The Interaction of X-rays with Matter and Radiation Safety

(prepared by James R. Connolly, for EPS400-002, Introduction to X-Ray Powder Diffraction, Spring 2005)

Introduction

Human tissue can be severely damaged if exposed to the X-rays used in X-ray diffraction. Long-term, chronic exposures at moderate levels can directly cause a variety of skin disorders, and chronic relatively low-level exposures may be a factor in increased cancer risk in exposed workers. Many early workers with X-rays developed serious ailments (from skin lesions to various forms of cancer) as a consequence of their work. Although there are safeguards associated with modern XRD equipment designed to minimize or eliminate radiation in the work environment, an awareness of the dangers of radiation exposure and associated safety issues is required for anyone desiring to use the laboratory.

During the first 6 weeks of this class, all students need to become familiar with radiation safety issues and take (and pass) an exam administered by UNM's Radiation Safety Office. This office is part of the UNM's department of Occupational Safety and Health. Some of the material in this section is abstracted from study materials provided by that office. Another source is the excellent online tutorial from the University of Illinois (http://www.ehs.uiuc.edu/rss/xray/xrayintro.htm). An excellent summary of safety issues will be found in the summary article by Jenkins and Haas (1973) available on our lab website (http://epswww.unm.edu/resources.htm). Each student should contact campus Radiation Safety Officer Larry Cleveland (277-0317) and pick up a copy of these materials before attempting to pass the exam. The exam covers topics in the following areas:

1. Radiation hazards associated with analytical x-ray equipment
2. Biological effects of X-rays including symptoms of acute localized exposures and risks associated with low-level exposures
3. Quantities and units of exposure, dose, and dose equivalent (roentgen, rad, rem)
4. Regulations concerning use and control of equipment.

While the interaction of X-rays with tissue is important to understand from the standpoint of safety, those same interactions with specimens provide the X-ray scattering and other effects that enable and complicate the interpretation of diffraction data.

Interaction of X-Rays with Matter

X-rays possess intrinsic energy may be imparted to the matter it interacts with. That interaction takes place as either absorption (transfer of energy from the X-ray photon to the absorbing material) or scattering (in which the X-ray photon is "redirected" by interaction with the scattering material). The process of scattering is the primary process responsible for diffraction, but both processes (which are, in many ways, interdependent) result in the production of potentially damaging secondary radiation. That radiation is capable of producing significant short- and long-term health effects in the event of exposure of human tissue.

The X-rays produced for diffraction analysis by an X-ray source consist of the characteristic radiation (dependent on the anode target) plus the continuous spectrum. Recall that the energy of X-rays and their wavelength are inversely proportional (higher energy = lower wavelength), and that the continuous spectrum minimum wavelength decreases as the accelerating voltage (kV) of the X-ray source increases. It is also important to understand is that an increase in filament current (ma) and kV (beyond the minimum value required to produce characteristic radiation for the target) will result in an increase in the intensity of the generated X-rays, but will not change their energy.

Energy Transfer

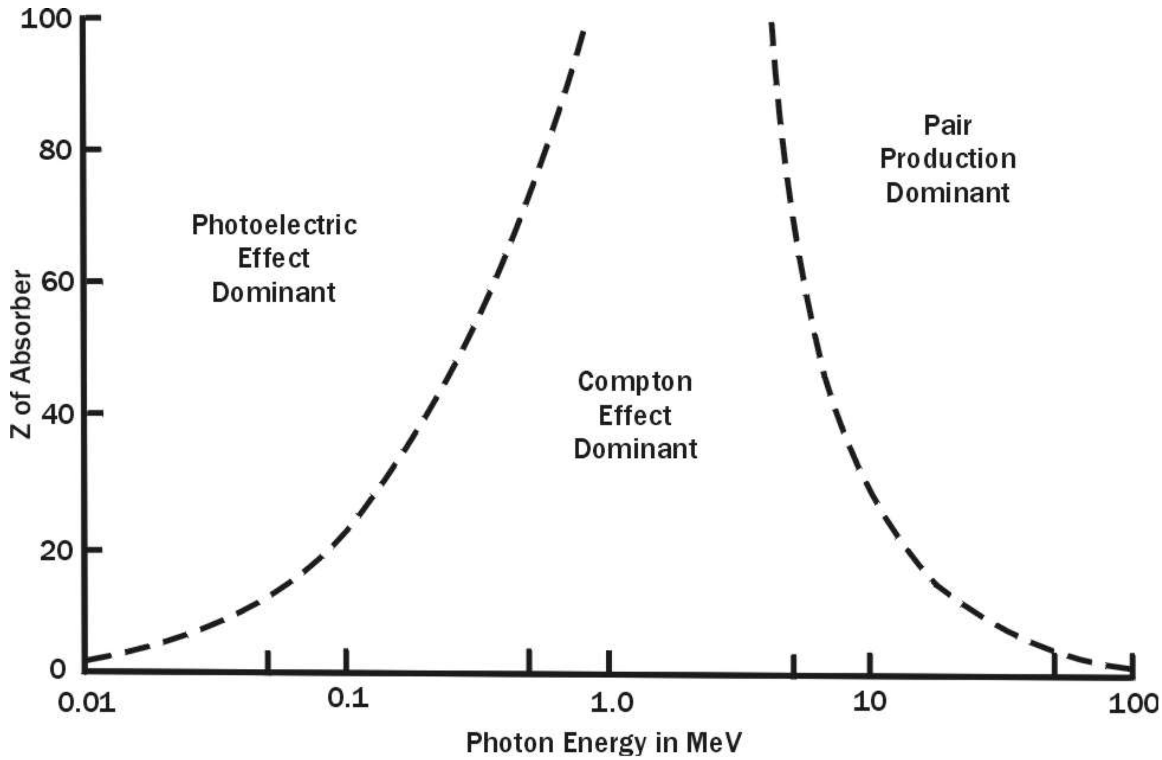
There are two basic types of energy transfer that may occur when X-rays interact with matter:

- Ionization, in which the incoming radiation causes the removal of an electron from an atom or molecule leaving the material with a net positive charge.
- Excitation, in which some of the X-ray's energy is transferred to the target material leaving it in an excited (or more energetic) state.

Theoretically there are twelve processes that can occur when X-rays interact with matter, but only three of these processes are important. These processes are:

- The photoelectric effect
- The Compton effect and
- Pair Production

Which process dominates is dependent on the mass absorption characteristics of the target (directly related to the atomic weight, Z) and the energy of the X-rays, as shown schematically in the graph below.



The Photoelectric Effect

Simply stated, the photoelectric effect occurs when photons interact with matter with resulting ejection of electrons from the matter. Photoelectric (PE) absorption of x-rays occurs when the x-ray photon is absorbed resulting in the ejection of electrons from the atom. This leaves the atom in an ionized (i.e., charged) state. The ionized atom then returns to the neutral state with the emission of an x-ray characteristic of the atom. Photoelectron absorption is the dominant process for x-ray absorption up to energies of about 500 KeV. Photoelectron absorption is also dominant for atoms of high atomic numbers.

The photoelectric effect is responsible for the production of characteristic x-rays in the x-ray tube, but the process is also important as a secondary process that occurs when x-rays interact with matter. An x-ray photon transfers its energy to an orbital electron, which is then dislodged and exits the atom at high speed with a kinetic energy equal to:

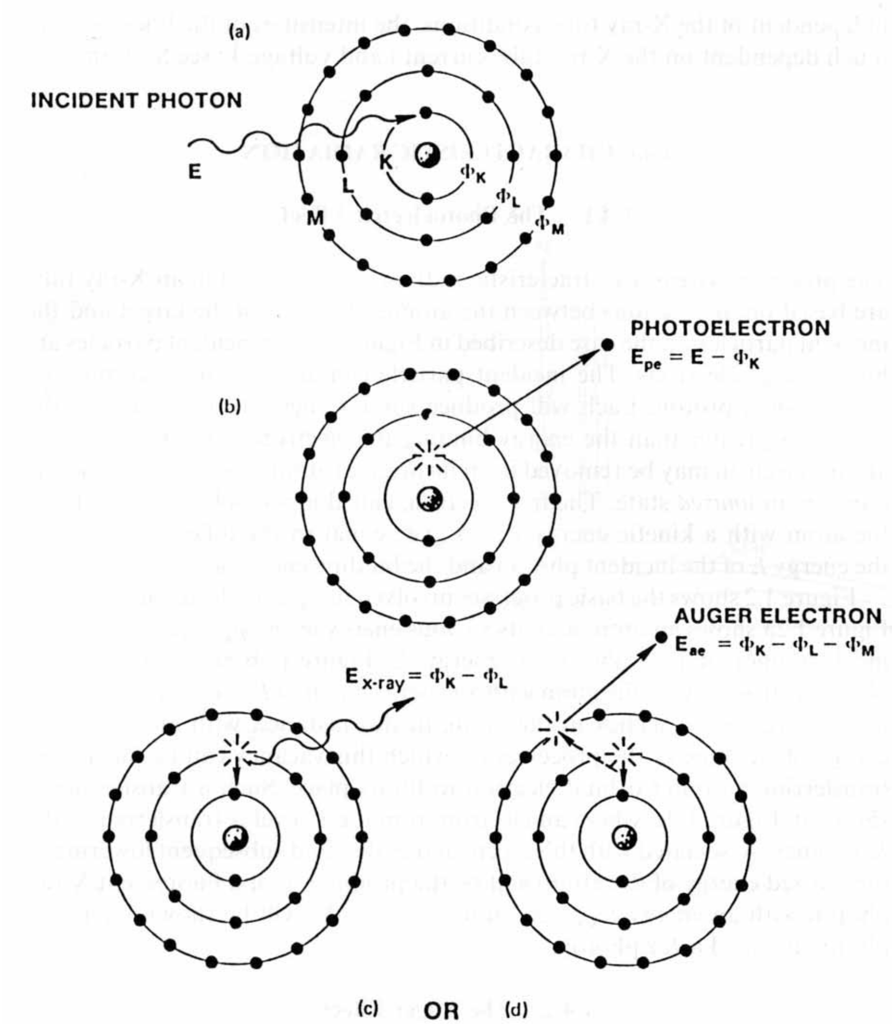
$$KE = E_x - P$$

Where KE is the kinetic energy of the photoelectron
E_x is the energy of the incident X-ray photon
P is the energy required to remove the electron or its binding energy in the atom

The energy of equivalent of the rest mass of an electron is $m_o c^2$, and is equal to about 0.51 MeV (m_o is the rest mass of an electron and c is the speed of light). When E_x is much lower than this value, the electron will exit at a high angle to the incident beam; when E_x is closer to this value, the electron will exit at close to parallel with the beam.

When the photoelectron is ejected, it has the capability, depending on its energy, to interact with subsequent electrons in other molecules or atoms in a chain reaction until all its energy is lost. If that interaction results in the ejection of an outer orbital electron, this is known as the Auger (au-jay) effect, and the electron called an Auger electron. The probability of producing a secondary photoelectron vs. an Auger electron is directly proportional to the KE of the photoelectron.

The production of photoelectric and Auger electron is shown diagrammatically in the following figure from Jenkins and Snyder (1996). In the diagram (a) shows the incident X-ray photon, (b) shows the production of a high-energy primary photoelectron. In (c) a lower energy electron moves into the vacated K-shell resulting in the production of an X-ray photon that leaves the atom, and in (d) the X-ray photon is absorbed by an outer shell electron resulting in the emission of a Auger electron.



It is easy to see how the photoelectric (and Auger) effect can significantly damage the molecular structure of soft tissues encountered by an X-ray beam.

The Compton Effect

The Compton effect or Compton scattering (C), also known a incoherent scattering, occurs when the incident x-ray photon ejects a electron from an atom and an x-ray photon of lower energy is scattered from the atom. Relativistic energy and momentum are conserved in this process[1] and the scattered x-ray photon has less energy and therefore greater wavelength than the incident photon. Compton Scattering is important for low atomic number specimens. At energies of 100 keV -- 10 MeV the absorption of radiation is mainly due to the Compton effect.

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[1] See http://www.student.nada.kth.se/~f93-jhu/phys_sim/compton/Compton.htm for an Javascript aplet demonstrating the Compton effect.

The Compton effect will occur with very low atomic weight targets even at relatively low X-ray energies. The effect may be thought of as a scattering of the photons by atomic electrons. In the process, also called Compton scattering, the incident X-ray changes direction and loses energy, imparting that energy to the electron (now called a Compton electron). The Compton electron will typically interact with other atoms producing secondary ionizations. Since they possess relatively low energy, the x-rays produced will generally be low energy also.

The maximum possible energy, *E*, of a Compton electron (the "Compton edge") is equal to:

$$E = \frac{E_x}{1+4E_x}$$

Where E_x is the energy of the incident photon. Qualitatively, it is easy to see that the Compton electrons will be significantly less energetic than photoelectrons for an equal value of E_x.

In x-ray diffraction, Compton scatter will contribute to the overall background in the x-ray data produced, but because of the relatively low energies of the incident x-rays and the higher mass of the specimens and specimen holders, the contribution will usually be very small.

Pair Production

Pair Production (PP) can occur when the x-ray photon energy is greater than 1.02 MeV, when an electron and positron are created with the annihilation of the x-ray photon. Positrons are very short lived and disappear (positron annihilation) with the formation of two photons of 0.51 MeV energy. Pair production is of particular importance when high-energy photons pass through materials of a high atomic number.

Pair production is a rare process and only occurs at high X-ray photon energies with high atomic weight targets. It is virtually nonexistent at the low-energies involved in X-ray diffraction work. Pair production is impossible unless the incident X-rays exceed 1.02 MeV and does not become important until this exceeds about 2 MeV.

Pair production is not a significant process at the X-ray energies involved in X-ray diffraction.

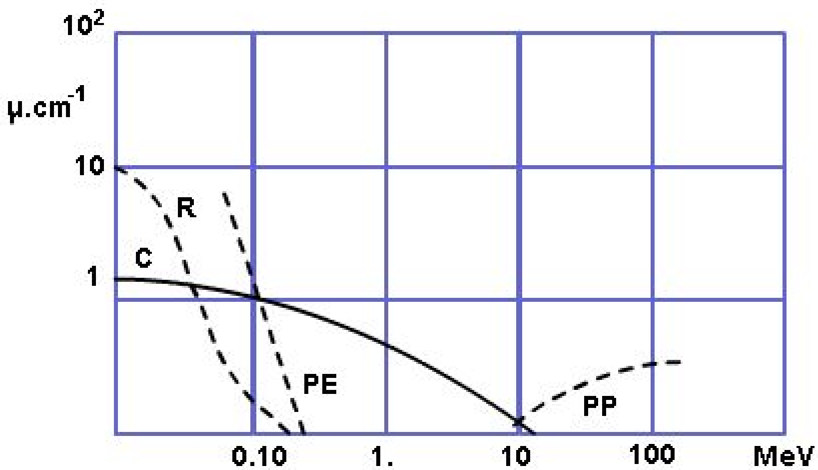
Other Effects

Thomson scattering (R), also known as Rayleigh, coherent, or classical scattering, occurs when the x-ray photon interacts with the whole atom so that the photon is scattered with no change in internal energy to the scattering atom, nor to the x-ray photon. Thomson scattering is never more than a minor contributor to the absorption coefficient. The scattering occurs without the loss of energy. Scattering is mainly in the forward direction. This effect is minor to when related to absorption, but is the primary effect which makes x-ray diffraction possible.

Photodisintegration (PD) is the process by which the x-ray photon is captured by the nucleus of the atom with the ejection of a particle from the nucleus when all the energy of the x-ray is given to the nucleus. Because of the enormously high energies involved, this process may be neglected for the energies of x-rays. It is the process harnessed in the development of nuclear fission.

Summary

The diagram below shows the absorption coefficient, μ, for four radiation-matter interactions as a function of radiation energy in MeV with an iron absorber. In the chart, PE = Photoelectric effect; C = Compton Scattering; PP = Pair Production; R = Thomson or Rayleigh scattering; PD = Photodisintegration. For lower density absorbers, curves will shift to lower energies. (Note that the radiation energy for Cu x-rays is about 8.0 KeV, which lies near the left edge of the chart.)



The common product of these types of x-ray interaction with matter is the production of high-speed electrons and x-rays that can cause secondary effects in the matter with which they interact. The "end" effect (which can cause significant damage in tissues, particularly at the low X-ray energies involved in diffraction) of heat production is preceded by interactions which create excited atoms, additional free electrons from ionization, and low-energy X-rays. These can do significant molecular damage (including chromosomal damage in tissues) leading to a number adverse health effects.

Measurement of Radiation Dose

To enable effective monitoring of radiation exposure among workers, standardized methods of measuring and evaluation a received dose of radiation are required.

The **roentgen** (**R**) is a unit of radiation exposure in air. It is defined as the amount of x-ray or gamma radiation that will generate 2.58×10^{-4} coulombs (a measure of electrical charge) per kilogram of air at standard temperature and pressure.

The absorption of radiation depends of the nature of the absorbing material, thus the actual energy transferred (i.e., ionization produced in the material) can differ considerably for different materials. We use two other units to measure this deposited energy.

- The **RAD** (Roentgen-Absorbed-Dose) rad is the amount of radiation that will deposit 0.01 Joules of energy in a kilogram (or 100 ergs/gm) of material. A roentgen in air can be approximated by 0.87 rad in air, 0.93 rad in tissue, and 0.97 rad in bone.

The Systeme Internationale (SI) unit of absorbed dose is the **gray (Gy)**, which has the units of Joules per kilogram. *A gray is equal to 100 rad*.

- The **REM** (Roentgen-Equivalent-Man) is the absorbed dose in RADS corrected for the equivalent absorption in living tissue. The REM is equal to the RAD multiplied by a *weighting factor* which varies according to the type of radiation. The weighting factor for x-rays is equal to 1. Therefore, **for x-rays, one rem is equal to one rad**.

  The Systeme Internationale (SI) unit used in place of the rem is the sievert (Sv). *A sievert is equal to 100 rem*.

Dosages are commonly expresses as R/hr (roentgen per hour) or mR/hr (milliroentgen per hour).

Standard survey meters are of two types: Geiger Counters and Ionization Chambers. To accurately measure radiation the must be calibrated by a known radioactive source, ideally with a wavelength similar to that to be measured.

Background Radiation and Permitted Dose

Normal background radiation levels are on the order of 0.01 – 0.1 mR/hr. Background radiation includes natural sources, occupational sources, consumer products, and medical X-rays and tests which use radioactive sources. The natural background varies depending on elevation above sea level, variations in cosmic and solar radiation, and geological conditions. On average one would expect to receive 0.05 x 24 = 1.2 mr of exposure per day ; this calculates to 1.2 x 365 or approximately 427 mR per year from terrestrial radiation.

According to a report from the National Council on Radiation Protection and Measurements (NCRP Report No. 93), the annual average effective dose equivalent received in the United States is approximately 360 mREM per person with an estimated breakdown as follows:

- Natural Sources (300 mREM): "Natural" background radiation consists of radiation from cosmic radiation, terrestrial radiation, internal radionuclides, and inhaled radon.
- Occupational Sources (0.9 mREM): According to NCRP Report No. 93, the average dose for workers that were actually exposed to radiation in 1980 was approximately 230 mREM.
- The Nuclear Fuel Cycle (0.05 mREM): Each step in the nuclear fuel cycle can produce radioactive effluents in the air or water.
- Consumer Products (5-13 mREM): The estimated annual dose from some commonly-used consumer products such as cigarettes (1.5 pack/day, 8,000 mREM) and smoke detectors (1 mREM) contribute to total annual dose.
- Miscellaneous Environmental Sources (0.6 mREM): A few environmental sources of background radiation are not included in the above categories.
- Medical Sources (53 mREM): The two contributors to the radiation dose from medical sources are diagnostic x-rays and nuclear medicine. Of the estimated 53

mREM dose received annually, approximately 39 mREM comes from diagnostic x-rays.

Table 1 below shows the maximum permissible doses for individuals working with radiation in a controlled environment, and to others (the "environs") outside of that controlled environment.

Table 1: Maximum permissible dose equivalent values for individuals working with Radiation in a controlled environment.*

	Average weekly[a] dose (rem[c])	Maximum 13 week dose (rem[c])	Maximum yearly dose (rem[c])	Maximum accumulated dose[b] (rem[c])
Radiation controlled areas:				
Whole body, gonads, blood-forming organs, and lens of eye	0.1	3	5	5(N - 18)[d]
Skin of whole body	–	10	30	–
Hands and forearms, head neck, feet, and ankles	–	25	75	–
Environs:				
Any part of body	.01	–	0.5	–

[a] For design purposes only.
[b] When the previous occupational exposure history of an individual is not definitely known, it shall be assumed that he has already received the full dose permitted by the formula 5(N - 18).
[c] The dose equivalent in rems may be assumed to be equal to the exposure in roentgens.
[d] N = Age in years (must be greater than 18).

***** From Permissible Dose from External Sources of Ionizing Radiation, National Bureau of Standards handbook 59 (1954) including 1958 Addendum and Statement by NCRP in Radiology 75 (1960).

In terms of absolute energy content, one RAD is not a lot, since 1 Watt is equivalent to 107 erg/sec. Most concerns with health and radiation exposure are related to possible chromosomal damage and the potential for the development of skin cancer. Medical research in this area suggests that this is of most concern with long-term chronic exposure at relatively low levels where the cumulative dose is high.

The annual occupational dose limits for minors are 10% of the annual occupational dose limits for adults. The limit on dose to an embryo/fetus is 500 mREM (0.5 rem) during the gestation period.

The goal for all radiation safety practice is to keep exposures ALARA (As Low As Reasonably Achievable).

Radiation Sources in X-Ray Diffraction Laboratories

The diffractometer is a source of very intense radiation. The primary beam emitting from the X-ray tube tower can deliver as much as 400,000 R/minute, but this is usually reduced by collimation and filtration such that about 5,000 – 50,000 R/min reaches the sample. The diffracted beam, radiating in all directions from a sample, can be as much as 80 R/hr. Clearly exposure of any part of the body to the primary beam can deliver hundreds of times the maximum permissible yearly dose in a second, and an hour of exposure to the diffracted beam can result in a year's worth of permissible exposure.

Whereas a primary beam exposure will produce noticeable skin damage very quickly, a diffracted beam exposure might not be physically noticed at all. This is the main reason why radiation monitoring devices must be worn in the laboratory any time X-rays are being generated in the diffractometer.

To minimize (and hopefully eliminate) the likelihood of workers being exposed to radiation in the laboratory, several strategies are required.

- Complete shielding of the X-ray source and diffracted beam such that all radiation is contained within an enclosed area.
- The spring-loaded shutters on the X-ray primary beam source such that the shutter is held closed unless a current is applied to a device (typically a solenoid or relay) that holds it open.
- Fail-safe Safety interlock(s) should be installed on the housing such that if it is opened, the X-ray shutter is closed. "Fail-safe" means that the interlock switch(es) are wired in series with the shutter opening device so that the device will not function if the circuit is open.
- A fail-safe indicator light should be present which is illuminated when the shutter is open and indicates that X-rays are on. This light must be wired in series with the shutter-opening device.
- All openings of the housing should be sealed to eliminate any possible leakage.
- The system should be checked for leakage periodically with the system at operating conditions using properly calibrated survey equipment. There is no required interval for this, but it must be requested if the following conditions exist:
    - Prior to the receipt of new equipment
    - Prior to a change in the arrangement, number , or type of local components in the system
    - Prior to any maintenance requiring the disassembly or removal of a local component in the system
    - Anytime a visual inspection of the system reveals an abnormal condition.
- High-voltage power supplies, if not functioning properly, can be the source of X-rays. It is important that the HV voltage multipliers and other circuitry be properly shielded to eliminate this as a possible radiation source.

For routine operations of modern X-ray powder diffractometers, the radiation exposure in routine operations should be virtually nonexistent.

Biological Effects of Radiation Exposure

Acute Whole-body Doses

High doses of radiation delivered in a very short period of time can result in serious illness and, in many cases, death over a period of days to weeks. Because of the localized nature of the high-intensity X-ray beam and the relatively low penetrating power of these relatively low-energy (but potentially very intense) sources, these sorts of whole-body exposures would not be possible in an X-ray diffraction laboratory setting, and are very rare occurrences. They are listed here for reference.

Dose (REM)	Syndrome and Effect
100-1000	*Hematopoietic syndrome*: loss of blood-forming organs; infection, anemia
1,000 – 5,000	*Gastrointestinal syndrome*: loss of cells lining the intestines; diarrhea, electrolyte imbalance
5,000 – 10,000	*Central Nervous System syndrome*: loss of central nervous system function; muscle coordination loss, seizures, coma

Long-Term Effects

Health concerns about radiation exposure are usually centered on long-term effects of exposure, and risks are usually framed in relation to the chance of a particular dose of radiation causing an increase in a particular disease within a population. The table below estimates the increase in several cancers estimated based on a one-time 10 REM dose in a population of 100,000.

Disease	Additional Cases per 100,000 (with one-time 10 REM dose) *
Adult leukemia	95
Cancer of digestive system	230
Cancer of respiratory system	170

* Source: Biological Effects of Ionizing Radiation V (BEIR V) Committee

The concept of **radiation-induced life shortening** has been seen in animal experiments. The life-shortening phenomenon is thought to be the result of accelerated aging. The effect, if it exists, is thought to result in the loss of a few days of life expectancy for every REM of radiation exposure.

Low dose, low-dose rate exposures: The effects mentioned above relate to the effects of an *acute, one-time exposure to radiation*, not low dose, low dose-rate radiation exposure. The effects these types of radiation exposure are in great dispute. It is thought that the effects of a protracted dose of radiation are not as great as with an acute dose because of biological repair mechanisms.

The **genetic effects** of radiation can be divided into two categories: *effects on the exposed individual* or *effects on offspring*.

Effects on the exposed individual: Radiation is known as a mutagen, that is, it is capable of causing changes to DNA. However, not all mutations are necessarily bad, or even result in any somatic effect. However, it is thought that a higher mutation rate increases risk for the development of cancer and other diseases. It is estimated that if 1 REM of radiation were given to each generation in perpetuity, the spontaneous mutation rate for the population would increase by about 1%.

Effects on offspring: Exposure to radiation *in utero*, that is, while in the womb, can have profound effects on offspring if it occurs during organogenesis. Organogenesis is the period during which the organs of the embryo are being formed and occurs from about the ninth day to the sixth week after conception. Since each organ system is formed during a specific period of time, the birth defects that may result depend heavily on the stage during which the embryo is irradiated. Defects that can occur as a result of irradiation during organogenesis include cleft palate, stunting of arms and legs, and defects to the brain.

Bioeffects – X-rays and Skin

Most radiation exposures that occur with analytical equipment affect the extremities, chiefly the fingers and hands. Although irradiation at low exposures of fingers or hands with x-rays at energies of about 5 - 30 keV does not seem to result in significant damage to blood-forming tissue, at high exposures some general somatic effects to the skin can occur. Very high exposures may necessitate skin grafting or amputation of the affected extremity. The table below summarizes the somatic effects of a variety of skin exposures to X-rays.

Exposure (R)	Time Period	Effects
< 300 R		Somatic effects generally not observed
		Temporary hair loss
300 – 800 R	24 – 48 hrs	Erythema
	8 – 14 days	Max. erythema pain
	1 month	Recurrence of erythema (lasts 2 –3 weeks)
>1500 R	Long term	Scar tissue, radiation dermatitis

The very high-energy X-rays used for medical radiology and imaging will pass through human tissue. It is important to understand that the relatively low energy X-rays used in our laboratory (Cu K-radiation is about 8 KeV) will not be able to penetrate more than a few mm of surface tissue. Since skin is constantly being shed and renewed, skin damaged by these X-rays will usually heal with no long-term effects. The production of heat and prolonged exposure to an intense (but low-energy) X-ray beam can result in burning and severe damage of tissue, sometimes with permanent scarring and, with intense exposure, damage of the deeper skin tissue and permanent skin loss.

Even low-energy X-rays can severely and permanently damage the surface of the eye. Special precautions should be taken to prevent this occurrence. If working in a laboratory with the chance of a diffracted beam being in the workspace, wearing eyeglasses or safety glasses will provide sufficient protection. This is not necessary in our laboratory because the X-rays are fully contained within a shielded cabinet.

Erythema (mentioned in the table above) is a reddening of the skin caused by the expansion of small blood vessels in the outer layers of the skin (the epidermis). Erythema caused by over exposure to solar radiation is called sunburn. Erythema on hands or fingers after working with X-rays is a sign of a possible problem, and should be reported to the lab manager and/or the radiation safety office immediately.

Everyone is encouraged to read the material in UNM's booklet on "Radiation Safety for Analytical X-ray Users." The articles presented on biological effects and health risks associated with radiation exposure provide a good overview of what is scientifically known and what is presumed by popular (for lack of a better term) belief.

Principles of Radiation Protection

There are three basic principles or radiation protection:

- **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. Although reducing time in the radiation field to reduce exposure is a very simple concept, it is a very effective concept as well.
- **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 and steel boxes (as with our Scintag PAD V system) to enclosures constructed of tin-impregnated polycarbonate.

There are four main causes of accidents in analytical X-ray laboratories. These are:

1. Poor equipment configuration, 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., shutter failure, warning light failure
4. Inadequate training or violation of procedure, e.g., incorrect use of equipment, overriding interlocks.

It should be noted that with the equipment operational in our laboratory, the production of significant exposures from items 1 – 3 would require a major disassembly of our diffractometer enclosure. We work hard to familiarize all users of the lab with proper procedures (#4), but the execution of those procedures is up to **you!**

We are not currently operating any of the older Phillips generators that could be used to do powder camera work. One of these units might be reactivated in the not-too-distant future. These systems have a higher potential for exposure of beam ports and other potentially dangerous situations.

A few guidelines for preventing accidents analytical X-ray laboratories are listed below:

- Know location and/or presence of primary and diffracted beams **at all times**.
- Provide and inspect shielding.
- Do not perform maintenance without confirming that tube is not energized.
- Perform check of safety devices at least once a month.
- Survey unit whenever moved or reconfigured.
- Cap off any unused ports.
- Keep your body parts out of the beam!

Training Requirements at UNM

All of the physical precautions are secondary to proper training of operators in proper procedures for safe operation of the equipment. For this reason, UNM has the following requirements in place for all users of X-Ray Diffraction equipment on campus:

- No persons will be allowed to use analytical X-ray equipment until authorized in writing by the Radiation Safety Office
- No individuals under 18 years of age may use or assist in the use of analytical X-ray equipment
- Operating procedures shall be written and available to users and inspectors of analytical X-ray equipment
- No person shall bypass a safety device without written authorization from the Radiation Safety Office.
- Extremity and whole-body dosimeters must be worn while operating analytical X-ray equipment.
- The Radiation Safety Office must be promptly notified whenever exposure is suspected.

Monitoring Devices

All users of the X-ray diffraction laboratory must wear radiation monitoring devices issued by UNM's Radiation Safety office while in the laboratory. The monitoring devices use thermoluminescent devices (TLDs) to record exposure, and are sensitive to x-rays as well as other forms of radiation. ***These devices do nothing to protect you from radiation exposure*** – they just record what you have been exposed to. Their primary value is to alert the lab manager to any potential problems reflected in above-normal exposures.

Each lab user (after completing radiation safety "self study" and passing the radiation safety exam) will be issued a clip-on "badge" (whole-body dosimeter) which is attached to clothing in the chest area and a "ring" (extremity dosimeter) that is worn on the left hand (the one closest to the tube tower when working with the diffractometer). Unless you work with radiation sources at some other location on campus, these should be left in the lab in a drawer designated for that purpose. The devices are exchanged quarterly, and a report of results is issued about a month after the exchange.

Over a 3-year period between 1999 and 2002 the maximum accumulated "whole body" (badge) dose for all monitored users of our laboratory ranged between 0 (no recorded exposure) to 268 mREM. The average exposure calculated for all users (n=36) was 23 mREM. The average multi-year exposure for those who had a nonzero record (n=16) was 50 mREM. It is clear from comparing these monitored exposures with background levels that the amount of radiation in our laboratory is within the range of normal background.