Industrial Radiography

History of Radiography

X-rays were discovered in 1895 by Wilhelm Conrad Roentgen (1845-1923) who was a Professor at Wuerzburg University in Germany. Working with a cathode-ray tube in his laboratory, Roentgen observed a fluorescent glow of crystals on a table near his tube. The tube that Roentgen was working with consisted of a glass envelope (bulb) with positive and negative electrodes encapsulated in it. The air in the tube was evacuated, and when a high voltage was applied, the tube produced a fluorescent glow. Roentgen shielded the tube with heavy black paper, and discovered a green colored fluorescent light generated by a material located a few feet away from the tube.

He concluded that a new type of ray was being emitted from the tube. This ray was capable of passing through the heavy paper covering and exciting the phosphorescent materials in the room. He found the new ray could pass through most substances casting shadows of solid objects. Roentgen also discovered that the ray could pass through the tissue of humans, but not bones and metal objects. One of Roentgen's first experiments late in 1895 was a film of the hand of his wife, Bertha. It is interesting that the first use of X-rays were for an industrial (not medical) application as Roentgen produced a radiograph of a set of weights in a box to show his colleagues.

Roentgen's discovery was a scientific bombshell, and was received with extraordinary interest by both scientist and laymen. Scientists everywhere could duplicate his experiment because the cathode tube was very well known during this period. Many scientists dropped other lines of research to pursue the mysterious rays. Newspapers and magazines of the day provided the public with numerous stories, some true, others fanciful, about the properties of the newly discovered rays.

Public fancy was caught by this invisible ray with the ability to pass through solid matter, and, in conjunction with a photographic plate, provide a picture of bones and interior body parts. Scientific fancy was captured by demonstration of a wavelength shorter than light. This generated new possibilities in physics, and for investigating the structure of matter. Much enthusiasm was generated about potential applications of rays as an aid in medicine and surgery. Within a month after the announcement of the discovery, several medical radiographs had been made in Europe and the United States which were used by surgeons to guide them in their work. In June 1896, only 6 months after Roentgen announced his discovery, X-rays were being used by battlefield physicians to locate bullets in wounded soldiers.

Prior to 1912, X-rays were used little outside the realms of medicine, and dentistry, though some X-ray pictures of metals were produced. The reason that X-rays were not used in industrial application before this date was because the X-ray tubes (the source of

the X-rays) broke down under the voltages required to produce rays of satisfactory penetrating power for industrial purpose. However, that changed in 1913 when the high vacuum X-ray tubes designed by Coolidge became available. The high vacuum tubes were an intense and reliable X-ray sources, operating at energies up to 100,000 volts.

In 1922, industrial radiography took another step forward with the advent of the 200,000-volt X-ray tube that allowed radiographs of thick steel parts to be produced in a reasonable amount of time. In 1931, General Electric Company developed 1,000,000 volt X-ray generators, providing an effective tool for industrial radiography. That same year, the American Society of Mechanical Engineers (ASME) permitted X-ray approval of fusion welded pressure vessels that further opened the door to industrial acceptance and use.

A Second Source of Radiation

Shortly after the discovery of X-rays, another form of penetrating rays was discovered. In 1896, French scientist Henri Becquerel discovered natural radioactivity. Many scientists of the period were working with cathode rays, and other scientists were gathering evidence on the theory that the atom could be subdivided. Some of the new research showed that certain types of atoms disintegrate by themselves. It was Henri Becquerel who discovered this phenomenon while investigating the properties of fluorescent minerals. Becquerel was researching the principles of fluorescence, certain minerals glow (fluoresce) when exposed to sunlight. He utilized photographic plates to record this fluorescence.

One of the minerals Becquerel worked with was a uranium compound. On a day when it was too cloudy to expose his samples to direct sunlight, Becquerel stored some of the compound in a drawer with his photographic plates. Later when he developed these plates, he discovered that they were fogged (exhibited exposure to light.) Becquerel questioned what would have caused this fogging? He knew he had wrapped the plates tightly before using them, so the fogging was not due to stray light. In addition, he noticed that only the plates that were in the drawer with the uranium compound were fogged. Becquerel concluded that the uranium compound gave off a type of radiation that could penetrate heavy paper and expose photographic film. Becquerel continued to test samples of uranium compounds and determined that the source of radiation was the element uranium. Bacquerel's discovery was, unlike that of the X-rays, virtually unnoticed by laymen and scientists alike. Only a relatively few scientists were interested in Becquerel's findings. It was not until the discovery of radium by the Curies two years later that interest in radioactivity became wide spread.

While working in France at the time of Becquerel's discovery, Polish scientist Marie Curie became very interested in his work. She suspected that a uranium ore known as pitchblende contained other radioactive elements. Marie and her husband, a French scientist, Pierre Curie started looking for these other elements. In 1898, the Curies discovered another radioactive element in pitchblende, they named it 'polonium' in honor of Marie Curie's native homeland. Later that year, the Curie's discovered another

radioactive element which they named 'radium', or shining element. Both polonium and radium were more radioactive than uranium. Since these discoveries, many other radioactive elements have been discovered or produced.

Radium became the initial industrial gamma ray source. The material allowed radiographing castings up to 10 to 12 inches thick. During World War II, industrial radiography grew tremendously as part of the Navy's shipbuilding program. In 1946, manmade gamma ray sources such as cobalt and iridium became available. These new sources were far stronger than radium and were much less expensive. The manmade sources rapidly replaced radium, and use of gamma rays grew quickly in industrial radiography.

Health Concerns

The science of radiation protection, or "health physics" as it is more properly called, grew out of the parallel discoveries of X-rays and radioactivity in the closing years of the 19th century. Experimenters, physicians, laymen, and physicists alike set up X-ray generating apparatus and proceeded about their labors with a lack of concern regarding potential dangers. Such a lack of concern is quite understandable, for there was nothing in previous experience to suggest that X-rays would in any way be hazardous. Indeed, the opposite was the case, for who would suspect that a ray similar to light but unseen, unfelt, or otherwise undetectable by the senses would be damaging to a person? More likely, or so it seemed to some, X-rays could be beneficial for the body.

Inevitably, the widespread and unrestrained use of X-rays led to serious injuries. Often injuries were not attributed to X-ray exposure, in part because of the slow onset of symptoms, and because there was simply no reason to suspect X-rays as the cause. Some early experimenters did tie X-ray exposure and skin burns together. The first warning of possible adverse effects of X-rays came from Thomas Edison, William J. Morton, and Nikila Tesla who each reported eye irritations from experimentation with X-rays and fluorescent substances.

Today, it can be said that radiation ranks among the most thoroughly investigated causes of disease. Although much still remains to be learned, more is known about the mechanisms of radiation damage on the molecular, cellular, and organ system than is known for most other health stressing agents. Indeed, it is precisely this vast accumulation of quantitative dose-response data that enables health physicists to specify radiation levels so that medical, scientific, and industrial uses of radiation may continue at levels of risk no greater than, and frequently less than, the levels of risk associated with any other technology.

X-rays and Gamma rays are electromagnetic radiation of exactly the same nature as light, but of much shorter wavelength. Wavelength of visible light is of the order of 6000 angstroms while the wavelength of x-rays is in the range of one angstrom and that of gamma rays is 0.0001 angstrom. This very short wavelength is what gives x-rays and gamma rays their power to penetrate materials that light cannot. These electromagnetic

waves are of a high energy level and can break chemical bonds in materials they penetrate. If the irradiated matter is living tissue the breaking of chemical bond may result in altered structure or a change in the function of cells. Early exposures to radiation resulted in the loss of limbs and even lives. Men and women researchers collected and documented information on the interaction of radiation and the human body. This early information helped science understand how electromagnetic radiation interacts with living tissue. Unfortunately, much of this information was collected at great personal expense.

Present State of Radiography

In many ways radiography has changed little from the early days of its use. We still capture a shadow image on film using similar procedures and processes technicians were using in the late 1800's. Today, however, we are able to generate images of higher quality, and greater sensitivity through the use of higher quality films with a larger variety of film grain sizes. Film processing has evolved to an automated state producing more consistent film quality by removing manual processing variables. Electronics and computers allow technicians to now capture images digitally. The use of "filmless radiography" provides a means of capturing an image, digitally enhancing, sending the image anywhere in the world, and archiving an image that will not deteriorate with time. Technological advances have provided industry with smaller, lighter, and very portable equipment that produce high quality X-rays. The use of linear accelerator provide a means of generating extremely short wavelength, highly penetrating radiation, a concept dreamed of only a few short years ago. While the process has changed little, technology has evolved allowing radiography to be widely used in numerous areas of inspection.

Radiography has seen expanded usage in industry to inspect not only welds and castings, but to radiographically inspect items such as airbags and caned food products. Radiography has found use in metallurgical material identification and security systems at airports and other facilities.

Gamma ray inspection has also changed considerably since the Curies' discovery of radium. Man-made isotopes of today are far stronger and offer the technician a wide range of energy levels and half-lives. The technician can select Co-60 which will effectively penetrate very thick materials, or select a lower energy isotope, such as Tm-170, which can be used to inspect plastics and very thin or low density materials. Today gamma rays find wide application in industries such as petrochemical, casting, welding, and aerospace.

Addressing Health Concerns

It was the Manhattan District of US Army Corps of Engineers that the name "health physics" was born, and great advances were made in radiation safety. From the onset, the leaders of the Manhattan District recognized that a new and intense source of radiation and radioactivity would be created. In the summer of 1942, the leaders asked Ernest O. Wollan, a cosmic ray physicist at the University of Chicago, to form a group to study and

control radiation hazards. Thus, Wollan was the first to bear the title of health physicist. He was soon joined by Carl G. Gamertsfelder, recently graduated physics baccalaureate, and Herbert M. Parker, the noted British-American medical physicist. By mid 1943, six others had been added. These six include Karl Z. Morgan, James C. Hart, Robert R. Coveyou, O.G. Landsverk, L.A. Pardue, and John E. Rose.

Within the Manhattan District, the name "health physicist" seems to have been derived in part from the need for secrecy (and hence a code name for radiation protection activities) and the fact that it was a group of mostly physicists working on health related problems. Activities included development of appropriate monitoring instruments, developing physical controls, administrative procedures, monitoring radiation areas, monitoring personnel, and radioactive waste disposal. In short, the entire spectrum of modern day radiation protection problems. It was in the Manhattan District that many of the modern concepts of protection were born, including the rem unit, which took into account the biological effectiveness of the radiation. It was in the Manhattan District that radiation protection concepts, realized maturity and enforceability.

Future Direction of Radiographic Education

Although many of the methods and techniques developed over a century ago remain in use, computers are slowly becoming a part of radiographic inspection. The future of radiography will likely see many changes. As noted earlier, companies are performing many inspections without the aid of film.

Radiographers of the future will capture images in digitized form and e-mail them to the customer when the inspection has been completed. Film evaluation will likely be left to computers. Inspectors may capture a digitized image, feed them into a computer and wait for a printout of the image with an accept/reject report. Systems will be able to scan a part and present a three dimensional image to the radiographer helping him or her to locate the defect within the part.

Inspectors in the future will be able to peal away layer after layer of a part evaluating the material in much greater detail. Color images, much like computer generated ultrasonic c-scans of today, will make interpretation of indications much more reliable and less time consuming.

Educational techniques and materials will need to be revised and updated to keep pace with technology and meet the requirements of industry. These needs may well be met with computers. Computer programs can simulate radiographic inspections using a computer aided design (CAD) models of a part to produce physically accurate simulated x-ray radiographic images. Programs allow the operator to select different parts to inspect, adjust the placement and orientation of the part to obtain the proper

equipment/part relationships, and adjust all the usual x-ray generator settings to arrive at the desired radiographic film exposure.

Computer simulation will likely have its greatest impact in the classroom allowing the student to see results in almost real-time. Simulators and computers may well become the primary tool for instructors as well as students in the technical classroom.

Nature of Penetrating Radiation

X-rays and gamma rays are part of the **electromagnetic spectrum.** They are waveforms as are light rays, microwaves, and radio wave, but 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 always travel in straight lines. They can be characterized by frequency, wavelength, and velocity. However, they act somewhat like a particle at times in that they occur as small "packets" of energy and are referred to as "**photon.**"

The Electromagnetic Spectrum
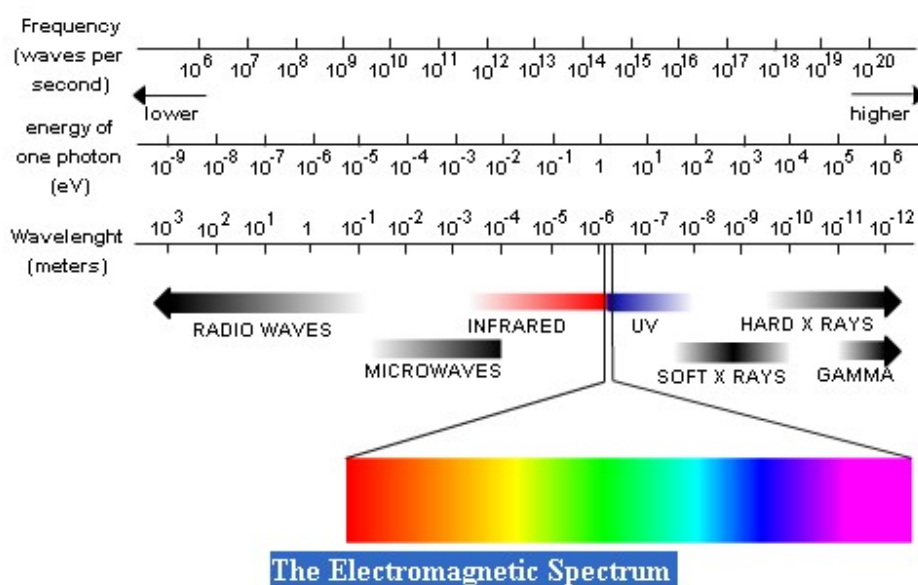
X-rays and gamma rays differ only in their source of origin. X-rays are produced by an x-ray generator, which will be discussed a little latter. Gamma radiation, which will be the focus of discussion here, is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. Over time the nuclei of unstable isotopes spontaneously disintegrate, or transform, in a process known as radioactive decay. Various types of ionizing radiation may be emitted from the nucleus and/or its surrounding electrons. Nuclides which undergo radioactive decay are called radionuclides. Any material which contains measurable amounts of one or more radionuclides is a radioactive material.

The degree of radioactivity or radiation producing potential of a given amount of radioactive material is measured in Curies (Ci). The curie which was originally defined as that amount of any radioactive material which disintegrates at the same rate as one gram

of pure radium. The curie has since been defined more precisely as a quantity of radioactive material in which 3.7 x 10^10 atoms disintegrate per second. 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 Cs-137 might have very different masses depending upon the relative proportion of non-radioactive atoms present in each source. Radioactivity is expressed as the number of curies or becquerels per unit mass or volume.

Each radionuclide 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 radionuclide. Half-life is defined as the time required for the activity of any particular radionuclide to decrease to one-half of its initial value, or one-half of the atoms to change to daughter atoms reverting to a stable state material. Half-lives of radionuclides range from microseconds to billions of years. Half-life of two widely used industrial isotopes are 75 days for Iridium-192, and 5.3 years for Cobalt-60. More exacting calculations can be made for the half-life of these materials, however, these times are commonly used by technicians.
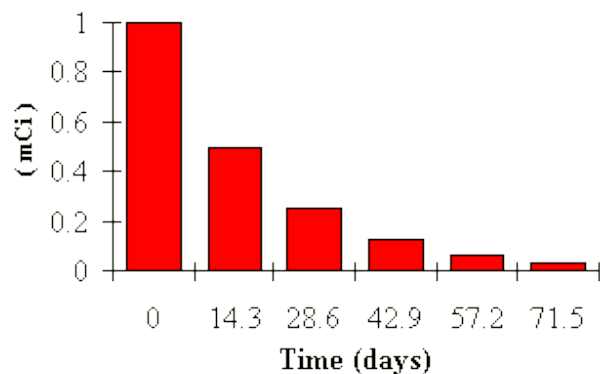
Types Ionizing Radiation

When an atom undergoes radioactive decay, it emits one or more forms of ionizing radiation, defined as radiation with sufficient energy to ionize the atoms with which it interacts. Ionizing radiation can consist 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 radionuclides of high atomic mass (Ra226, U238, Pu239) decay by the emission of alpha particles. These alpha particles are tightly bound units of two neutrons and two protons each (He4 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. This results in a net change of one unit of atomic number (Z). Beta particles have a negative charge and the beta particles emitted by a specific radionuclide 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 may emit one or more photons (packets of electromagnetic radiation) 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.

X-rays are also part of the electromagnetic spectrum and are distinguished from gamma rays only by their source (orbital electrons rather than the nucleus). X-rays are emitted with discrete energies by electrons as they shift orbits following certain types of nuclear decay processes. Internal conversion occurs in a isotope when the energy is transferred to an atomic origin electron that is then ejected with kinetic energy equal to the expected gamma ray, but minus the electron's binding energy. The vacancy in the atomic structure is filled by an external electron, resulting in the production of x-rays. Thulium-170 is a good example of this type of disintegration. When Thulium-170 looses its energy it will exhibit a 60 % probability of interaction with an orbital electron thus producing x-radiation.

Neutrons are typically produced by one of three methods. Large amounts of neutrons are produced in nuclear reactors due to the nuclear fission process. High energy neutrons are also produced by accelerating deuterons that causes them to interact with tritium nuclei. The third method of producing neutrons is by bombarding beryllium with alpha particles. Neutron sources can be made using the alpha-neutron reaction on beryllium by making a mixture of powered alpha emitter and beryllium and sealing it in a metal container. Early neutron sources used radium as the alpha emitter. Modern neutron sources typically use plutonium or americium as the alpha source. The radium-beryllium (RaBe) sources were also sources of large amounts of gamma radiation while the plutonium-beryllium (PuBe) sources and the americium-beryllium (AmBe) sources only produce small amounts of very low energy gamma radiation. Thus, as neutron sources, PuBe and AmBe sources tend to be less hazardous to handle. The older RaBe sources also had a tendency to develop leaks over time and give off radon gas, one of the products of radium decay.

Ionizing Radiation - Interaction with Matter

As ionizing 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 ionizing 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. In describing the intensity of ionization, the term "specific ionization" is often used. This is defined as the number of ion pairs formed per unit path length for a given type of radiation.

Because of their double charge and relatively slow velocity, alpha particles have a high specific ionization and a relatively short range in matter (a few centimeters in air and only fractions of a millimeter in tissue). Beta particles have a much lower specific ionization than alpha particles and, generally, a greater range. For example, the relatively energetic beta particles from P32 have a maximum range of 7 meters in air and 8 millimeters in tissue. The low energy betas from H3, on the other hand, are stopped by only 6 millimeters of air or 6 micrometers of tissue
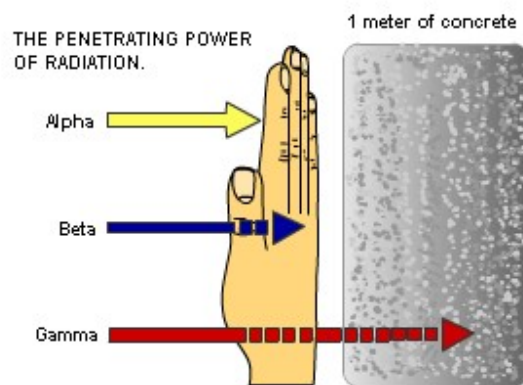
Gamma-rays, x-rays, and neutrons are referred to as indirectly ionizing radiation since, having no charge, they do not directly apply impulses to orbital electrons as do alpha and beta particles. Electromagnetic radiation proceed through matter until there is a chance of interaction with a particle. 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, indirectly ionizing radiation (e.g. gamma, x-rays, and neutrons) can cause the liberation of directly ionizing particles (electrons) deep inside a medium. Because these neutral radiations undergo only chance encounters with matter, they do not have finite ranges, but rather are attenuated in an exponential manner. **In other words, a given gamma ray has a definite probability of passing through any medium of any depth.**

Neutrons lose energy in matter by collisions which transfer kinetic energy. This process is called moderation and is most effective if the matter the neutrons collide with has about the same mass as the neutron.

Once slowed down to the same average energy as the matter being interacted with (thermal energies), the neutrons have a much greater chance of interacting with a nucleus. Such interactions can result in material becoming radioactive or can cause radiation to be given off.

The quantity which expresses the degree of radioactivity or radiation producing potential of a given amount of radioactive material is activity. 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 curies. Iridium-192 will contain 350 curies for every gram of material. The shorter half-life, the less amount of material that will be required to produce a given activity or curies. 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 geometric unsharpness requirements on the radiograph. These unsharpness requirements may not be met if a source with a low specific activity were used at similar source to film distances.

ACTIVITY (of radionuclides) (A)

terabecquerel	TBq

$\downarrow$ 27.0270

1000 | curie | Ci |

$\downarrow$ 37

| gigabecquerel | GBq |

$\downarrow$ 27.0270

1000 | millicurie | mCi |

$\downarrow$ 37

| megabecquerel | MBq |

10^6

[1/s] — 1 — | becquerel | Bq |

$\downarrow$ 1

| disintegrations per second |
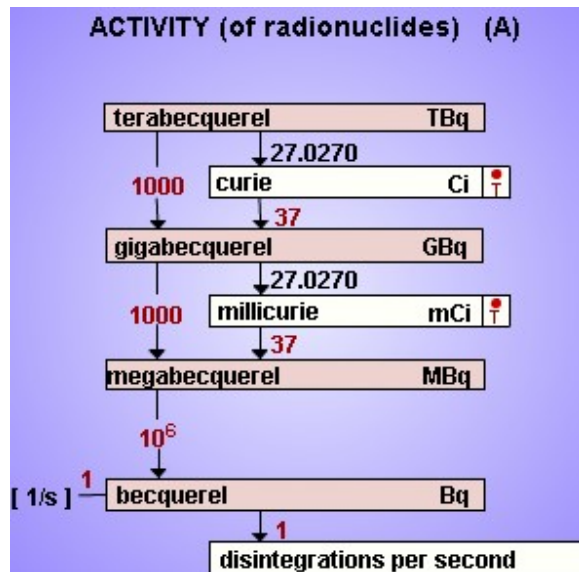
Newton's Inverse Square Law

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 radius (r) is the source strength divided by the area of the sphere. Being strictly geometric in its origin, the inverse square law applies to diverse phenomena. Point sources of gravitational force, electric field, light, sound, or radiation obey the inverse square law. As one of the fields which obey the general inverse square law, a point radiation source can be characterized by the diagram above whether you are talking about Roentgens, rads, or rems. All measures of exposure will drop off by the inverse square law. For example, if the radiation exposure is 100 mR/hr at 1 inch from a source, the exposure will be 0.01 mR/hr at 100 inches.
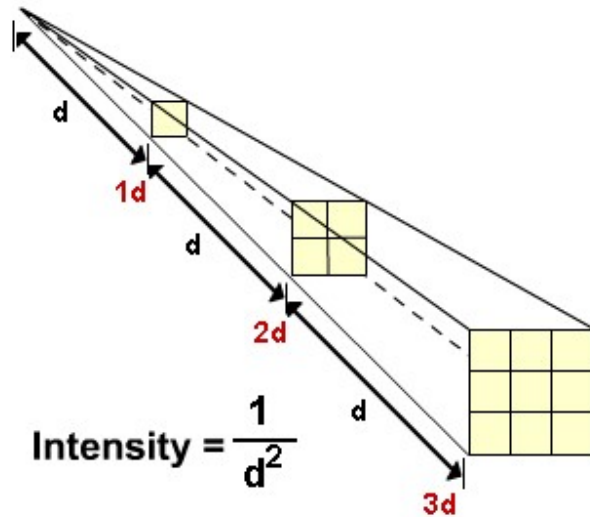
$$\text{Intensity} = \frac{1}{d^2}$$

Isotope Decay Rate

Gamma-rays are electromagnetic radiation emitted by the disintegration of a radioactive isotope and have energy from about 100 keV to well over 1 MeV, corresponding to about 0.01 to 0.001 Å. The most useful gamma-emitting radioactive isotopes for radiological purposes are found to be cobalt (Co60), iridium (Ir192), cesium (Cs137), ytterbium (Yb169), and thulium (Tm170).

Carbon-14 Dating

cosmic-ray
proton

collision with
atmosphere

collision of neutron
with ^{14}N nucleus

^{14}C

carbon combines with oxygen

$^{14}CO_2$

biosphere
absorbs ^{14}C

oceans contain
most of the ^{14}C

buried matter:
C decays and is not
replaced with fresh ^{14}C
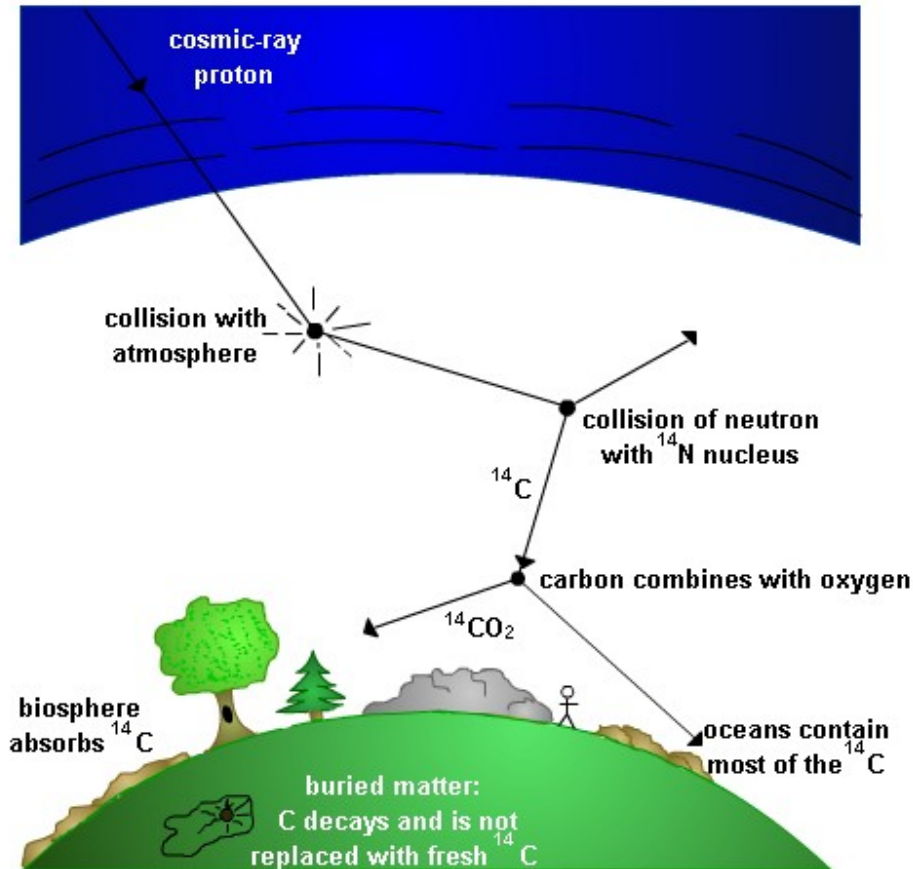
Radio-carbon dating is a method of obtaining age estimates on organic materials which has been used to date samples as old as 50,000 years. The method was developed immediately following World War II by Willard F. Libby and coworkers and has provided age determinations in archeology, geology, geophysics, and other branches of science. Radiocarbon determinations can be obtained on wood, charcoal, marine and freshwater shell, bone and antler, and peat and organic-bearing sediments. They can also be obtained from carbonate deposits such as tufa, calcite, marl, dissolved carbon dioxide, and carbonates in ocean, lake and groundwater sources.

Each sample type has specific problems associated with its use for dating purposes, including contamination and special environmental effects. While the impact of radiocarbon dating has been most profound in archeological research and particularly in prehistoric studies, extremely significant contributions have also been made in hydrology and oceanography. In addition, in the 1950's the testing of thermonuclear weapons injected large amounts of artificial radiocarbon ("Radiocarbon Bomb") into the atmosphere, permitting it to be used as a geochemical tracer.

Carbon dioxide is distributed on a worldwide basis into various atmospheric, biospheric, and hydrospheric reservoirs on a time scale much shorter than its half-life. Metabolic processes in living organisms and relatively rapid turnover of carbonates in surface ocean waters maintain radiocarbon levels at approximately constant levels in most of the biosphere.

Most living organisms absorb carbon. During its lifetime, an organism continually replenishes its supply of carbon just by breathing and eating. Carbon (C) has three naturally occurring isotopes. Both C-12 and C-13 are stable, but C-14 decays by very weak beta decay to nitrogen-14 with a half-life of approximately 5,730 years. Naturally occurring Radiocarbon is produced as a secondary effect of cosmic-ray bombardment of the upper atmosphere.

After the organism dies and becomes a fossil, Carbon-14 continues to decay without being replaced. To measure the amount of radiocarbon left in a fossil, scientists burn a small piece to convert it into carbon dioxide gas. Radiation counters are used to detect the electrons given off by decaying C-14 as it turns into nitrogen. The amount of C-14 is compared to the amount of C-12, the stable form of carbon, to determine how much radiocarbon has decayed, therefore, dating the fossil.

Exponential Decay Formula: **$A = A_o * 2^{(-t/k)}$**

Where "A" is the present amount of the radioactive isotope, "Ao" is the original amount of the radioactive isotope that is measured in the same units as "A." "t" is the time it takes to reduce the original amount of the isotope to the present amount, and "k" is the half-life of the isotope, measured in the same units as "t."

It has long been recognized that if radiocarbon atoms could be detected directly, rather than by waiting for their decay, smaller samples could be used for dating and older dates could be measured. A simple hypothetical example to illustrate this point is a sample containing only one atom of radiocarbon. To measure the age (that is, the abundance of radiocarbon), the sample can be placed into a mass spectrometer and that atom counted, or the sample can be placed into a Geiger counter and counted, requiring a wait on the average of 8,000 years (the mean life of radiocarbon) for the decay. In practice, neither the atoms nor the decays can be counted with 100% efficiency.

Interaction Between Penetrating Radiation and Matter

Interaction between penetrating radiation and matter is not a simple process in which the primary x-ray photon changes to some other form of energy and effectively disappears. The diagram below shows the absorption coefficient, **μ**, for four radiation-matter interactions as a function of radiation energy in MeV. The graph is representative of radiation interacting with Iron. Absorption will be covered in greater detail in a later page.
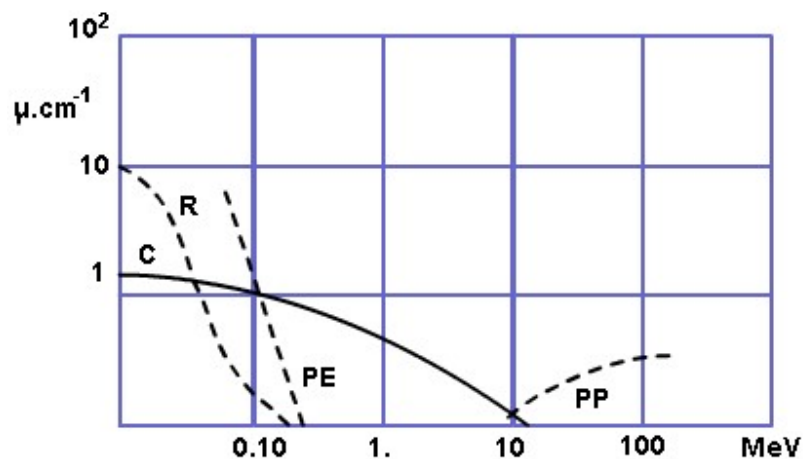
Summary of different mechanisms that reduce intensity of an incident x-ray beam

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, resulting in 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. Photoelectron absorption is also dominant for atoms of high atomic numbers.
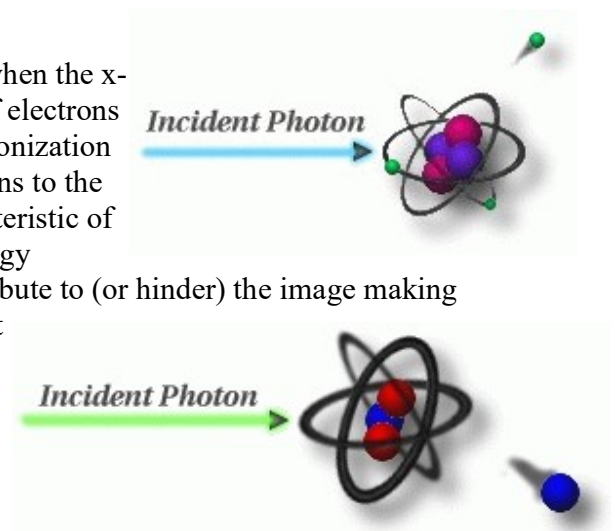
Compton Scattering (C), also known a **incoherent scattering**, occurs when the incident x-ray photon ejects a electron from an atom and an x-ray photon of lower energy is scattered from the atom. Relativistic energy and momentum are conserved in this process (demonstrated in the applet below) and the scattered x-ray photon has less energy and therefore greater wavelength than the incident photon. Compton Scattering is important for low atomic number specimens. At energies of 100 keV -- 10 MeV the absorption of radiation is mainly due to the Compton effect.
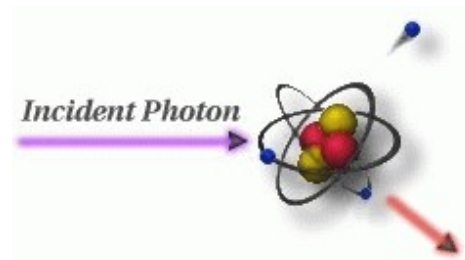
Pair Production (PP) can occur when the x-ray photon energy is greater than 1.02 MeV, when an electron and positron are created with the annihilation of the x-ray photon. Positrons are very short lived and disappear (positron annihilation) with the formation of two photons of 0.51 MeV energy. Pair production is of particular importance when high-energy photons pass through materials of a high atomic number. Energy: > 1.02 MeV
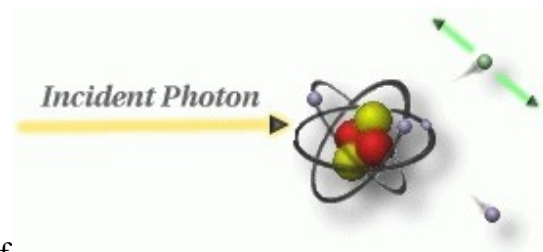
Below are other interaction phenomenon that can occur. Under special circumstances these may need to be considered, but are generally negligible.

Thomson scattering (R), also known as Rayleigh, **coherent**, or classical scattering, occurs when the x-ray photon interacts with the whole atom so that the photon is scattered with no change in internal energy to the scattering atom, nor to the x-ray photon. Thomson scattering is never more than a minor contributor to the absorption coefficient. The scattering occurs without the loss of energy. Scattering is mainly in the forward direction.
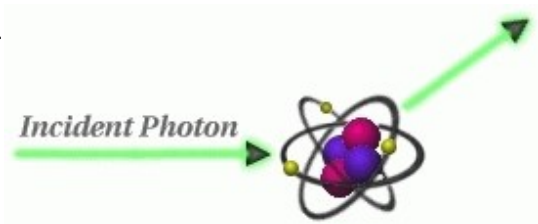
Photodisintegration (PD) is the process by which the x-ray photon is captured by the nucleus of the atom with the ejection of a particle from the nucleus when all the energy of the x-ray is given to the nucleus. Because of the enormously high energies involved, this process may be neglected for the energies of x-rays used in radiography.

Compton Scattering

Together with the scattering of photons on free electrons, the photoelectric effect, and pair production, Compton scattering contributes to the attenuation of x-rays in matter. As the binding energy of electrons in atoms is low compared to that of passing near-relativistic particles, this is the relevant process in radiography. Closely related are Thompson scattering (classical treatment of photon scattering) and Rayleigh scattering (coherent scattering on atoms).
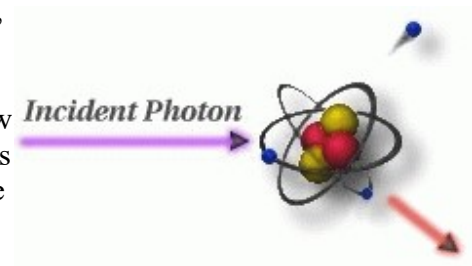
Incident Photon

Compton Scattering, also known as incoherent scattering, occurs when the incident x-ray photon ejects a electron from an atom and an x-ray photon of lower energy is scattered from the atom. Relativistic energy and momentum are conserved in this process (demonstrated in the applet below) and the scattered x-ray photon has less energy and therefore a longer wavelength than the incident photon. Compton scattering is important for low atomic number specimens.

The change in wavelength of the scattered photon is given by:

$$\frac{c}{v'} - \frac{c}{v_0} = \lambda' - \lambda_0 = \frac{h}{m_e c}\left(1 - \cos\theta\right)$$

Theta is the scattering angle of the scattered photon. Note the fundamental constants for the speed of light, Planck constant, and electron mass.

Absorption

Absorption characteristics of materials are important in the development of contrast in a radiograph. Absorption characteristics will increase or decrease as the energy of the x-ray is increased or decreased. A radiograph with higher contrast will provide greater probability of detection of a given discontinuity. An understanding of the relationship between material thickness, absorption properties, and photon energy is fundamental to producing a quality radiograph. An understanding of absorption is also necessary when designing x- and gamma ray shielding, cabinets, or exposure vaults.

Attenuation of x-rays in solids takes place by several different mechanisms, some due to absorption, others due to the scattering of the beam. Thompson scattering (also known as Rayleigh, coherent, or classical scattering) and Compton Scattering (also known as incoherent scattering) were introduced in the material titled "Interaction Between Penetrating Radiation and Matter" and "Compton Scattering." This needs careful attention because a good radiograph can only be achieved if there is minimum x-ray scattering.

The figure below shows an approximation of the Absorption coefficient, **μ**, in red, for Iron plotted as a function of radiation energy.
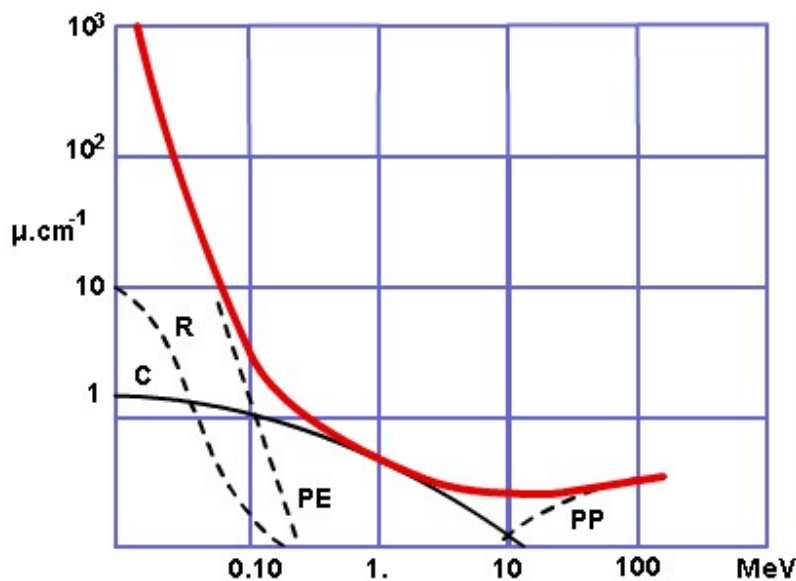
The attenuation or absorption, usually defined as the linear absorption coefficient, **μ**, is defined for a narrow well-collimated, monochromatic x-ray beam. The linear absorption coefficient is the sum of contributions of the following:

1. Thomson **scattering** (R) (also known as Rayleigh, coherent, or classical scattering) occurs when the x-ray photon interacts with the whole atom so that the photon is scattered with no change in internal energy to the scattering atom, nor to the x-ray photon.
2. 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, resulting in 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.
3. Compton **Scattering** (C) (also known a incoherent scattering) occurs when the incident x-ray photon ejects an electron from an atom and a x-ray photon of lower energy is scattered from the atom.
4. Pair Production (PP) can occur when the x-ray photon energy is greater than 1.02 MeV, when an electron and positron are created with the annihilation of the x-ray photon (**absorption**).
5. Photodisintegration (PD) is the process by which the x-ray photon is captured by the nucleus of the atom with the ejection of a particle from the nucleus when all the energy of the x-ray is given to the nucleus (**absorption**). This process may be neglected for the energies of x-rays used in radiography.
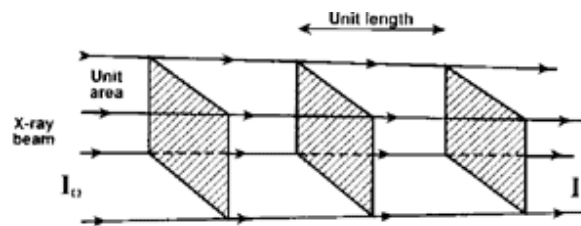
A narrow beam of monoenergetic photons with an incident intensity **Io**, penetrating a layer of material with mass thickness **x** and density **p**, emerges with intensity **I** given by the exponential attenuation law,

$$I/Io = \exp(-(\mu/p)x)$$

which can be rewritten as:

$$\mu/p = \ln(Io/I)/x$$

from which can be obtained from measured values of **Io**, **I** and **x**. Note that the mass thickness is defined as the mass per unit area, and is obtained by multiplying the thickness **t** by the density, i.e., **x = t**. These conditions, generally do not apply to radiography. Scattered x-rays leave the beam and and contribute to the decrease in intensity.

Geometry and X-ray Resolution

Source to film distance, object to film distance, and source size directly affect the degree of penumbra shadow and geometric unsharpness of a radiograph. Codes and standards used in industrial radiography require that geometric unsharpness be limited.

The three factors controlling unsharpness are source size, source to object distance, and object to detector distance. The source size is obtained by referencing manufacturers specifications for a given x- or gamma ray source. Industrial x-ray tubes often have source (anode) sizes of 1.5 mm squared. A balance must be maintained between duty cycle, killovoltage applied, and source size. X-ray sources (anodes) may be reduced to sizes as small as microns for special applications. As the source (anode) size is increased or decreased, distance to the object can be increased or decreased and geometric unsharpness will remain constant. Source to object distance is primarily dependent on source size. Object to detector (object to film) distance is maintained as close as the particle. If the object is suspended above the detector an increase in unsharpness will result. Another result of the object being some distance from the film is geometric enlargement. This technique is used on small components. Industrial radiographers will use an externally small source and the object suspended above the detector that produces an enlarged image on the radiograph. Radiography of transistors and computer chips is one application of this technique.

Additionally, it is generally accepted that an x-ray beam's intensity is not uniform throughout its entirety. Illustrated at the right, as x-radiation is emitted from the target area in a conical shape, measurements have determined that the intensity in the direction of the anode (AC) is lower (over and above the difference caused by the Inverse Square Law) than the intensity in the direction of the cathode (AB). The fact that the intensities vary in such a manner causes visible differences in the density produced on the radiographs. This phenomenon is called heel effect. Radiographers should be aware of this phenomenon as codes require a minimum density through the area of interest. On low density radiographs the heal effect could cause a portion of the radiograph to not meet these requirements.
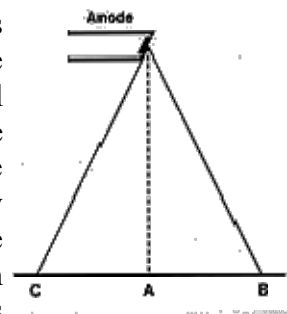
The decreased intensity at "C" results from emission which is nearly parallel to the angled target where there is increasing absorption of the x-ray photons by the target itself. This phenomenon is readily apparent in rotating anode tubes because they utilize steeply angled anodes of generally 17 degrees or less. Generally, the steeper the anode, the more severe or noticeable the heel effect becomes.

The greater the focus film distance, the less noticeable the heel effect due to the smaller cone of radiation used to cover a given area. Heel effect is less significant on small films. This is due to the fact that the intensity of an x-ray beam is much more uniform near the central ray.

Filters in Radiography

At x-ray energies, filters consist of material placed in the useful beam to absorb, preferentially, radiations based on energy level or 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. The use of filters produce a cleaner image by absorbing the lower energy x-ray photons that tend to scatter more.

The total filtration of the beam includes the inherent filtration (composed of part of the x-ray tube and tube housing) and the added filtration (thin sheets of a metal inserted in the x-ray beam). Filters are typically placed at or near the x-ray port in the direct path of the x-ray beam. Placing a thin sheet of copper between the part and the film cassette has also proven an effective method of filtration.

For industrial radiography, the filters added to the x-ray beam are most often constructed of high atomic number materials such as lead, copper, or brass. Filters for medical radiography are usually made of aluminum (Al). The amount of both the inherent and the added filtration are stated in mm of Al or mm of Al equivalent. The amount of filtration of the x-ray beam is specified by and based on the kVp used to produce the beam. The thickness of filter materials is dependent on atomic numbers, kilovoltage settings, and the desired filtration factor.

Gamma radiography produces relatively high energy levels at essentially monochromatic radiation, therefore filtration is not a useful technique and is seldom used.

Secondary (Scatter) Radiation and Undercut Control

Secondary (Scatter) Radiation

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. Side scatter originates from walls, or objects on the source side of the film. 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.

It is often called back scatter when it comes from objects behind the film. Industry codes and standards often require that a lead letter "B" be placed on the back of the cassette to verify the control of back scatter. If the letter "B" shows as a "ghost" image on the film the letter has absorbed the back scatter radiation indicating a significant amount of radiation reaching the film. Control of back scatter radiation is achieved by backing the film in the cassette with sheets of lead typically 0.010 inch thick. It is a common practice in industry to place 0.005 lead screen in front and 0.010 backing the film.
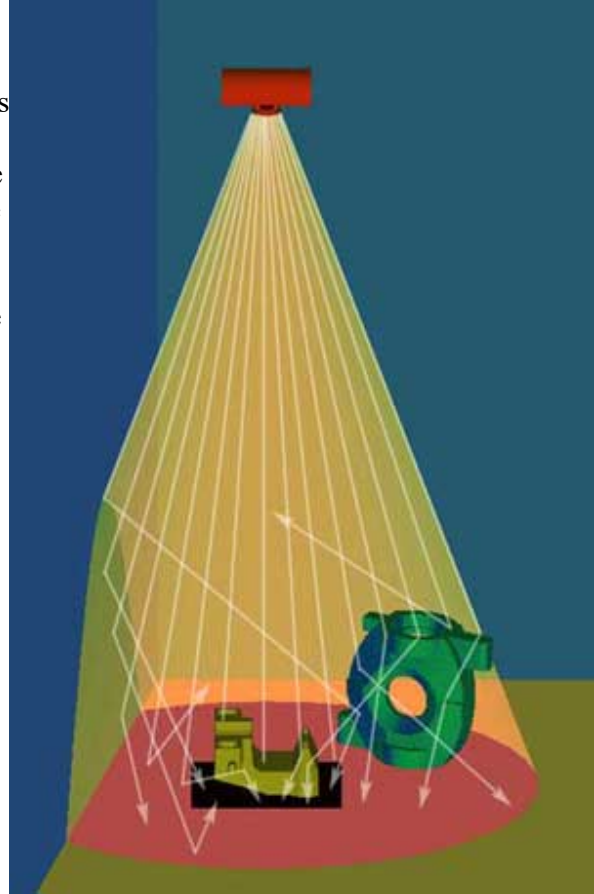
Undercut

Another condition that must often be controlled when producing a radiograph is called undercut. Parts with holes, hollow areas, or abrupt thickness changes are likely to suffer from undercut if controls are not put in place. Undercut appears as lightening of the radiograph in the area of the thickness transition. This results in a loss of resolution or blurring at the transition area. Undercut occurs due to scattering within the film. At the edges of a part or areas where the part transitions from thick to thin, the intensity of the radiation reaching the film is much greater than in
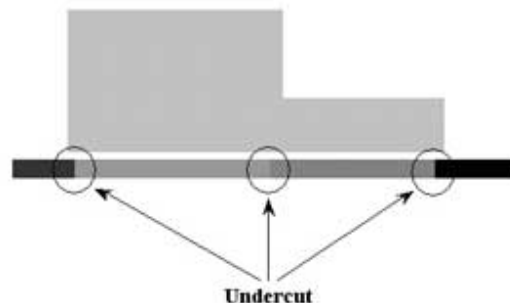
the thicker areas of the part. The high level of radiation intensity reaching the film results in a high level of scattering within the film. It should also be noted that the faster the film speed, the more undercut that is likely to occur. Scattering from within the walls of the part also contributed some to undercut but research has shown that scattering within the film is the primary cause. Masks are used to control undercut. Sheets of lead cut to fill holes or surround the part and metallic shot and liquid absorbers are often used as masks.

Radiation Safety

Radionuclides in various chemical and physical forms have become extremely important tools in modern research. The ionizing radiation emitted by these materials, however, can pose a hazard to human health. For this reason, special precautions must be observed when radionuclides are used.

The possession and use of radioactive materials in the United States is governed by strict regulatory controls. The primary regulatory authority for most types and uses of radioactive materials is the federal Nuclear Regulatory Commission (NRC). However, more than half of the states in the US (including Iowa) have entered into "agreement" with the NRC to assume regulatory control of radioactive material use within their borders. As part of the agreement process, the states must adopt and enforce regulations comparable to those found in Title 10 of the Code of Federal Regulations. Regulations for control of radioactive material use in Iowa are found in Chapter 136C of the Iowa Code.
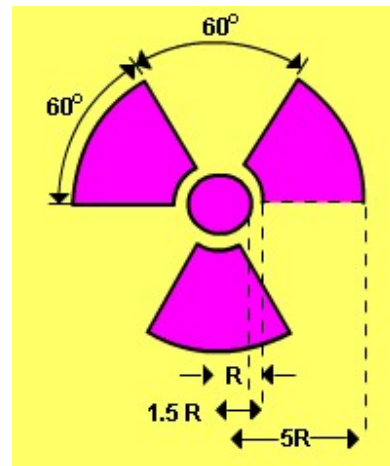
For most situations, the types and maximum quantities of radioactive materials possessed, the manner in which they may be used, and the individuals authorized to use radioactive materials are stipulated in the form of a "specific" license from the appropriate regulatory authority. In Iowa, this authority is the Iowa Department of Public Health. However, for certain institutions which routinely use large quantities of numerous types of radioactive materials, the exact quantities of materials and details of use may not be specified in the license. Instead, the license grants the institution the authority and responsibility for setting the specific requirements for radioactive material use within its facilities. These licensees are termed "broadscope" and require a Radiation Safety Committee and usually a full-time Radiation Safety Officer.

The quantity which expresses the degree of radioactivity or radiation producing potential of a given amount of radioactive material is activity. The special unit for activity is the curie (Ci) which was originally defined as that amount of any radioactive material which disintegrates at the same rate as one gram of pure radium. The curie has since been defined more precisely as a quantity of radioactive material in which 3.7×10^{10} atoms disintegrate per second. 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 activity of a given amount of radioactive material not depend upon the mass of material present. For example, two one-curie sources of Cs-137 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 the specific activity. Specific activity is expressed as the number of curies or becquerels per unit mass or volume.
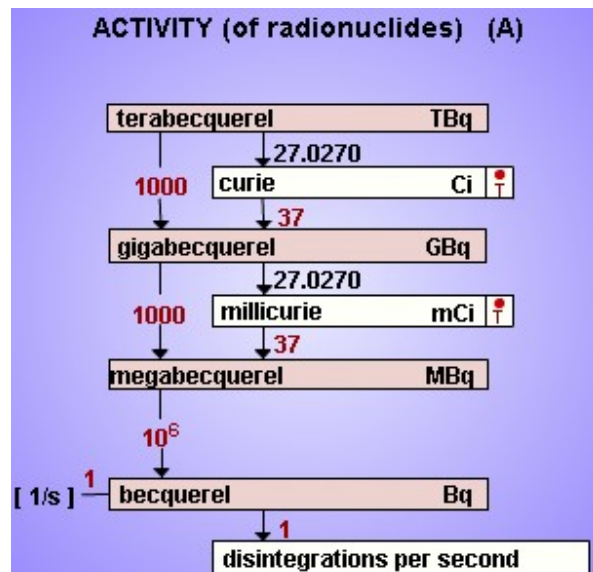
EXPOSURE
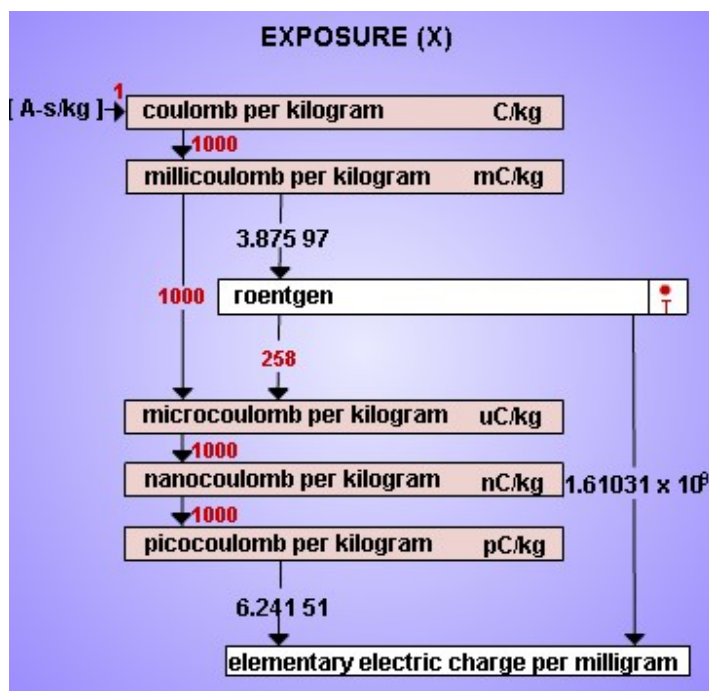
The Roentgen is a unit used to measure a quantity called exposure. This can only be used to describe an amount of gamma and x-rays, and it can only be in air. Specifically it is the amount of photon energy required to produce 1.610 x 10^12 ion pairs in one cubic centimeter of dry air at 0°C. One Roentgen is equal depositing to 2.58 x 10^-4 coulombs per kg of dry air. It is a measure of the ionization of the molecules in a mass of air. The main advantage of this unit is that it is easy to measure directly, but it is limited because it is only for deposition in air, and only for gamma and x-rays.

Historically, the roentgen is no longer used in radiation protection, as it applies only to photons (gamma and X-rays), and it is related only to their effect in air and can only be measured for radiation less than 3.0 MeV. The roentgen was however preferable to the previous unit the "erythema dose" which was measured by the quantity of gamma or x-radiation required to produce visible reddening on the skin of the hand or arm.

ABSORBED DOSE - RAD (Radiation Absorbed Dose)

The absorbed dose is the quantity that expresses the amount of energy which ionizing radiation imparts to a given mass of matter. The special unit for absorbed dose is the RAD (Radiation Absorbed Dose), which is defined as a dose of 100 ergs of energy per gram of matter. The SI unit for absorbed dose is the gray (Gy), which is defined as a dose of one joule per kilogram. Since one joule equals 10^7 ergs, and since one kilogram equals 1000 grams, 1 Gray equals 100 rads. The size of the absorbed dose is dependent upon the strength (or activity) of the radiation source, the distance from the source to the irradiated material, and the time over which the material is irradiated. The activity of the source will determine the dose rate which can be expressed in rad/hr, mrad/hr, mGy/sec, etc.
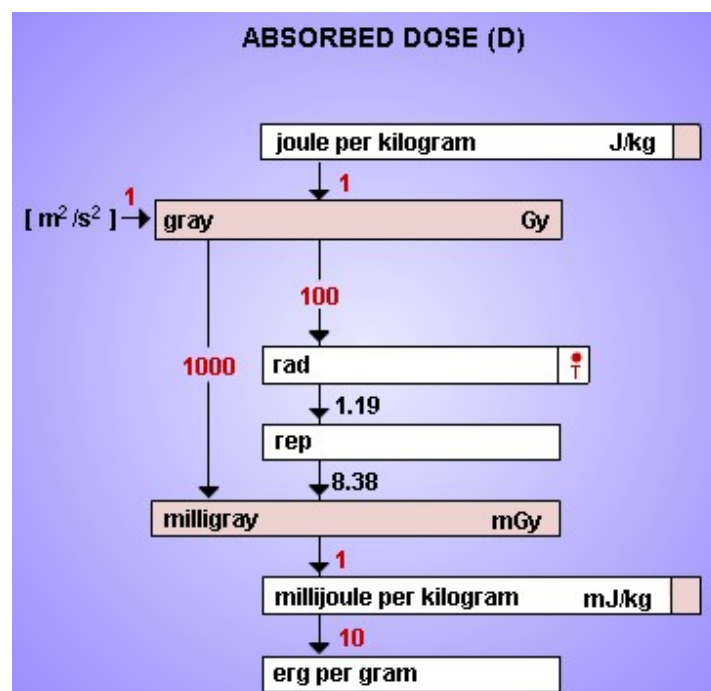
DOSE EQUIVALENT - REM (Roentgen Equivalent Man)

Although the biological effects of radiation are dependent upon the absorbed dose, some types of particles produce greater effects than others for the same amount of energy imparted. For example, for equal absorbed doses, alpha particles may be 20 times as damaging as beta particles. In order to account for these variations when describing human health risk from radiation exposure, the quantity called dose equivalent is used. This is the absorbed dose multiplied by certain "quality" and "modifying" factors (QF) indicative of the relative biological damage potential of the particular type of radiation. The special unit for dose equivalent is the rem (Roentgen Equivalent Man). The SI unit for dose equivalent is the sievert (Sv).
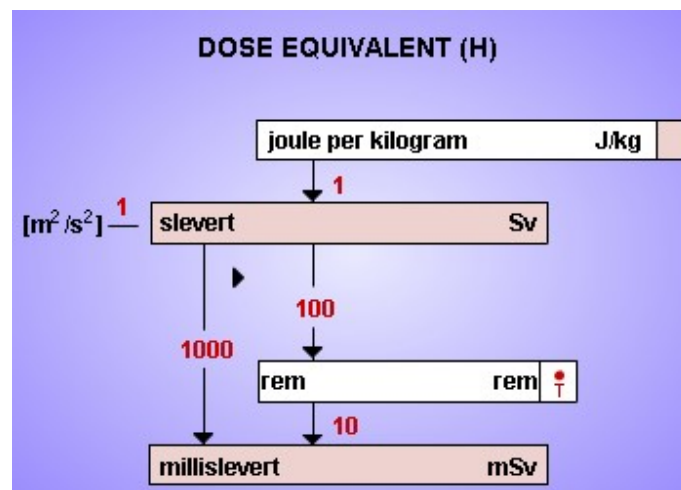
X-ray Sources
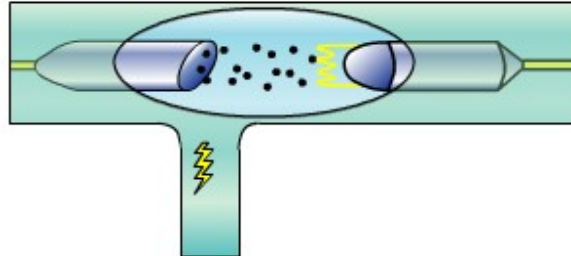
X-rays are just like any other kind of electromagnetic radiation. They can be produced in parcels of energy called photons, just like light. There are two different atomic processes that can produce X-ray photons. One is called Bremsstrahlung and is a German term meaning "braking radiation." The other is called K-shell emission. They can both occur in the heavy atoms of tungsten. Tungsten 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 changes. The negativity charged electron slows down after swinging around the nucleus of a positively charged tungsten atom. This energy loss produces X-radiation. Electrons are scattered elastically and inelastically by the positively charged nucleus. The inelastically scattered electron loses energy, which appears as Bremsstrahlung. Elastically scattered electrons (which include backscattered electrons) are generally scattered through larger angles. In the interaction, many photons of different wavelengths are produced, but none of the photons have more energy than the electron had to begin with. After emitting the spectrum of X-ray radiation the original electron is slowed down or stopped.

Bremsstrahlung Radiation

X-ray tubes produce x-ray photons by accelerating a stream of electrons to energies of several hundred kilovolts with velocities of several hundred kilometers per hour and colliding them into a heavy target material. The abrupt acceleration of the charged particles (electrons) produces Bremsstrahlung photons. X-ray radiation with a continuous spectrum of energies is produced ranging from a few keV to a maximum of energy of the electron beam. Target materials for industrial tubes are typically tungsten, which means that the wave functions of the bound tungsten electrons are required. The inherent filtration of an X-ray tube must be computed, this is controlled by the amount that the electron penetrates into the surface of the target and by the type of vacuum window present.
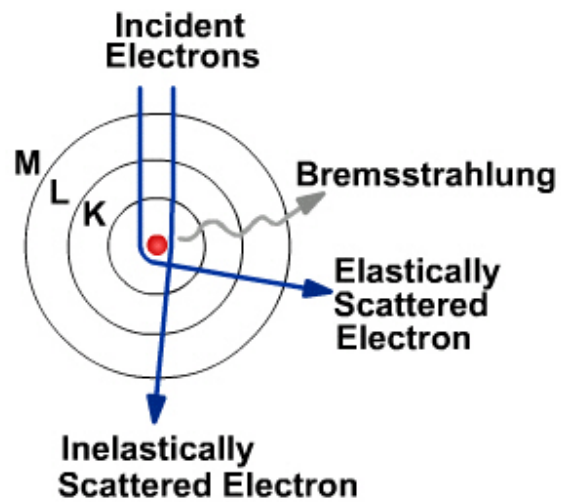
The bremsstrahlung photons generated within the target material are attenuated as they pass out through typically 50 microns of target material. The beam is further attenuated by the aluminum or beryllium vacuum window. The results are an elimination of the low energy photons, I keV through l5 keV, and 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 in an emitted x-ray photon. Meanwhile, higher energy electrons fall into the vacated energy state in the outer shell, and so on. K-shell emission produces higher-intensity x-rays than Bremsstrahlung, and the x-ray photon comes out at a single wavelength.
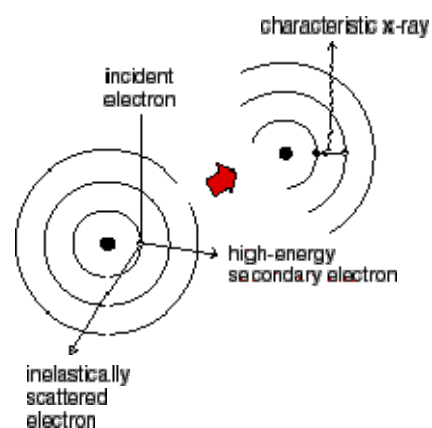
When outer-shell electrons drop into inner shells, they emit a **quantized** photon "characteristic" of the element. The energies of the characteristic X-rays produced are only very weakly dependent on the chemical structure in which the atom is bound, indicating that the nonbonding shells of atoms are the X-ray source. The resulting characteristic spectrum is superimposed on the continuum as shown in the graphs below. An atom remains ionized for a very short time (about 10E-14 second) and thus an atom can be repeatedly ionized by the incident electrons which arrive about every 10E-12 second.

Sprectrum from a Molybdenum Target
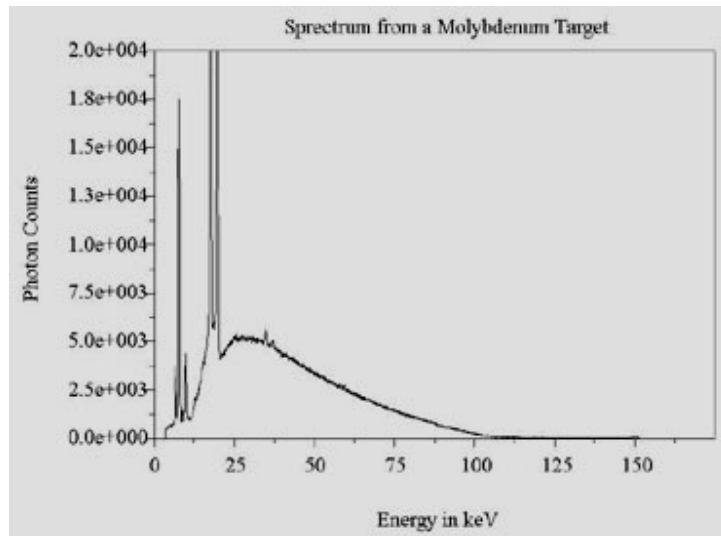
Radio Isotope (Gamma) Sources

Emitted gamma radiation is one of the three types of natural radioactivity. It is the most energetic form of electromagnetic radiation, with a very short wavelength of less than one-tenth of a nano-meter. Gamma rays are essentially very energetic x-rays emitted by excited nuclei. They often accompany alpha or beta particles, because a nucleus emitting those particles may be left in an excited (higher-energy) state.

In medicine gamma-ray sources are used to treat cancer, for diagnostic purposes, and to sterilize equipment and supplies. In industry they are used in the inspection of castings and welds and in food processing to kill microorganisms and retard spoilage.

Man made sources are produced by introducing an extra neutron to atoms of the source material. As the material rids itself of the neutron, energy is released in the form of gamma rays. Two of the more common industrial Gamma-ray sources are iridium-192 and cobalt-60. These isotopes emit radiation in two or three discreet wavelengths. Cobalt-60 will emit a 1.33 and a 1.17 MeV gamma ray, and iridium-192 will emit 0.31, 0.47, and 0.60 MeV gamma rays. Physical size of isotope materials will very from manufacturer, but generally an isotope is a pellet 1.5 mm x 1.5 mm. Depending on the activity (curies) desired a pellet or pellets are loaded into a stainless steel capsule and sealed by welding. New sources of cobalt will have an activity of 20 curies, and new sources of iridium will have an activity of 100 curies.

Advantages of gamma ray sources include portability and the ability to penetrate thick materials in a relativity short time. As can be noted above cobalt will produce energies comparable to a 1.25 MeV x-ray system. Iridium will produce energies comparable to a 460 kV x-ray system. Not requiring electrical sources the gamma radiography is well adapted for use in remote locations.

Disadvantages include shielding requirements and safety considerations. Depleted uranium is used as a shielding material for sources. The storage container (camera) for iridium sources will contain 45 pounds of shielding materials. Cobalt will require 500 pounds of shielding. Cobalt cameras are often fixed to a trailer and transported to and from inspection sites. Iridium is used whenever possible, and not all companies using source material will have a cobalt source. Source materials are constantly generating very penetrating radiation and in a short time considerable damage can be done to living tissue. Technicians must be trained in potential hazards to themselves and the public associated with use of gamma radiography.

Because of safety issues source materials are regulated by Federal or State jurisdictions. The Nuclear Regulation Commission (NRC) has developed and enforces regulations for source material. The commission allows states to regulate materials if they follow guidelines of the commission. These states are identified as "Agreement States". In either case, obtaining and maintaining a license is a costly and well regulated process that protects workers and the public from the hazards of gamma radiation.

Typically gamma radiography is used for inspection of castings and weldments. However, other techniques and applications are being developed. Profile radiography is one example. Profile radiography is used for corrosion under insulation. Exposures are made of a small section of the pipe wall. A cooperator block such as a Ricki T is used to calculate the blowout factor for the exposure in order to calculate the remaining wall thickness of the pipe. The exposure source is usually iridium-192, with cobalt-60 used for the pipes of heavier wall.

Radio Isotope - Th232 Half life: 1.405E10 Years

Radio Isotope - Ir192 Half life: 73.830 Days

Radio Isotope - Tm170 Half life: 128.6 Days
Radio Isotope - Yb169 Half life: 32.026 Days

Radio Isotope - Cs137 Half life: 30.07 Years

Radio Isotope - Co60 Half life: 1925.1 Days

	N15	N16	N17	N18	N19	N20	N21	N22	N23	N24	N25	N26	N27	N28	N29	N30	N31	N32	N33	N34	N35
Co												Co53	Co54	Co55	Co56	Co57	Co58	Co59	Co60	Co61	Co62
Fe									Fe49	Fe50	Fe51	Fe52	Fe53	Fe54	Fe55	Fe56	Fe57	Fe58	Fe59	Fe60	Fe61
Mn										Mn49	Mn50	Mn51	Mn52	Mn53	Mn54	Mn55	Mn56	Mn57	Mn58	Mn59	
Cr							Cr45	Cr46	Cr47	Cr48	Cr49	Cr50	Cr51	Cr52	Cr53	Cr54	Cr55	Cr56	Cr57		
V							V44		V46	V47	V48	V49	V50	V51	V52	V53	V54	V55			
Ti					Ti41	Ti42	Ti43	Ti44	Ti45	Ti46	Ti47	Ti48	Ti49	Ti50	Ti51	Ti52	Ti53				
Sc					Sc40	Sc41	Sc42	Sc43	Sc44	Sc45	Sc46	Sc47	Sc48	Sc49	Sc50	Sc51					
Ca			Ca37	Ca38	Ca39	Ca40	Ca41	Ca42	Ca43	Ca44	Ca45	Ca46	Ca47	Ca48	Ca49	Ca50					
K		K35	K36	K37	K38	K39	K40	K41	K42	K43	K44	K45	K46	K47	K48	K49	K50				
Ar	Ar33	Ar34	Ar35	Ar36	Ar37	Ar38	Ar39	Ar40	Ar41	Ar42	Ar43	Ar44	Ar45	Ar46							
Cl	Cl32	Cl33	Cl34	Cl35	Cl36	Cl37	Cl38	Cl39	Cl40	Cl41	Cl42	Cl43									
S	S31	S32	S33	S34	S35	S36	S37	S38	S39	S40											
P	P30	P31	P32	P33	P34	P35	P36	P37	P38	P39											

Axis labels: 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36

Legend

| Color	Meaning
Magenta	1 day to 10 days
Yellow	10 days to 100 days
Green	100 days to 10 years
Cyan	10 years to 10,000 years
Black	Natural Radioactive
Blue	Stable
Gray	> 10,000 years

Radiographic Film

X-ray films for general radiography consist of an emulsion-gelatin containing a radiation sensitive silver halide and a flexible, transparent, blue-tinted base. The emulsion is different from those used in other types of photography films to account for the distinct characteristics of gamma rays and x-rays, but X-ray films are sensitive to light. Usually, the emulsion is coated on both sides of the base in layers about 0.0005 inch thick. Putting emulsion on both sides of the base doubles the amount of radiation-sensitive silver halide, and thus increases the film speed. The emulsion layers are thin enough so developing, fixing, and drying can be accomplished in a reasonable time. A few of the films used for radiography only have emulsion on one side which produces the greatest detail in the image.
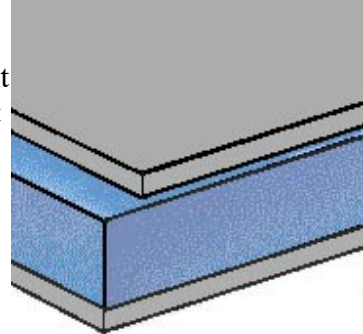
When x-rays, gamma rays, or light strike the grains of the sensitive silver halide in the emulsion, a change takes place in the physical structure of the grains. This change is of such a nature that it cannot be detected by ordinary physical methods. However, when the exposed film is treated with a chemical solution (developer), a reaction takes place, causing formation of black, metallic silver. It is this silver, suspended in the gelatin on both sides of the base, that creates an image

Film Selection

The selection of a film when radiographing any particular component depends on a number of different factors. Listed below are some of the factors that must be considered when selected a film and developing a radiographic technique.

1. the composition, shape, and size of the part being examined and, in some cases, its weight and location.
2. the type of radiation used, whether x-rays from an x-ray generator or gamma rays from a radioactive source.
3. the kilovoltages available with the x-ray equipment or the intensity of the gamma radiation.
4. the relative importance of high radiographic detail or quick and economical results.
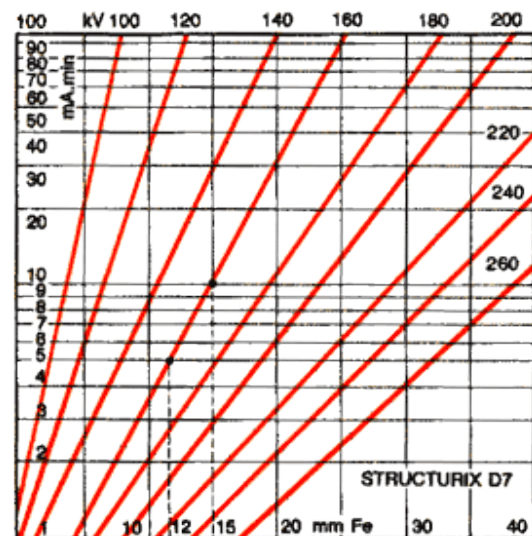
Selecting the proper film and developing the optimal radiographic technique usually involves arriving at a balance between a number of opposing factors. For example, if high resolution and contrast sensitivity is of overall importance, a slower and hence finer grained film should be used in place of a faster film.

Film Packaging

Radiographic film can be purchased in a number of different packaging options. 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 the darkroom to protect it from exposure to light. The sheet are available in a variety of sizes and can be purchased with or without interleaving paper. Interleaved packages have a layer of paper that separates each piece of film. The interleaving paper is removed before the film is loaded into the film holder. Many users find the interleaving paper useful in separating the sheets of film and offer some protection against scratches and dirt during handling.

Photo Coutesy of AGFA-Gevaert Group

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. This form of packaging has the advantage of eliminating the process of loading the film holders in the darkroom. The film is completely protected from finger marks and dirt until the time the film is removed from the envelope for processing.

Packaged film is also available in rolls, which 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. The film is wrapped around the outside of a structure and the radiation source is positioned on axis inside allowing for examination of a large area with a single exposure.

Envelope packaged film can be purchased with the film sandwiched between two lead oxide screens. The screens function to reduce scatter radiation at energy levels below 150kV and as intensification screens above 150 kV.

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 semiflexible holders and external clamping devices are used, care should be taken to be sure pressure is uniform. If a film holder bears against a few high spots, such as on an un-ground weld, the pressure may be great enough to produce desensitized areas in the radiograph. This precaution is particularly important when using envelope-packed films.

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. A supply of clean towels should be kept close at hand as an incentive to dry the hands often and well. Use of envelope-packed films avoids many of these problems until the envelope is opened for processing.

Another important precaution is to avoid drawing film rapidly from cartons, exposure holders, or cassettes. Such care will help to eliminate circular or treelike black markings in the radiograph that sometimes result due to static electric discharges.

Exposure Vaults & Cabinets

Exposure vaults and cabinets allow personnel to work safely in the area while exposures are taking place. Exposure vaults tend to be larger walk in rooms with shielding provided by high-density concrete block and lead.

Exposure cabinets are often self-contained units with integrated x-ray equipment and are typically shielded with steel and lead to absorb x-ray radiation.

Exposure vaults and cabinets are equipped with protective interlocks that disable the system if anything interrupts the integrity of the enclosure. Additionally walk in vaults are equipped with emergency "kill buttons" that allow radiographers to shut down the system if it should accidentally be started while they were in the vault.

Image Considerations

The most common detector used in industrial [radiography](#) is film. The high sensitivity to ionizing [radiation](#) provides excellent detail and sensitivity to density changes when producing images of industrial materials. Image quality is determined by a combination of variables: **radiographic contrast** and **definition**. Many variables affecting radiographic contrast and definition are summarized below and addressed in following sections.

Radiographic Contrast

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 detector or film contrast.

Subject contrast is determined by the following variables:
- Absorption differences in the specimen
- Wavelength of the primary radiation
- Scatter or secondary radiation

Film contrast is determined by the following:
- Grain size or type of film
- Chemistry of film processing chemicals
- Concentrations of film processing chemicals
- Time of development
- Temperature of development
- Degree of mechanical agitation (physical motion)

Exposing the film to produce higher film densities will generally increase contrast. In other words, darker areas will increase in density faster than lighter areas because in any given period of time more x-rays are reaching the darker areas. Lead screens in the thickness range of 0.004 to 0.015 inch typically reduce scatter radiation at energy levels below 150, 000 volts. Above this point they will emit electrons to provide more exposure of the film to ionizing radiation thus increasing the density of the radiograph. Fluorescent screens produce visible light when exposed to radiation and this light further exposes the film.

Definition

Radiographic definition is the abruptness of change in going from one density to another. There are a number of geometric factors of the X-ray equipment and the radiographic setup that have an effect on definition. These geometric factors include:
- Focal spot size, which is the area of origin of the radiation. The focal spot size should be as close to a point source as possible to produce the most definition.
- Source to film distance, which is the distance from the source to the part. Definition increases as the source to film distance increase.
- Specimen to detector (film) distance, which is the distance between the specimen and the detector. For optimal definition, the specimen and detector should be as close together as possible. .
- Abrupt changes in specimen thickness may cause distortion on the radiograph.
- Movement of the specimen during the exposure will produce distortion on the radiograph.
- Film graininess, and screen mottling will decrease definition. The grain size of the film will affect the definition of the radiograph. Wavelength of the radiation will influence apparent graininess. As the wavelength shortens and penetration increases, the apparent graininess of the film will increase. Also, increased development of the film will increase the apparent graininess of the radiograph.

Film Processing

Processing film 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 the highest possible degree of consistency and quality control.

Manual Processing & Darkrooms

Manual processing begins with the darkroom. The darkroom should be located in a central location, adjacent to the reading room and a reasonable distance from the exposure area. For portability darkrooms are often mounted on pickups or trailers.

Film should be located in a light, tight compartment, which is most often a metal bin that is used to store and protect the film. An area next to the film bin that is dry and free of dust and dirt should be used to load and unload the film. While another area, the wet side, will be used to process the film. Thus protecting the film from any water or chemicals that may be located on the surface of the wet side.

Each of step in film processing must be excited properly to develop the image, wash out residual processing chemicals, and to provide adequate shelf life of the radiograph. The objective of processing is two fold. First to produce a radiograph adequate for viewing, and secondly to prepare the radiograph for archival storage. A radiograph may be retrieved after 5 or even 20 years in storage.

Automatic Processor Evaluation

The automatic processor is the essential piece of equipment in every x-ray department. The automatic processor will reduce film processing time when compared to manual development by a factor of four. To monitor the performance of a processor, apart from optimum temperature and mechanical checks, chemical and sensitometric checks should be performed for developer and fixer. Chemical checks involve measurement of pH values for developer and replenisher, fixer and replenisher, measurement of specific gravity and fixer silver levels. Ideally pH should be measured daily and it is important to record these measurements, as regular logging provides very useful information. The daily measurements of pH values for developer and fixer can then be plotted to observe the trend of variations in these values compared to normal pH operating levels to identify problems.

Sensitometric checks may be carried out to evaluate if the performance of films in the automatic processors is being maximized. These checks involve measurement of basic fog level, speed and average gradient made at 1° C intervals of temperature. The range of temperature measurement depends on the type of chemistry in use, whether cold or hot developer. These three measurements: fog level, speed, and average gradient, should then be plotted against temperature and compared with the manufacturer's supplied figures.

Viewing Radiographs

Radiographs (developed film exposed to x-ray or gamma radiation) are generally viewed on a light-box. However, it is becoming increasingly common to digitize radiographs and view them on a high resolution monitor. Proper viewing conditions are very important when interpreting a radiograph. The viewing conditions can enhance or degrade the subtle details of radiographs.

Viewing Radiographs

Before beginning the evaluation of a radiograph, the viewing equipment and area should be considered. The area should be clean and free of distracting materials. Magnifying aids, masking aids, and film markers should be close at hand. Thin cotton gloves should be available and worn to prevent fingerprints on the radiograph. Ambient light levels should be low. Ambient light levels of less than 2 fc are often recommended, but subdued lighting, rather than total darkness, is preferable in the viewing room. The brightness of the surroundings should be about the same as the area of interest in the radiograph. Room illumination must be arranged so that there are no reflections from the surface of the film under examination.

Electrical Circuit Breaker
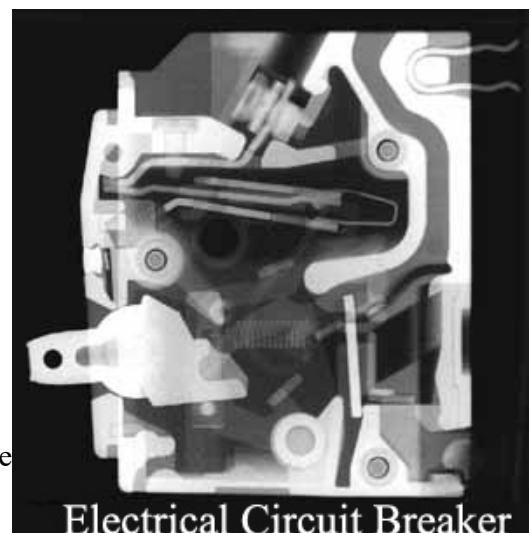
Film viewers should be clean and in good working condition. There are four groups of film viewers. These include: strip viewers, area viewers, spot viewers, and a combination of spot and area viewers. Film viewers should provide a source of defused, adjustable, and relativity cool light as heat from viewers can cause distortion of the radiograph. A film having a measured density of 2.0 will allow only 1.0 percent of the incident light to pass. A film containing a density of 4.0 will allow only 0.01 percent of the incident light to pass. With such low levels of light passing through the radiograph the delivery of a good light source is important.

The radiographic process should be performed in accordance with a written procedure or code, or as required by contractual documents. The required documents should be available in the viewing area and referenced as necessary when evaluating components. Radiographic film quality and acceptability, as required by the procedure, should first be determined. It should be verified that the radiograph was produced to the correct density on the required film type, and that it contains the correct identification information. It should also be verified that the proper image quality indicator was used and that the required sensitivity level was met. Next, the radiograph should be checked to ensure that it does not contain processing and handling artifacts that could mask discontinuities or other details of interest. The technician should develop a standard process for evaluating the radiographs so that details are not overlooked.

Once a radiograph passes these initial checks it is ready for interpretation. Radiographic film interpretation is an acquired skill combining, visual acuity with knowledge of materials, manufacturing processes, and their associated discontinues. If the component is inspected while in service, an understanding of applied loads and history of the component is helpful. A process for viewing radiographs, left to right top to bottom etc., is helpful and will prevent overlooking an area on the radiograph. This process is often developed over time and individualized. One part of the interpretation process, sometimes overlooked, is rest. The mind as well as the eyes need to occasionally rest when interpreting radiographs.

When viewing a particular region of interest, techniques such as using a small light source and moving the radiograph over the small light source, or changing the intensity of the light source will help the radiographer identify relevant indications. Magnifying tools should also be used when appropriate to help identify and evaluate indications. Viewing the actual component being inspected is very often helpful in developing an understanding of the details seen in a radiograph.

Interpretation of radiographs is an acquired skill that is perfected over time. By using the proper equipment and developing consistent evaluation processes, the interpreter will increase his or her probability of detecting defects.

Contrast and Definition

The first subjective criteria for determining radiographic quality is radiographic contrast. Essentially, radiographic contrast is the degree of density difference between adjacent areas on a radiograph.

It is entirely possible to radiograph a particular subject and, by varying factors, produce two radiographs possessing entirely different contrast levels. With an x-ray source of low kilovoltage, we see an illustration of extremely high radiographic contrast, that is, density difference between the two adjacent areas (A and B) is high. It is essential that sufficient contrast exist between the defect of interest and the surrounding area. There is no viewing technique that can extract information that does not already exist in the original radiograph.
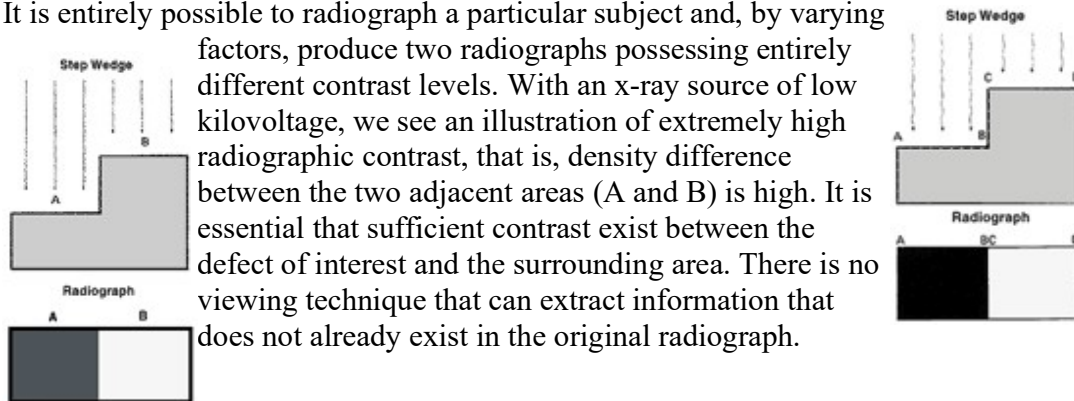
With an x-ray source of high kilovoltage, we see a sample of relatively low radiographic contrast, that is, the density difference between the two adjacent areas (A and B) is low.

Definition

Besides radiographic contrast as a subjective criteria for determining radiographic quality, there exists one other, radiographic detail. Essentially, radiographic definition is the abruptness of change in going from one density to another. For example, it is possible to radiograph a particular subject and, by varying certain factors, produce two radiographs which possess different degrees of definition.

In the example to the left, a two-step step tablet with the transition from step to step represented by Line BC is quite sharp or abrupt. Translated into a radiograph, we see that the transition from the high density to the low density is abrupt. The Edge Line BC is still a vertical line quite similar to the step tablet itself. We can say that the detail portrayed in the radiograph is equivalent to physical change present in the step tablet. Hence, we can say that the imaging system produced a faithful visual reproduction of the step table. It produced essentially all of the information present in the step tablet on the radiograph.
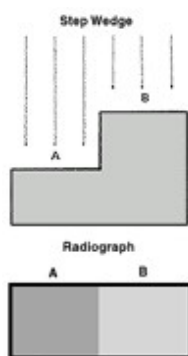
In the example on the right, the same two-step step tablet has been radiographed. However, here we note that, for some reason, the imaging system did not produce a faithful visual reproduction. The Edge Line BC on the step tablet is not vertical. This is evidenced by the gradual transition between the high and low density
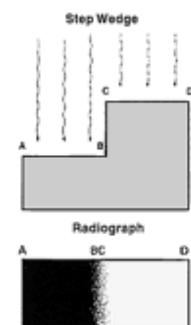
areas on the radiograph. The edge definition or detail is not present because of certain factors or conditions which exist in the imaging system.

In review, it is entirely possible to have radiographs with the following qualities:

- Low contrast and poor detail
- High contrast and poor definition
- Low contrast and good definition
- High contrast and good definition

One must bear in mind that radiographic contrast and definition are not dependent upon the same set of factors. If detail in a radiograph is originally lacking, then attempts to manipulate radiographic contrast will have no effect on the amount of detail present in that radiograph

Radiographic Density

Film speed, gradient, and graininess are all responsible for the performance of the film during exposure and processing. As these combine with processing variables a final product or the radiograph is produced. In viewing the radiograph, requirements have been established for acceptable radiographs in industry. The density of a radiograph in industry will determine if further viewing is possible.

Density considerations date back to early day radiography. Hurder and Drifield have been credited with developing much of the early information on the characteristic curve and density of a radiograph. Codes and standards will typically require densities of a radiograph to be maintained between 1.8 to 4.0 H&D (Hurder and Drifield) for acceptable viewing. As density increases, contrast will also increase. This is true above 4.0 H&D, however as density reaches 4.0 H&D an extremely bright viewing light is necessary for evaluation.

Density, technically should be stated "Transmitted Density" when associated with transparent-base film. This density is the log of the intensity of light incident on the film to the intensity of light transmitted through the film. A density reading of 2.0 H&D is the result of only 1 percent of the transmitted light reaching the sensor. At 4.0 H&D only 0.01% of transmitted light reaches the far side of the film.

Controlling Radiographic Quality

One of the methods of controlling the quality of a radiograph is through the use of image quality indicators (IQI). IQIs provide a means of visually informing the film interpreter of the contrast sensitivity and definition of the radiograph. The IQI indicates that a specified amount of material thickness change 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.

Image quality indicators take many shapes and forms due to the various codes or standards that invoke their use. In the United States two IQI styles are prevalent; the placard, or hole-type and the wire IQI. IQIs comes in a variety of material types so that one with radiation absorption characteristics similar to the material being radiographed can be used.
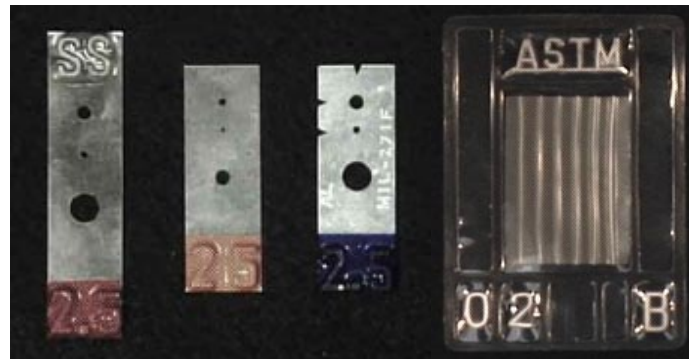
Hole-Type IQIs

ASTM Standard E1025 gives detailed requirements for the design and material group classification of hole-type image quality indicators. E1025 designates eight groups of shims based on their radiation absorption characteristics. A notching system is incorporated into the requirements allowing the radiographer to easily determine if the penetrameter is the correct material type for the product. The thickness in thousands of an inch is noted on each pentameter by a lead number 0.250 to 0.375 inch wide depending on the thickness of the shim. Military or Government standards require a similar penetrameter but use lead letters to indicate the material type rather than notching system as shown on the left in the image above.

Image quality levels are typically designated using a two part expression such as 2-2T. The first term refers to the IQI thickness expressed as a percentage of the region of interest of the part being inspected. The second term in the expression refers to the diameter of the hole that must be revealed and it is expressed as a multiple of the IQI thickness. Therefore, a 2-2T call-out would mean that the shim thickness should be two percent of material thickness and that a hole that is twice the IQI thickness must be detectable on the radiograph. This presentation of a 2-2T IQI in the radiograph verifies

that the radiographic technique is capable of showing a material loss of 2% in the area of interest.It should be noted that even if 2-2T sensitivity is indicated on a radiograph, a defect of the same diameter and material loss may not be visible. The holes in the penetrameter represent sharp boundaries, and a small thickness change. Discontinues within the part may contain gradual changes, and are often less visible. The penetrameter is used to indicate quality of the radiographic technique and not intended to be used as a measure of size of cavity that can be located on the radiograph.

Wire Penetrameters

ASTM Standard E747 covers the radiographic examination of materials using wire penetrameters (IQIs) to control image quality. Wire IQIs consist of a set of six wires arranged in order of increasing diameter and encapsulated between two sheets of clear plastic. E747 specifies four wire IQIs sets, which control the wire diameters. The set letter (A, B, C or D) is shown in the lower right corner of the IQI. The number in the lower left corner indicates the material group. The same image quality levels and expressions (i.e. 2-2T) used for hole-type IQIs are typically also used for wire IQIs. The wire sizes that correspond to various hole-type quality levels can be found in a table in E747 or can be calculated using the following formula.

$$F^3 d^3 l = T^2 H^2 \left(\frac{\pi}{4} \right)$$

Where:
F = 0.79 (constant form factor for wire)
D = wire diameter (mm or inch)
L = 7.6 mm or 0.3 inch (effective length of wire)
T = Hole-type IQI thickness (mm or inch)
H = Hole-type IQI hole diameter (mm or inch)

Placement of IQIs

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 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 atleast three of its edges are visible in the radiograph.

Exposure Calculations

Properly exposing a radiograph is often a trial and error process, as there are many variables that affect the final radiograph. In this section we make the assumptions of a generic (and fixed characteristic) x-ray source, fixed film type, and fixed quality of development.

The applet below estimates the density of the radiograph based on material, thickness, geometry, energy (voltage), current, and, of course, time. The effect of the energy and the physical setup are shown by looking at the film density after exposure. It should be noted that the applet will differ considerably from industrial x-ray configurations, and is designed for demonstration of variables in an x-ray system.

Radiograph Interpretation - Welds

In addition to producing high quality radiographs, the radiographer must also be skilled in radiographic interpretation. Interpretation of radiographs takes place in three basic steps which are (1) detection, (2) interpretation, and (3) evaluation. All of these steps make use of the radiographer's visual acuity. Visual acuity is the ability to resolve a spatial pattern in an image. The ability of an individual to detect discontinuities in radiography is also affected by the lighting condition in the place of viewing, and the experience level for recognizing various features in the image. The following material was developed to help students develop an understanding of the types of defects found in weldments and how they appear in a radiograph.

Discontinuities

Discontinuities are interruptions in the typical structure of a material. These interruptions may occur in the base metal, weld material or "heat affected" zones. Discontinuities, which do not meet the requirements of the codes or specification used to invoke and control an inspection, are referred to as defects.

General Welding Discontinuities

The following discontinuities are typical of all types of welding.

Cold lap is a condition where the weld filler metal does not properly fuse with the base metal or the previous weld pass material (interpass cold lap). The arc does not melt the base metal sufficiently and causes the slightly molten puddle to flow into base material without bonding.
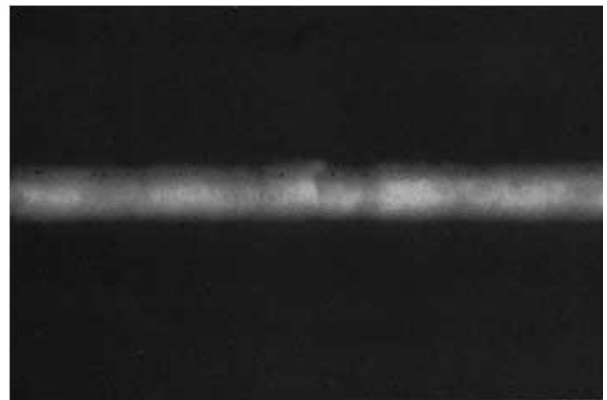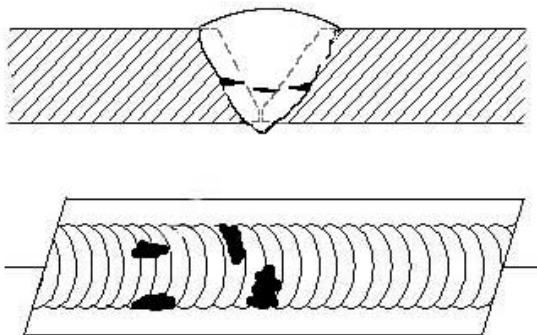
Porosity is the result of gas entrapment in the solidifying metal. Porosity can take many shapes on a radiograph but often appears as dark round or irregular spots or specks appearing singularly, in clusters or rows. Sometimes porosity is elongated and may have the appearance of having a tail This is the result of gas attempting to escape while the metal is still in a liquid state and is called wormhole porosity. All porosity is a void in the material it will have a radiographic density more than the surrounding area.

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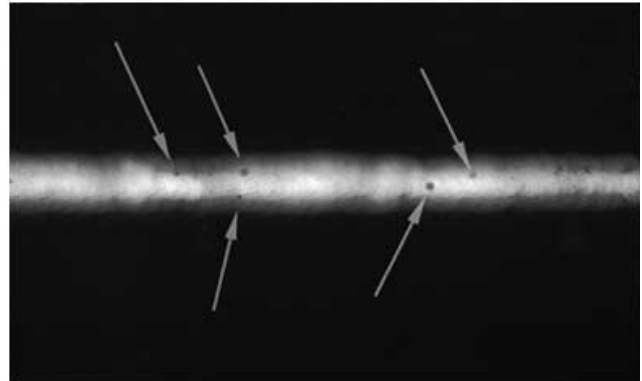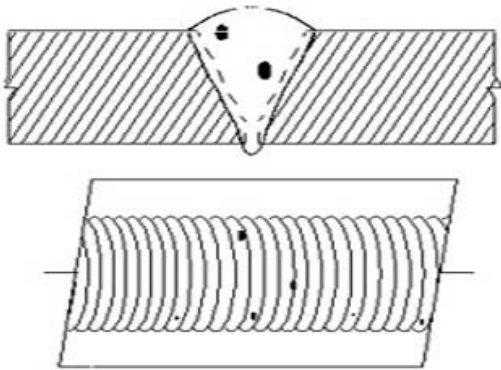
Cluster porosity is caused when flux coated electrodes are contaminated with moisture. The moisture turns into gases when heated and becomes trapped in the weld during the welding process. Cluster porosity appear just like regular porosity in the radiograph but the indications will be grouped close together.
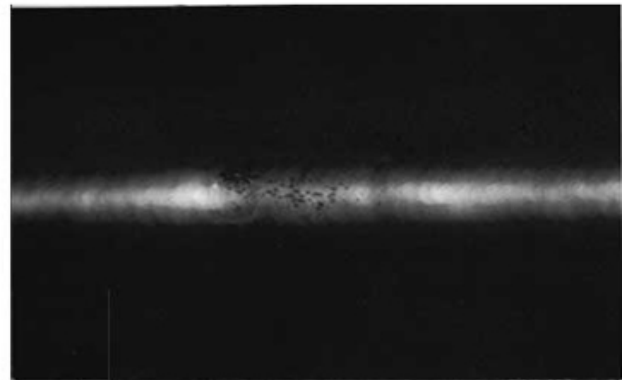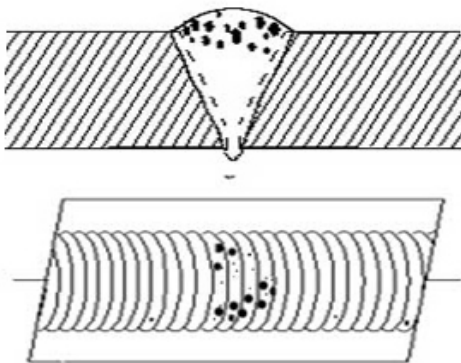
Slag inclusions are nonmetallic solid material entrapped in weld metal or between weld and base metal. In a radiograph, dark, jagged asymmetrical shapes within the weld or along the weld joint areas are indicative of slag inclusions.
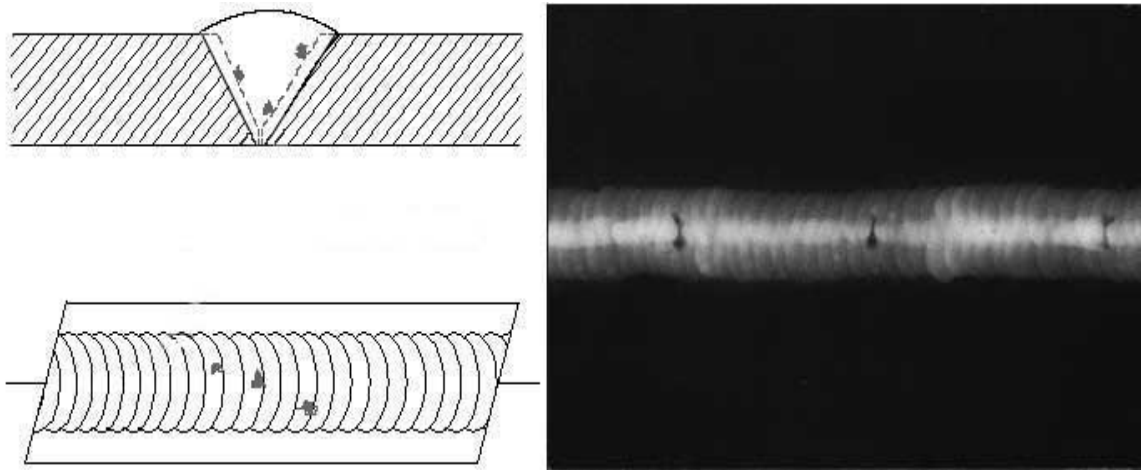
Incomplete penetration (IP) or lack of penetration (LOP) occurs when the weld metal fails to penetrate the joint. It is one of the most objectionable weld discontinuities. Lack of penetration allows a natural stress riser from which a crack may propagate. The appearance on a radiograph is a dark area with well-defined, straight edges that follows the land or root face down the center of the weldment.
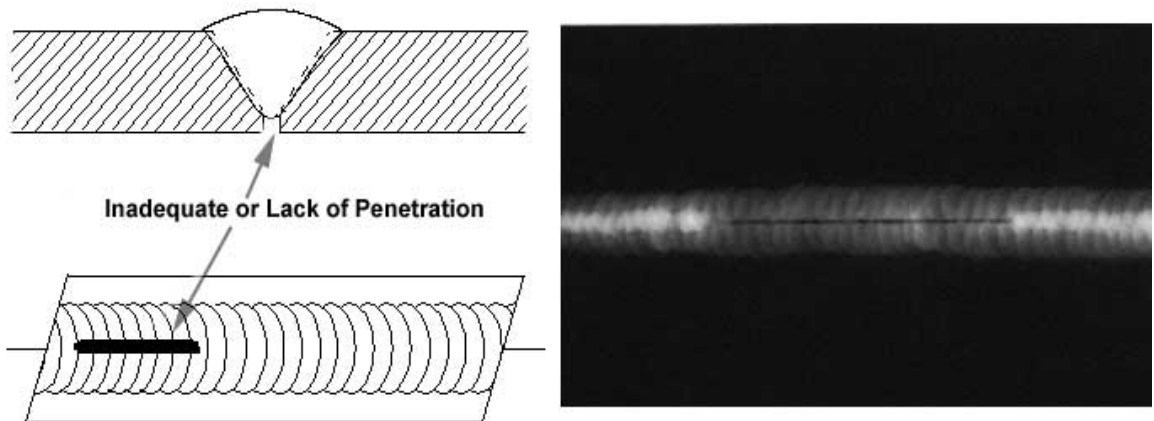
Incomplete fusion is a condition where the weld filler metal does not properly fuse with the base metal. Appearance on radiograph: usually appears as a dark line or lines oriented in the direction of the weld seam along the weld preparation or joining area.
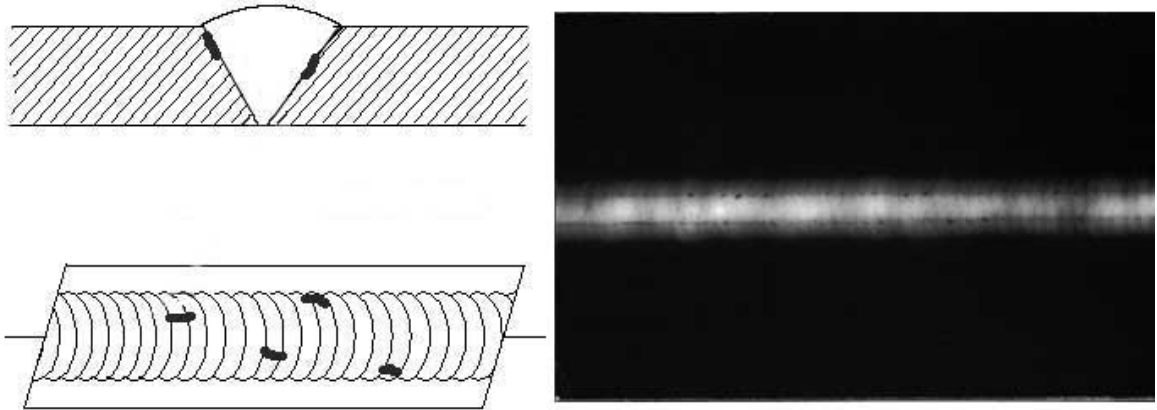
Internal concavity or suck back is condition where the weld metal has contracted as it cools and has been drawn up into the root of the weld. On a radiograph it looks similar to lack of penetration but the line has irregular edges and it is often quite wide in the center of the weld image.
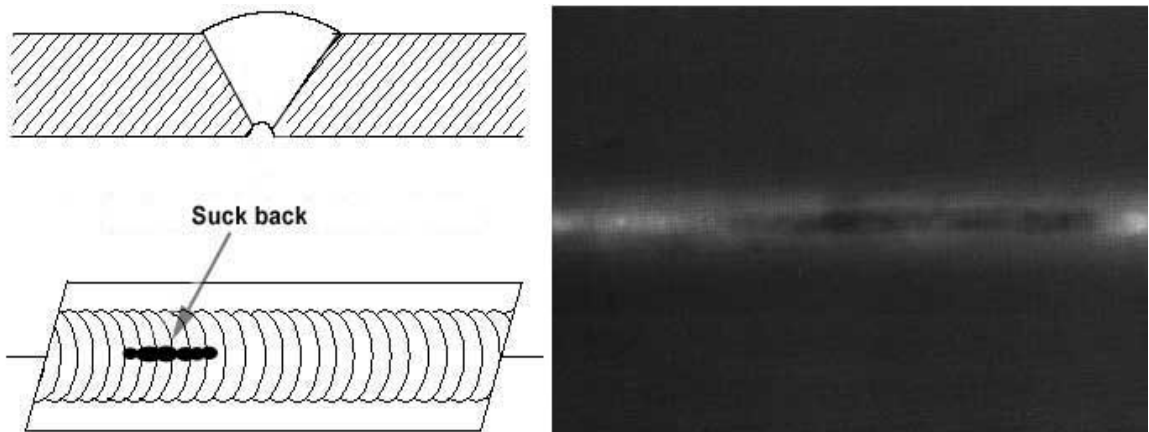
Internal or root undercut is an erosion of the base metal next to the root of the weld. In the radiographic image it appears as a dark irregular line offset from the centerline of the weldment. Undercutting is not as straight edged as LOP because it does not follow a ground edge.
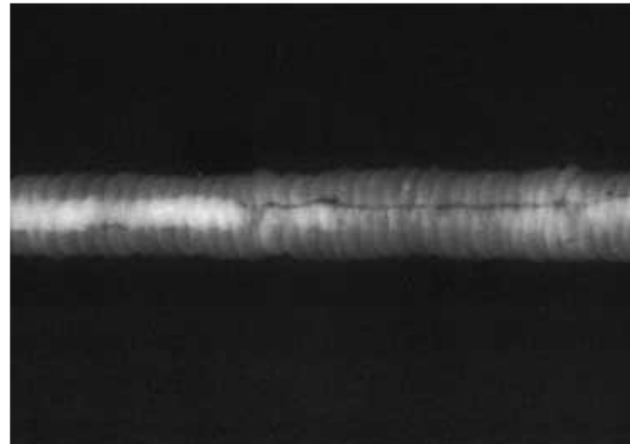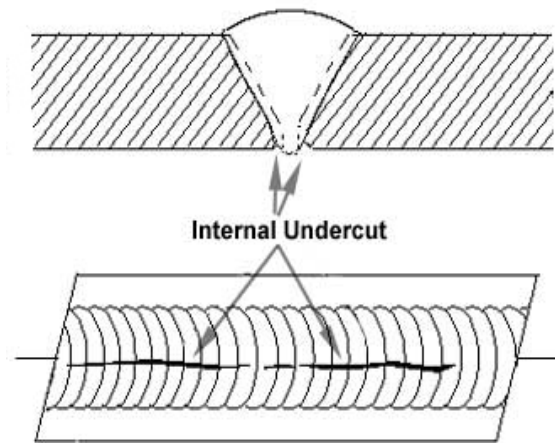
External or crown undercut is an erosion of the base metal next to the crown of the weld. In the radiograph, it appears as a dark irregular line along the outside edge of the weld area.
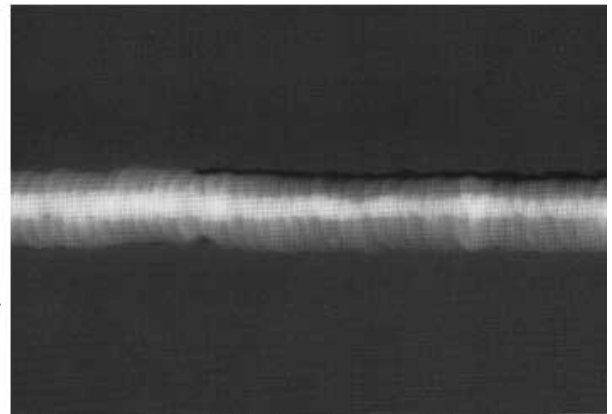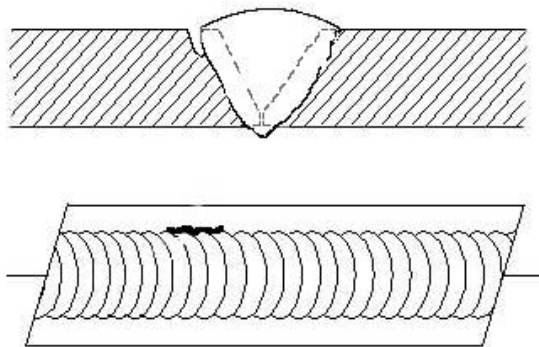
Offset or mismatch are terms associated with a condition where two pieces being welded together are not properly aligned. The radiographic image is a noticeable difference in density between the two pieces. The difference in density is caused by the difference in material thickness. The dark, straight line is caused by failure of the weld metal to fuse with the land area.


Offset or Mismatch
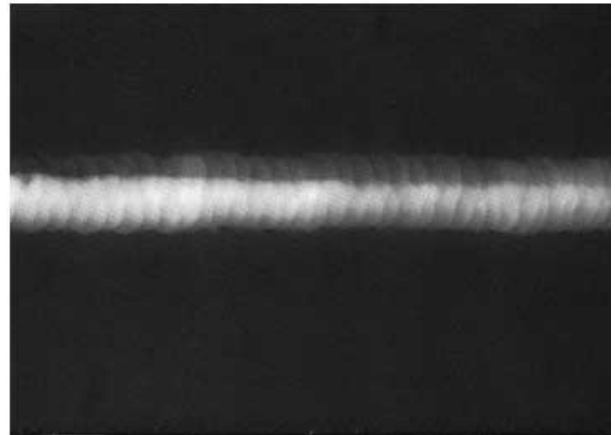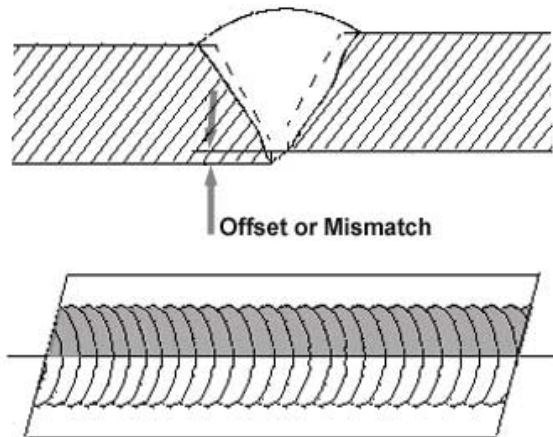
Inadequate weld reinforcement is an area of a weld where the thickness of weld metal deposited is less than the thickness of the base material. It is very easy to determine by radiograph if the weld has inadequate reinforcement, because the image density in the area of suspected inadequacy will be more (darker) than the image density of the surrounding base material.
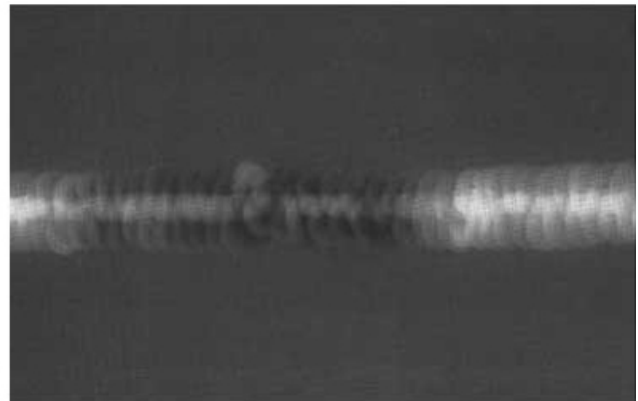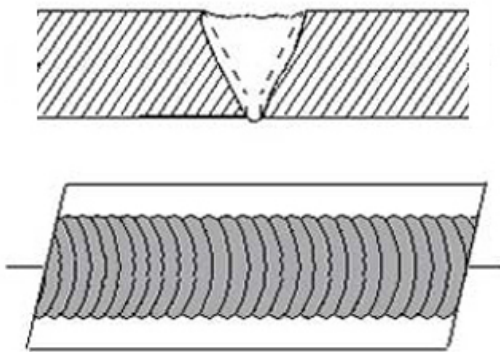
Excess weld reinforcement is an area of a weld that has weld metal added in excess of that specified by engineering drawings and codes. The appearance on a radiograph is a localized, lighter area in the weld. A visual inspection will easily determine if the weld reinforcement is in excess of that specified by the engineering requirements.
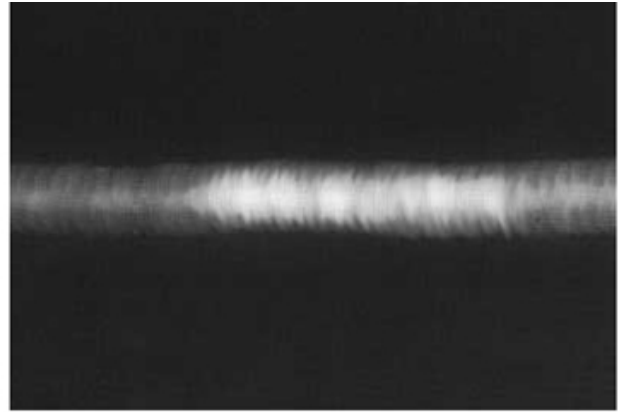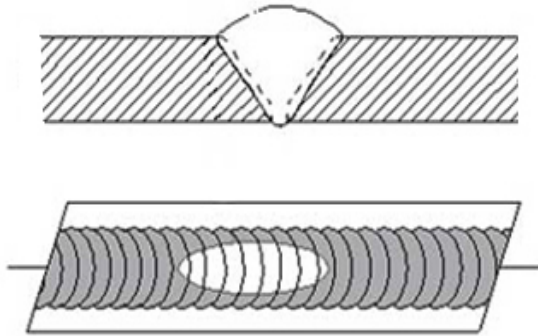

Cracks can be detected in a radiograph only when they are propagating in a direction that produces a change in thickness that is parallel to the x-ray beam. Cracks will appear as jagged and often very faint irregular lines. Cracks can sometimes appear as "tails" on inclusions or porosity.
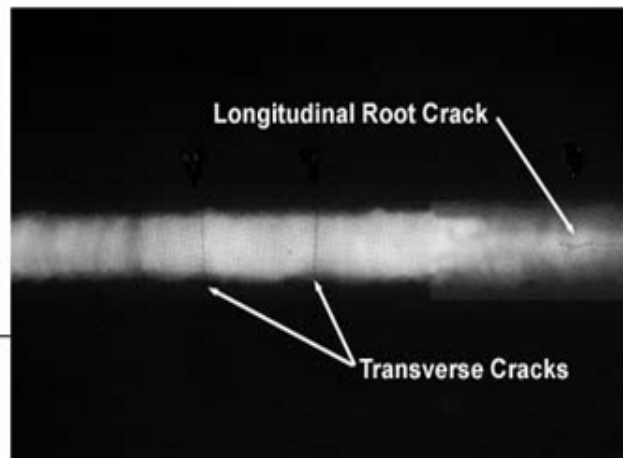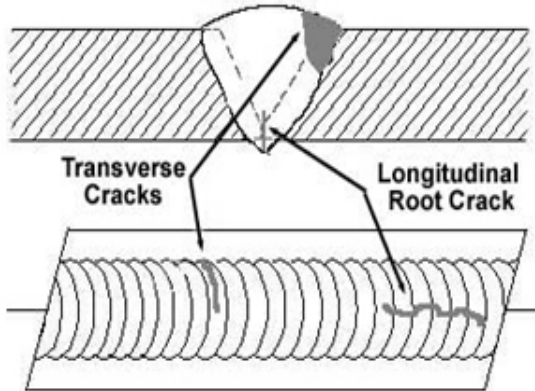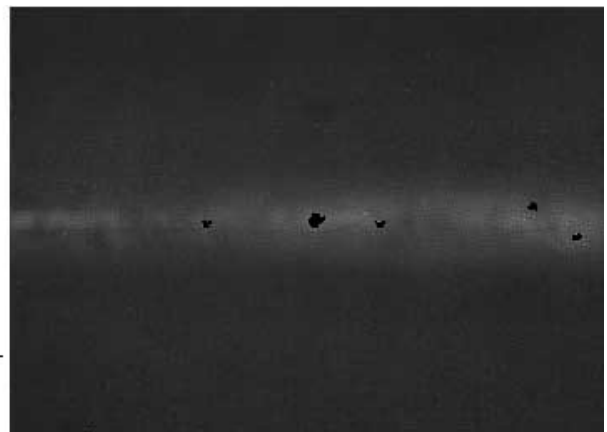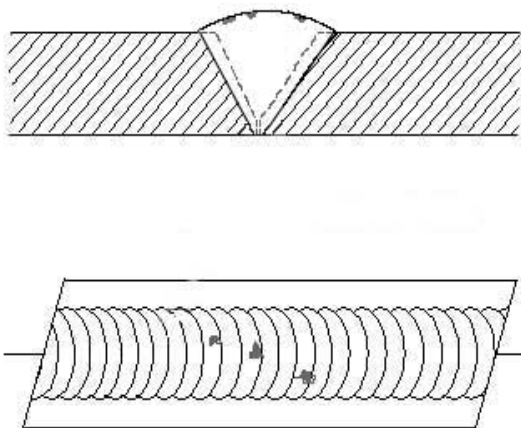
Discontinuities in TIG welds

The following discontinuities are peculiar to the TIG welding process. These discontinuities occur in most metals welded by the process including aluminum and stainless steels. The TIG method of welding produces a clean homogeneous weld which when radiographed is easily interpreted.

Tungsten inclusions. Tungsten is a brittle and inherently dense material used in the electrode in tungsten inert gas welding. If improper welding procedures are used, tungsten may be entrapped in the weld. Radiographically, tungsten is more dense than aluminum or steel; therefore, it shows as a lighter area with a distinct outline on the radiograph.
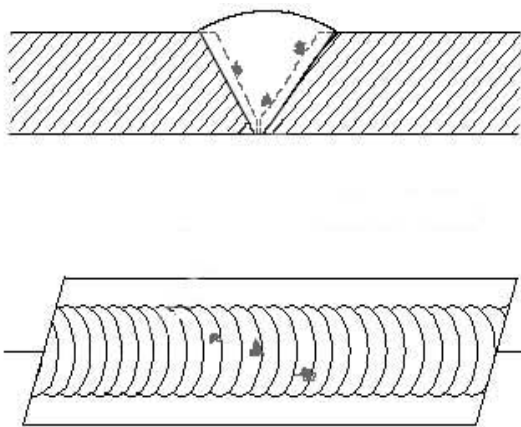
Oxide inclusions are usually visible on the surface of material being welded (especially aluminum). Oxide inclusions are less dense than the surrounding materials and, therefore, appear as dark irregularly shaped discontinuities in the radiograph.

Discontinuities in Gas Metal Arc Welds (GMAW)

The following discontinuities are most commonly found in GMAW welds.

Whiskers are short lengths of weld electrode wire, visible on the top or bottom surface of the weld or contained within the weld. On a radiograph they appear as light, "wire like" indications.

Burn-Through results when too much heat causes excessive weld metal to penetrate the weld zone. Often lumps of metal sag through the weld creating a thick globular condition on the back of the weld. These globs of metal are referred to as icicles. On a radiograph, burn through appears as dark spots, which are often surrounded by light globular areas (icicles).
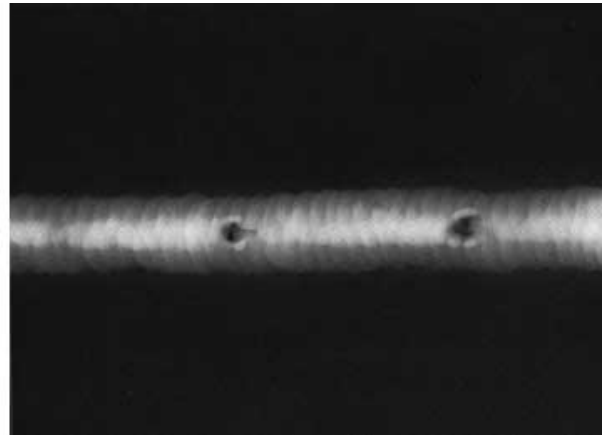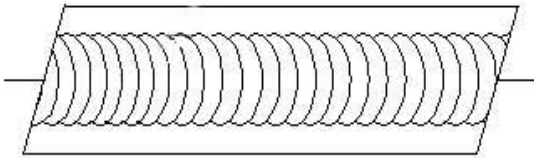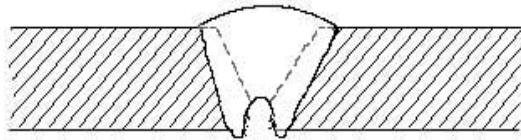
Radiograph Interpretation - Castings

The major objective of radiographic testing of castings is the disclosure of defects that adversely affect the strength of the product. Casting are a product form that often receive radiographic inspection since many of the defects produced by the casting process are volumetric in nature and, thus, relatively easy to detect with this method. These discontinuities of course, are related to casting process deficiencies, which, if properly understood, can lead to accurate accept-reject decisions as well as to suitable corrective measures. Since different types and sizes of defects have different effects of the performance of the casting, it is important that the radiographer is able to identify the type and size of the defects. ASTM E155, Standard for Radiographs of castings has been produced to help the radiographer make a better assessment of the defects found components. The castings used to produce the standard radiographs have been destructively analyzed to confirm the size and type of discontinuities present. The following is a brief description of the most common discontinuity types included in existing reference radiograph documents (in graded types or as single illustrations).

RADIOGRAPHIC INDICATIONS FOR CASTINGS

Gas porosity or blow holes are caused by accumulated gas or air which is trapped by the metal. These discontinuities are usually smooth-walled rounded cavities of a spherical, elongated or flattened shape. If the sprue is not high enough to provide the necessary heat transfer needed to force the gas or air out of the mold, the gas or air will be trapped as the molten metal begins to solidify. Blows can also be caused by sand that is too fine, too wet, or by sand that has a low permeability so that gas can't escape. Too high a moisture content in the sand makes it difficult to carry the excessive volumes of water vapor away from the casting. Another cause of blows can be attributed to using green ladles, rusty or damp chills and chaplets.
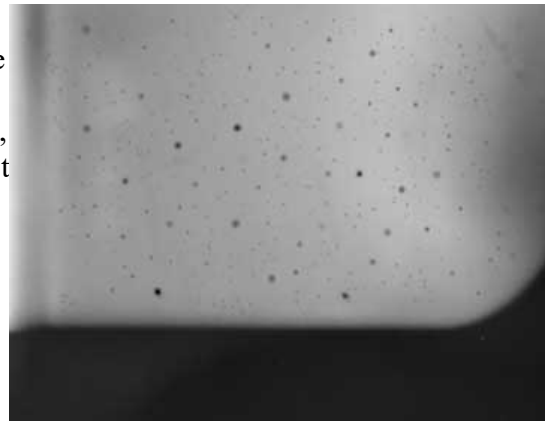
Sand inclusions and dross are nonmetallic oxides, appearing on the radiograph as irregular, dark blotches. These come from disintegrated portions of mold or core walls and/or from oxides (formed in the melt) which have not been skimmed off prior to introduction of the metal into the mold gates. Careful control of the melt, proper holding time in the ladle and skimming of the melt during pouring will minimize or obviate this source of trouble.
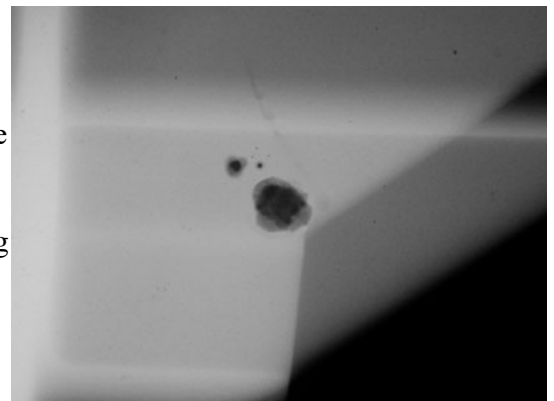
Shrinkage is a form of discontinuity that appears as dark spots on the radiograph. Shrinkage assumes various forms but in all cases it occurs because molten metal shrinks as it solidifies, in all portions of the final casting. Shrinkage is avoided by making sure that the volume of the casting is adequately fed by risers which sacrificially retain the shrinkage. Shrinkage can be recognized in a number of characteristic by varying appearances on radiographs. There are at least four types: (1) cavity; (2) dendritic; (3) filamentary; and (4) sponge types. Some documents designate these types by numbers, without actual names, to avoid possible misunderstanding.

Cavity shrinkage appears as areas with distinct jagged boundaries. It may be produced when metal solidifies between two original streams of melt, coming from opposite directions to join a common front; cavity shrinkage usually occurs at a time when the melt has almost reached solidification temperature and there is no source of supplementary liquid to feed possible cavities.
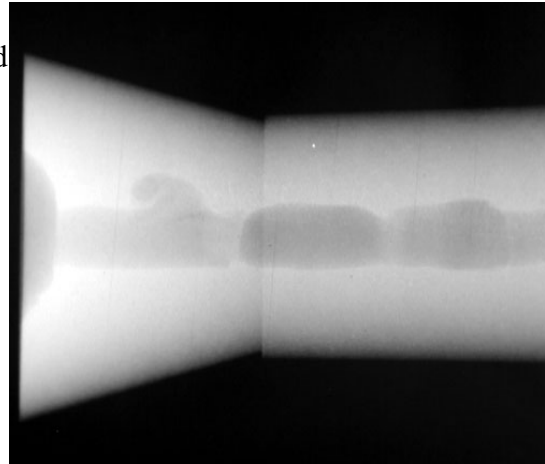
Dendritic shrinkage is a distribution of very fine lines or small elongated cavities that may vary in density and are usually unconnected.
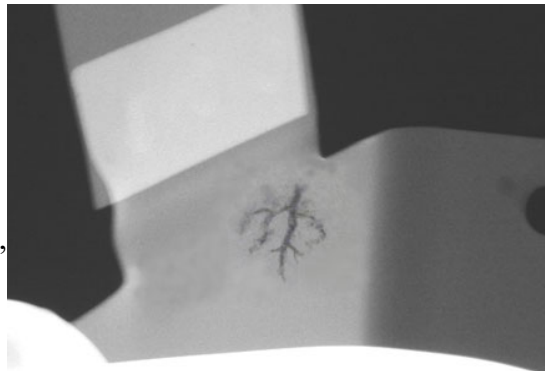
Filamentary shrinkage usually occurs as a continuous structure of connected lines or branches of variable length, width and density, or occasionally as a network.
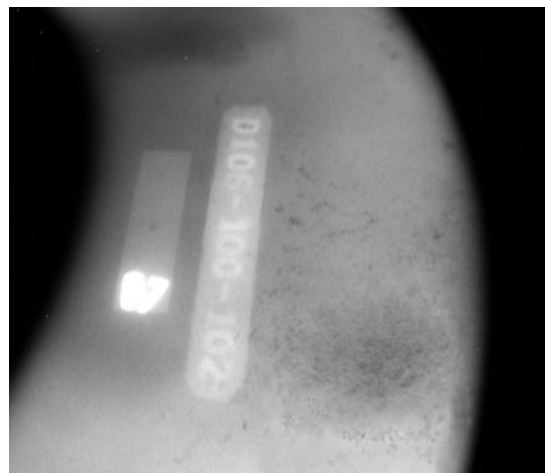
Sponge shrinkage shows itself as areas of lacy texture with diffuse outlines, generally toward the mid-thickness of heavier casting sections. Sponge shrinkage may be dendritic or filamentary shrinkage; filamentary sponge shrinkage appears more blurred because it is projected through the relatively thick coating between the discontinuities and the film surface.

**Cracks** are thin (straight or jagged) linearly disposed discontinuities that occur after the melt has solidified. They generally appear singly and originate at casting surfaces.

Cold shuts generally appear on or near a surface of cast metal as a result of two streams of liquid meeting and failing to unite. They may appear on a radiograph as cracks or seams with smooth or rounded edges.
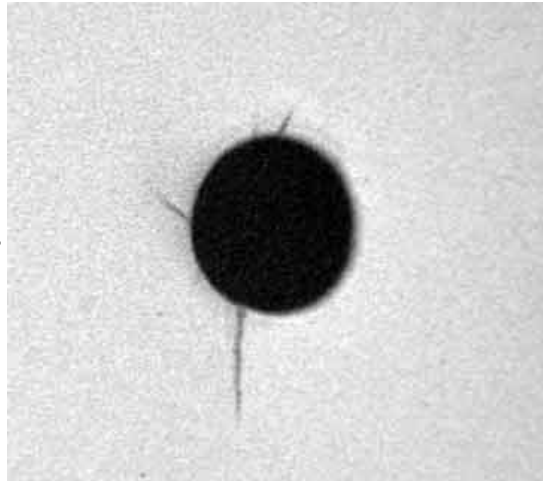
Inclusions are nonmetallic materials in a supposedly solid metallic matrix. They may be less or more dense than the matrix alloy and will appear on the radiograph, respectively, as darker or lighter indications. The latter type is more common in light metal castings.
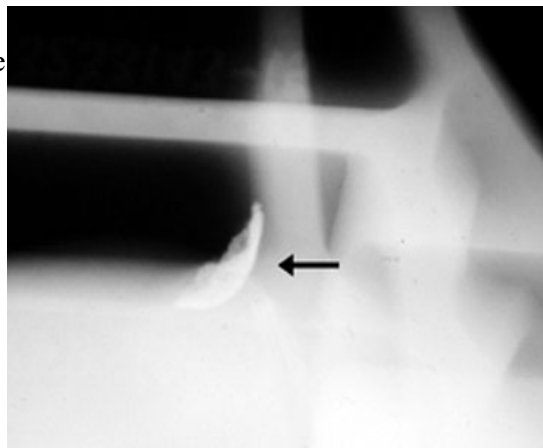
Core shift shows itself as a variation in section thickness, usually on radiographic views representing diametrically opposite portions of cylindrical casting portions.
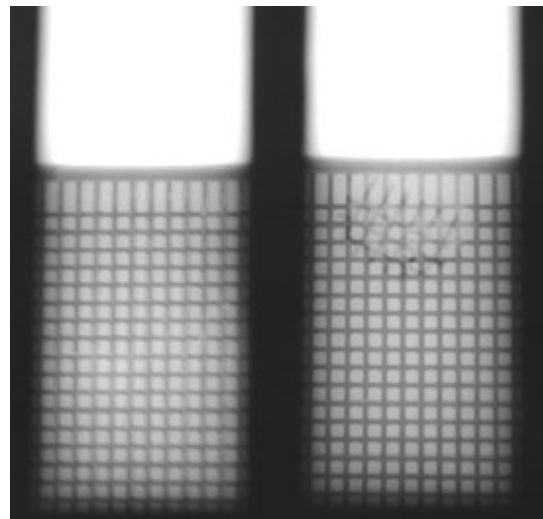
Hot tears are linearly disposed indications that represent fractures formed in a metal during solidification because of hindered contraction. The latter may occur due to overly hard (completely unyielding) mold or core walls. The effect of hot tears, as a stress concentration, is similar to that of an ordinary crack; how tears are usually systematic flaws. If flaws are identified as hot tears in larger runs of a casting type, they may call for explicit improvements in technique.

Misruns appear on the radiograph as prominent dense areas of variable dimensions with a definite smooth outline. They are mostly random in occurrence and not readily eliminated by specific remedial actions in the process.

Mottling is a radiographic indication that appears as an indistinct area of more or less dense images. The condition is a diffraction effect that occurs on relatively vague, thin-section radiographs, most often with austenitic stainless steel. Mottling is caused by interaction of the object's grain boundary material with low-energy X-rays (300 kV or lower). Inexperienced interpreters may incorrectly consider mottling as indications of unacceptable casting flaws. Even experienced interpreters often have to check the condition by re-radiography from slightly different source-film angles. Shifts in mottling are then very pronounced, while true casting discontinuities change only slightly in appearance.

Radiographic Indications for Casting Repair Welds

Most common alloy castings require welding either in upgrading from defective conditions or in joining to other system parts. It is mainly for reasons of casting repair that these descriptions of the more common weld defects are provided here. The terms appear as indication types in ASTM E390. For additional information, see the Nondestructive Testing Handbook, Volume 3, Section 9 on the "Radiographic Control of Welds."

Slag is nonmetallic solid material entrapped in weld metal or between weld material and base metal. Radiographically, slag may appear in various shapes, from long narrow indications to short wide indications, and in various densities, from gray to very dark.

Porosity is a series of rounded gas pockets or voids in the weld metal, and is generally cylindrical or elliptical in shape.

Undercut is a groove melted in the base metal at the edge of a weld and left unfilled by weld metal. It represents a stress concentration that often must be corrected, and appears as a dark indication at the toe of a weld.

Incomplete penetration, as the name implies, is a lack of weld penetration through the thickness of the joint (or penetration which is less than specified). It is located at the center of a weld and is a wide, linear indication.

Incomplete fusion is lack of complete fusion of some portions of the metal in a weld joint with adjacent metal; either base or previously deposited weld metal. On a radiograph, this appears as a long, sharp linear indication, occurring at the centerline of the weld joint or at the fusion line.

Melt-through is a convex or concave irregularity (on the surface of backing ring, strip, fused root or adjacent base metal) resulting from complete melting of a localized region but without development of a void or open hole. On a radiograph, melt-through generally appears as a round or elliptical indication.

Burn-through is a void or open hole into a backing ring, strip, fused root or adjacent base metal.

Arc strike is an indication from a localized heat-affected zone or a change in surface contour of a finished weld or adjacent base metal. Arc strikes are caused by the heat generated when electrical energy passes between surfaces of the finished weld or base metal and the current source.

Weld spatter occurs in arc or gas welding as metal particles which are expelled during welding and which do not form part of the actual weld: weld spatter appears as many small, light cylindrical indications on a radiograph.

Tungsten inclusion is usually denser than base-metal particles. Tungsten inclusions appear most linear, very light radiographic images; accept/reject decisions for this defect are generally based on the slag criteria.

Oxidation is the condition of a surface which is heated during welding, resulting in oxide formation on the surface, due to partial or complete lack of purge of the weld atmosphere. Also called sugaring.

Root edge condition shows the penetration of weld metal into the backing ring or into the clearance between backing ring or strip and the base metal. It appears in radiographs as a sharply defined film density transition.

Root undercut appears as an intermittent or continuous groove in the internal surface of the base metal, backing ring or strip along the edge of the weld root.

Real-time Radiography

Real-time radiography (RTR), or real-time radioscopy, is a nondestructive test (NDT) method whereby an image is produced electronically rather than on film so that very little lag time occurs between the item being exposed to radiation and the resulting image. In most instances, the electronic image that is viewed, results from the radiation passing through the object being inspected and interacting with a screen of material that fluoresces or gives off light when the interaction occurs. The fluorescent elements of the screen form the image much as the grains of silver form the image in film radiography. The image formed is a "positive image" since brighter areas on the image indicate where higher levels of transmitted radiation reached the screen. This image is the opposite of the negative image produced in film radiography. In other words, with RTR, the lighter, brighter areas represent thinner sections or less dense sections of the test object.

Real-time radiography is a well-established method of NDT having applications in automotive, aerospace, pressure vessel, electronic, and munition industries, among others. The use of RTR is increasing due to a reduction in the cost of the equipment and resolution of issues such as the protecting and storing digital images. Since RTR is being used increasingly more, these educational materials were developed by the North Central Collaboration for NDT Education (NCCE) to introduce RTR to NDT technician students.