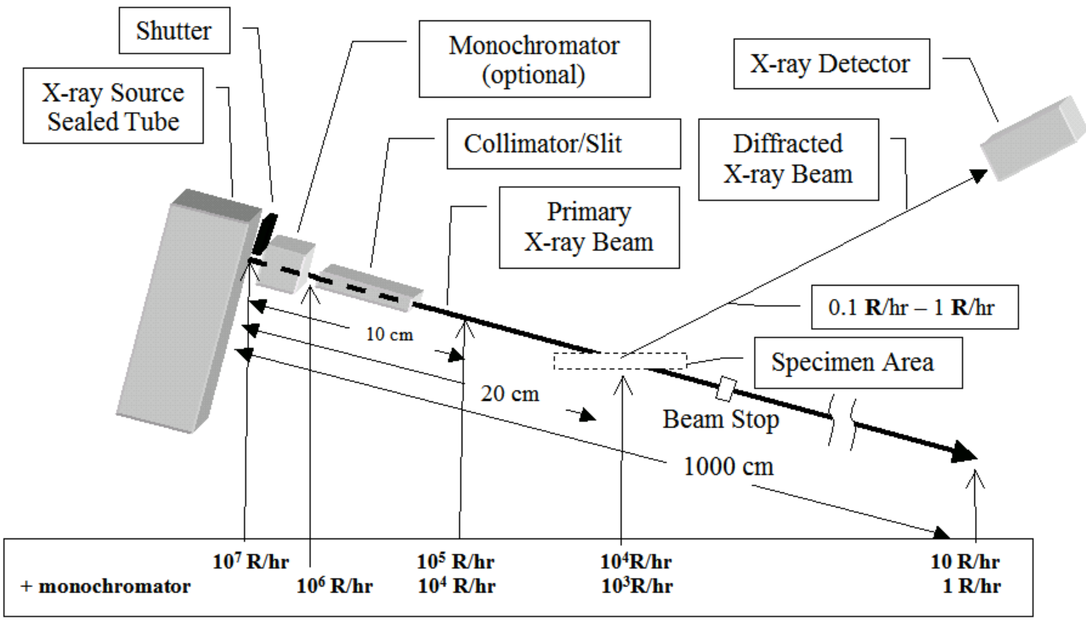
The beam stop is also an important safety device; however it is not as important on modern instrument where shutters and instrument enclosures limit the ordinary user from access to open X-ray beams. The beam stop on an instrument set up in the reflection mode is the specimen itself, while transmission instruments rely on small metallic devices that are positioned after the specimen and before the detector. The main safety feature of the beam stop is to shorten the pathway of the X-ray beam and to attenuate X-rays that are not employed in the experiment.

Air will attenuate X-rays as well as monochromators, slits, filters and other instrument attachments. The attenuation of radiation by air for sealed tube X-ray sources can be estimated by the equation (Lubenau, 1971):

$$R/hr \cong 2432 \times \frac{kV \times mA}{d^2} \times Z$$

where kV x mA is the power applied to the X-ray tube, Z is the atomic number of the target element of the tube and d is the distance, in cm, from the source. Monochromators that are positioned in the X-ray path will attenuate the radiation by about 25% for multi-layer mirrors, 50% for Nickel Filters (0.015mm thick) and about 75% for pyrolytic graphite crystals. Collimators and slits that are positioned in the X-ray path, will effect its direction, separate the users from the source and reduce the area of the X-ray beam.

For the user it is critical to evaluate the X-ray pathway and to know the radiation exposure limits. The figure below is an estimate based on the known X-ray flux for a Copper sealed tube (at its maximum power rate), the inverse rate law and the attenuation factor for the X-ray monochromators (Jenkins and Haas, 1975; Shapiro, 2002). The real radiation doses will vary with the age of the X-ray tube, the specific monochromators, slits and filters.



In some localities users are required to wear personal dosimetery in the form of Thermo-Luminescence Devices (TLD) that will detect accidental radiation exposure. The active area of a TLD consists of a small Lithium Fluoride material that can detect radiation doses between .002 to 10^5 **rad**. TLDs are used in both lapel and extremity badges. The lapel badge is normally worn at the level of the X-ray beam while the extremity badge is normally a ring that can be worn on your finger.

The advantage of the badges is that they are often the first documented indication of accidental exposure. The disadvantage of such devices is their usefulness in analytical X-ray instrumentation where the directionality of the primary beam and the size of the badge itself reduce the chance that an accident will be detected. For example given the area of possible X-ray exposure (the upper torso), the size of the X-ray beam and the size of the dosimeter, the likelihood of a stray X-ray photon striking a lapel badge is about 1 in 10,000 and for the extremity badge it increases to 1 in 100. Given these odds and the few accidental exposures for normal usage, the personal dosimeters have been discontinued in many analytical X-ray laboratories.

The health risk of exposure to X-ray radiation is roughly proportional to the square of the dose. Exposures less than 0.1 **rem** are not considered significant while exposures greater than 3000 **rem** will cause cell sterilization. No visible skin damage is seen for X-ray exposures below 300 **rem**, however the cancer risks for such exposures are unknown. For most radiation workers a 100 **rem**/life shows only a statistical decrease in life expectancy of about 1%. On average one will lose one day of life for each **rem** of exposure (Lindel, 1968; Lubenau et al., 1969; Steidley et al., 1981).

Given these facts exposures greater than 1000 **rem** will produce noticeable physiological effects. For soft tissue the depth of exposure of 10-20 keV X-rays is 1.3-4.3 mm ($t_{1/2}$). In the first hour some tingling is experienced. In the first week swelling, blistering, pain, erythema, hair loss (epilation), skin loss (desquamation) is seen. In the first month ulcers (sores that will not heal) and gangrene can occur. In the first year, a 1000 **rem** exposure could lead to loss of digits or skin graphs and cardiacs in the eyes. Any radiation dose greater than 0.1 **rem** is considered significant and should be documented.

If you believe you have been exposed do not ignore it. If you are exposed you may not feel any pain for at least 1 to 6 hours and by then it will be too late. You should stop what you are doing and deactivate the instrument. Leave the instrument *as is*, a radiation safety officer will need to investigate the sight and to ascertain the extent of the radiation exposure. You must contact your supervisor, the laboratory manager and the radiation safety officer for your institution. You must immediately document where, when and how you were exposed to the radiation, in the instrument log, not only for yourself but also for anyone else that may use that particular instrument (or procedure) in the future. Immediately return any personal dosimeters (if any) to your radiation safety officer. Finally, you should take a complete physical as soon as possible to document your current health status. It is important to know what to do in case of such emergences and how to secure the instrument to prevent future accidental exposures.

Modern analytical X-ray instruments are amongst the safest machines of their type in the laboratory. Still these devices are classified as "ultra hazardous" and as such strict liability, use-of-tools and assumption of risk arguments are all valid. In the end, the procedures set forth by your national, state and local radiation safety offices must be followed by the user exactly, any deviations are not legal. You are the first radiation safety officer when it comes to prevention of accidental radiation exposure and your own good health.

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