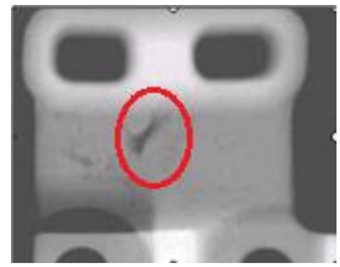
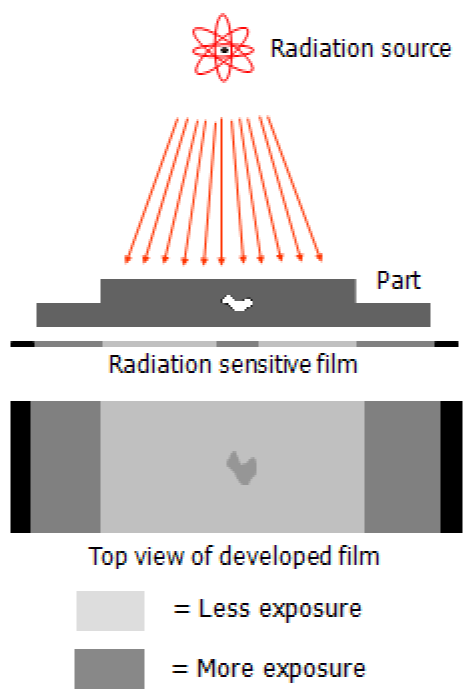
Radiographic Testing

Radiography is used in a very wide range of aplications including medicine, engineering, forensics, security, etc. In NDT, radiography is one of the most important and widely used methods. Radiographic testing (RT) offers a number of advantages over other NDT methods, however, one of its major disadvantages is the health risk associated with the radiation.



In general, RT is method of inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (high energy photons) to penetrate various materials. The intensity of the radiation that penetrates and passes through the material is either captured by a radiation sensitive film (*Film Radiography*) or by a planer array of radiation sensitive sensors (*Real-time Radiography*). Film radiography is the oldest approach, yet it is still the most widely used in NDT.

Basic Principles



In radiographic testing, the part to be inspected is placed between the radiation source and a piece of radiation sensitive film. The radiation source can either be an X-ray machine or a radioactive source (*Ir-192, Co-60, or in rare cases Cs-137*). The part will stop some of the radiation where thicker and more dense areas will stop more of the radiation. The radiation that passes through the part will expose the film and forms a shadowgraph of the part. The film darkness (*density*) will vary with the amount of radiation reaching the film through the test object where darker areas indicate more exposure (*higher radiation intensity*) and lighter areas indicate less exposure (low*er radiation intensity*).

This variation in the image darkness can be used to determine thickness or composition of material and would also reveal the presence of any flaws or discontinuities inside the material.

Advantages and Disadvantages

The primary advantages and disadvantages as compared to other NDT methods are:

Advantages

- Both surface and internal discontinuities can be detected.
- Significant variations in composition can be detected.
- It has a very few material limitations.
- Can be used for inspecting hidden areas (*direct access to surface is not required*)
- Very minimal or no part preparation is required.
- Permanent test record is obtained.
- Good portability especially for gamma-ray sources.

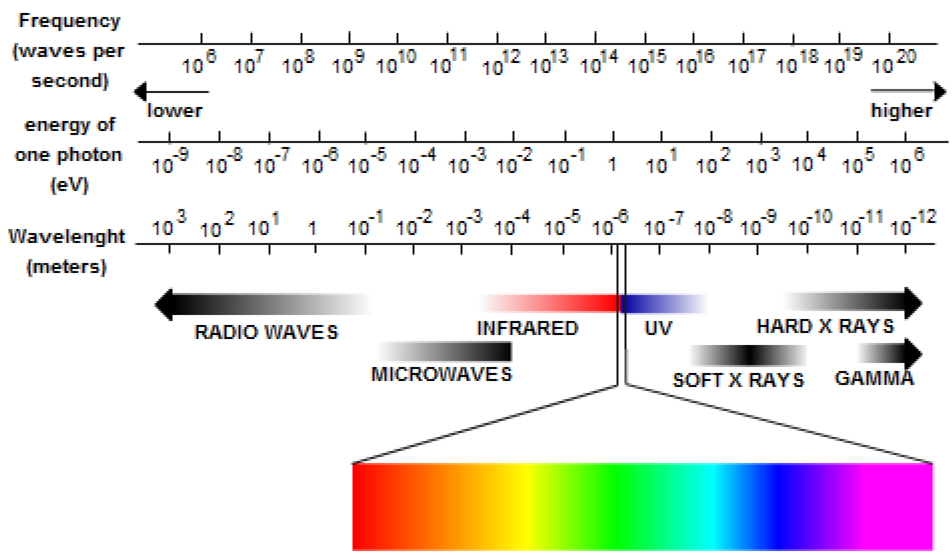
Disadvantages

- Hazardous to operators and other nearby personnel.
- High degree of skill and experience is required for exposure and interpretation.
- The equipment is relatively expensive (*especially for x-ray sources*).
- The process is generally slow.
- Highly directional (*sensitive to flaw orientation*).
- Depth of discontinuity is not indicated.
- It requires a two-sided access to the component.

PHYSICS OF RADIATION

Nature of Penetrating Radiation

Both X-rays and gamma rays are electromagnetic waves and on the electromagnetic spectrum they ocupy frequency ranges that are higher than ultraviolate radiation. In terms of frequency, gamma rays generaly have higher frequencies than X-rays as seen in the figure. The major distenction between X-rays and gamma rays is the origion where X-rays are usually artificially produced using an X-ray generator and gamma radiation is the product of radioactive materials. Both X-rays and gamma rays are waveforms, as are light rays, microwaves, and radio waves. X-rays and gamma rays cannot been seen, felt, or heard. They possess no charge and no mass and, therefore, are not influenced by electrical and magnetic fields and will generally travel in straight lines. However, they can be diffracted (bent) in a manner similar to light.



The Electromagnetic Spectrum

Electromagentic radiation <u>act somewhat like a particle at times</u> in that they occur as small "packets" of energy and are referred to as "*photons*". Each photon contains a certain amount (*or bundle*) of energy, and all electromagnetic radiation consists of these photons. The only difference between the various types of electromagnetic radiation is the amount of energy found in the photons. Due to the short wavelength of X-rays and gamma rays, they have more energy to pass through matter than do the other forms of energy in the electromagnetic spectrum. As they pass through matter, they are scattered and absorbed and the degree of penetration depends on the kind of matter and the energy of the rays.

Properties of X-Rays and Gamma Rays

- They are not detected by human senses (cannot be seen, heard, felt, etc.).
- They travel in straight lines at the speed of light.
- Their paths cannot be changed by electrical or magnetic fields.
- They can be diffracted, refracted to a small degree at interfaces between two different materials, and in some cases be reflected.
- They pass through matter until they have a chance to encounter with an atomic particle.
- Their degree of penetration depends on their energy and the matter they are traveling through.
- They have enough energy to ionize matter and can damage or destroy living cells.

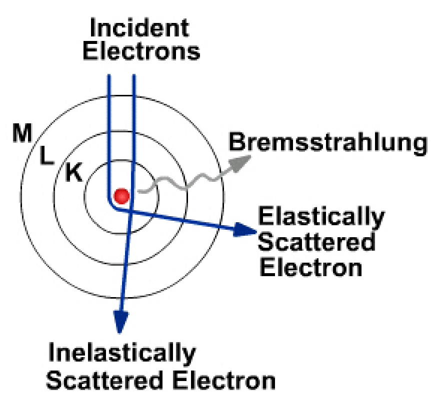
X-Radiation

X-rays are just like any other kind of electromagnetic radiation. They can be produced in packets of energy called photons, just like light. There are two different atomic processes that can produce X-ray photons. One is called *Bremsstrahlung* (*a German term meaning "braking radiation"*) and the other is called *K-shell emission*. They can both occur in the heavy atoms of tungsten which is often the material chosen for the target or anode of the X-ray tube.

Both ways of making X-rays involve a change in the state of electrons. However, Bremsstrahlung is easier to understand using the classical idea that radiation is emitted when the velocity of the electron shot at the tungsten target changes. The negatively charged electron slows down after swinging around the nucleus of a positively charged tungsten atom and this energy loss produces X-radiation. Electrons are scattered elastically or inelastically by the positively charged nucleus. The inelastically scattered electron loses energy, and thus produces X-ray photon, while the elastically scattered electrons generally change their direction significantly but without loosing much of their energy.

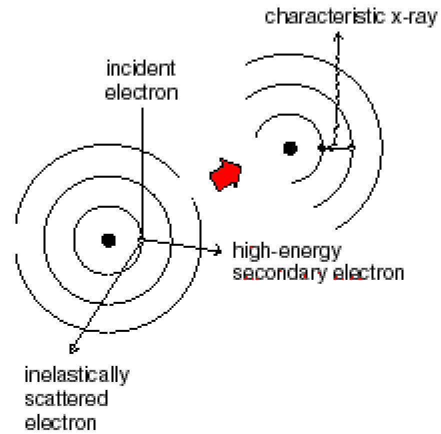
Bremsstrahlung Radiation

X-ray tubes produce X-ray photons by accelerating a stream of electrons to energies of several hundred kiloelectronvolts with velocities of several hundred kilometers per hour and colliding them into a heavy target material. The abrupt deceleration of the charged particles (electrons) produces Bremsstrahlung photons. X-ray radiation with a continuous spectrum of energies is produced with a range from a few *keV* to a maximum of the energy of the electron beam.



The Bremsstrahlung photons generated within the target material are attenuated as they pass through, typically, 50 microns of target material. The beam is further attenuated by the aluminum or beryllium vacuum window. The results are the elimination of the low energy photons, *1 keV* through *15 keV*, and a significant reduction in the portion of the spectrum from *15 keV* through *50 keV*. The spectrum from an X-ray tube is further modified by the filtration caused by the selection of filters used in the setup.

K-shell Emission Radiation



Remember that atoms have their electrons arranged in closed "shells" of different energies. The K-shell is the lowest energy state of an atom. An incoming electron can give a K-shell electron enough energy to knock it out of its energy state. About *0.1%* of the electrons produce K-shell vacancies; most produce heat. Then, a tungsten electron of higher energy (from an outer shell) can fall into the K-shell. The energy lost by the falling electron shows up as an emitted X-ray photon. Meanwhile, higher energy electrons fall into the vacated energy state in the outer shell, and so on. After losing an electron, an atom remains ionized for a very short time (about 10^{-14} second) and thus an atom can be repeatedly ionized by the incident electrons which arrive about every 10^{-12} second. Generally, K-shell emission produces higher-intensity X-rays than Bremsstrahlung, and the X-ray photon comes out at a single wavelength.

Gamma Radiation

Gamma radiation is one of the three types of natural radioactivity. Gamma rays are electromagnetic radiation just like X-rays. The other two types of natural radioactivity are alpha and beta radiation, which are in the form of particles. Gamma rays are the most energetic form of electromagnetic radiation.

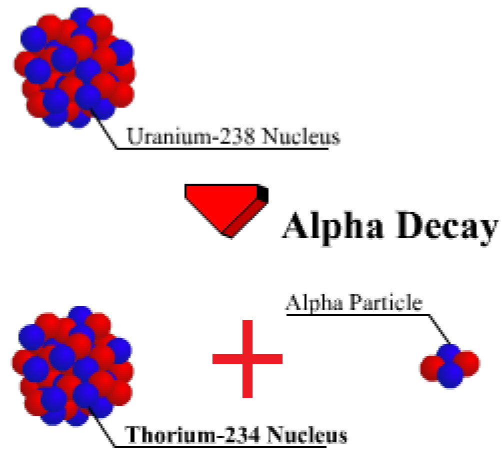
Gamma radiation is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. When the binding energy is not strong enough to hold the nucleus of an atom together, the atom is said to be unstable. Atoms with unstable nuclei are constantly changing as a result of the imbalance of energy within the nucleus. Over time, the nuclei of unstable isotopes spontaneously disintegrate, or transform, in a process known as "*radioactive decay*" and such material is called "*radioactive material*".

Types of Radiation Produced by Radioactive Decay

When an atom undergoes radioactive decay, it emits one or more forms of high speed subatomic particles ejected from the nucleus or electromagnetic radiation (gamma-rays) emitted by either the nucleus or orbital electrons.

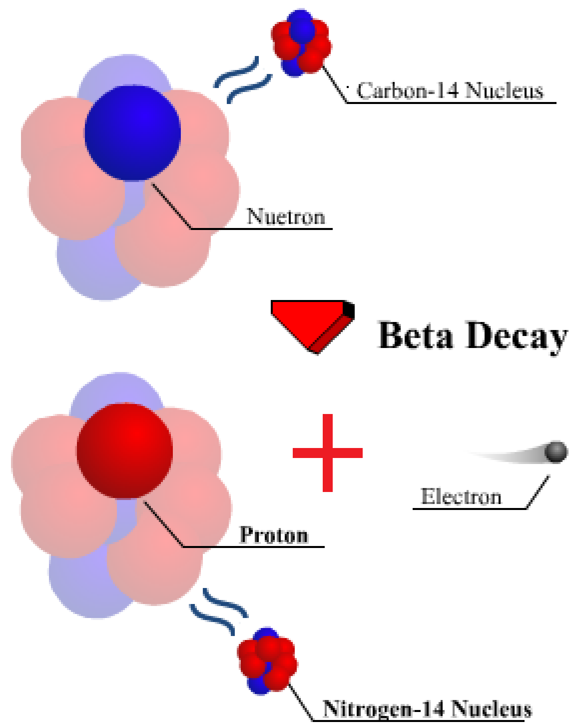
Alpha Particles

Certain radioactive materials of high atomic mass (*such as Ra-226, U-238, Pu-239*), decay by the emission of alpha particles. These alpha particles are tightly bound units of two neutrons and two protons each (*He-4 nucleus*) and have a positive charge. Emission of an alpha particle from the nucleus results in a decrease of two units of atomic number (*Z*) and four units of mass number (*A*). Alpha particles are emitted with discrete energies characteristic of the particular transformation from which they originate. All alpha particles from a particular radionuclide transformation will have identical energies.



Beta Particles

A nucleus with an unstable ratio of neutrons to protons may decay through the emission of a high speed electron called a beta particle. In beta decay a neutron will split into a positively charged proton and a negatively charged electron. This results in a net change of one unit of atomic number (*Z*) and no change in the mass number (*A*). Beta particles have a negative charge and the beta particles emitted by a specific radioactive material will range in energy from near zero up to a maximum value, which is characteristic of the particular transformation.

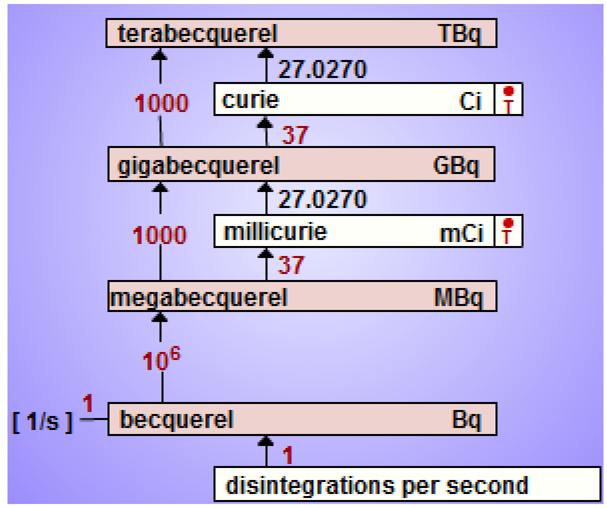


Gamma-rays

A nucleus which is in an excited state (*unstable nucleus*) may emit one or more photons of discrete energies. The emission of gamma rays does not alter the number of protons or neutrons in the nucleus but instead has the effect of moving the nucleus from *a higher to a lower energy state* (*unstable to stable*). Gamma ray emission frequently follows beta decay, alpha decay, and other nuclear decay processes.

Activity (*of Radioactive Materials*)

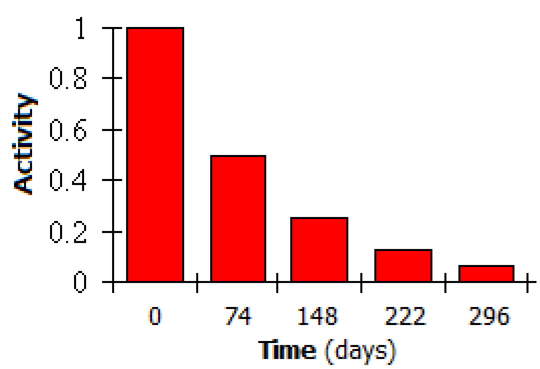
The quantity which expresses the radiation producing potential of a given amount of radioactive material is called "*Activity*". The *Curie* (***Ci***) was originally defined as that amount of any radioactive material that disintegrates at the same rate as one gram of pure radium. The International System (SI) unit for activity is the *Becquerel* (***Bq***), which is that quantity of radioactive material in which one atom is transformed per second. The radioactivity of a given amount of radioactive material does not depend upon the mass of material present. For example, two one-curie sources of the same radioactive material might have very different masses depending upon the relative proportion of non-radioactive atoms present in each source.



The concentration of radioactivity, or the relationship between the mass of radioactive material and the activity, is called "*specific activity*". Specific activity is expressed as the number of *Curies* or *Becquerels* per unit mass or volume. Each gram of Cobalt-60 will contain approximately *50 Ci*. Iridium-192 will contain *350 Ci* for every gram of material. The higher specific activity of iridium results in physically smaller sources. This allows technicians to place the source in closer proximity to the film while maintaining the sharpness of the radiograph.

Isotope Decay Rate (Half-Life)

Each radioactive material decays at its own unique rate which cannot be altered by any chemical or physical process. A useful measure of this rate is the "*half-life*" of the radioactivity. Half-life is defined as the time required for the activity of any particular radionuclide to decrease to one-half of its initial value. In other words one-half of the atoms have reverted to a more stable state material. Half-lives of radioactive materials range from microseconds to billions of years. Half-life of two widely used industrial isotopes are; *74 days for Iridium-192, and 5.3 years for Cobalt-60*.



In order to find the remaining activity of a certain material with a known half-life value after a certain period of time, the following formula may be used. The formula calculates the decay fraction (*or the remaining fraction of the initial activity*) as:

$$\boxed{f_D = \frac{A}{A_o} = (0.5)^{\frac{t}{L_H}}}$$

Where;

f_D : decay fraction (i.e., remaining fraction of the initial activity)
L_H : Half-Life value (*hours, days, years, etc.*)
t : Elapsed time (*hours, days, years, etc.*)

Or alternatively, the equitation can be solved to find the time required for activity to decay to a certain level as:

$$\boxed{t = L_H\left(\frac{\log f_D}{\log 0.5}\right)}$$

Radiation Energy, Intensity and Exposure

Different radioactive materials and X-ray generators produce radiation at different energy levels and at different rates. It is important to understand the terms used to describe the energy and intensity of the radiation.

Radiation Energy

The energy of the radiation is responsible for its ability to penetrate matter. Higher energy radiation can penetrate more and higher density matter than low energy radiation. The energy of ionizing radiation is measured in *electronvolts* (***eV***). One electronvolt is an extremely small amount of energy so it is common to use kiloelectronvolts (***keV***) and megaelectronvolt (***MeV***). An electronvolt is a measure of energy, which is different from a volt which is a measure of the electrical potential between two positions. Specifically, an electronvolt is the kinetic energy gained by an electron passing through a potential difference of one volt. X-ray generators have a control to adjust the radiation energy, *keV* (or *kV*).

The energy of a radioisotope is a characteristic of the atomic structure of the material. Consider, for example, Iridium-192 and Cobalt-60, which are two of the more common industrial Gamma ray sources. These isotopes emit radiation in two or three discreet wavelengths. Cobalt-60 will emit *1.17 and 1.33 MeV* gamma rays, and Iridium-192 will emit *0.31, 0.47, and 0.60 MeV* gamma rays. It can be seen from these values that the energy of radiation coming from Co-60 is more than twice the energy of the radiation coming from the Ir-192. From a radiation safety point of view, this difference in energy is important because the Co-60 has more material penetrating power and, therefore, is more dangerous and requires more shielding.

Intensity and Exposure

Radiation intensity is the amount of energy passing through a given area that is perpendicular to the direction of radiation travel in a given unit of time. One way to measure the intensity of X-rays or gamma rays is to measure the amount of ionization they cause in air. The amount of ionization in air produced by the radiation is called the exposure. Exposure is expressed in terms of a scientific unit called a *Roentgen* (***R***). The unit roentgen is equal to the amount of radiation that ionizes $1\ cm^3$ of dry air (at 0°C and standard atmospheric pressure) to one electrostatic unit of charge, of either sign. Most portable radiation detection safety devices used by radiographers measure exposure and present the reading in terms of *Roentgens* or *Roentgens/hour*, which is known as the "*dose rate*".

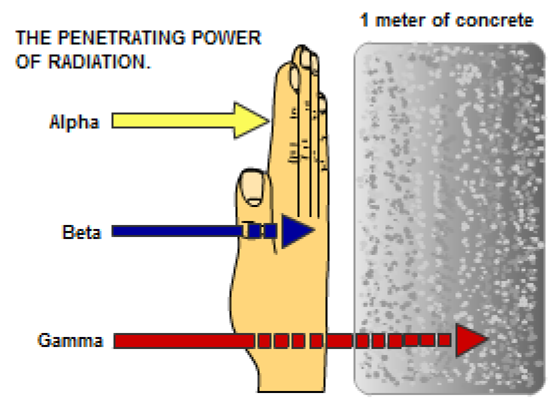
Ionization

As penetrating radiation moves from point to point in matter, it loses its energy through various interactions with the atoms it encounters. The rate at which this energy loss occurs depends upon the type and energy of the radiation and the density and atomic composition of the matter through which it is passing.

The various types of penetrating radiation impart their energy to matter primarily through excitation and ionization of orbital electrons. The term "*excitation*" is used to describe an interaction where electrons acquire energy from a passing charged particle but are not removed completely from their atom. Excited electrons may subsequently emit energy in the form of X-rays during the process of returning to a lower energy state. The term "*ionization*" refers to the complete removal of an electron from an atom following the transfer of energy from a passing charged particle.

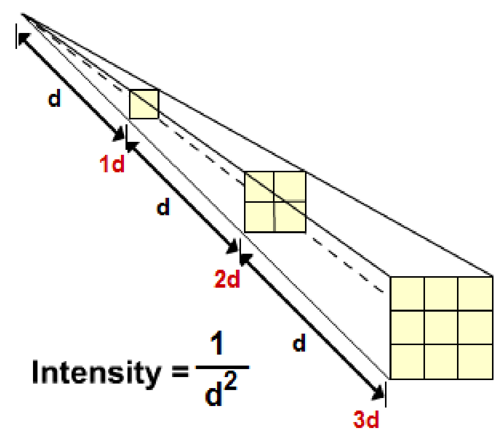
Because of their double charge and relatively slow velocity, alpha particles have a relatively short range in matter (a few centimeters in air and only fractions of a millimeter in tissue). Beta particles have, generally, a greater range.

Since they have no charge, gamma-rays and X-rays proceeds through matter until there is a chance of interaction with a particle. If the particle is an electron, it may receive enough energy to be ionized, whereupon it causes further ionization by direct interactions with other electrons. As a result, gamma-rays and X-rays can cause the liberation of electrons deep inside a medium. As a result, a given gamma or X-ray has a definite probability of passing through any medium of any depth.



Newton's Inverse Square Law

Any point source which spreads its influence equally in all directions without a limit to its range will obey the inverse square law. This comes from strictly geometrical considerations. The intensity of the influence at any given distance (***d***) is the source strength divided by the area of a sphere having a radius equal to the distance (***d***). Being strictly geometric in its origin, the inverse square law applies to diverse phenomena. Point sources of gravitational force, electric field, light, sound, and radiation obey the inverse square law.



As one of the fields which obey the general inverse square law, the intensity of the radiation received from a point radiation source can be characterized by the diagram above. The relation between intensity and distance according to the inverse square law can be expresses as:

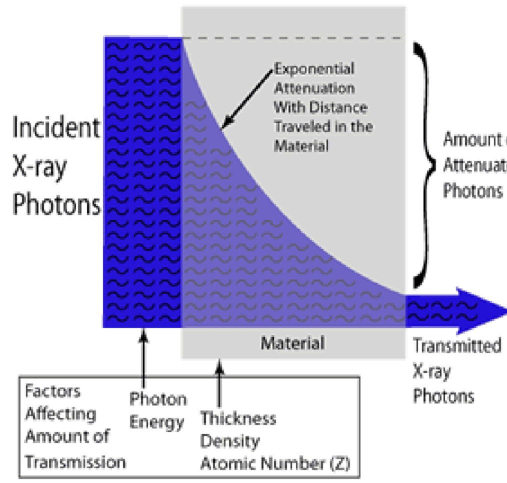
$$\boxed{I_1 {d_1}^2 = I_2 {d_2}^2}$$

Where I_1 & I_2 are the intensities at distances d_1 & d_2 form the source, respectively.

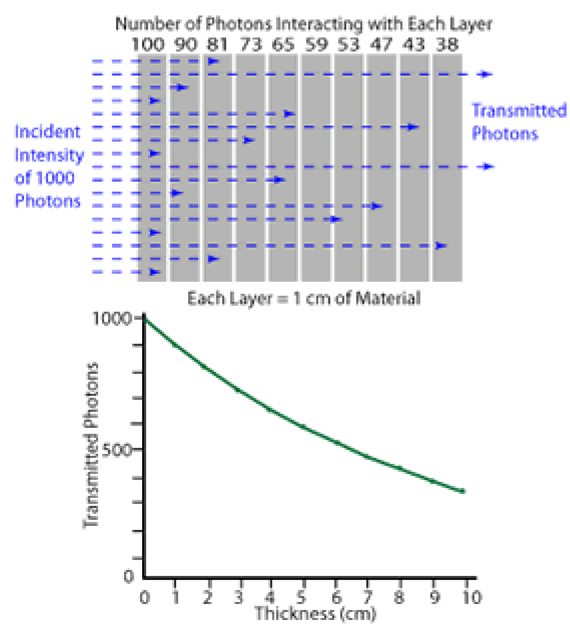
All measures of exposure or dose rate will drop off by the inverse square law. For example, if the received dose of radiation is *100 mR/hr* at *2 cm* from a source, it will be *0.01 mR/hr* at *2 m*.

Interaction between Penetrating Radiation and Matter (*Attenuation*)

When X-rays or gamma rays are directed into an object, some of the photons interact with the particles of the matter and their energy can be absorbed or scattered. This absorption and scattering is called "*Attenuation*". Other photons travel completely through the object without interacting with any of the material's particles. The number of photons transmitted through a material depends on the thickness, density and atomic number of the material, and the energy of the individual photons.



Even when they have the same energy, photons travel different distances within a material simply based on the probability of their encounter with one or more of the particles of the matter and the type of encounter that occurs. Since the probability of an encounter increases with the distance traveled, the number of photons reaching a specific point within the matter decreases exponentially with distance traveled. As shown in the graphic to the right, if 1000 photons are aimed at ten 1 cm layers of a material and there is a 10% chance of a photon being attenuated in this layer, then there will be 100 photons attenuated. This leaves 900 photos to travel into the next layer where 10% of these photos will be attenuated. By continuing this progression, the exponential shape of the curve becomes apparent.



The formula that describes this curve is:

$$\boxed{I = I_0 e^{-\mu x}}$$

Where;

I_0 : initial (*unattenuated*) intensity
μ : linear attenuation coefficient per unit distance
x : distance traveled through the matter

Linear and Mass Attenuation Coefficients

The "*linear attenuation coefficient*" (μ) describes the fraction of a beam of X-rays or gamma rays that is absorbed or scattered per unit thickness of the absorber (*10% per cm thickness for the previous example*).

Using the transmitted intensity equation above, linear attenuation coefficients can be used to make a number of calculations. These include:

- The intensity of the energy transmitted through a material when the incident X-ray intensity, the material and the material thickness are known.
- The intensity of the incident X-ray energy when the transmitted X-ray intensity, material, and material thickness are known.
- The thickness of the material when the incident and transmitted intensity, and the material are known.
- The material can be determined from the value of μ when the incident and transmitted intensity, and the material thickness are known.

Linear attenuation coefficients can sometimes be found in the literature. However, it is often easier to locate attenuation data in terms of the "*mass attenuation coefficient*". Tables and graphs of the mass attenuation coefficients for chemical elements and for several compounds and mixtures as a function of radiation energy (*in* ***keV***) are available in literature (*such information can be found at the National Institute for Standards and Technology website: http://www.nist.gov/pml/data/xraycoef/*).

Since a linear attenuation coefficient is dependent on the density of a material, the mass attenuation coefficient is often reported for convenience. Consider water for example. The linear attenuation for water vapor is much lower than it is for ice because the molecules are more spread out in vapor so the chance of a photon encounter with a water particle is less. Normalizing μ by dividing it by the density of the element or compound will produce a value that is constant for a particular element or compound. This constant (μ/ρ) is known as the mass attenuation coefficient and has units of cm^2/gm. The mass attenuation coefficient can simply be converted to a linear attenuation coefficient by multiplying it by the density (ρ) of the material.

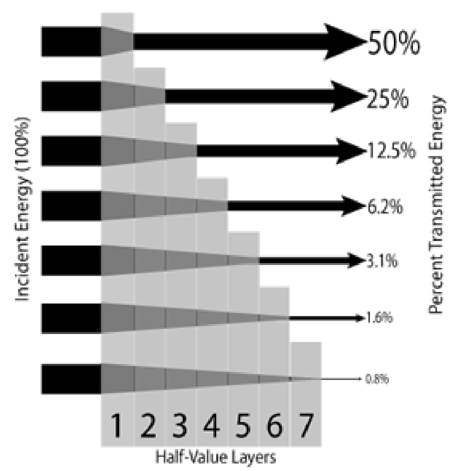
Half-Value Layer

The thickness of any given material where 50% of the incident energy has been attenuated is known as the half-value layer (***HVL***). The *HVL* is expressed in units of distance (*mm or cm*). Like the attenuation coefficient, it is photon energy dependant. Increasing the penetrating energy of a stream of photons will result in an increase in a material's *HVL*.

The *HVL* is inversely proportional to the attenuation coefficient. If an incident energy of ***1*** and a transmitted energy of ***0.5*** are plugged into the intensity attenuation equation introduced earlier, solving for x which will correspond to the *HVL* gives:

$$0.5 = 1e^{-\mu x} \quad \Rightarrow \quad \boxed{HVL = \frac{0.693}{\mu}}$$

The *HVL* is often used in radiography simply because it is easier to remember values and perform simple calculations. In a shielding calculation, such as illustrated to the right, it can be seen that if the thickness of one *HVL* is known, it is possible to quickly determine how much material is needed to reduce the intensity to less than 1%.



In order to calculate the ratio of intensity attenuation (*or reduction*) resulting from passing through a certain thickness of a material for which the *HVL* is known, the following equation may be used:

$$\boxed{r_I = \frac{I}{I_o} = (0.5)^{\frac{Thickness}{HVL}}}$$

Where r_I is intensity reduction ratio.

Or alternatively, the equitation can be solved to find the material thickness required for reducing the intensity to a certain level as:

$$\boxed{Thickness = HVL\left(\frac{\log r_I}{\log 0.5}\right)}$$

Sometimes instead of specifying the *HVL*, the Tenth Value Layer (*TVL*) is specified. The *TVL* is the thickness that attenuates 90% of the intensity (only 10% passes through).

In that case, the equation becomes:

$$r_I = \frac{I}{I_o} = (0.1)^{\frac{Thickness}{TVL}}$$

Approximate *HVL* for various materials when radiation is from a gamma-ray source:

	Half-Value Layer (*mm*)				
Source	**Concrete**	**Steel**	**Lead**	**Tungsten**	**Uranium**
Iridium-192	*44.5*	*12.7*	*4.8*	*3.3*	*2.8*
Cobalt-60	*60.5*	*21.6*	*12.5*	*7.9*	*6.9*

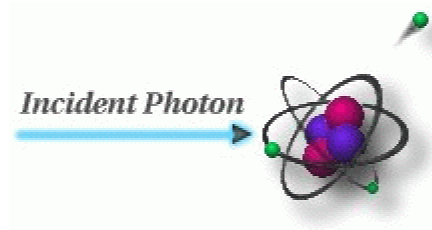
Approximate *HVL* for some materials when radiation is from an X-ray source:

	Half-Value Layer (*mm*)	
X-ray Tube Voltage (*kV*)	**Lead**	**Concrete**
50	*0.06*	*4.32*
100	*0.27*	*15.10*
150	*0.30*	*22.32*
200	*0.52*	*25.0*
250	*0.88*	*28.0*
300	*1.47*	*31.21*
400	*2.5*	*33.0*
1000	*7.9*	*44.45*

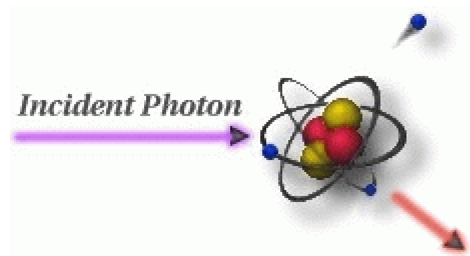
Sources of Attenuation

The attenuation that results due to the interaction between penetrating radiation and matter is not a simple process. A single interaction event between a primary X-ray photon and a particle of matter does not usually result in the photon changing to some other form of energy and effectively disappearing. Several interaction events are usually involved and the total attenuation is the sum of the attenuation due to different types of interactions. These interactions include the photoelectric effect, scattering, and pair production.

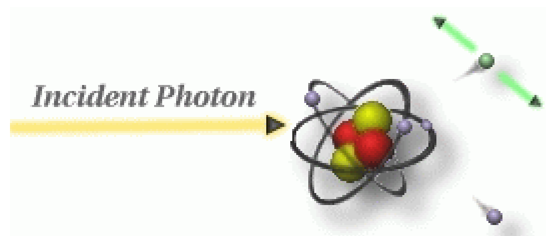
- *Photoelectric (**PE**) absorption* of X-rays occurs when the X-ray photon is absorbed, resulting in the ejection of electrons from the outer shell of the atom, and hence the ionization of the atom. Subsequently, the ionized atom returns to the neutral state with the emission of an X-ray characteristic of the atom. This subsequent emission of lower energy photons is generally absorbed and does not contribute to (or hinder) the image making process. Photoelectron absorption is the dominant process for X-ray absorption up to energies of about *500 keV*. Photoelectric absorption is also dominant for atoms of high atomic numbers.



- *Compton scattering (**C**)* occurs when the incident X-ray photon is deflected from its original path by an interaction with an electron. The electron gains energy and is ejected from its orbital position. The X-ray photon loses energy due to the interaction but continues to travel through the material along an altered path. Since the scattered X-ray photon has less energy, it, therefore, has a longer wavelength than the incident photon.



- *Pair production (**PP**)* can occur when the X-ray photon energy is greater than *1.02 MeV*, but really only becomes significant at energies around *10 MeV*. Pair production occurs 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.

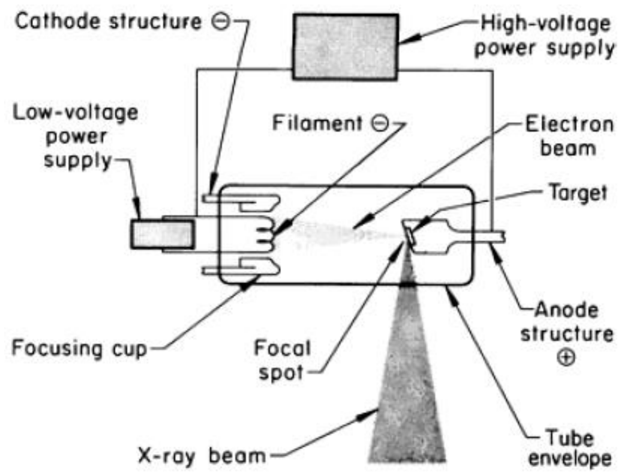


EQUIPMENT & MATERIALS

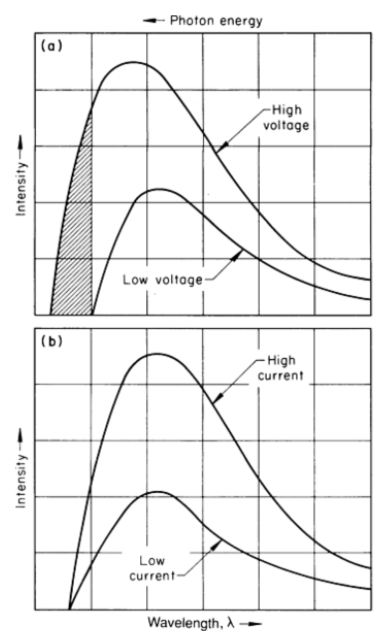
X-ray Generators

The major components of an X-ray generator are the tube, the high voltage generator, the control console, and the cooling system. As discussed earlier in this material, X-rays are generated by directing a stream of high speed electrons at a target material such as tungsten, which has a high atomic number. When the electrons are slowed or stopped by the interaction with the atomic particles of the target, X-radiation is produced. This is accomplished in an X-ray tube such as the one shown in the figure.

The tube cathode (*filament*) is heated with a low-voltage current of a few amps. The filament heats up and the electrons in the wire become loosely held. A large electrical potential is created between the cathode and the anode by the high-voltage generator. Electrons that break free of the cathode are strongly attracted to the anode target. The stream of electrons between the cathode and the anode is the tube current. The tube current is measured in milliamps and is controlled by regulating the low-voltage heating current applied to the cathode. The higher the temperature of the filament, the larger the number of electrons that leave the cathode and travel to the anode. The milliamp or current setting on the control console regulates the filament temperature, which relates to the intensity of the X-ray output.



The high-voltage between the cathode and the anode affects the speed at which the electrons travel and strike the anode. The higher the kilovoltage, the more speed and, therefore, energy the electrons have when they strike the anode. Electrons striking with more energy result in X-rays with more penetrating power. The high-voltage potential is measured in kilovolts, and this is controlled with the voltage or kilovoltage control on the control console. An increase in the kilovoltage will also result in an increase in the intensity of the radiation. The figure shows the spectrum of the radiated X-rays associated with the voltage and current settings. The top figure shows that increasing the kV increases both the energy of X-rays and also increases the intensity of radiation (*number of photons*). Increasing the current, on the other hand, only increases the intensity without shifting the spectrum.



A focusing cup is used to concentrate the stream of electrons to a small area of the target called the "*focal spot*". The focal spot size is an important factor in the system's ability to produce a sharp image. Much of the energy applied to the tube is transformed into heat at the focal spot of the anode. As mentioned above, the anode target is commonly made from tungsten, which has a high melting point in addition to a high atomic number. However, cooling of the anode by active or passive means is necessary. Water or oil re-circulating systems are often used to cool tubes. Some low power tubes are cooled simply with the use of thermally conductive materials and heat radiating fins.

In order to prevent the cathode from burning up and to prevent arcing between the anode and the cathode, all of the oxygen is removed from the tube by pulling a vacuum. Some systems have external vacuum pumps to remove any oxygen that may have leaked into the tube. However, most industrial X-ray tubes simply require a warm-up procedure to be followed. This warm-up procedure carefully raises the tube current and voltage to slowly burn any of the available oxygen before the tube is operated at high power.

In addition, X-ray generators usually have a filter along the beam path (*placed at or near the x-ray port*). Filters consist of a thin sheet of material (*often high atomic number materials such as lead, copper, or brass*) placed in the useful beam to modify the spatial distribution of the beam. Filtration is required to absorb the lower-energy X-ray photons emitted by the tube before they reach the target in order to produce a cleaner image (*since lower energy X-ray photons tend to scatter more*).

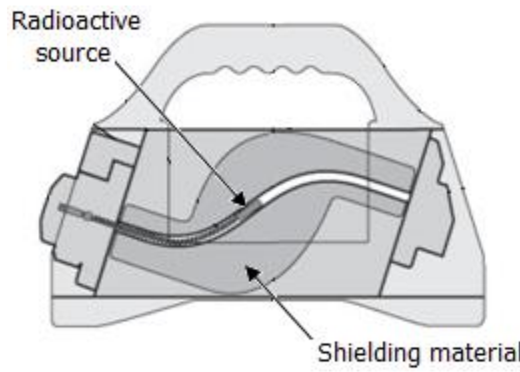
The other important component of an X-ray generating system is the control console. Consoles typically have a keyed lock to prevent unauthorized use of the system. They will have a button to start the generation of X-rays and a button to manually stop the generation of X-rays. The three main adjustable controls regulate the tube voltage in *kilovolts*, the tube amperage in *milliamps*, and the exposure time in *minutes and seconds*. Some systems also have a switch to change the focal spot size of the tube.

Radio Isotope (*Gamma-ray*) Sources

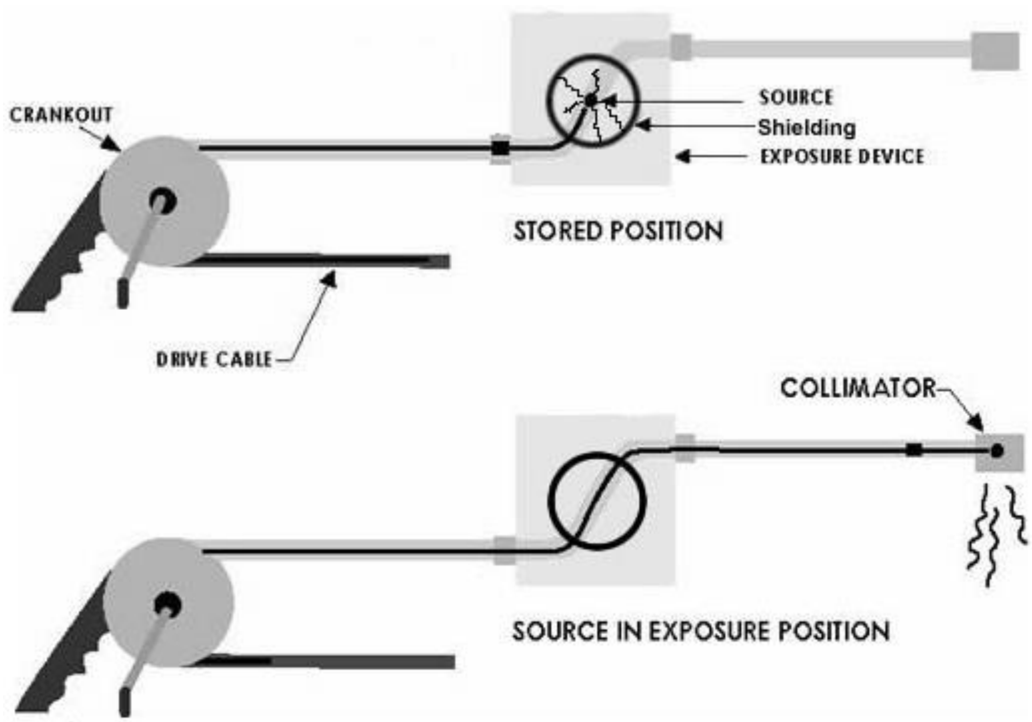
Manmade radioactive sources are produced by introducing an extra neutron to atoms of the source material. As the material gets rid of the neutron, energy is released in the form of gamma rays. Two of the most common industrial gamma-ray sources for industrial radiography are Iridium-192 and Cobalt-60. In comparison to an X-ray generator, Cobalt-60 produces energies comparable to a *1.25 MV* X-ray system and Iridium-192 to a *460 kV* X-ray system. These high energies make it possible to penetrate thick materials with a relatively short exposure time. This and the fact that sources are very portable are the main reasons that gamma sources are widely used for field radiography. Of course, the disadvantage of a radioactive source is that it can never be turned off and safely managing the source is a constant responsibility.

Physical size of isotope materials varies between manufacturers, but generally an isotope material is a pellet that measures *1.5 mm* x *1.5 mm*. Depending on the level of activity desired, a pellet or pellets are loaded into a stainless steel capsule and sealed by welding. The capsule is attached to short flexible cable called a pigtail.

The source capsule and the pigtail are housed in a shielding device referred to as a exposure device or camera. Depleted uranium is often used as a shielding material for sources. The exposure device for Iridium-192 and Cobalt-60 sources will contain *22 kg* and *225 kg* of shielding materials, respectively. Cobalt cameras are often fixed to a trailer and transported to and from inspection sites. When the source is not being used to make an exposure, it is locked inside the exposure device.

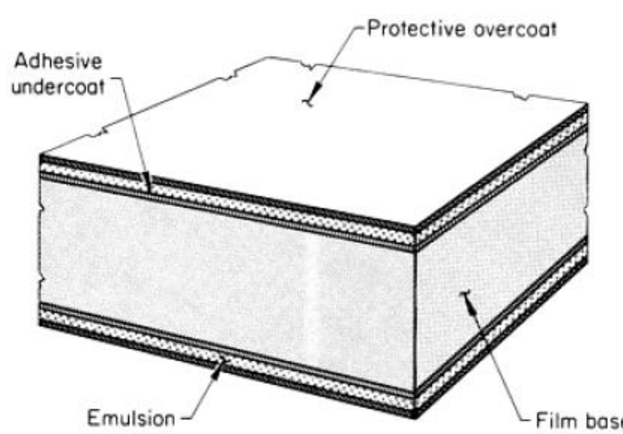


To make a radiographic exposure, a crank-out mechanism and a guide tube are attached to opposite ends of the exposure device. The guide tube often has a collimator (*usually made of tungsten*) at the end to shield the radiation except in the direction necessary to make the exposure. The end of the guide tube is secured in the location where the radiation source needs to be to produce the radiograph. The crank-out cable is stretched as far as possible to put as much distance as possible between the exposure device and the radiographer. To make the exposure, the radiographer quickly cranks the source out of the exposure device and into position in the collimator at the end of the guide tube. At the end of the exposure time, the source is cranked back into the exposure device. There is a series of safety procedures, which include several radiation surveys, that must be accomplished when making an exposure with a gamma source.



Radiographic Film

X-ray films for general radiography basically consist of an emulsion-gelatin containing radiation-sensitive silver halide crystals (*such as silver bromide or silver chloride*). The emulsion is usually coated on both sides of a flexible, transparent, blue-tinted base in layers about *0.012 mm* thick. An adhesive undercoat fastens the emulsion to the film base and a very thin but tough coating covers the emulsion to protect it against minor abrasion. The typical total thickness of the X-ray film is approximately *0.23 mm*. Though films are made to be sensitive for X-ray or gamma-ray, yet they are also sensitive to visible light. When X-rays, gamma-rays, or light strike the film, some of the halogen atoms are liberated from the silver halide crystal and thus leaving the silver atoms alone. This change is of such a small nature that it cannot be detected by ordinary physical methods and is called a "*latent (hidden) image*". When the film is exposed to a chemical solution (*developer*) the reaction results in the formation of black, metallic silver.



Film Selection

Selecting the proper film and developing the optimal radiographic technique for a particular component depends on a number of different factors;

- Composition, shape, and size of the part being examined and, in some cases, its weight and location.
- Type of radiation used, whether X-rays from an X-ray generator or gamma rays from a radioactive source.
- Kilovoltage available with the X-ray equipment or the intensity of the gamma radiation.
- Relative importance of high radiographic detail or quick and economical results.

Film Packaging

Radiographic film can be purchased in a number of different packaging options and they are available in a variety of sizes. The most basic form is as individual sheets in a box. In preparation for use, each sheet must be loaded into a cassette or film holder in a darkroom to protect it from exposure to light.

Industrial X-ray films are also available in a form in which each sheet is enclosed in a light-tight envelope. The film can be exposed from either side without removing it from the protective packaging. A rip strip makes it easy to remove the film in the darkroom for processing.

Packaged film is also available in the form of rolls where that allows the radiographer to cut the film to any length. The ends of the packaging are sealed with electrical tape in the darkroom. In applications such as the radiography of circumferential welds and the examination of long joints on an aircraft fuselage, long lengths of film offer great economic advantage.

Film Handling

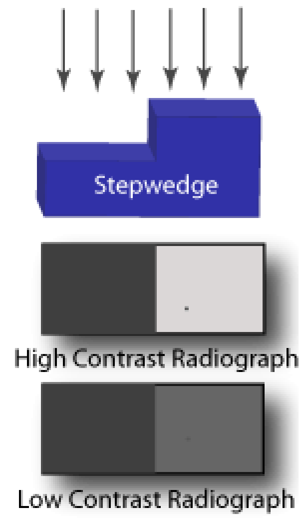
X-ray film should always be handled carefully to avoid physical strains, such as pressure, creasing, buckling, friction, etc. Whenever films are loaded in semi-flexible holders and external clamping devices are used, care should be taken to be sure pressure is uniform. Marks resulting from contact with fingers that are moist or contaminated with processing chemicals, as well as crimp marks, are avoided if large films are always grasped by the edges and allowed to hang free. Use of envelope-packed films avoids many of these problems until the envelope is opened for processing.

RADIOGRAPHY CONSIDERATIONS & TECHNIQUES

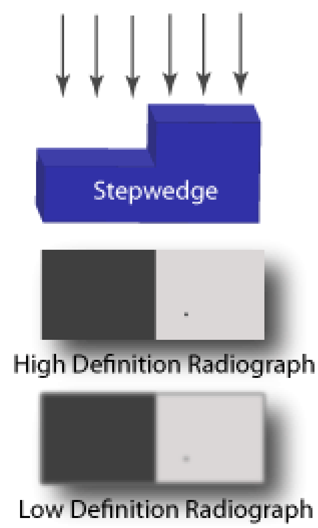
Radiographic Sensitivity

The usual objective in radiography is to produce an image showing the highest amount of detail possible. This requires careful control of a number of different variables that can affect image quality. Radiographic sensitivity is a measure of the quality of an image in terms of the smallest detail or discontinuity that may be detected. Radiographic sensitivity is dependant on the contrast and the definition of the image.

Radiographic contrast is the degree of density (*darkness*) difference between two areas on a radiograph. Contrast makes it easier to distinguish features of interest, such as defects, from the surrounding area. The image to the right shows two radiographs of the same stepwedge. The upper radiograph has a high level of contrast and the lower radiograph has a lower level of contrast. While they are both imaging the same change in thickness, the high contrast image uses a larger change in radiographic density to show this change. In each of the two radiographs, there is a small dot, which is of equal density in both radiographs. It is much easier to see in the high contrast radiograph.



Radiographic definition is the abruptness of change in going from one area of a given radiographic density to another. Like contrast, definition also makes it easier to see features of interest, such as defects, but in a totally different way. In the image to the right, the upper radiograph has a high level of definition and the lower radiograph has a lower level of definition. In the high definition radiograph it can be seen that a change in the thickness of the stepwedge translates to an abrupt change in radiographic density. It can be seen that the details, particularly the small dot, are much easier to see in the high definition radiograph. It can be said that a faithful visual reproduction of the stepwedge was produced. In the lower image, the radiographic setup did not produce a faithful visual reproduction. The edge line between the steps is blurred. This is evidenced by the gradual transition between the high and low density areas on the radiograph.



Radiographic "Image" Density

After taking a radiographic image of a part and processing the film, the resulting darkness of the film will vary according to the amount of radiation that has reached the film through the test object. As mentioned earlier, the darker areas indicate more exposure and lighter areas indicate less exposure. The processed film (*or image*) is usually viewed by placing it in front of a screen providing white light illumination of uniform intensity such that the light is transmitted through the film such that the image can be clearly seen. The term "radiographic density" is a measure of the degree of film darkening (*darkness of the image*). Technically it should be called "transmitted density" when associated with transparent-base film since it is a measure of the light transmitted through the film. Radiographic density is the logarithm of two measurements: the intensity of light incident on the film (I_o) and the intensity of light transmitted through the film (I_t). This ratio is the inverse of transmittance.

$$\boxed{Density = \log \frac{I_o}{I_t}}$$

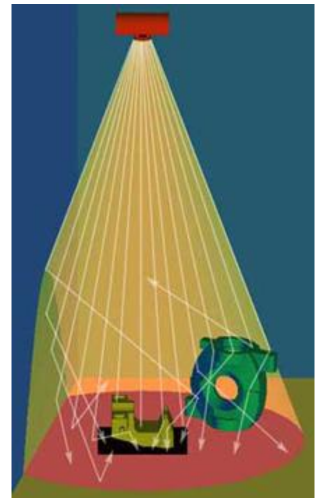
Similar to the decibel, using the log of the ratio allows ratios of significantly different sizes to be described using easy to work with numbers. The following table shows numeric examples of the relationship between the amount of transmitted light and the calculated film density.

Transmittance (I_t/I_0)	**Transmittance** (%)	**Inverse of Transmittance (I_0/I_t)**	**Density ($Log(I_0/I_t)$)**
1.0	100%	1	0
0.1	10%	10	1
0.01	1%	100	2
0.001	0.1%	1000	3
0.0001	0.01%	10000	4

From the table, it can be seen that a density reading of *2.0* is the result of only one percent of the incident light making it through the film. At a density of *4.0* only *0.01%* of transmitted light reaches the far side of the film. Industrial codes and standards typically require a radiograph to have a density between *2.0* and *4.0* for acceptable viewing with common film viewers. Above 4.0, extremely bright viewing lights is necessary for evaluation.

Film density is measured with a "*densitometer*" which simply measures the amount of light transmitted through a piece of film using a photovoltic sensor.

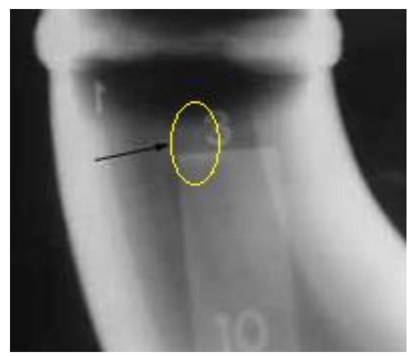
Secondary (Scatter) Radiation Control



Secondary or scatter radiation must often be taken into consideration when producing a radiograph. The scattered photons create a loss of contrast and definition. Often, secondary radiation is thought of as radiation striking the film reflected from an object in the immediate area, such as a wall, or from the table or floor where the part is resting.

Control of side scatter can be achieved by moving objects in the room away from the film, moving the X-ray tube to the center of the vault, or placing a collimator at the exit port, thus reducing the diverging radiation surrounding the central beam.

When scarered radiation comes from objects behind the film, it is often called "backscatter". Industry codes and standards often require that a lead letter "*B*" be placed on the back of the cassette to verify the control of backscatter. If the letter "*B*" shows as a "*ghost*" image on the film, a significant amount of backscatter radiation is reaching the film. The image of the "*B*" is often very nondistinct as shown in the image to the right. The arrow points to the area of backscatter radiation from the lead "*B*" located on the back side of the film.



The control of backscatter radiation is achieved by backing the film in the cassette with a sheet of lead that is at least *0.25 mm* thick such that the sheet will be behind the film when it is exposed. It is a common practice in industry to place thin sheets of lead (*called "lead screens"*) in front and behind the film (*0.125 mm thick in front and 0.25 mm thick behind*).

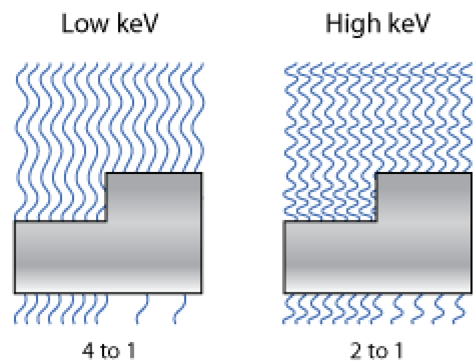
Radiographic Contrast

As mentioned previously, radiographic contrast describes the differences in photographic density in a radiograph. The contrast between different parts of the image is what forms the image and the greater the contrast, the more visible features become. Radiographic contrast has two main contributors; subject contrast and film (*or detector*) contrast.

Subject Contrast

Subject contrast is the ratio of radiation intensities transmitted through different areas of the component being evaluated. It is dependant on the absorption differences in the component, the wavelength of the primary radiation, and intensity and distribution of secondary radiation due to scattering.

It should be no surprise that absorption differences within the subject will affect the level of contrast in a radiograph. The larger the difference in thickness or density between two areas of the subject, the larger the difference in radiographic density or contrast. However, it is also possible to radiograph a particular subject and produce two radiographs having entirely different contrast levels. Generating X-rays using a low kilovoltage will generally result in a radiograph with high contrast. This occurs because low energy radiation is more easily attenuated. Therefore, the ratio of photons that are transmitted through a thick and thin area will be greater with low energy radiation.

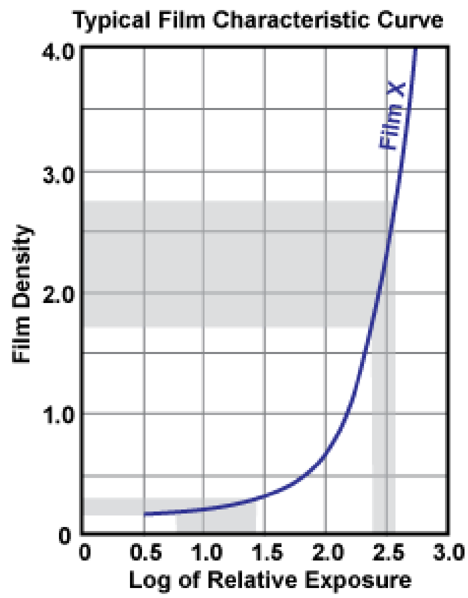


There is a tradeoff, however. Generally, as contrast sensitivity increases, the latitude of the radiograph decreases. Radiographic latitude refers to the range of material thickness that can be imaged. This means that more areas of different thicknesses will be visible in the image. Therefore, the goal is to balance radiographic contrast and latitude so that there is enough contrast to identify the features of interest but also to make sure the latitude is great enough so that all areas of interest can be inspected with one radiograph. In thick parts with a large range of thicknesses, multiple radiographs will likely be necessary to get the necessary density levels in all areas.

Film Contrast

Film contrast refers to density differences that result due to the type of film being used, how it was exposed, and how it was processed. Since there are other detectors besides film, this could be called detector contrast, but the focus here will be on film. Exposing a film to produce higher film densities will generally increase the contrast in the radiograph.

A typical film characteristic curve, which shows how a film responds to different amounts of radiation exposure, is shown in the figure. From the shape of the curves, it can be seen that when the film has not seen many photon interactions (*which will* *result in a low film density*) the slope of the curve is low. In this region of the curve, it takes a large change in exposure to produce a small change in film density. Therefore, the sensitivity of the film is relatively low. It can be seen that changing the log of the relative exposure from *0.75* to *1.4* only changes the film density from *0.20* to about *0.30*. However, at film densities above *2.0*, the slope of the characteristic curve for most films is at its maximum. In this region of the curve, a relatively small change in exposure will result in a relatively large change in film density. For example, changing the log of relative exposure from *2.4* to *2.6* would change the film density from *1.75* to *2.75*. Therefore, the sensitivity of the film is high in this region of the curve. In general, the highest overall film density that can be conveniently viewed or digitized will have the highest level of contrast and contain the most useful information.



As mentioned previously, thin lead sheets (*called "lead screens"*) are typically placed on both sides of the radiographic film during the exposure (*the film is placed between the lead screens and inserted inside the cassette*). Lead screens in the thickness range of *0.1 to 0.4 mm* typically reduce the scattered radiation at energy levels below *150 kV*. Above this energy level, they will emit electrons to provide more exposure of the film, thus increasing the density and contrast of the radiograph.

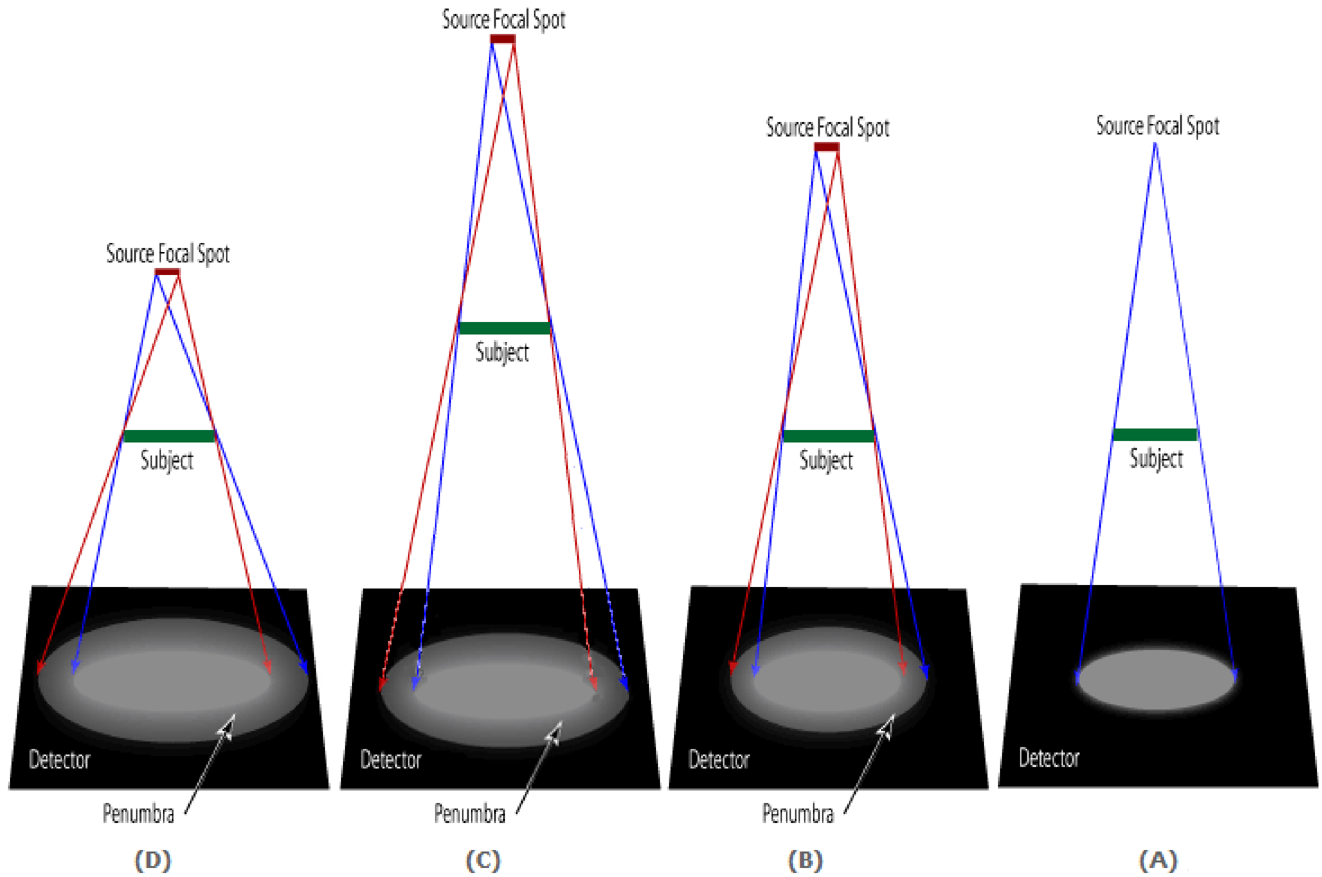
Other type of screens called "fluorescent screens" can alternatively be used where they produce visible light when exposed to radiation and this light further exposes the film and increases density and contrast.

Radiographic Definition

As mentioned previously, radiographic definition is the abruptness of change from one density to another. Both geometric factors of the equipment and the radiographic setup, and film and screen factors have an effect on definition.

Geometric Factors

The loss of definition resulting from geometric factors of the radiographic equipment and setup is refered to as "*geometric unsharpness*". It occurs because the radiation does not originate from a single point but rather over an area. The three factors controlling unsharpness are source size, source to object distance, and object to detector (film) distance. The effects of these three factors on image defenetion is illustrated by the images below (*source size effect; compare **A** & **B**, source to object distance; compare **B** & **D**, and object to detector distance; compare **B** & **C***).

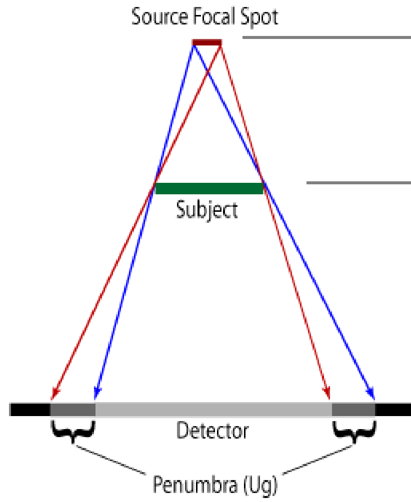


The source size is obtained by referencing manufacturers specifications for a given X-ray or gamma ray source. Industrial X-ray tubes often have focal spot sizes of *1.5 mm* squared but microfocus systems have spot sizes in the *30 micron* range. As the source size decreases, the geometric unsharpness also decreases. For a given size source, the unsharpness can also be decreased by increasing the source to object distance, but this comes with a reduction in radiation intensity. The object to detector distance is usually kept as small as possible to help minimize unsharpness. However, there are situations, such as when using geometric enlargement, when the object is separated from the detector, which will reduce the definition.

In general, in order to produce the highest level of definition, the focal-spot or source size should be as close to a point source as possible, the source-to-object distance should be as large as practical, and the object-to-detector distance should be a small as practical.

Codes and standards used in industrial radiography require that geometric unsharpness be limited. In general, the allowable amount is *1/100 of the material thickness up to a maximum of 1 mm*. These values refer to the width of penumbra shadow in a radiographic image.

The amount of geometric unsharpness (U_g) can be calculated using the following geometric formula:

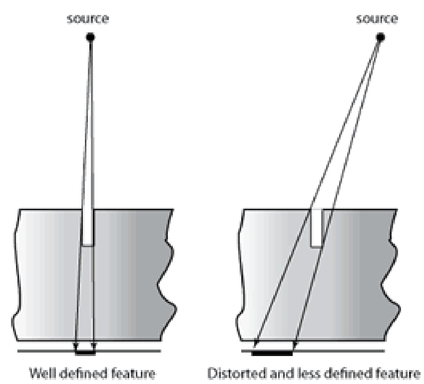


$$\boxed{U_g = d_s \frac{b}{a}}$$

Where;

- d_s : source focal-spot size
- a : distance from the source to the front surface of the object
- b : distance from the front surface of the object to the detector (*or the thickness of the object if a thick object is placed immediately on top of the detector*)

The angle between the radiation and some features will also have an effect on definition. If the radiation is parallel to an edge or linear discontinuity, a sharp distinct boundary will be seen in the image. However, if the radiation is not parallel with the discontinuity, the feature will appear distorted, out of position and less defined in the image.



Abrupt changes in thickness and/or density will appear more defined in a radiograph than will areas of gradual change. For example, consider a circle. Its largest dimension will be a cord that passes through its centerline. As the cord is moved away from the centerline, the thickness gradually decreases. It is sometimes difficult to locate the edge of a void due to this gradual change in thickness.

Lastly, any movement of the specimen, source or detector during the exposure will reduce definition. Similar to photography, any movement will result in blurring of the image. Vibration from nearby equipment may be an issue in some inspection situations.

Film and Screen Factors

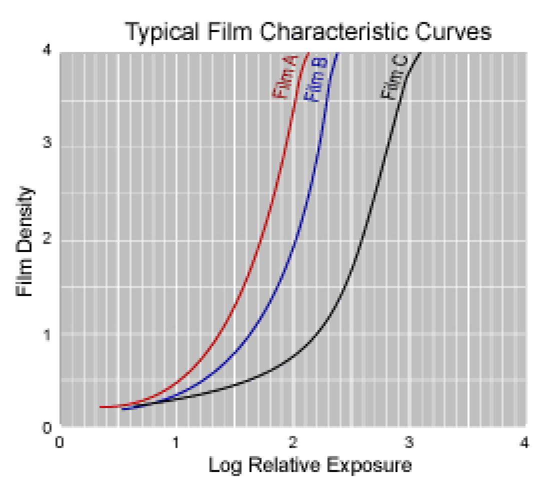
The last set of factors concern the film and the use of fluorescent screens. A <u>fine grain</u> film is capable of producing an image with a <u>higher level of definition</u> than is a coarse grain film. Wavelength of the radiation will influence apparent graininess. As the wavelength shortens and penetration increases, the apparent graininess of the film will increase. Also, <u>increased development of the film</u> will increase the apparent graininess of the radiograph.

The use of <u>fluorescent screens</u> also results in <u>lower definition</u>. This occurs for a couple of different reasons. The reason that fluorescent screens are sometimes used is because incident radiation causes them to give off light that helps to expose the film. However, the light they produce spreads in all directions, exposing the film in adjacent areas, as well as in the areas which are in direct contact with the incident radiation. Fluorescent screens also <u>produce screen mottle on radiographs</u>. Screen mottle is associated with the statistical variation in the numbers of photons that interact with the screen from one area to the next.

<u>Film Characteristic Curves</u>

In film radiography, the number of photons reaching the film determines how dense the film will become when other factors such as the developing time are held constant. The number of photons reaching the film is a function of the intensity of the radiation and the time that the film is exposed to the radiation. The term used to describe the control of the number of photons reaching the film is "exposure".

Different types of radiographic films respond differently to a given amount of exposure. Film manufacturers commonly characterize their film to determine the relationship between the applied exposure and the resulting film density. This relationship commonly varies over a range of film densities, so the data is presented in the form of a curve such as the one for *Kodak AA400* shown to the right. This plot is usually called a film characteristic curve or density curve. A log scale is sometimes used for the *x*-axis or it is more common that the values are reported in <u>log units</u> on a linear scale as seen in the figure. Also, relative exposure values (*unitless*) are often used. Relative exposure is the ratio of two exposures. For



example, if one film is exposed at *100 kV* for *6 mA.min* and a second film is exposed at the same energy for *3 mA.min*, then the relative exposure would be *2*.

The location of the characteristic curves of different films along the *x*-axis relates to the speed of the film. The farther to the right that a curve is on the chart, the slower the film speed (*Film A has the highest speed while film C has the lowest speed*). The shape of the characteristic curve is largely independent of the wavelength of the X-ray or gamma ray, but the location of the curve along the *x*-axis, with respect to the curve of another film, does depend on radiation quality.

Film characteristic curves can be used to adjust the exposure used to produce a radiograph with a certain density to an exposure that will produce a second radiograph of higher or lower film density. The curves can also be used to relate the exposure produced with one type of film to exposure needed to produce a radiograph of the same density with a second type of film.

Example 1: *Adjusting the Exposure to Produce a Different Film Density*

> A type *B* Film was exposed with *140 kV* at *1 mA* for *10 seconds* (*i.e., 10 mA.s*) and the resulting radiograph had a density of *1.0*. If the desired density is 2.5, what should be the exposure?

From the graph, the log of the relative exposure of a density of *1.0* is *1.62* and the log of the relative exposure when the density of the film is *2.5* is *2.12*.

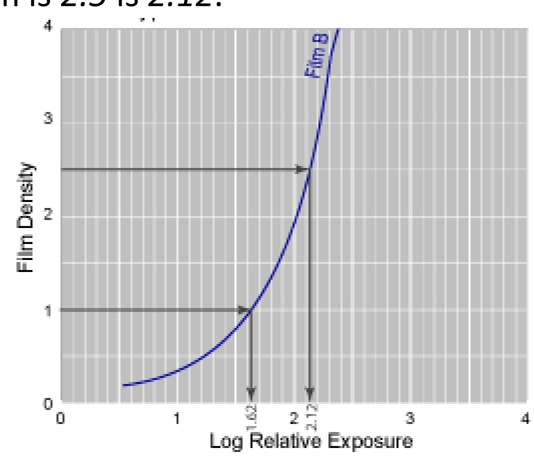
The difference between the two values is *0.5*.

$10^{0.5} = 3.16$

Therefore, the exposure used to produce the initial radiograph with a *1.0* density needs to be multiplied by *3.16* to produce a radiograph with the desired density of *2.5*.

So the new exposure must be:

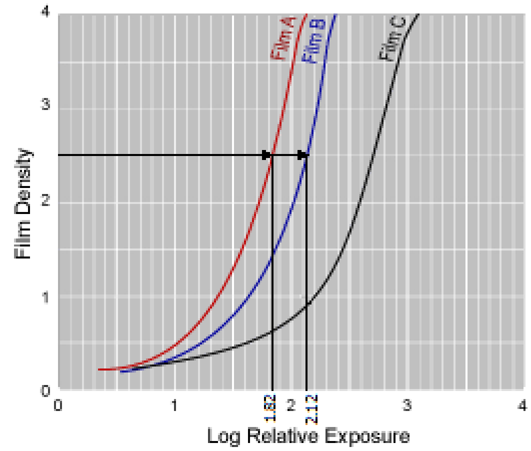
10 mA.s x *3.16* = *31.6 mA.s* (at *140 kV*)



Example 2: *Adjusting the Exposure to Allow Use of a Different Film Type*

> Suppose an acceptable radiograph with a density of *2.5* was produced by exposing *Film A* for *30 seconds* at *1mA* and *130 kV*. What should be the exposure if we want to produce the same density using *Film B*?

From the graph, the log of the relative exposure that produced a density of *2.5* on *Film A* is *1.82* and the log of the relative exposure that produces the same density on *Film B* is *2.12*.
The difference between the two values is *0.3*.
$10^{0.3} = 2$
So the exposure for *Film B* must be:
30 mA.s x *2* = *60 mA.s* (at *130 kV*)



<u>Exposure Calculations</u>

Properly exposing a radiograph is often a <u>trial and error process</u>, as there are many variables that affect the final radiograph. Some of the variables that affect the density of the radiograph include:

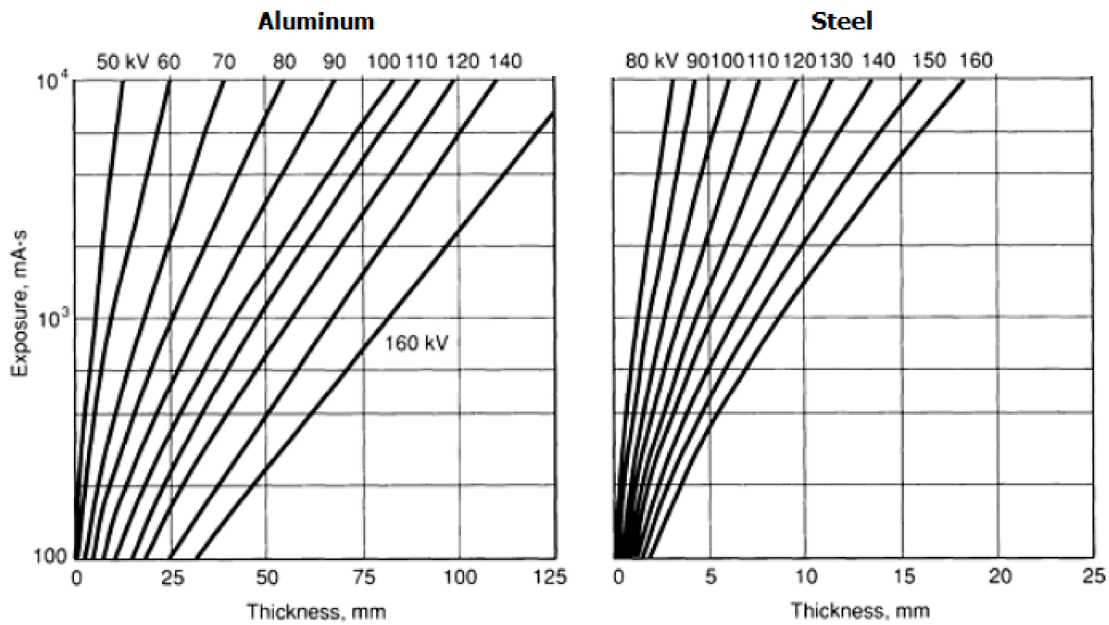
- The spectrum of radiation produced by the X-ray generator.
- The voltage potential used to generate the X-rays (*kV*).
- The amperage used to generate the X-rays (*mA*).
- The exposure time.
- The distance between the radiation source and the film.
- The material of the component being radiographed.
- The thickness of the material that the radiation must travel through.
- The amount of scattered radiation reaching the film.
- The film being used.
- The use of lead screens or fluorescent screens.
- The concentration of the film processing chemicals and the contact time.

The current industrial practice is to develop a procedure that produces an acceptable density by <u>trail</u> for each specific X-ray generator. This process may <u>begin using published exposure charts</u> to determine a starting exposure, which usually requires some refinement.

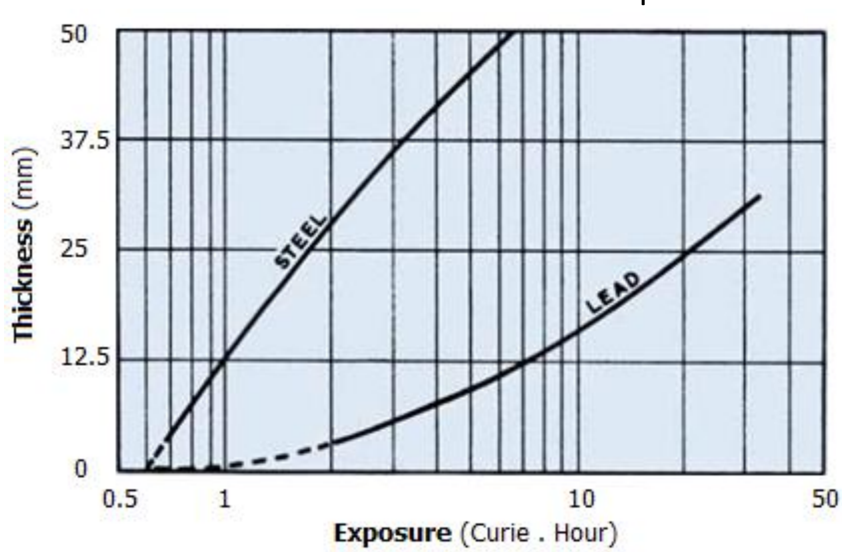
However, it is possible to calculate the density of a radiograph to an acceptable degree of accuracy when the spectrum of an X-ray generator has been characterized. The calculation cannot completely account for scattering but, otherwise, the relationship between many of the variables and their effect on film density is known. Therefore, the change in film density can be estimated for any given variable change. For example, from Newton's Inverse Square Law, it is known that the intensity of the radiation varies inversely with the square of the distance from the source. It is also known that the intensity of the radiation transmitted through a material varies exponentially with the linear attenuation coefficient and the thickness of the material. By calculating the intensity from these equations one can directly calculate the required exposure knowing that the exposure is inversely related to the intensity as:

$$Intensity_1 \times Exposure_1 = Intensity_2 \times Exposure_2$$

The figure below shows exemplary exposure charts for two materials for a specific X-ray generator for the flowing parameters: film density of *2.0* without screens, *910 mm* source-to-film distance, *Industrex AA* film & *7* minutes development time.



For gamma-ray sources, however, the required exposure can be more easily calculated since the radiation spectrum is well known for each different radiation source. The exposure is usually expressed in Curie-Time units and the data can be represented in the form of chars or in tabulated form. The figure shows a typical exposure chart for *Ir-192* at the following parameters: film density of *1.75* without screens, *455 mm* source-to-film distance, *Il-ford* film & *6* minutes development time.



It should be noted that such charts are valid for the specified parameters, but of course using the data in the charts one can calculate the exposure for different set of parameters such as different source-to-film distance, different type of film, or different density.

Example 1:

A *25 mm* thick Aluminum plate is to be radiographed on *type C film* without screens using X-ray generator at *80 kV* and *500 mm* distance. What is the minimum required exposure time to get *3.0* density (*for same development parameters as used for the chart, and considering the film used for the chart to be type A*) knowing that the max current setting for the X-ray machine is *20 mA*?

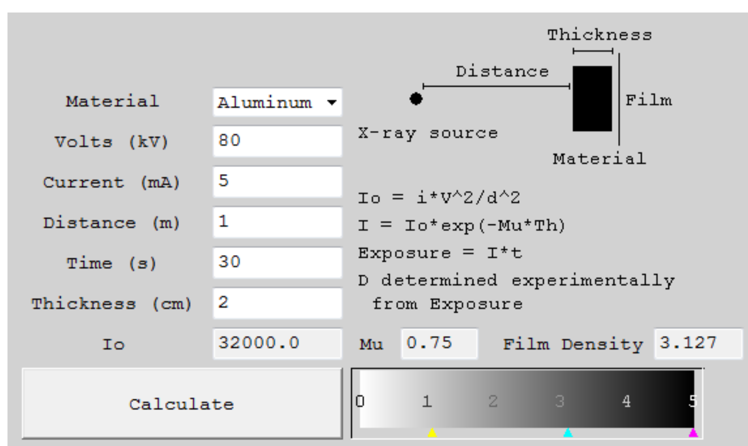
Answer: *190 s*

Example 2:

A *12.5 mm* thick Steel plate is to be radiographed without screens using Ir-192 source at 45*5 mm* distance. Knowing that the source activity was *100 Ci* before *30 days*, what is the required exposure time (*for same density, film type, and development parameters as used for the chart*) if the plate is to be place behind a *50 mm* thick concrete wall while it is being exposed?

Answer: *104 s*

To make such calculations more easy, radiographic modeling calculators and programs can be used. A number of such programs are available from different sources and some are available online. These programs can provide a fair representation of the radiograph that will be produced with a specific setup and parameters. The figure shows a screen shot of an online calculator available at the (www.ndt-ed.org) website.



Controlling Radiographic Quality

One of the methods of controlling the quality of a radiograph is through the use of image quality indicators (IQIs), which are also referred to as *penetrameters*. IQIs provide means of visually informing the film interpreter of the contrast sensitivity and definition of the radiograph. The IQI indicates that a specified amount of change in material thickness will be detectable in the radiograph, and that the radiograph has a certain level of definition so that the density changes are not lost due to unsharpness. Without such a reference point, consistency and quality could not be maintained and defects could go undetected.

IQIs should be placed on the source side of the part over a section with a material thickness equivalent to the region of interest. If this is not possible, the IQI may be placed on a block of similar material and thickness to the region of interest. When a block is used, the IQI should be the same distance from the film as it would be if placed directly on the part in the region of interest. The IQI should also be placed slightly away from the edge of the part so that at least three of its edges are visible in the radiograph.

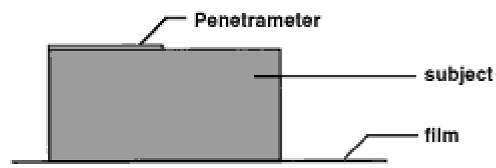
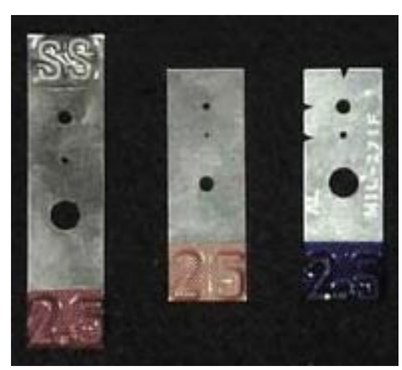


Image quality indicators take many shapes and forms due to the various codes or standards that invoke their use. The two most commonly used IQI types are: the hole-type and the wire IQIs. IQIs come in a variety of material types so that one with radiation absorption characteristics similar to the material being radiographed can be used.

Hole-Type IQIs

ASTM Standard E1025 gives detailed requirements for the design and material group classification of hole-type image quality indicators. Hole-type IQIs are classified in eight groups based on their radiation absorption characteristics. A notching system is used to indicate the IQI material. The numbers on the IQI indicate the sample thickness that the IQI would typically be placed on. Also, holes of different sizes are present where these holes should be visible on the radiograph. It should be noted however that the IQI is used to indicate the quality of the radiographic technique and not intended to be used as a measure of the size of a cavity that can be located on the radiograph.



Wire IQIs

ASTM Standard E747 covers the radiographic examination of materials using wire IQIs to control image quality. Wire IQIs consist of a set of <u>six wires arranged in order</u> of increasing diameter and encapsulated between two sheets of clear plastic. Wire IQIs are grouped in <u>four sets</u> each having different range of wire diameters. The <u>set letter</u> (***A***, ***B***, ***C*** or ***D***) is shown in the lower right corner of the IQI. The <u>number</u> in the lower left corner indicates the <u>material group</u>.

Film Processing

As mentioned previously, radiographic film consists of a transparent, blue-tinted base coated on both sides with an emulsion. The emulsion consists of gelatin containing microscopic, radiation sensitive silver halide crystals, such as silver bromide and silver chloride. When X-rays, gamma rays or light rays strike the crystals or grains, some of the *Br-* ions are liberated leaving the *Ag+* ions. In this condition, the radiograph is said to contain a latent (hidden) image because the change in the grains is virtually undetectable, but the exposed grains are now more sensitive to reaction with the developer.

When the film is processed, it is exposed to several <u>different chemical solutions</u> for <u>controlled periods of time</u>. Film processing basically involves the following <u>five steps</u>:

<u>Development</u>: The developing agent gives up electrons to convert the silver halide grains to metallic silver. Grains that have been <u>exposed to the radiation develop more rapidly</u>, but given enough time the developer will convert all the silver ions into silver metal. Proper temperature control is needed to convert exposed grains to pure silver while keeping unexposed grains as silver halide crystals.

<u>Stopping the development</u>: The stop bath simply stops the development process by diluting and washing the developer away with water.

<u>Fixing</u>: Unexposed silver halide crystals are <u>removed</u> by the fixing bath. The fixer dissolves only silver halide crystals, leaving the silver metal behind.

<u>Washing</u>: The film is washed with water to remove all the processing chemicals.

<u>Drying</u>: The film is dried for viewing.

Film processing is a strict science governed by rigid rules of chemical concentration, temperature, time, and physical movement. Whether processing is done by hand or automatically by machine, excellent radiographs require a high degree of consistency and quality control.

Viewing Radiographs

After the film processing, radiographs are viewed using a light-box (*or they can be digitized and viewed on a high resolution monitor*) in order to be interpreted. In addition to providing diffused, adjustable white illumination of uniform intensity, specialized industrial radiography light-boxes include magnifying and masking aids. When handing the radiographs, thin cotton gloves should be worn to prevent fingerprints on the radiographs.

RADIATION SAFETY

Radiation Health Risks

As mentioned previously, the health risks associated with the radiation is considered to be one the major disadvantages of radiogaphy. The amount of risk depends on the amount of radiation dose received, the time over which the dose is received, and the body parts exposed. The fact that X-ray and gamma-ray radiation are not detectable by the human senses complicates matters further. However, the risks can be minimized and controlled when the radiation is handled and managed properly in accordance to the radiation safety rules. The active laws all over the world require that individuals working in the field of radiography receive training on the safe handling and use of radioactive materials and radiation producing devices.

Today, it can be said that radiation ranks among the most thoroughly investigated (and somehow understood) causes of disease. The primary risk from occupational radiation exposure is an increased risk of cancer. Although scientists assume low-level radiation exposure increases one's risk of cancer, medical studies have not demonstrated adverse health effects in individuals exposed to small chronic radiation doses.

The occurrence of particular health effects from exposure to ionizing radiation is a complicated function of numerous factors including:

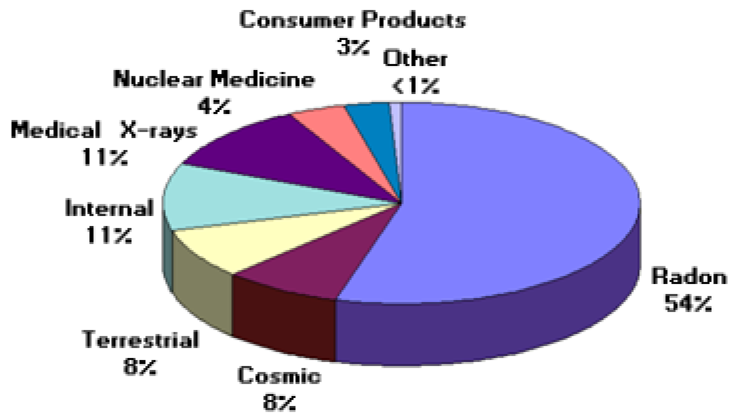
- *Type of radiation involved*. All kinds of ionizing radiation can produce health effects. The main difference in the ability of alpha and beta particles and gamma and X-rays to cause health effects is the amount of energy they have. Their energy determines how far they can penetrate into tissue and how much energy they are able to transmit directly or indirectly to tissues.
- *Size of dose received*. The higher the dose of radiation received, the higher the likelihood of health effects.
- *Rate at which the dose is received*. Tissue can receive larger dosages over a period of time. If the dosage occurs over a number of days or weeks, the results are often not as serious if a similar dose was received in a matter of minutes.
- *Part of the body exposed*. Extremities such as the hands or feet are able to receive a greater amount of radiation with less resulting damage than blood forming organs housed in the upper body.
- *The age of the individual*. As a person ages, cell division slows and the body is less sensitive to the effects of ionizing radiation. Once cell division has slowed, the

effects of radiation are somewhat less damaging than when cells were rapidly dividing.

- *Biological differences*. Some individuals are more sensitive to radiation than others. Studies have not been able to conclusively determine the cause of such differences.

Sources of High Energy Radiation

There are many sources of harmful, high energy radiation. Industrial radiographers are mainly concerned with exposure from X-ray generators and radioactive isotopes. However, it is important to understand that eighty percent of human exposure comes from natural sources such as radon gas, outer space, rocks and soil, and the human body. The remaining twenty percent comes from man-made radiation sources, such as those used in medical and dental diagnostic procedures.



One source of natural radiation is cosmic radiation. The earth and all living things on it are constantly being bombarded by radiation from space. The sun and stars emit electromagnetic radiation of all wavelengths. The dose from cosmic radiation varies in different parts of the world due to differences in elevation and the effects of the earth's magnetic field. Radioactive materials are also found throughout nature where they occur naturally in soil, water, plants and animals. The major isotopes of concern for terrestrial radiation are uranium and the decay products of uranium, such as thorium, radium, and radon. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested with food and water, while others, such as radon, are inhaled. The dose from terrestrial sources varies in different parts of the world. Locations with higher concentrations of uranium and thorium in their soil have higher dose levels. All people also have radioactive isotopes, such as potassium-40 and carbon-14, inside their bodies. The variation in dose from one person to another is not as great as the variation in dose from cosmic and terrestrial sources.

There are also a number of manmade radiation sources that present some exposure to the public. Some of these sources include tobacco, television sets, smoke detectors, combustible fuels, certain building materials, nuclear fuel for energy production, nuclear weapons, medical and dental X-rays, nuclear medicine, X-ray security systems and industrial radiography. By far, the most significant source of man-made radiation exposure to the average person is from medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy.

Measures Relative to the Biological Effects of Radiation Exposure

There are four measures of radiation that radiographers will commonly encounter when addressing the biological effects of working with X-rays or gamma-rays. These measures are: Exposure, Dose, Dose Equivalent, and Dose Rate. A short description of these measures and their units is given below

Exposure: Exposure is a measure of the strength of a radiation field at some point in air (*the amount of charge produced in a unit mass of air when the interacting photons are completely absorbed in that mass*). This is the measure made by radiation survey meters since it can be easily and directly measured. The most commonly used unit of exposure is the "*roentgen*" (***R***).

Dose or Absorbed Dose: While *exposure* is defined for air, the *absorbed dose* is the amount of energy that ionizing radiation imparts to a given mass of matter. In other words, the dose is the amount of radiation absorbed by and object. The *SI* unit for absorbed dose is the "*gray*" (***Gy***), but the "***rad***" (*Radiation Absorbed Dose*) is commonly used (*1* ***Gy*** = *100* ***rad***). Different materials that receive the same exposure may not absorb the same amount of radiation. In human tissue, one ***Roentgen*** of X-ray or gamma radiation exposure results in about one ***rad*** of absorbed dose. The size of the absorbed dose is dependent upon the intensity (or activity) of the radiation source, the distance from the source, and the time of exposure to radiation.

Dose Equivalent: The dose equivalent relates the absorbed dose to the biological effect of that dose. The absorbed dose of specific types of radiation is multiplied by a "*quality factor*" to arrive at the dose equivalent. The *SI* unit is the "*Sievert*" (***Sv***), but the "***rem***" (*Roentgen Equivalent in Man*) is commonly used (*1* ***Sv*** = *100* ***rem***). The table below presents the "*Q* factors" for several types of radiation.

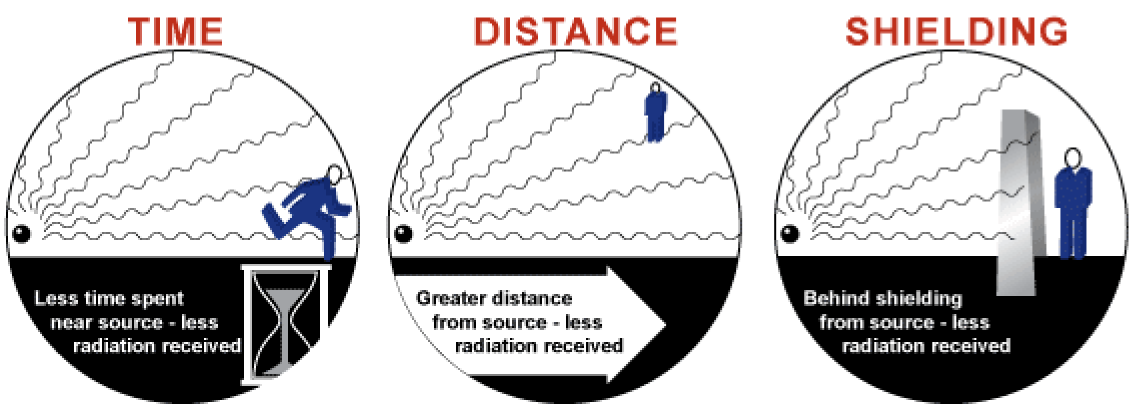
Type of Radiation	Rad	Q Factor	Rem
X-Ray	1	1	1
Gamma Ray	1	1	1
Beta Particles	1	1	1
Thermal Neutrons	1	5	5
Fast Neutrons	1	10	10
Alpha Particles	1	20	20

Dose Rate: The dose rate is a measure of how fast a radiation dose is being received. Dose rate is usually presented in terms of *mR/hr, mrem/hr, rad/min, mGy/sec*, etc. Knowing the dose rate, allows the dose to be calculated for a period of time.

Controlling Radiation Exposure

When working with radiation, there is a concern for two types of exposure: acute and chronic. An acute exposure is a single accidental exposure to a high dose of radiation during a short period of time. An acute exposure has the potential for producing both non-stochastic and stochastic effects. Chronic exposure, which is also sometimes called "continuous exposure", is long-term, low level overexposure. Chronic exposure may result in stochastic health effects and is likely to be the result of improper or inadequate protective measures.

The three basic ways of controlling exposure to harmful radiation are: ***1***) limiting the time spent near a source of radiation, ***2***) increasing the distance away from the source, ***3***) and using shielding to stop or reduce the level of radiation.



Time

The radiation dose is directly proportional to the time spent in the radiation. Therefore, a person should not stay near a source of radiation any longer than necessary. If a survey meter reads *4 mR/h* at a particular location, a total dose of *4 mR* will be received if a person remains at that location for one hour. The received dose can be simply calculated as: *Dose = Dose Rate x Time*

When using a gamma camera, it is important to get the source from the shielded camera to the collimator (*a device that shields radiation in some directions but allow it pass in one or more other directions*) as quickly as possible to limit the time of exposure to the unshielded source.

Distance

Increasing distance from the source of radiation will reduce the amount of radiation received. As radiation travels from the source, it spreads out becoming less intense. This phenomenon can be expressed by the *Newton inverse square law*, which states that as the radiation travels out from the source, the dosage decreases inversely with the square of the distance: $I_1 / I_2 = D_2^2 / D_1^2$

Shielding

The third way to reduce exposure to radiation is to place something between the radiographer and the source of radiation. In general, the more dense the material the more shielding it will provide. Lead and concrete are the most commonly used radiation shielding materials primarily because they are easy to work with and are readily available materials. Concrete is commonly used in the construction of radiation vaults. Some vaults will also be lined with lead sheeting to help reduce the radiation to acceptable levels on the outside.

Exposure Limits

Over the years, numerous recommendations regarding occupational exposure limits have been developed by international radiation safety commissions. In general, the guidelines established for radiation exposure have had two principal objectives: ***1***) to prevent acute exposure; and ***2***) to limit chronic exposure to "acceptable" levels.

Current guidelines are based on the conservative assumption that there is no safe level of exposure. This assumption has led to the general philosophy of not only keeping exposures below recommended levels or regulation limits but also maintaining all exposure "***as low as reasonably achievable***" (*ALARA*). ALARA is a basic requirement of current radiation safety practices. It means that every reasonable effort must be made to keep the dose to workers and the public as far below the required limits as possible.

In general, most international radiation safety codes specify that the dose rate must not exceed *2mR/hour* in any unrestricted area. The specifications for the accumulated dose per year differ between radiation workers and non-workers. The limits are as follows:

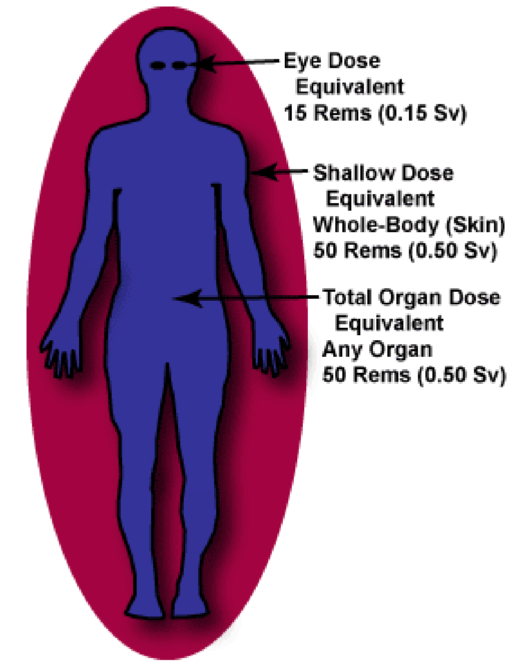
Regulatory Limits for Occupational Exposure

Most international codes set the annual limit of exposure for industrial radiographers who generally are not concerned with an intake of radioactive material as follows:

1) the more limiting of:
   - A total effective dose equivalent of *5 rem* (*0.05 Sv*)

     or
   - The sum of the deep-dose equivalent to any individual organ or tissue other than the lens of the eye being equal to *50 rem* (*0.5 Sv*).

2) The annual limits to the lens of the eye, to the skin, and to the extremities, which are:
   - A lens dose equivalent of *15 rem* (*0.15 Sv*)
   - A shallow-dose equivalent of *50 rem* (*0.50 Sv*) to the skin or to any extremity.



The *shallow-dose equivalent* is the external dose to the skin of the whole-body or extremities from an external source of ionizing radiation. This value is the dose equivalent at a tissue depth of *0.007 cm* averaged over an area of *10 cm^2*.

The *lens dose equivalent* is the dose equivalent to the lens of the eye from an external source of ionizing radiation. This value is the dose equivalent at a tissue depth of *0.3 cm*.

The *deep-dose equivalent* is the whole-body dose from an external source of ionizing radiation. This value is the dose equivalent at a tissue depth of *1 cm*.

The *total effective dose equivalent* is the dose equivalent to the whole-body.

Declared Pregnant Workers and Minors

Because of the increased health risks to the rapidly developing embryo and fetus, pregnant women can receive no more than *0.5 rem* during the entire gestation period (*this is 10% of the dose limit that normally applies to radiation workers*). The same limit also applies to persons under the age of 18 years.

Non-radiation Workers and the General Public

The dose limit to non-radiation workers and members of the public is only *2%* of the annual occupational dose limit. Therefore, a non-radiation worker can receive a whole body dose of no more that *0.1 rem/year* from industrial ionizing radiation. This exposure would be in addition to the *0.3 rem/year* from natural background radiation and the *0.05 rem/year* from man-made sources such as medical X-rays.

Over-Dose Health Symptoms

Listed below are some of the probable prompt and delayed effects of certain doses of radiation when the doses are received by an individual within a twenty-four hour period.

- *0-25 rem* No injury evident. First detectable blood change at *5 rem*.
- *25-50 rem* Definite blood change at *25 rem*. No serious injury.
- *50-100 rem* Some injury possible.
- *100-200 rem* Injury and possible disability.
- *200-400 rem* Injury and disability likely, death possible.
- *400-500 rem* Median Lethal Dose (MLD) 50% of exposures are fatal.
- *500-1,000 rem* Up to 100% of exposures are fatal.
- *Over 1,000 rem* 100% likely fatal.

The delayed effects of radiation may be due either to a single large overexposure or continuing low-level overexposure.

Example dosages and resulting symptoms when an individual receives an exposure to the whole body within a twenty-four hour period.

100 - 200 rem

First Day No definite symptoms

First Week No definite symptoms

Second Week No definite symptoms

Third Week	Loss of appetite, malaise, sore throat and diarrhea
Fourth Week	Recovery is likely in a few months unless complications develop because of poor health

400 - 500 rem

First Day	Nausea, vomiting and diarrhea, usually in the first few hours
First Week	Symptoms may continue
Second Week	Epilation, loss of appetite
Third Week	Hemorrhage, nosebleeds, inflammation of mouth and throat, diarrhea, emaciation
Fourth Week	Rapid emaciation and mortality rate around 50%

Radiation Detectors

Instruments used for radiation measurement fall into two broad categories:

- Rate measuring instruments.
- Personal dose measuring instruments.

Rate measuring instruments measure the rate at which exposure is received (*more commonly called the radiation intensity*). Survey meters, audible alarms and area monitors fall into this category. These instruments present a radiation intensity reading relative to time, such as *R/hr* or *mR/hr*. An analogy can be made between these instruments and the speedometer of a car because both are measuring units relative to time.

Dose measuring instruments are those that measure the total amount of exposure received during a measuring period. The dose measuring instruments, or dosimeters, that are commonly used in industrial radiography are small devices which are designed to be worn by an individual to measure the exposure received by the individual. An analogy can be made between these instruments and the odometer of a car because both are measuring accumulated units.

Survey Meters

The survey meter is the most important resource a radiographer has to determine the presence and intensity of radiation. There are many different models of survey meters available to measure radiation in the field. They all basically consist of a detector and a readout display. Analog and digital displays are available. Most of the survey meters used for industrial radiography use a gas filled detector.

Gas filled detectors consists of a gas filled cylinder with two electrodes having a voltage applied to them. Whenever the device is brought near radioactive substances, the gas becomes ionized. The electric field created by the potential difference between the anode and cathode causes the electrons of each ion pair to move to the anode while the positively charged gas atom is drawn to the cathode. This results in an electrical signal that is amplified, correlated to exposure and displayed as a value.

Audible Alarm Rate Meters

Audible alarms are devices that emit a short "beep" or "chirp" when a predetermined exposure has been received. It is required that these electronic devices be worn by an individual working with gamma emitters. These devices reduce the likelihood of accidental exposures in industrial radiography <u>by alerting the radiographer to exposure levels or dosages of radiation above a preset amount</u>. It is important to note that audible alarms are not intended to be and should not be used as replacements for survey meters. Modern survey meters have this alarm feature already built in.

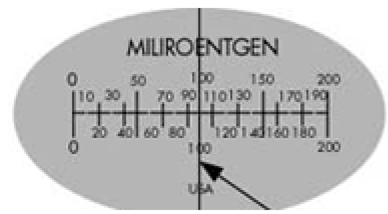
Pocket Dosimeter

Pocket dosimeters are used to provide the wearer with an immediate reading of his or her exposure to X-rays or gamma rays. As the name implies, they are commonly worn in the pocket. The principal advantage of a pocket dosimeter is its ability to provide the wearer an immediate reading of his or her radiation exposure. It also has the advantage of being reusable. The limited range, inability to provide a permanent record, and the potential for discharging and reading loss due to dropping or bumping are a few of the main disadvantages of a pocket dosimeter.

The two types commonly used in industrial radiography are the Direct Read Pocket Dosimeter and the Digital Electronic Dosimeter.

Direct Read Pocket Dosimeter

A direct reading pocket ionization dosimeter is generally of the size and shape of a fountain pen. The accumulated dose value can be read by pointing the instrument at a light source and observing the internal fiber through a system of built-in lenses. The fiber is viewed on a translucent scale which is graduated in units of exposure. Typical industrial radiography pocket dosimeters have a full scale reading of *200 mR* but there are designs that will record higher amounts. During the shift, the dosimeter reading should be checked frequently. The measured exposure should be recorded at the end of each shift.



Digital Electronic Dosimeter

These dosimeters measure both dose information and dose rate and display them in digital form. Also, some Digital Electronic Dosimeters include an audible alarm feature which emits an audible signal or chirp with each recorded increment of exposure. Consequently, the frequency or chirp rate of the alarm is proportional to the radiation intensity. Some models can also be set to provide a continuous audible signal when a preset exposure has been reached.

Film Badges

Personnel dosimetry film badges are commonly used to measure and record radiation exposure due to gamma rays, X-rays and beta particles. The detector is, as the name implies, a piece of radiation sensitive film. The film is packaged in a light proof, vapor proof envelope preventing light, moisture or chemical vapors from affecting the film. Film badges need to be worn correctly so that the dose they receive accurately represents the dose the wearer receives. Whole body badges are worn on the body between the neck and the waist, often on the belt or a shirt pocket.

The film is contained inside a film holder or badge. The badge incorporates a series of filters to determine the quality of the radiation. Radiation of a given energy is attenuated to a different extent by various types of absorbers. Therefore, the same quantity of radiation incident on the badge will produce a different degree of darkening under each filter. By comparing these results, the energy of the radiation

can be determined and the dose can be calculated knowing the film response for that energy. The badge holder also contains an open window to determine radiation exposure due to beta particles (*since beta particles are shielded by a thin amount of material*).

The major advantages of a film badge as a personnel monitoring device are that it provides a permanent record, it is able to distinguish between different energies of photons, and it can measure doses due to different types of radiation. It is quite accurate for exposures greater than 100 *mR*. The major disadvantages are that it must be developed and read by a processor (*which is time consuming*) and prolonged heat exposure can affect the film.

Thermoluminescent Dosimeter (TLD)

Thermoluminescent dosimeters (*TLD*) are often used instead of the film badge. Like a film badge, it is worn for a period of time (*usually 3 months or less*) and then must be processed to determine the dose received, if any. *TLD*s can measure doses as low as *1 mR* and they have a precision of approximately 15% for low doses which improves to approximately 3% for high doses. *TLD*s are reusable, which is an advantage over film badges. However, no permanent record or re-readability is provided and an immediate, on the job readout is not possible.

A *TLD* has a phosphor, such as lithium fluoride (LiF) or calcium fluoride (CaF), in a solid crystal structure. When a *TLD* it is exposed to ionizing radiation at ambient temperatures, the radiation interacts with the phosphor crystal causing some of the atoms in the material to produce free electrons and become ionized. The free electrons are trapped and locked into place in the imperfections in the crystal lattice structure.

Heating the crystal causes the crystal lattice to vibrate, releasing the trapped electrons in the process. Released electrons return to the original ground state, releasing the captured energy from ionization as light, hence the name thermoluminescent. Instead of reading the optical density (blackness) of a film, as is done with film badges, the amount of light released versus the heating of the individual pieces of thermoluminescent material is measured. The "glow curve" produced by this process is then related to the radiation exposure. The process can be repeated many times.

Safety Controls

Since X-ray and gamma radiation are not detectable by the human senses and the resulting damage to the body is not immediately apparent, a variety of safety controls are used to limit exposure. The two basic types of radiation safety controls used to provide a safe working environment are engineered and administrative controls. Engineered controls include shielding, interlocks, alarms, warning signals, and material containment. Administrative controls include postings, procedures, dosimetry, and training.

Engineered controls such as shielding and door interlocks are used to contain the radiation in a cabinet or a "radiation vault". Fixed shielding materials are commonly high density concrete and/or lead. Door interlocks are used to immediately cut the power to X-ray generating equipment if a door is accidentally opened when X-rays are being produced. Warning lights are used to alert workers and the public that radiation is being used. Sensors and warning alarms are often used to signal that a predetermined amount of radiation is present. Safety controls should never be tampered with or bypassed.

When portable radiography is performed, most often it is not practical to place alarms or warning lights in the exposure area. Ropes (*or cordon off tape*) and signs are used to block the entrance to radiation areas and to alert the public to the presence of radiation. Occasionally, radiographers will use battery operated flashing lights to alert the public to the presence of radiation.

Safety regulations classify the areas surrounding the location where ionizing radiation is present into restricted areas and controlled areas according to the radiation intensity level:

Restricted areas: Areas with a dose rate higher than *300 mR/h* must be secure so that nobody can enter this area. If anybody accidently enters this area, radiation must be terminated and the person must be checked. Access is only permitted under specific conditions and if there is an absolute need for it, the body dose should be calculated and the personal dose measured.

Control areas: These are areas with dose rates which are equivalent to or higher than *0.75 mR/h*. Control areas must be cordoned off and provided with a radiation warning signs.