X – Ray and Accelerator Radiation Safety Program

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Environmental Health and Safety
University of Nevada Reno

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1. Introduction

Particle accelerators can produce high levels of radiation. The types of radiation it can produce include x-ray, gamma ray, and neutron. X-ray is the primary concern of the UNR radiation safety program because x-ray is the only radiation with potential exposure from UNR's radiation producing machine (RPM) operation. Potential x-ray sources in RPM include source bottle, beam tube, bending magnets, target assembly, and high voltage supply in a typical accelerator. The pictures below are of a high voltage generator, the Van de Graaff.

Figure 1.1. Van de Graff Accelerator

Analytical x-ray machines can produce extremely high intensity x-ray beams within a small area. The exposure rates in primary beams may be in the order of 10,000 R/sec. Therefore, exposure to primary beams for even a fraction of a second could cause serious injury. All required safety precautions must be strictly observed. An analytical x-ray unit consists of three major components: x-ray tube assembly, sample (target) assembly, and high voltage power supply.

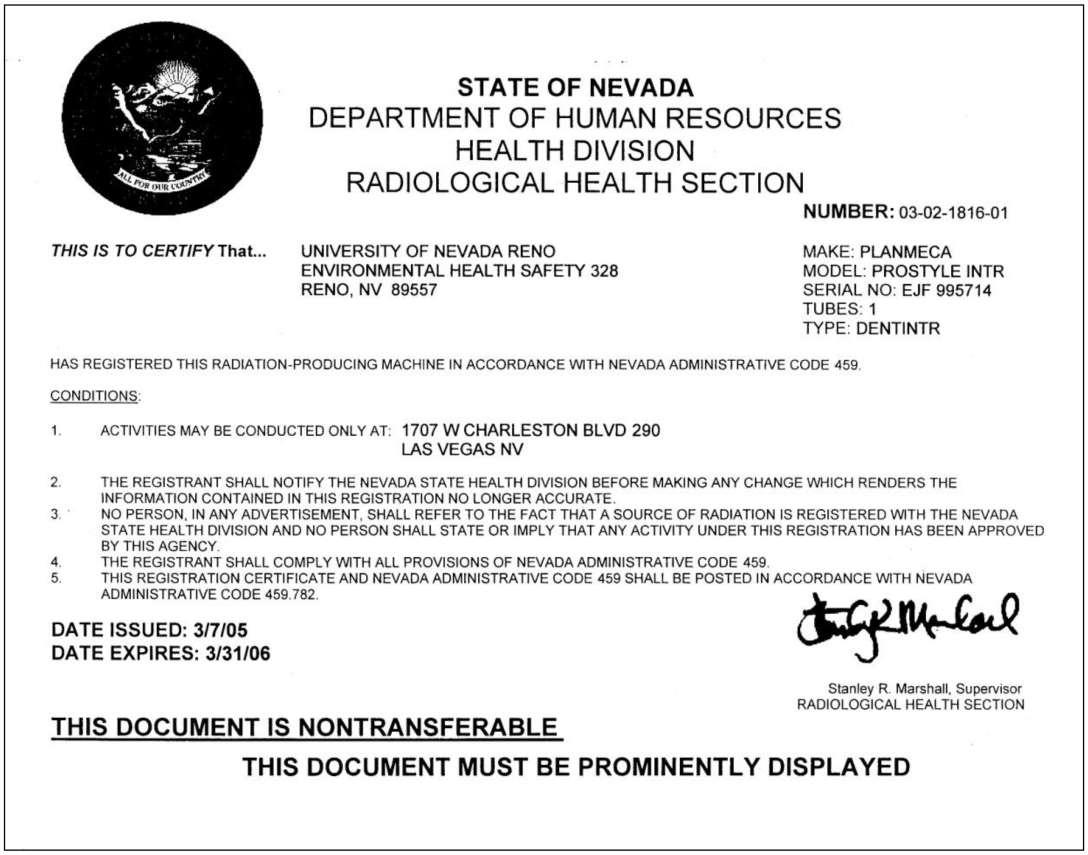
Figure 1.2 Analytical c-ray machine

There may be other hazards associated working with RPM, for instance, electrical hazards, cryogenic hazards, compressed gas, and more, in addition to radiation. All hazards must be adequately addressed to operate a RPM safely. All standard operating procedures need to be followed, and only trained; authorized personnel may operate an RPM.

2. Requirements and responsibilities

2.1 Regulatory and UNR requirements

Occupational radiation safety requirements are specified in detail in the UNR Radiation Safety Manual and NAC 459.320-374, 640-664, and 780-794. Following sections describe the requirements.



STATE OF NEVADA
DEPARTMENT OF HUMAN RESOURCES
HEALTH DIVISION
RADIOLOGICAL HEALTH SECTION

NUMBER: 03-02-1816-01

THIS IS TO CERTIFY That... UNIVERSITY OF NEVADA RENO
ENVIRONMENTAL HEALTH SAFETY 328
RENO, NV 89557

MAKE: PLANMECA
MODEL: PROSTYLE INTR
SERIAL NO: EJF 995714
TUBES: 1
TYPE: DENTINTR

HAS REGISTERED THIS RADIATION-PRODUCING MACHINE IN ACCORDANCE WITH NEVADA ADMINISTRATIVE CODE 459.

CONDITIONS:

1. ACTIVITIES MAY BE CONDUCTED ONLY AT: 1707 W CHARLESTON BLVD 290 LAS VEGAS NV
2. THE REGISTRANT SHALL NOTIFY THE NEVADA STATE HEALTH DIVISION BEFORE MAKING ANY CHANGE WHICH RENDERS THE INFORMATION CONTAINED IN THIS REGISTRATION NO LONGER ACCURATE.
3. NO PERSON, IN ANY ADVERTISEMENT, SHALL REFER TO THE FACT THAT A SOURCE OF RADIATION IS REGISTERED WITH THE NEVADA STATE HEALTH DIVISION AND NO PERSON SHALL STATE OR IMPLY THAT ANY ACTIVITY UNDER THIS REGISTRATION HAS BEEN APPROVED BY THIS AGENCY.
4. THE REGISTRANT SHALL COMPLY WITH ALL PROVISIONS OF NEVADA ADMINISTRATIVE CODE 459.
5. THIS REGISTRATION CERTIFICATE AND NEVADA ADMINISTRATIVE CODE 459 SHALL BE POSTED IN ACCORDANCE WITH NEVADA ADMINISTRATIVE CODE 459.782.

DATE ISSUED: 3/7/05
DATE EXPIRES: 3/31/06

Stanley R. Marshall, Supervisor
RADIOLOGICAL HEALTH SECTION

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Figure 2.1. Registration certificate

2.2 Registration

RPM must be registered with the State Radiologic Health office. The Principal Investigator (PI) is responsible for notifying EH&S. The Radiation Safety Office (RSO) is a part of EH&S. EH&S will assist in x-ray registration. There is a registration fee required by the state of Nevada. It is advisable to consult with EH&S prior to purchase, construction, or installation of RPM. Installation and use of RPM may produce a radiation field that may restrict normal use of the adjacent facility during RPM operation. This situation could be avoided with adequate planning and installation. Any changes in RPM location, repair, and maintenance must be reported to EH&S.

2.3 Principal Investigator

The PI is responsible for safe operation and security from unauthorized use of RPM. The PI is responsible for ensuring that all safety devices of RPMs are in good working order and all RPM operators are properly trained prior to operation.

2.4 Area posting

X-ray and/or radiation warning labels must be posted in entry ways. The "NOTICE TO EMPLOYEE" (Form NRC-1) must be posted in the RPM facility. Warning labels and Form NRC-1 are available from the RSO. The PI and operator are to maintain a RPM operating log which includes date, operator, voltage and current, duration of operation, and purpose of operation.

2.5 Training

In order to become an authorized user of a RPM, the person must receive a radiation safety training course. The PI is responsible for notifying EH&S and new personnel of the training requirement and ensuring only authorized personnel use and operate RPMs. The training requirement may be exempted only if UNR’s Radiation Safety Committee or its designee determines it unnecessary due to the person’s knowledge and experience.

2.6 Operators

The RPM operator must follow the operating procedure and safety precautions. RPM operators must have radiation safety training and must be adequately instructed in the safe operating procedures and safety precautions, and be competent in the safe use of the equipment. Written safety procedures and rules must be provided to each person operating the equipment and include any restrictions. The operator must be able to demonstrate familiarity with these rules. The operating procedure and a list of authorized users must be posted at or near the applicable RPM.

2.7 Radiation Dosimetry

Dosimeters must be worn by all RPM users or operators during operation of RPM if dosimeters are issued to the person. Dosimeters not in use must be returned to designated location in the facility while not in use.

3. Radiation (x-ray) production mechanism

RPM at UNR consists mainly of Particle Accelerators and x-ray machines. The particle accelerator is a device for increasing the velocity and energy of charged particles such as electrons, protons, deuterons and helium ions (alpha). High energy charged particles from the accelerator may produce x-ray and other types of radiation, such as gamma or neutron radiation, when they collide with target material. The charged particle beam in an accelerator beam tube can hit the side wall of the accelerator tube or bending magnet producing x-ray if the beam is not properly aligned. Electrons generated in the source bottle during ion generation may produce high intensity x-ray.

An x-ray machine is a type of electron accelerator comprised of x-ray tube assembly, high voltage power supply, and control panel. An x-ray tube consists of an anode and a cathode in a vacuum. High voltages, usually 10's to 100's of kilovolts, are applied between the anode and the cathode. Electrons in the cathode are excited and ejected from their orbits. The ejected, negatively charged electrons experience the electric field of high voltage and are attracted to the positively charged anode. The accelerating electrons gain high speed (high kinetic energy) which may reach close to the speed of light toward the target anode. When fast-moving electrons collide with target material that has a high atomic number, such as tungsten, they lose most of their kinetic energy as heat generation.

A small portion of their kinetic energy, normally less than 1 percent, is transformed into electromagnetic waves (x-ray). There are two mechanisms of x-ray production.

Bremsstrahlung Radiation

When high speed electrons approach a target and overcome the repulsive forces of orbiting electrons of that target, they are attracted to the positively charged nucleus of the target material. The electrons accelerate (normal change in direction of motion due to the attractive force between electrons and nucleus) toward the target nucleus. In the process, electrons may loose all or part of their energy in the form of x-rays.

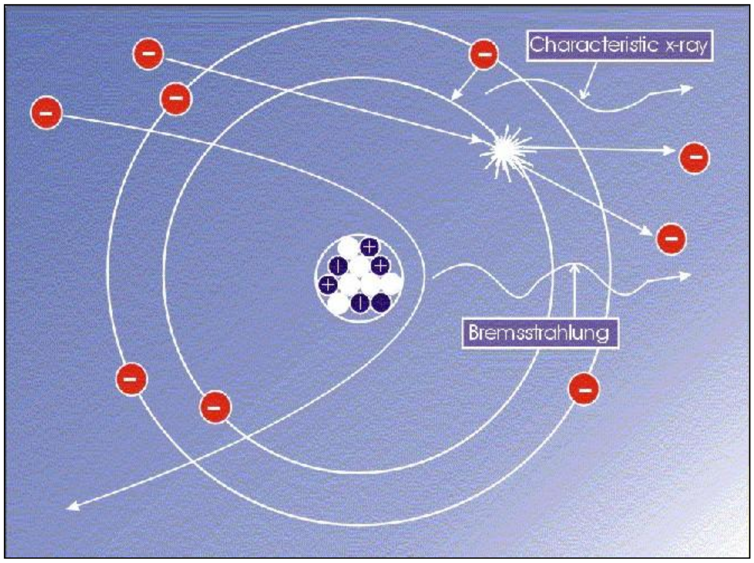

Figure 3.1. X-ray production mechanism

Bremsstrahlung x-ray production is proportional to the applied voltage and square of the target atomic number.

Characteristic x-ray

Characteristic x-rays are produced when high speed electrons interact and eject electrons from the inner orbits of the target atoms. The atom, with a vacant inner orbit electron shell, is in the excited state and electrons from the outer shell quickly drop to fill the vacant shell. This results in the emission of x-rays with discrete energy between the orbital binding energies of the electrons.

4. Gamma and x-ray interaction with matter

The predominant interactions that occur between gamma or x rays and atoms of matter depend on the photon energy and the atomic number of the material. The word photon is used to imply the particle-like behavior of an electromagnetic wave. The photon can be absorbed by what is called the photoelectric effect; it can be scattered by Compton scattering; and it can be converted to particles of mass by pair production. The photoelectric effect has the highest probability with a low energy photon and a high atomic number absorber. For intermediate energy photons, Compton scattering is the most frequent interaction. At higher photon energies, pair production is the predominant interaction. Effective shielding materials from gamma and x-ray are dense material like lead or thick concrete. Leaded glass or plastics are used for low energy gamma and x-ray shielding.

4.1 Photoelectric effect:

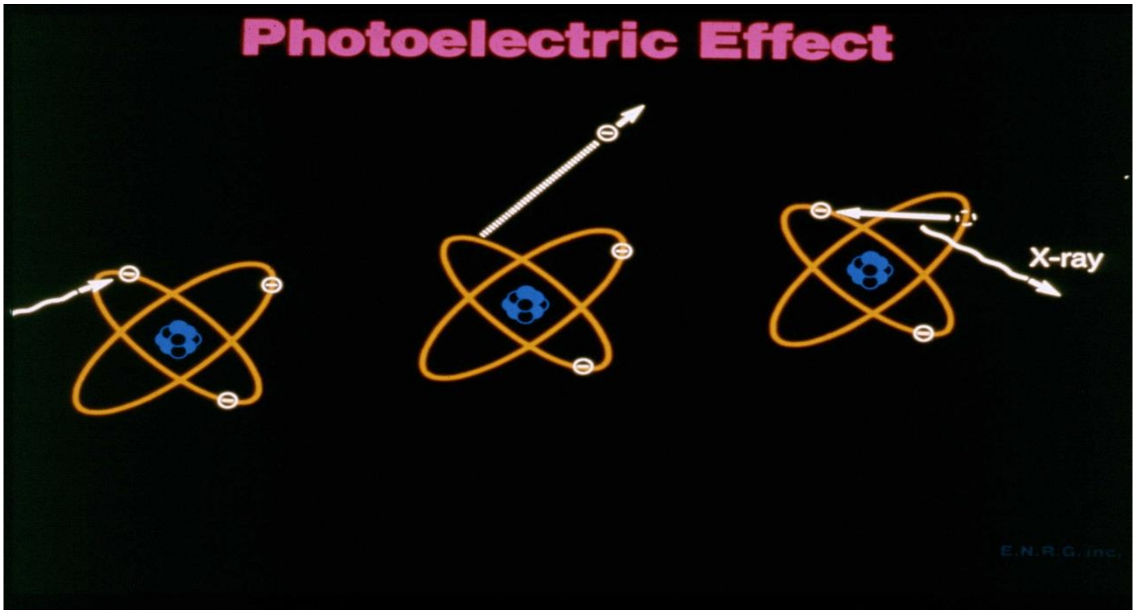

Figure 4.1. Photoelectric effect

The incoming photon is absorbed and imparts all of it's energy to an orbital electron. Then the electron is ejected from the atom. This electron then causes ionization just like a beta particle. Subsequent to the ejection of an inner shell electron, an x-ray is often emitted when the vacancy is filled.

4.2 Compton Scattering:

Compton scattering is scattering of a gamma or x-ray by an electron in an atom. The photon changes direction looses partial energy, and the electron is knocked out of the atom. The electron and the scattered photon cause further ionization. The actual energy change depends on the incident energy and the angle at which the photon is scattered. The attenuated photon may experience a photoelectric absorption or another Compton scattering if enough energy remains.

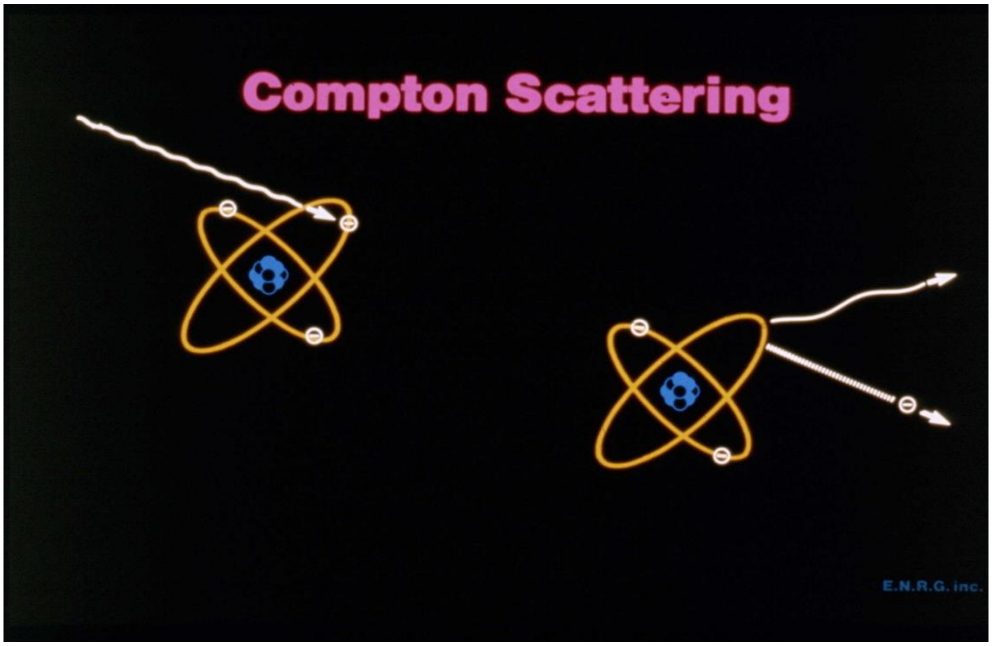

Figure 4.2. Compton scattering

4.3 Pair Production:

The incident photon, if energetic enough, vanishes and its energy is transformed into two electrons, one bearing a negative charge, the other positive (positron). Both of these charged particles cause ionization. After the positron has lost most of its kinetic energy, it will quickly react with a nearby electron and both are annihilated. The annihilation photons always have energies of 0.511 MeV. In this process, mass is converted into energy and energy is converted into mass.

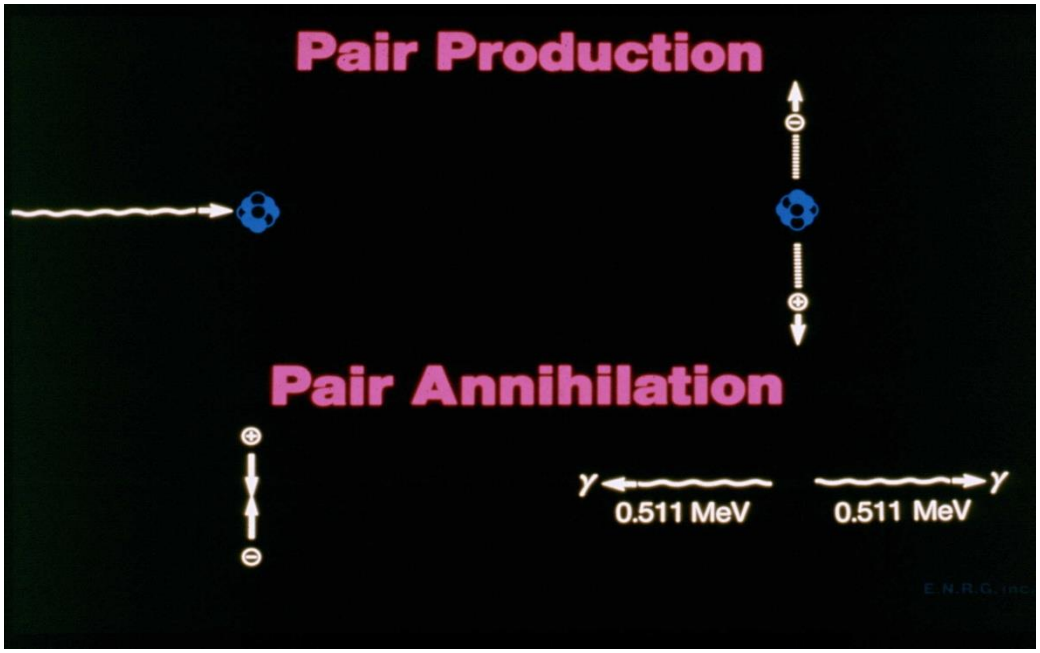

Figure 4.3. Pair production

5. Units of Radioactivity and Radiation Exposure

Table 5.1. Units of radioactivity and radiation exposure

	Traditional units		SI units		Relations
	Unit	Definition	Unit	Definition	
Radioactivity	Curie (Ci)	3.7 E10 disintegrations per second (dps)	Becquerel (Bq)	1 dps	Ci = 3.7 E10 Bq
Exposure	Roentgen (R)	2.58 E-4 coulomb per kg of air	R		
Absorbed dose	rad	100 ergs/g	Gray (Gy)	1 joule/kg	100 rad = 1 Gy
Dose equivalent	rem	Rad x quality factor (Q)	Sievert (Sv)	Gy x Radiation weighting factor (W_R)	100 rem = 1 Sv

Table 5.2. Quality factor (Q) and radiation weighting factors (W_R)

Radiation	Q	W_R
X, gamma, beta	1	1
Alpha	20	20

5.1 Radioactivity:

The Becquerel (Bq) and the Curie (Ci) are commonly used as units of radioactivity. The Bq is defined as one disintegration per second. The Ci is defined as 3.7×10^{10} disintegrations per second. Commonly used multiples and sub-multiples of the units are mega Bq (MBq, million Bq), giga Bq (GBq, billion Bq), millicurie (1/1000 of Ci), and microcurie (1/1,000,000 of Ci). The half life described in the next section describes how long the radioactive material might last and the number of Bq or Ci tells how "active" this material is now.

5.2 Radiation Exposure:

The unit of exposure is the Roentgen (R). The Roentgen is defined by how gamma and x-rays interact in air. It is defined as the quantity of gamma or x rays which, when interacting with one kilogram of air, liberate energetic electrons that produce 0.000258 Coulombs of charge by ionization when the electrons are completely stopped.

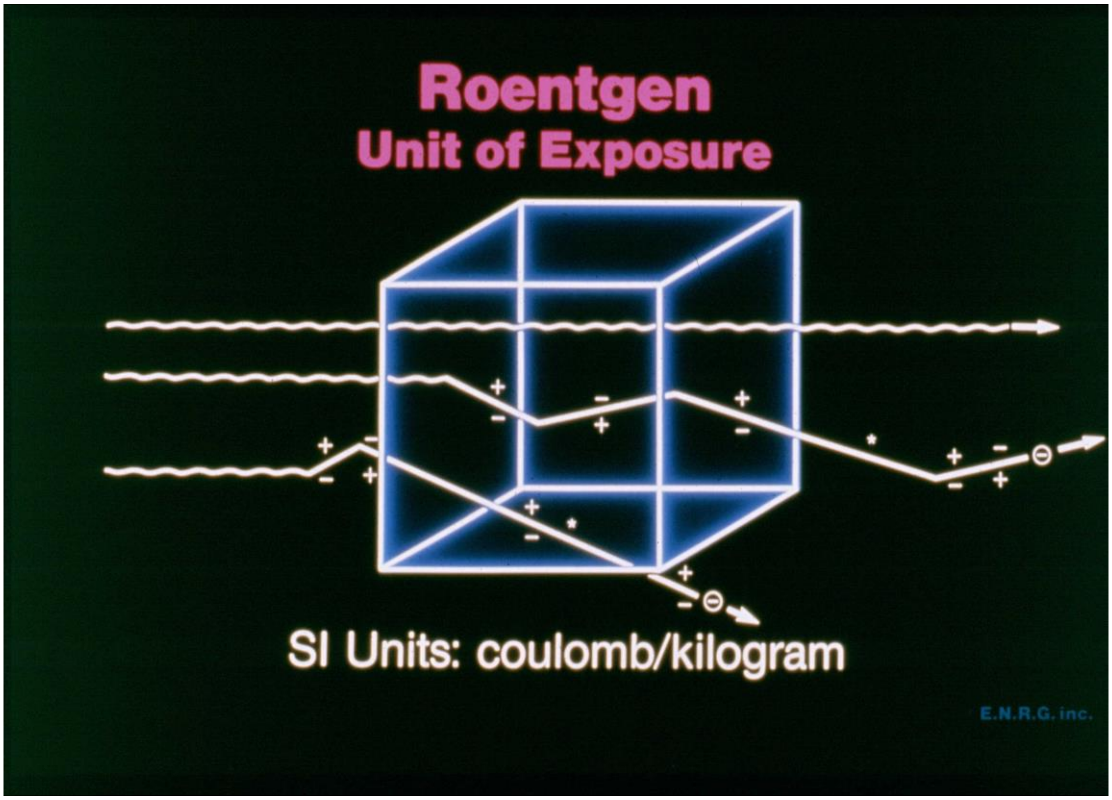

Figure 5.1. Roentgen

5.3 Absorbed Dose

The absorbed dose is defined as the energy imparted by radiation per mass of absorbing material; the material here includes all types of exposed material. The absorbed dose is a quantity that refers to how much energy is deposited in material by the radiation. The term "RAD" is derived from the expression "Radiation Absorbed Dose".

The units are: 1 rad = 100 ergs/gram of material,
1 Gy (Gray, SI unit) = 1 Joule/kg of material, and
1 Gy = 100 rad.

5.4 Dose Equivalent

The dose equivalent is obtained by modifying the absorbed dose according to the types of radiation involved. The dose equivalent is the product of the absorbed dose and the quality factor (Q) of a given radiation (rad x Q). The quality factor is based on the type and energy of the radiation causing damage. It is based on the density of ionization along the radiation path. The quality factors for different types of radiation are: 20 for alpha, 1 for beta, gamma, and x-ray, 10 for neutrons of unknown energy (energy dependent), and 10 for high energy protons.

The dose equivalent units are:
Rem (Radiation Equivalent Man) = rad x Q,
1 rad of alpha radiation = 20 rem or 0.2 Sv.
The rem (or Sv) is designed to be a unit of biological risk.

5.5 Effective Dose Equivalent (EDE)

Different organs or tissues in the body have varying degree of sensitivity to radiation. The tissue weighting factor (W_T) may be used to estimate risks, Effective Dose Equivalent (H_E), of a whole body exposure when radiation exposure is limited to only a portion of the body. For example, if a person's stomach receives 10 rem, the EDE is 1.2 rem (10 rem x 0.12).

Table 5.3. Tissue weighting factors, W_T

Tissue or organ	WT, ICRP60
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Reminder	0.05

6. Biological Effects of Radiation

As a principle of radiation protection, it is assumed that any amount of radiation is harmful, no matter how small the exposure is. This may be called "The Linear-No Threshold Theory". This theory is widely accepted as a principle of radiation protection even though it has not been proven.

6.1 Factors Determining Biological Effects of Radiation Exposure

The biological effects resulting from radiation exposure depend on a number of factors:

6.1.1 Total exposure:

How much exposure or dose has occurred to the tissue.

6.1.2 Exposure rate:

Our bodies have the ability to repair damage even during radiation exposure. How quickly radiation exposure is accumulated is important for both early and late biological effects.

6.1.3 Portions of the body exposed:

Some portions of the human body are more resistant to radiation than others due to their physiological function and cellular activity. Exposure to limited portions of the body has less effect than equal exposure to the whole body. A massive dose that would be fatal if delivered to the whole body might not even cause sickness if delivered to, for example, only the extremities.

6.1.4 Type of Radiation Received:

The three main types of radiation, alpha, beta, and gamma have different penetrating abilities. Alpha radiation to external skin is no hazard because it is likely that the outer (dead) layer of the skin stops all alpha radiation. But if alpha radiation is received internally the damage to the surrounding tissue is expected to be 20 times more harmful than the expected damages from beta or gamma radiation. The Quality Factor (or Radiation Weighting Factor) for alpha is 20.

6.1.5 Biological Factors:

Age, sex, state of health, body size, body weight and other biological factors react differently to radiation exposure even under identical conditions. Actively dividing cells have increased sensitivity to radiation exposure.

6.1.5.1 Cell Sensitivity to Radiation

The sensitivity of cells and tissues to radiation exposure is commonly proportional to the rate of cell division. One type of cancer treatment is the use of radiation because cancer cells are multiplying at a rapid rate. Children are more sensitive to radiation than adults. Fetuses are especially sensitive to radiation exposure.

For an adult, white blood cells are most sensitive due to their rate of cell division. White blood cells, bone marrow, skin cells, and the gastrointestinal tract lining are very sensitive. Tendons, ligaments, and other connective tissues are moderately sensitive. Muscle, nerve cells, and brain cells are the most resistant cells in the body.

6.1.5.2 Radiation Effects on Live Cells

Radiation causes ionization that causes physical and chemical effects to the atoms and cells with which it interacts. Radiation passes through tissue and causes ionization within the cells of the tissue. The ions produced within the cell are electrically charged and chemically active. These charged, chemically active ions tend to react quickly with surrounding atoms and molecules of the cell and alter the cell structure and/or produce chemically active free radicals.

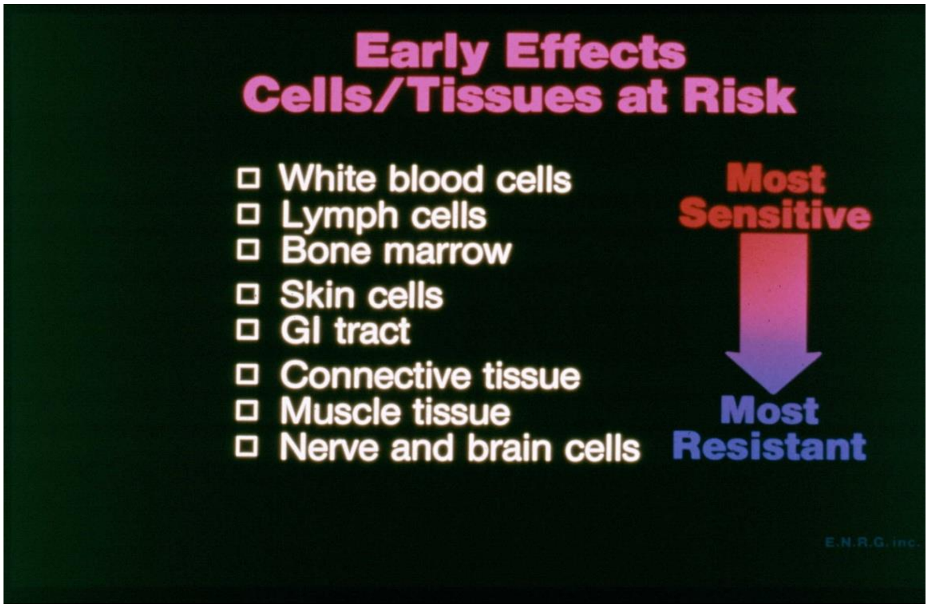

Figure 6.1. Cell sensitivity to radiation

For an example, water is a primary constituent of a living cell. As a result of ionizing radiation interaction, the bonds between hydrogen and oxygen may be broken. The dissociated hydrogen and oxygen from water may not recombine as water molecules but may recombine in many different combinations between oxygen, hydrogen, and electrons i.e. H_2O_2, HO_2, OH, e-, etc.

Radiation interaction can happen in any location of a cell such as the DNA or the chromosome, which if damaged, could be fatal for the cell's survival. If a large enough cell population damage occurs, radiation effects may be immediate and fatal to the living organism. The radiation effects may show up in a matter of days, as acute effects, or years after the exposure, as latent effects.

6.1.5.3 Damaged Cell Repair Mechanism

Cells may be damaged by many factors such as life style, chemical exposure, radiation exposure, etc. Most cells are capable of repairing damage including damage to the genetic material if given enough time (rate of exposure). But major damage might not be repaired and may result in cell death. Ability to repair damaged cells may depend on the type of chemicals produced by radiation in the cell and/or surrounding the cell.

If the chemicals produced are less active and stay away from genetic material (DNA) or other vital components necessary for cell survival, the cells would likely be less susceptible to radiation damage. The rate at which people recover from radiation exposure is not well known and variations among individuals are great.

6.1.5.4 Acute and Chronic Exposure

Acute exposure or an acute dose means the exposure is delivered in a short period of time. The exact time frame is not well defined but exposures received in hours or days are considered acute. The acute exposure does not necessarily mean a large and a lethal dose. It just mean a short time frame. Chronic exposure is exposure spread out through a longer period of time.

6.1.5.5 Acute Effects, Delayed Somatic Effects, and Genetic Effects

A sufficiently large (hundreds of rems) acute radiation dose to the whole body can cause severe biological damage to the body or death. Acute radiation syndrome is the collection of symptoms and effects characteristic of massive radiation exposure. The symptoms of radiation sickness may vary largely but the gross symptoms are vomiting, nausea, diarrhea, fatigue, and decrease in blood counts.

Delayed somatic effects are biological effects which appear in the exposed persons but may take a long time to show up. Examples are development of cancer, life shortening, and cataracts. Somatic effects can be stochastic or non-stochastic.

Genetic effects are the radiation exposure effects manifested in the offspring of exposed parent(s).

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Table 1C. Acute Radiation Syndrome*

Feature or Illness	**Effects of Whole-Body absorbed Dose, from external radiation or internal absorption, by dose range in rad**				
	0-100	100-200	200-600	600-800	>800
Nausea, vomiting	None	5-50%	50-100%	75-100%	90-100%
Time of onset		3-6 h	2-4 h	1-2 h	<1 h to minutes
Duration		<24 h	<24 h	<48 h	<48 h
Lymphocyte count	Unaffected	Minimally decreased	<1000 at 24 h	<500 at 24 h	Decrease within hours
Central nervous system function	No impairment	No impairment	Cognitive impairment for 6-20 h	Cognitive impairment for >20 h	Rapid incapacitation
Mortality	None	Minimal	Low with aggressive therapy	High	Very high; significant neurological systems indicate lethal dose

*Prompt health effects with whole-body absorbed dose within a few.
Source: Medical Management of Radiological Casualties, Second Edition, Armed Forces Radiobiology Research Institute, Bethesda, MD, April 2003
Note: rad and rem may be interchanged for this listing.

6.2 Database of Biological Effects of Radiation Exposure

6.2.1 Natural Background Radiation Exposure

Energetic radiation from outer space and the sun are continually bombarding us. Soil contains naturally radioactive material such as potassium, uranium, thorium, and their progenies. Radon, one progeny of uranium and thorium, contributes the largest natural radiation exposure to humans. The background radiation exposure may vary with location due to differing radionuclide concentrations in rock and soil, water, and an increase of cosmic radiation with altitude. The food we eat, the water we drink, and the air we breath contains radioactive material. Total average annual effective dose to members of the US population is estimated to be 320 mrem per year (3.2 mSv/year). Additionally, man made radiation sources such as medical x rays and nuclear medicine contributes about 300 mrem per year (3 mSv per year) exposure to Americans. The average effective annual dose equivalent from all sources to members of the US population is 620 mrem.

Naturally Occurring Long-lived Radio nuclides in Human Body

Isotope	^{238}U	^{226}Ra	^{228}Ra	^{210}Pb	^{210}Po	^{40}K	^{14}C	^{3}H	^{87}Rb	^{90}Sr
Activity, pCi	26	120	50	600	200	130k	87k	27.7k	29k	2.9k

The total radioactivity in the body is 277,582 pCi. This is 10,270 radioactive decays per second (dps) and 887,374,138 (887 million) disintegration per day in the body. Each radioactive decay produces radiation.

Source: Radiation Protection (pages 56, 370), Shapiro, 1990, Harvard Press.

Natural Radioactivity in a Banana

Bananas are a good source of potassium, a very important nutrient. All natural potassium contains 0.0117% potassium-40 (40K) which is radioactive potassium. A medium size banana contains about 451 mg of potassium. The amount of 40K contained in a banana is 0.0528 mg. This is equivalent to 14 dps or 0.00037 uCi. The dose equivalent, if a banana is eaten, is about 0.01 mrem. Sometimes this is called the banana equivalent dose.

Sources: Food Values of Portion Commonly Used, 16th edition, Bosen and Church.
Chart of Nuclide, F. William Walker et al.

6.2.2 Low Level Radiation Exposure Studies

Background radiation exposes the entire world population. Due to that reason alone, it is very difficult to determine the effects of low level radiation exposure. More information is available about high level exposure and its effects. A radiation effect in low level exposure is extrapolated from the high level exposure. Regulatory Guide 8.29 from the US Nuclear Regulatory Commission stated that there is a risk of 4 in 10,000 of a 1,000 mrem (0.01 Sv) dose causing a fatal cancer". Because the effects of low level radiation are not well known, it is assumed that any amount of radiation is harmful, no matter how small it is. This is not a proven fact but widely accepted.

However, there have been studies which have reported a beneficial effect of low level radiation exposure. One study was conducted in areas of Yangjiang, China where the background radiation is 2.64 times higher than the average background level. The group of population who lived there more than 6 generations was studied and compared to a similar life style population group with average background radiation level. The period of study started in 1972 and lasted until 1986. This study examined the cancer mortality data between 1970 to 1986 and observed over one million person-years in each area of the high background and the controlled area (CA).

The back ground radiation in the high background area was 547 mrem (5.47 mSv) per year and 207 mrem (2.07 mSv) per year in the controlled area. The study concluded that "No increase of cancer mortality has been found in high background radiation area

(HBRA), but on the contrary, there was a tendency for the cancer mortality in HBRA to be lower than that in CA...It is likely that there may be a dose threshold for cancer incident, but this remains to be determined by further research."

Dr. Bernard L. Cohen studied lung cancer mortality rates and average radon concentration in homes in 1601 US counties to "Test the Linear-No threshold Theory...". Dr. Cohen stated in the paper "... there is a strong tendency for lung cancer rates to decrease with increasing radon exposure, in sharp contrast to the increase expected from the theory. There is now a substantial body of evidence indicating that the low level radiation does indeed stimulate such biological defense mechanisms...". The beneficial effects of low level radiation are not generally accepted.

6.2.3 Uncertainties associated with the Low Level Exposure

The National Research Council in BEIR V report stated "In this report it is estimated if 100,000 persons of all ages received a whole body dose of 0.1 Gy (10 rad) of gamma radiation in a single brief exposure, about 800 extra cancer deaths would be expected to occur during their remaining lifetimes in addition to the nearly 20,000 cancer deaths that occur in the absence of the radiation. Because the extra cancer deaths would be indistinguishable from those that occurred naturally, even to obtain a measure of how many extra deaths occurred is a difficult statistical estimation problem." It is assumed that radiation is harmful even at low levels but there are high uncertainties associated with this assumption and it has not been proven.

6.2.4 High Level Radiation Exposure Studies

A lot more data is available in high level radiation exposure studies: A large number of bomb survivors after world war II in Japan, patients who received a large amount of medical use radiation during 1930's to 50’s, a few hundred radium dial painters, uranium minors, and animal studies have been examined. Radiation effects of high level exposure are reasonably well established.

7. Radiation Exposure Limits

Occupational Dose Limits:
Whole body (Total Effective Dose Equivalent) = 5 rem/year,
Sum of individual organs or tissue = 50 rem/year,
Eye dose (lens of eye) = 15 rem/year,
Skin or any extremity = 50 rem/year,
Dose to embryos of declared pregnant woman = 0.5 rem for the entire pregnancy, and
Minors = 10% of above limits.
Member of public = 0.1 rem/year.

Note: The average American receives 320 mrem per year from natural background and 300 mrem from medical exposures.

8. Potential ionizing radiation (x-ray) sources from x-ray unit

Radiation hazard is not just limited to the primary beam. The following areas should be noted as potential radiation sources, and appropriate precautions be taken while working with RPM

- Primary beam : X-ray exposure rate may be **5,000 – 50,000 R/min**
- leakage from primary and scattered beam
- scattering from shutter, collimator, and shielding
- scattering from target
- high voltage supply
- source bottle
- accelerator tube
- bending magnet
- target assembly
- cracks in shielding and housing

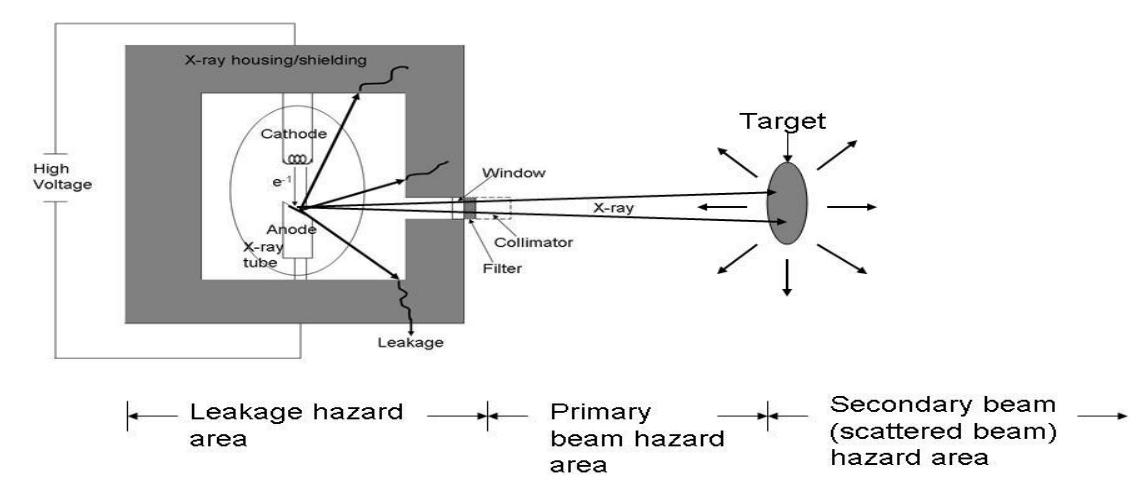

Figure 8.1. X-ray hazards

9. Radiation Safety Principles and Practices for RPM

Radiation protection is the responsibility of everyone who is involved with utilization of radiation sources. Radiation exposure must be maintained to As Low As Reasonably Achievable (ALARA) and minimized whenever possible. The followings must be observed during RPM operation:

1. Never put any body part, hands or fingers, into the beam path
2. Only authorized personal are allowed to operate RPMs. RPM must be secured to prevent unauthorized use.
3. By-pass of interlocks and safety procedures is prohibited.

4. Warning signs and labels such as “x-ray on” indicators must be in place and strictly observed.
5. Stay clear of unauthorized areas.
6. During sample changes RPMs x-ray beam must be turned off position.
7. Interlocks must not be used as “on” and “off” mechanisms.
8. Covers/housing, shielding material, beam stop, shutters, collimator, and any other devices associated with x-ray production and radiation shielding must be in place during operation.
9. A radiation survey must be performed after repair and/or maintenance of a RPM.
10. Wear appropriate dosimeter(s) during RPM work.

External Radiation Protection
External radiation can be reduced by limiting the duration of an exposure period, increasing distance between the external radiation source and the person, and placing a shielding material between the external radiation source and the person.

Time: Radiation exposure can be reduced by minimizing the time of exposure. Practice runs without the source may help to reduce exposure times when an actual experiment is performed. If limitation of the stay time in the vicinity of an external radiation source is not possible because of the time required to perform a given task, then other means of reducing exposure should be utilized.

Distance: Distance is a simple, inexpensive, and very effective method of dose reduction. If a distance between a person and a point isotropic source is doubled (increased by 2) then the exposure rate is decreased by 4. This is called the "Inverse Square Law".

Example:
An exposure rate is 100 mR/h at 1 meter. What is the expected exposure at 2 meter, 3 meter, and 4 meter?

$I_1D^2=I_2d^2$, or $I_2 = I_1(D^2/d^2)$, or $I_1/I_2=D^2/d^2$ where
I_1: intensity (exposure rate) at distance D,
I_2: intensity (exposure rate) at distance d, and
D, d: distances from a fixed point source.
at 2 meters, $(100 \text{ mR/hr})(12\text{m})^2=I_2(22\text{m})^2$, $I_2=(100 \text{ mR/hr})/4=25$ mR/hr.
at 3 meters, $I_2=(100 \text{ mR/hr})/9=11.11$ mR/hr.
at 4 meters, $I_2=(100 \text{ mR/hr})/16=6.25$ mR/hr.

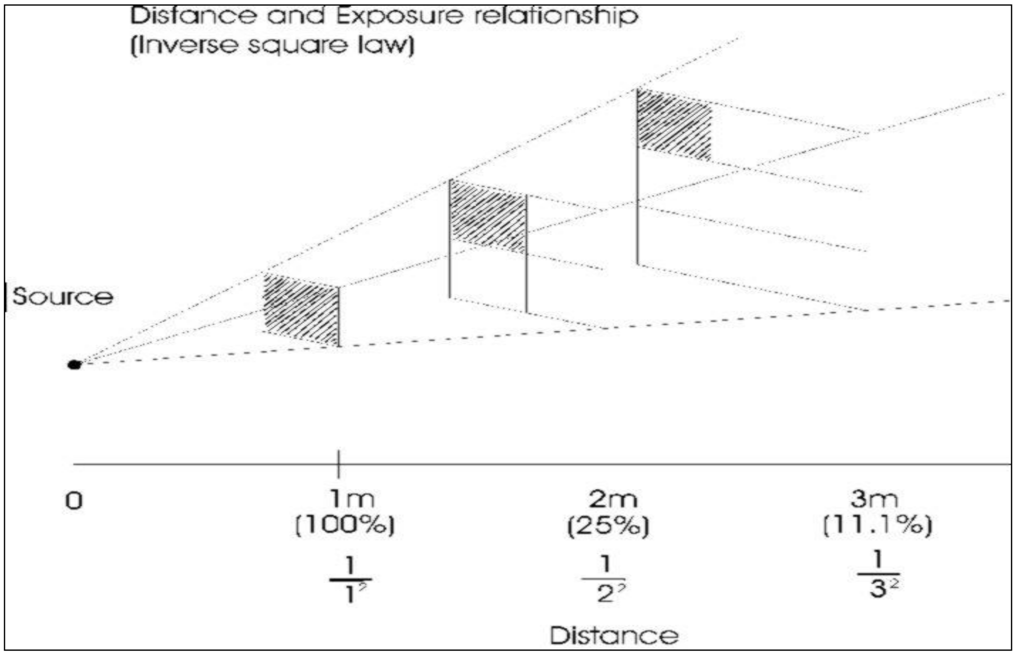

Figure 9.1. Inverse square law

Shielding: Shielding requires placing a material which will interact with radiation between a source and a person (or location of interest) to reduce exposure. Alpha radiation requires no shielding. High Beta radiation can be effectively shielded by low atomic number material such as lucite and plastic. Gamma and x-rays require a high density material such as lead. Shielding can be a very effective method for reducing exposure, but it may be more expensive. Shielding material selection is dependent on the type and energy of the radiation used.