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CHAPTER 6
RADIOGRAPHIC INSPECTION METHOD

SECTION I RADIOGRAPHIC (RT) INSPECTION METHOD

6.1 GENERAL CAPABILITIES OF RADIOGRAPHIC INSPECTION.

6.1.1 Introduction to Radiographic Inspection. This chapter will provide guidance for radiographic inspection. Additional helpful material is cited in the form of references, primarily books and standards. References are listed at the end of this chapter.

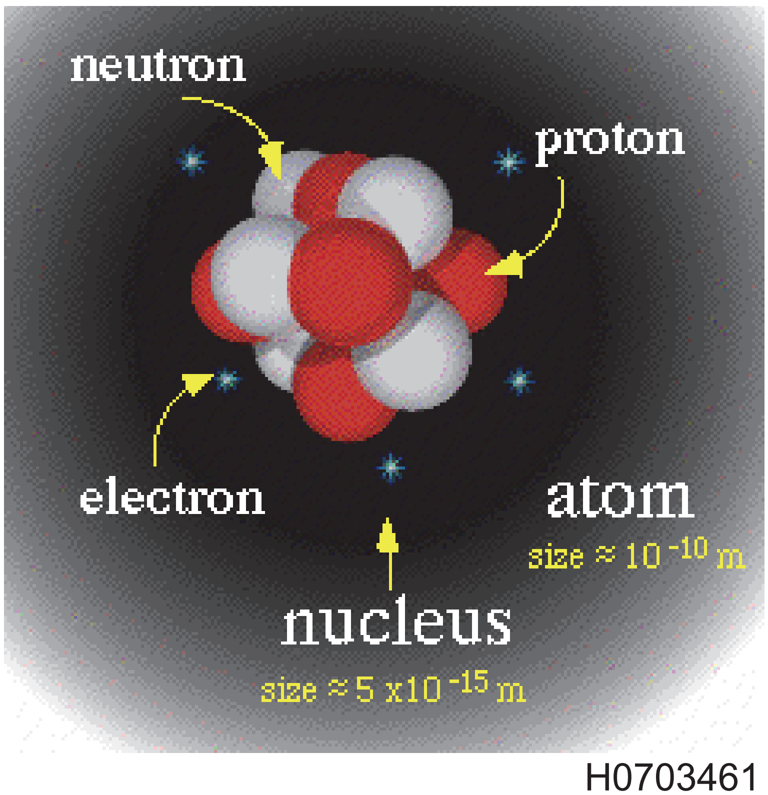


Figure 6-1. Nuclear Structure

6.1.1.1 Nuclear Structure. An atom consists of an extremely small, positively charged nucleus surrounded by a cloud of negatively charged electrons. Although typically the nucleus is less than one ten-thousandth the size of the atom, the nucleus contains more than 99.9% of the mass of the atom. Nuclei consist of positively charged protons and electrically neutral neutrons held together by the so-called strong or nuclear force. This force is much stronger than the familiar electrostatic force that binds the electrons to the nucleus, but its range is limited to distances approximately a few $x10^{-15}$ meters.

6.1.1.1.1 The number of protons in the nucleus, “Z” is called the atomic number. This determines what chemical element the atom is. “N” denotes the number of neutrons in the nucleus. The atomic mass of the nucleus, “A” is equal to Z + N. A given element can have many different isotopes, which differ from one another by the number of neutrons contained in the nuclei. In a neutral atom, the number of electrons orbiting the nucleus equals the number of protons in the nucleus. Since the electric charges of the proton and the electron are +1 and -1 respectively (in units of the proton charge), the net charge of the atom is zero. At present, there are 118 known elements which range from the lightest, hydrogen, to the recently named element 118, Ununoctium. All of the elements heavier than uranium are manmade. Among the elements are approximately 270 stable isotopes, and more than 2000 unstable isotopes.

6.1.2 History of X- and Gamma Radiation. X-rays were discovered by chance in 1895 by W.C. Roentgen. He noticed a screen painted in barium platinocyanide fluoresced when placed in close proximity to a cathode-ray tube. He called these X-rays, because their nature was unknown. In 1912, M. von Laue and other investigators identified X-rays as electromagnetic waves similar in nature to visible light; however, X-rays are invisible and they have far greater penetrating power than light.

6.1.2.1 Radium emits alpha and beta particles and gamma rays, which are penetrating in the same manner as X-rays. In 1898, Marie Curie termed the emanations of this element radioactivity. Besides radium, many radioactive elements have since been discovered. At present, not only the rays emitted by such radioactive sources, but beams emitted in nuclear reactions are also derived from radioactivity. Of these radioactive sources, X- and gamma radiation are widely used in industrial radiography. X-radiation has a continuously heterogeneous energy spectrum, while gamma radiation has a discrete spectrum characteristic to the particular radioactive element involved. Other important discoveries in the history of radiation are explored in Table 6-1.

Table 6-1. History of X- and Gamma Radiation

Year	Scientist(s)	Discovery
1704	Isaac Newton	Proposed a mechanical universe with small solid masses in motion.
1803	John Dalton	Proposed an “atomic theory” with spherical solid atoms based upon measurable properties of mass.
1832	Michael Faraday	Studied the effect of electricity on solutions, coined term “electrolysis” as a splitting of molecules with electricity, developed laws of electrolysis. Faraday himself was not a proponent of atomism.
1859	J. Plucker	Built one of the first gas discharge tubes (“cathode ray tube”).
1869	Dmitri Mendeleev	Arranged elements into 7 groups with similar properties. He discovered that the properties of elements were periodic functions of their atomic weights. This became known as the Periodic Law.
1873	James Clerk Maxwell	Proposed electric and magnetic fields filled the void.
1874	G.J. Stoney	Proposed that electricity was made of discrete negative particles he called electrons.
1879	Sir William Crookes	Discovered cathode rays had the following properties: travel in straight lines from the cathode; cause glass to fluoresce; impart a negative charge to objects they strike; are deflected by electric fields and magnets to suggest a negative charge; cause pinwheels in their path to spin indicating they have mass.
1886	E. Goldstein	Used a CRT to study “canal rays” which had electrical and magnetic properties opposite of an electron.
1895	Wilhelm Roentgen	Using a CRT, he observed that nearby chemicals glowed. Further experiments found very penetrating rays coming from the CRT that were not deflected by a magnetic field. He named them “X-rays.”
1896	Henri Becquerel	While studying the effect of x-rays on photographic film, he discovered some chemicals spontaneously decompose and give off very penetrating rays.
1897	J.J. Thomson	Used a CRT to experimentally determine the charge to mass ratio (e/m) of an electron =1.759 x 10^{8}coulombs/gram.
1897	J.J. Thomson	Studied ‘‘canal rays’’ and found they were associated with the proton H^{+}.
1898	Rutherford	Studied radiations emitted from uranium and thorium and named them *alpha* and *beta*.
1898	Marie Sklodowska Curie	Studied uranium and thorium and called their spontaneous decay process “radioactivity.” She and her husband Pierre also discovered the radioactive elements polonium and radium.

Table 6-1. History of X- and Gamma Radiation - Continued

Year	Scientist(s)	Discovery
1900	Soddy	Observed spontaneous disintegration of radioactive elements into variants he called “isotopes” or totally new elements, discovered “half-life,” made initial calculations on energy released during decay.
1900	Max Planck	Used the idea of quanta (discrete units of energy) to explain hot glowing matter.
1903	Nagaoka	Postulated a “Saturnian” model of the atom with flat rings of electrons revolving around a positively charged particle.
1904	Abegg	Discovered that inert gases had a stable electron configuration which lead to their chemical inactivity.
1906	Hans Geiger	Developed an electrical device to “click” when hit with alpha particles.
1909	R.A. Millikan	Oil drop experiment determined the charge (e=1.602 x 10^{-19} coulomb) and the mass (m = 9.11 x 10^{-28}gram) of an electron.
1911	Ernest Rutherford	Using alpha particles as atomic bullets, probed the atoms in a piece of thin (0.00006 cm) gold foil. He established that the nucleus was very dense, very small and positively charged. He also assumed that the electrons were located outside the nucleus.
1914	H.G.J. Moseley	Using x-ray tubes, determined the charges on the nuclei of most atoms. He wrote, “The atomic number of an element is equal to the number of protons in the nucleus.” This work was used to reorganize the periodic table based upon atomic number instead of atomic mass.
1919	Aston	Discovered the existence of isotopes using a mass spectrograph.
1922	Niels Bohr	Developed an explanation of atomic structure that underlies regularities of the periodic table of elements. His atomic model had atoms built up of successive orbital shells of electrons.
1923	de Broglie	Discovered that electrons had a dual nature-similar to both particles and waves. Particle/wave duality. Supported Einstein.
1927	Heisenberg	Described atoms by means of formula connected to the frequencies of spectral lines. Proposed Principle of Indeterminacy - you cannot know both the position and velocity of a particle.
1929	Cockcroft/Walton	Built an early linear accelerator and bombarded lithium with protons to produce *alpha particles*.
1930	Schrodinger	Viewed electrons as continuous clouds and introduced “wave mechanics” as a mathematical model of the atom.
1930	Paul Dirac	Proposed *anti-particles*. Anderson discovered the anti-electron (positron) in 1932 and Segre/Chamberlain detected the anti-proton in 1955.
1932	James Chadwick	Using alpha particles discovered a neutral atomic particle with a mass close to a proton. Thus was discovered the neutron.
1938	Lise Meitner, Hahn, Strassman	Conducted experiments verifying that heavy elements capture neutrons and form unstable products which undergo fission. This process ejects more neutrons continuing the fission chain reaction.
1941 - 1951	Glenn Seaborg	Synthesized 6 transuranium elements and suggested a change in the layout of the periodic table.
1942	Enrico Fermi	Conducted the first controlled chain reaction releasing energy from the atom’s nucleus.

6.1.3 Factors of Radiographic Inspection. X- and gamma radiographic inspection uses the penetrating abilities of electromagnetic radiation to examine the interior of objects. Three prime factors determine the amount of information radiography can provide about an object: 1) The composition of the object, 2) The density of the material making up the object, 3) The energy of the X- or gamma rays incident upon the object. Discontinuities within the object can cause localized changes in the first two characteristics above and thus, become detectable.

6.1.4 The Physics of X-rays. X-rays are high-energy photons that are produced when electrons make transitions from one atomic orbit to another. These transitions can be generated via the photoelectric effect as illustrated in (Figure 6-13). If you send a photon into an atom with an energy greater than the binding energy of an electron in that atom, the photon can knock that electron out of its orbit, leaving a hole (or vacancy). This hole can then be filled by another electron in the atom, giving off an x-ray in the transition to conserve energy. This process is known as fluorescence. Many different atomic electrons of different binding energies can fill this hole, so you would expect to see many energy peaks in an x-ray spectrum.

6.1.4.1 The Nature of Radiation. All together, X-rays and gamma rays, visible light, ultraviolet light, infrared radiation, microwaves, and radio waves make up the electromagnetic spectrum (Figure 6-2). Electromagnetic radiation is dualistic; meaning it exhibits some characteristics of a wave and some characteristics of a particle. In this case, the particle is called a photon, which is a quantum of light. Depending upon the application, X-rays might exhibit a more wave-like behavior or more quantum-like behavior.

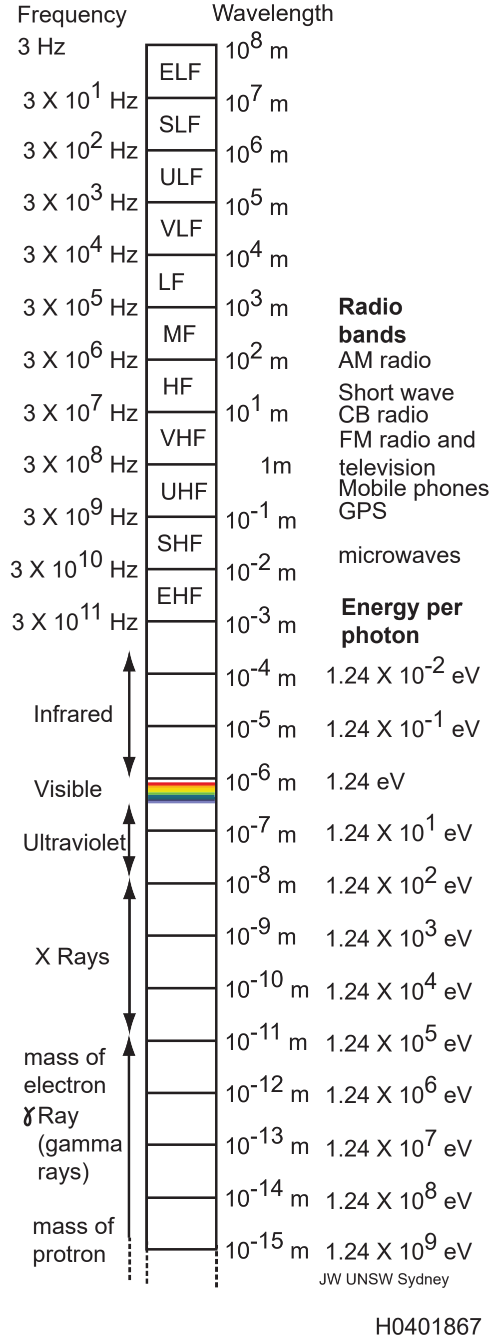


Figure 6-2. Wavelength

WARNING

Exposure to excessive X- or gamma radiation is harmful to human beings. While most X-ray equipment is designed to minimize the danger of exposure to direct or stray radiation, certain precautions SHALL be observed. Radiation protection requirements are discussed in (paragraph 6.8) of this chapter.

6.1.4.2 The most distinguishing characteristic of X-rays is their short wavelength. The penetrating ability of X-rays is directly proportional to their energy, which in turn, is inversely proportional to their wavelength; that is, the shorter the wavelength, the higher the energy; the longer the wavelength, the lower the energy. Short wavelength X-rays are commonly described as "hard" while long wavelength X-rays are referred to as "soft."

6.1.5 Properties of X- and Gamma Radiation. There are several properties which X-rays and gamma rays possess making them useful for radiographic inspection. X-rays and gamma rays are the same form of energy as visible light; both are part of the electromagnetic spectrum. Like light, both are refracted when they pass through glass, such as a lens, or any other medium; however, the amount of refraction of X- or gamma rays using visible-light optics is so slight as to be unnoticeable. Although the properties of X-and gamma rays and visible light are theoretically similar, the differences in application make it most convenient to consider X- and gamma rays as being different, since their observable effects are quite different from those of light. This is noted particularly in the ability to penetrate matter. Some general properties of X-and gamma rays may be summarized as follows:

- They are invisible to humans.
- They propagate in straight lines in free space.
- In special cases they are reflected, diffracted, refracted, and polarized as light, but to a much smaller degree.
- They propagate at a velocity of $3x10^{8}$meters per second as does light.
- They consist of transverse electromagnetic vibrations as does light.
- X-rays have energies between roughly 1 kilo electron volt (keV) and 50 MeV.
- X-rays for NDI are produced by the interaction of high-energy electrons or ions with matter.
- Gamma rays are produced in nuclear transformations, such as radioactive decay.
- X-rays and gamma rays expose (darken) photographic film.
- They stimulate fluorescence and phosphorescence in some materials.
- They are capable of ionizing gases and changing the electrical properties of some liquids and solids.
- They are able to damage and kill living cells and to produce genetic mutations.
- They are differentially absorbed or scattered by different media.
- X-rays may be diffracted by the crystalline structure of materials, which acts like a grating.
- They do not affect fuel cells or munitions.

6.1.5.1 All of these properties contribute in some degree to the understanding of the radiographic process. Most important of these in terms of usefulness to NDI are the differential absorption of radiation in matter and the ability of radiation to expose film. In the remainder of this chapter the term "X-rays" will be more prevalent since that form of radiation is most used. Except where noted the discussion will also apply to gamma rays.

6.1.6 Differential Absorption of Radiation in Matter. A material discontinuity, such as a void or change in configuration Figure 6-3), changes the effective thickness of a material, and thus changes the degree of radiation absorption. Since all radiation not absorbed or scattered within a material is transmitted, the amount of transmitted radiation varies with localized changes in effective material thickness.

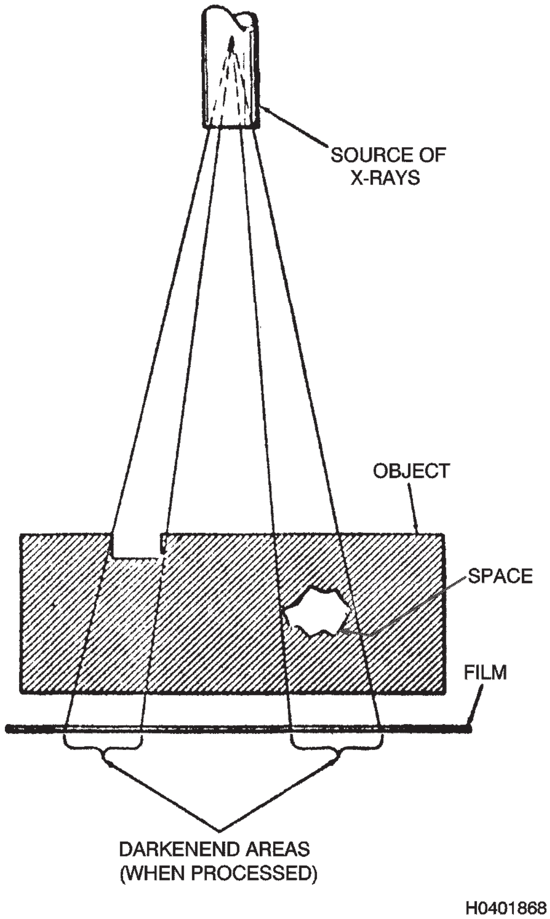


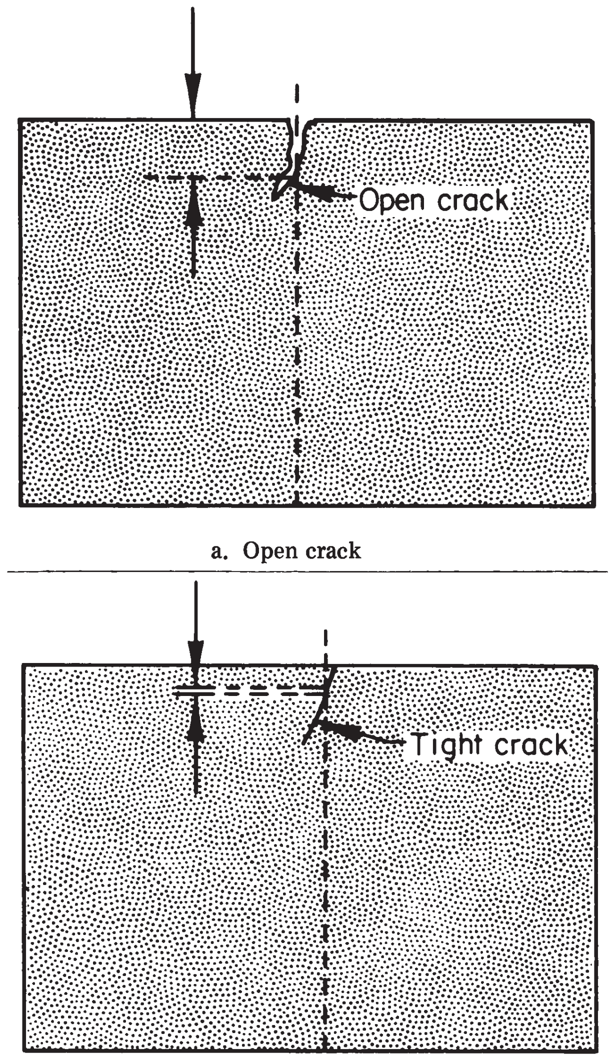
Figure 6-3. Diagram of Radiographic Exposure

6.1.6.1 It is the transmitted radiation intensity generally used to find a material defect. If the material discontinuity represented in (Figure 6-4) were a foreign material inclusion, it also would cause a change in the apparent composition of the material and again result in a change in the transmitted radiation intensity. The degree of this change would be dependent on the relative effects of the test object and the included material on the incident radiation.

6.1.6.1.1 Some voids are difficult to detect, because they present a very slight change in material thickness to a beam of radiation. An important example of this type of defect is a crack, which represents a tear or rupture within a homogeneous material. If a crack is open, meaning the opening is wide (Figure 6-4a), it appears to the radiation beam as a significant change in effective material thickness and is thus readily detected. However, if a crack is under compression and is very tight or closed, as illustrated in Figure 6-4b), then its detection may become very difficult, if not impossible, because the apparent change in material thickness is negligible. It is important to note, crack orientation to the primary beam has a very significant effect on the detectability of the crack using a radiographic technique. If the crack in (Figure 6-4b) were oriented parallel with the radiation beam, the effective change in material thickness would be enough to make the crack easily detectable. However, in most situations the probability of aligning a beam with a tight crack is low, so other NDI techniques SHOULD be relied upon as backup inspections. The problems associated with crack detection will be dealt with at length in later paragraphs.

NOTE

Although radiography will reveal the interior of opaque objects, it cannot detect all types of irregularities or discontinuities. Small defects such as fine cracks or indentations in thick objects are difficult to detect. In applying radiography as an inspection method, the sensitivity of the method must be kept in mind. The limitations of radiography will become more apparent in subsequent discussions.



a. Open crack

b. Tight crack

Figure 6-4. Effect of Change in Thickness Cracks

6.1.7 Exposure of Film to Radiation. X- or gamma radiation differs from ordinary light in their action on photographic film. Examination of microscopic sections through the sensitive layer of exposed films has shown radiation, unlike light, produces an equal distribution of grains of reduced silver throughout the entire thickness of the layer, whereas light produces an effect mainly on the surface of the emulsion. Consequently, a greater blackening of the emulsion can be produced by increasing the thickness of the emulsion and by coating both sides of the base of radiographic film. This darkening effect MAY then be used to obtain a photographic record, or radiograph, which is produced by the passage of X-rays or gamma rays through an object and onto a film. Thus a radiograph is a shadow picture of an object and its interior; dark regions on the film represent the more penetrable regions of the part and lighter areas on the film represent the more dense areas of the part. Film MAY be coupled with various screens to improve the image and reduce problems associated with scattered radiation.

6.1.7.1 The term exposure, as used in this manual, refers to the amount of radiation energy reaching a particular area of the film. It could be expressed as "ergs-per-square-centimeter," but it is more convenient for practical use when expressed in terms of "dimensionless-relative-units," one particular exposure value being used as a reference for other exposures. Characteristic curves are used to relate the action of exposure to radiation on a film, which becomes apparent in varying degrees of blackening in the processed film.

6.1.8 When to use Radiography. Radiography satisfies the three primary requirements of any nondestructive inspection:

- There is an energy form that can be usefully produced in a controlled manner.
- This energy form is capable of interacting with material in a manner that causes a change in the energy form, but not in the material.
- After such interaction, the energy form MAY be detected and MAY be interpreted to define what material condition produced the observed result.

6.1.8.1 Guidelines for Using Radiography. Here are some basic guidelines that MAY be followed to determine situations in which radiography is applicable:

- The area/defect of interest must cause a detectable change in apparent thickness, density, or composition of the test material.
- The material SHOULD be reasonably homogeneous, so an indication of a defect can be recognized.
- The part SHALL be configured so the inspector will have access to both sides of the area that must be inspected. This is a requirement to ensure the area to be inspected is between the primary beam and the film.
- The defect to be detected SHOULD be properly oriented in the path of the radiation beam.

6.1.8.2 Limitations to Radiographic Inspection. Radiography is not a cure-all and SHOULD only be used when the above conditions are satisfied. Multiple film techniques and other special methods, which will be covered in (paragraph 6.4.17.2.2), make radiography a versatile tool for material evaluation.

6.1.8.3 Typical Uses for Radiographic Inspection.

6.1.8.3.1 Radiography is a useful nondestructive inspection method for detecting internal discontinuities in many materials.

6.1.8.3.2 Radiography MAY be applied to the inspection of castings, welds, and assembled components. Various metals, both ferrous and nonferrous, as well as non-metallic substances, such as ceramics and plastics, can successfully be inspected.

6.1.9 Unique Properties of Gamma Radiation.

6.1.9.1 Introduction to Gamma Radiography. Gamma radiography is basically the same as X-radiography. The differences in material properties and effects between them are largely a matter of degree. The major advantage of using gamma rays over X-rays is the fact gamma ray sources are small and provide access to small spaces, thereby simplifying exposure technique. A downside to using gamma rays is the fact that the exposure period is generally longer with gamma ray sources, and the gamma ray source cannot be turned off like an X-ray unit can.

6.1.9.2 Phenomenon of Gamma Radiation. Many atoms exhibit a property called radioactivity, which is a phenomenon of spontaneous disintegration or decay. This characteristic is believed to be caused by the instability of the complex structure of the atom under the action of the electric, magnetic, and gravitational forces existing within. This energy release is uncontrolled and is a result of forces in the atom. Radium is one of the elements with a natural unbalance that releases energy in the form of gamma rays to achieve a more stable condition. Radium-226 has no gamma energies over 0.27 MeV. In addition to the gamma rays, some alpha particles (helium nuclei) and beta particles (electrons) are allowed to escape. The atomic structure of many materials can be artificially made to release energy by subjecting them to strong fields of neutrons generated in nuclear reactors. These neutron fields add energy to the atom, which upsets the balance within the nucleus and causes the atom to emit one or more types of energy. Cobalt is one element commonly made artificially radioactive and used in NDI since the energy it releases is a very penetrating form of gamma rays. Co-60 has energies above 1 MeV. An example of nuclear disintegration and the release of energy is shown (Figure 6-5).

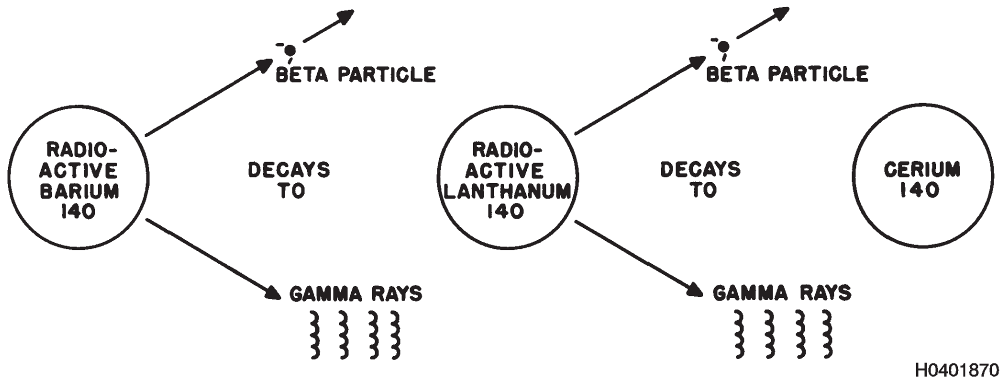


Figure 6-5. Diagram of Nuclear Disintegration

6.1.9.3 Typical Gamma Ray Source. The typical gamma ray source is composed of a metal container, called a camera, which contains a radioactive element, and has provisions to allow the element to be moved to a desired exposure position. Cameras are made of very dense material in order to shield the radioactive material. Typical gamma ray sources contain such artificially radioactive elements as cobalt -60, iridium -192, cesium-137, thulium-170, and ytterbium-169.

SECTION II PRINCIPLES AND THEORY OF RADIOGRAPHIC INSPECTION

6.2 HOW X-RAYS ARE PRODUCED.

6.2.1 Generating X-Radiation.

6.2.1.1 Basic Requirements. There are three basic requirements, which must be met to produce X-rays; 1) supply electrons, 2) move electrons, and 3) impinge electrons onto the target.

6.2.1.1.1 Supply Electrons. Since all matter is generally considered to be composed of electrons and other minute particles, electron sources are readily obtainable. Electrons can be supplied by simply raising the temperature of a suitable material. To excite the electron, it is necessary to sufficiently heat the material. As the temperature rises, the electrons become more and more agitated until they finally "escape" or "boil-off" the material. The excited electrons will surround the material in the form of an electron cloud (Figure 6-6), commonly known as thermionic emission. In an X-ray tube, the heated material is called the filament, which is similar to the filament in a light bulb. Just as in a light bulb the filament is heated by passing electrical current through it. This cloud of electrons simply hovers around and returns to the emitting substance unless some external action or force pulls it away. Therefore, electron emission is facilitated by heating a filament which is incorporated into the cathode.

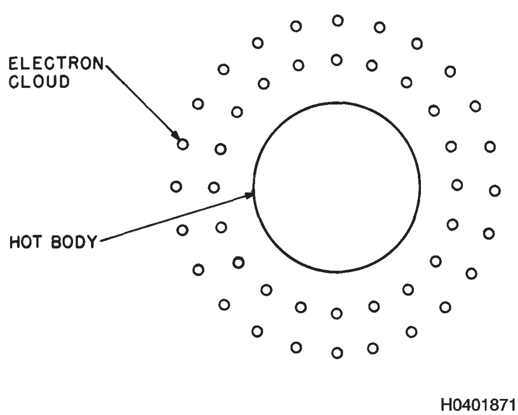


Figure 6-6. Electron Cloud

6.2.1.1.2 Move Electrons. As high voltage, direct current is applied between the cathode and the anode, the cathode emits electrons which flow toward the anode. This movement is brought about due to the repelling and attracting forces inherent in an electric circuit. The fundamental law of electrostatics states: "like charges repel and unlike charges attract." Electrons are negative charges, thus repel each other, however, a stronger attracting force is needed to accelerate the electrons to a higher velocity. Therefore, a strong opposite (positive) charge is used to move the electrons from one point to another. This voltage force, which drives electrons from the cathode to the anode, is known as kilovoltage with a unit symbol "kVp." It is important this movement is conducted in a good vacuum; otherwise the electrons collide with air molecules and lose energy through ionization and scattering. In an X-ray tube, the anode (target) is given a positive charge with respect to the filament, which is part of the cathode. A focusing cup in the cathode is used to direct the stream of electrons to the target.

6.2.1.1.3 Impinge Electrons Onto the Target. The voltage applied between the cathode and anode is called the X-ray tube voltage, and the surface of the anode which is struck by electrons is called the target. When the rapidly moving electrons collide with the target stopping their rapid motion, a small portion of their energy is transformed into X-rays. The remainder of the energy is turned into heat, raising the temperature of the target (anode). Because the target is heated to extremely high temperatures, it is made of a high melting point material like tungsten.

6.2.1.1.3.1 The number of electrons emitted from the cathode and the dose of X-rays generated off the target of the anode can be adjusted by changing the filament current of the X-ray tube. When the X-ray tube voltage is changed, the speed at which electrons strike the target is changed, causing a change in the energy level of the X-rays and their wavelength. X-rays which have relatively short wavelengths are called hard X-rays, and those with relatively long wavelengths are called soft X-rays.

6.2.2 Type of Radiation Produced by a Tube Head.

6.2.2.1 The Continuous Radiation. When the electrons bombard the target, they are brought to an abrupt halt. Unfortunately most of the electrons' kinetic energy is converted into heat, which must be dissipated by the target material. Only a small percentage of the energy available in the electron beam is converted into X-ray photons, which can have energies ranging from zero to a maximum determined by the original kinetic energy of the electrons and by how rapidly the electrons are decelerated. This process produces the continuous portion of the X-ray spectrum and is known either by the German term "Bremsstrahlung," meaning braking radiation, or by the term "white radiation" (paragraph 6.2.7.1). X-rays are produced regardless of the material bombarded, whether it is a solid, liquid, or gas. In the X-ray tube, a solid material is used for the target. For efficient X-ray production, the target material must have a high atomic number.

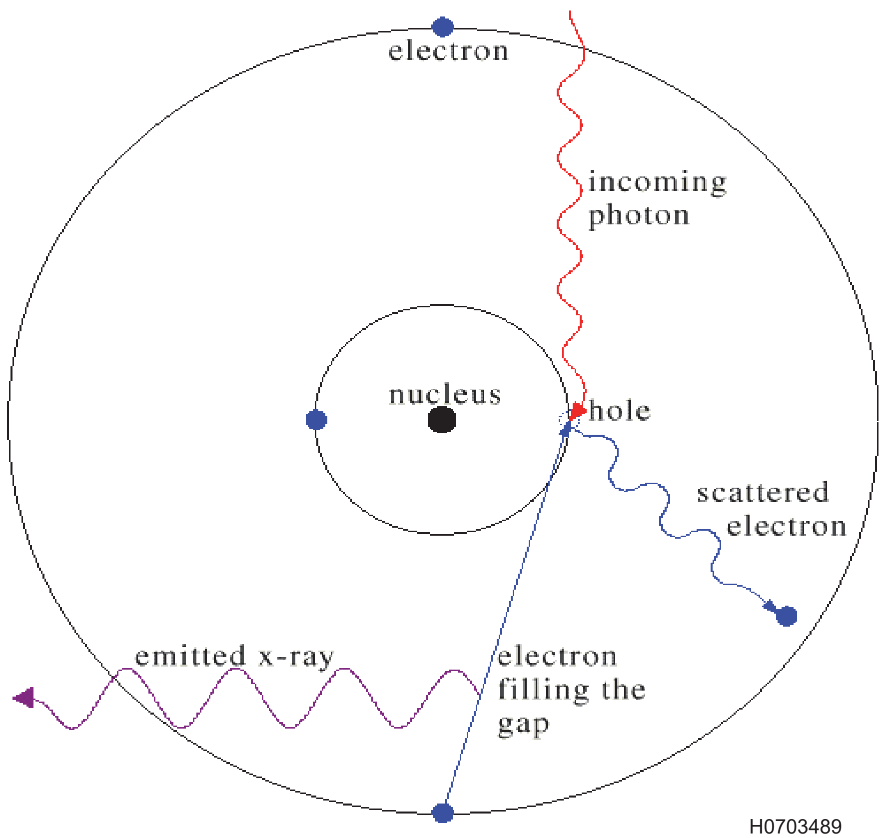


Figure 6-7. X-ray Production

6.2.2.2 Characteristic Radiation. In addition to "white radiation" (paragraph 6.2.7.1), there are several other characteristic spikes in a typical X-ray spectrum. These intensity spikes are caused by interaction between the impinging stream of high-speed electrons and the electrons bound tightly to the atomic nuclei of the target material. If an atom is considered as a planetary system with the nucleus of protons and neutrons at the center and the electrons moving in orbits around the nucleus, modern physics predicts the orbital electrons near the nucleus will have very well defined energies, and electrons in different orbits having different energy levels. If an electron from an external beam collides with an orbital electron with sufficient energy, and knocks it from its orbit, an electron from a higher energy level would, after a time, drop down to fill the void and restore atomic stability. When that electron drops to the lower energy level, it gives off a photon with energy equal to the difference in energy levels. Since these energy levels depend strictly upon a particular atom, the radiation emitted is called "characteristic radiation." The "characteristic radiation" emitted by the target material is superimposed upon the "continuous spectrum." A typical X-ray spectrum of radiation generated by an X-ray tube would appear as (Figure 6-8). The K- and L-series of characteristic radiation designate the radiation emitted from different electron orbits around the nucleus of the atom. As energy levels increase, electrons are dislodged from the various orbits with the K-series being the closest to the nucleus.

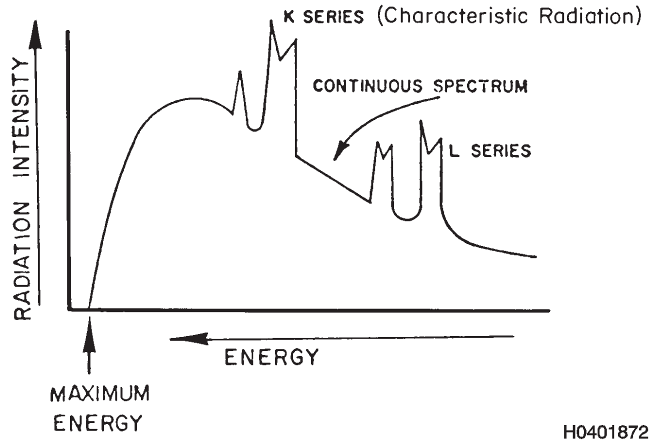


Figure 6-8. Typical X-ray Spectrum

6.2.3 Effects of Voltage and Amperage on X-ray Production.

6.2.3.1 Effect of Voltage. In different equipment, different methods are used to accelerate the electrons. In the smaller X-ray generators, up to and including two-million volt units, acceleration is accomplished with transformers to step-up the incoming power line voltage and applies it between the anode and the cathode of the X-ray tube. Since X-ray generators operate at very high voltages, the unit kilovolt (kV) is used to designate one thousand volts. As the kilovoltage (the potential causing the electrons to accelerate) is changed, the kinetic energy of the moving electrons is changed, altering the energy of the resulting X-radiation. Also, as the kilovoltage is increased, the efficiency of converting the electrical energy into X-rays is increased. Therefore, when kilovoltage is changed, the penetrating capability (the quality) of the generated radiation is changed, and the "quantity" of radiation is altered due to the efficiency of electrical energy converted into X-rays. Selecting the proper kilovoltage is very important in industrial radiographic applications.

6.2.3.2 Effect of Amperage. Amperage is a measure of the amount of electrical current applied to the filament. It is also a direct measurement of the number of free electrons available in the X-ray tube and is independent of variations in kilovoltage. Thus the "quantity" of X-radiation is in direct relation to the filament current. Typically, the amount of current is small, so the unit milliampere (mA) is used to designate one one-thousandth of an ampere. The effect of mA changes on the radiation output is shown (Figure 6-9).

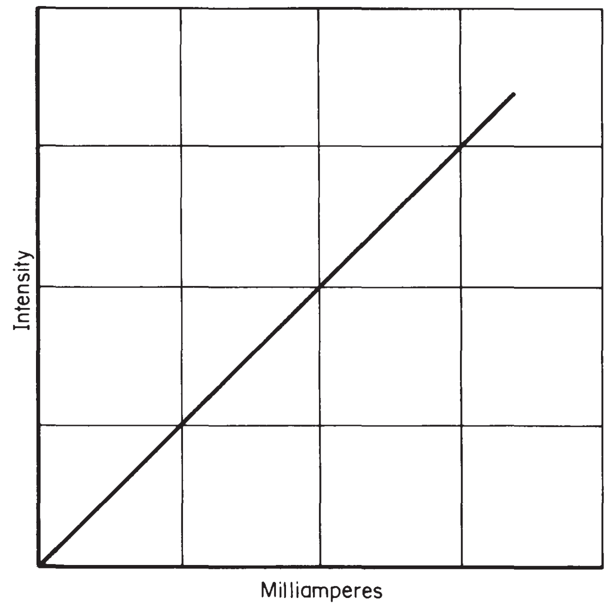


Figure 6-9. Effect of Filament Current on Radiation Quantity (Intensity)

6.2.4 X-ray Generators.

6.2.4.1 What are X-ray Generators. X-ray generators are man-made electronic devices designed to produce X-radiation. X-ray generators are obtained commercially and the equipment is either portable or stationary. Portable X-ray generators are used for inspection of test objects either impossible or very difficult to transport or safely inspect. Stationary X-ray generators are used in shielded facilities where the objects to be tested can be readily transported to the X-ray equipment (paragraph 6.3).

6.2.4.2 Components and Properties of an X-ray Tube. The X-ray tube houses the cathode "negative terminal" and the anode "positive terminal" under a high vacuum. Traditionally, this tube has been a glass envelope with a reduced thickness at the window (the point where the X-rays exit) to reduce X-ray absorption. The high vacuum reduces the problem of the electrons colliding with, and being absorbed by, molecules of air and provides electrical insulation between the cathode and anode. In some designs, a "beryllium window" is incorporated to further reduce absorption of the X-ray beam, particularly the lower energies. In many applications metal-ceramic envelopes are replacing glass envelopes. These tubes usually involve a metal cylinder with a ceramic disk at each end to hold and insulate the cathode and anode assemblies. The metal-ceramic tube is more durable than the glass tube and is less susceptible to thermal and mechanical shock.

6.2.4.2.1 Glass Envelope. It is important this movement of electrons is conducted in a good vacuum; otherwise the electrons collide with air molecules and lose energy through ionization and scattering. A glass envelope with a strong vacuum is needed to ensure this happens.

6.2.4.2.2 Cathode. A structure known as the cathode serves as the electron source (Figure 6-10). Actually, it is a "filament" or "coil" of thoriated tungsten wire that emits electrons when heated to a high temperature. Since the filament gives off electrons in all directions, some means must be used to focus them on a target. The filament is centered within a "reflector" or "focusing cup" within the cathode structure and serves to focus the electron beam like a light is focused by a flashlight reflector.

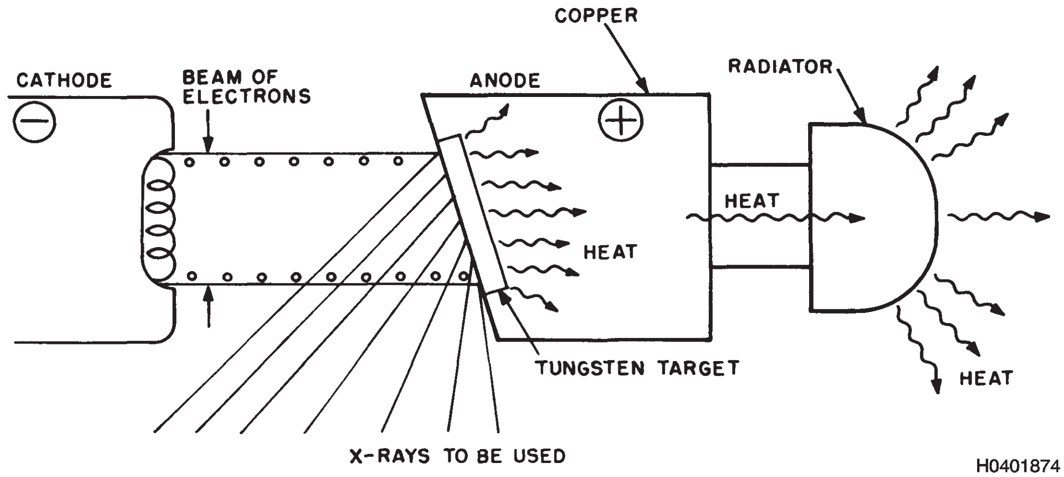


Figure 6-10. Fundamentals of X-ray Tube

6.2.4.2.3 Focusing Cup. A negatively charged focusing cup is used to direct the stream of electrons toward the anode (target).

6.2.4.2.4 Anode. There must be a target for the electron beam to strike before X-rays are actually produced. In radiographic tubes the target material is generally made of tungsten. The choice of tungsten as a target for industrial radiography is based on four material characteristics:

- High Atomic Number (74). The higher the atomic number of a material the more efficient is the conversion from electrical energy into X-ray energy.
- High Melting Point (6170°F). Most of the energy in the electrons bombarding the target is dissipated in the form of heat. The extremely high melting point of tungsten (W) permits operation of the target at very high temperatures.
- High Thermal Conductivity. This permits rapid removal of heat from the target, allowing maximum energy input for a given area size.
- Low Vapor Pressure. This reduces the amount of target material vaporized during operation.

6.2.4.2.4.1 The tungsten (W) target material is usually imbedded into a massive copper rod. Copper is an excellent thermal conductor and is used to remove the heat from the target, which then, depending on tube design and operation, is dissipated by air, oil, or water-cooling. This target acts as the anode, and to produce X-rays, it SHALL be at a positive potential (voltage) with respect to the cathode in order to attract the electrons available at the cathode.

6.2.4.2.5 Focal Spot. The focal spot is the area of the target bombarded by the electrons from the cathode. The focal spot is determined by the shape and size of the focusing cup of the cathode along with the length and diameter of the filament. The size of the focal spot has a very important effect upon the quality of the X-ray image. The smaller the focal spot, the better the detail of the image. The electron stream from the filament is focused as a narrow rectangle on the anode target. The typical target face is made at an angle of about 20-degrees to the cathode. When the rectangular focal spot is viewed from below, in the position of the film, it appears to be more like a small square. Thus, effective area of the focal spot is only a fraction of its actual area (Figure 6-11). By using the X-rays that emerge at this angle, a small focal spot is created, improving radiographic definition. Because the electron stream is spread over a greater area of the target, heat dissipation by the anode is improved.

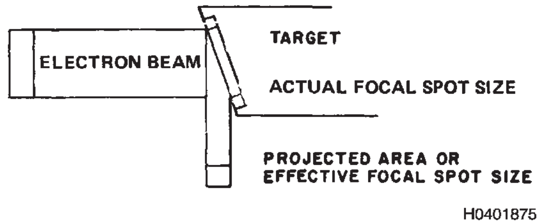


Figure 6-11. Effective Focal Spot Size

6.2.4.3 Inherent Filtration. Inherent filtration is the filtration or reduction in radiation energy due to absorption by the material necessary to provide the vacuum, the electrical insulation, and mechanical rigidity of the X-ray tube. In construction of some glass X-ray tubes, the port is reduced in thickness to provide less inherent filtration. In some other tubes, the port is made of beryllium, which is a light metal of low atomic number and low X-ray absorption. Because of tremendous pressures exerted by the atmosphere on large evacuated containers, X-ray ports must be designed with sufficient thickness to withstand these pressures without implosion. In center-grounded X-ray equipment, it is also necessary to provide gas (e.g., sulfur hexafluoride SF_6) and solid insulation for electrical isolation of the X-ray tube. Excessive inherent filtration reduces the X-ray output as well as the radiographic contrast on equipment of a given rating. In normal practice, it is acceptable to tolerate inherent filtration equivalent to 1-mm of aluminum up to 100 kVp (kilovolts peak); 3-mm of aluminum up to 175 kVp; 5-mm of aluminum equivalent up to 250 kVp; and higher filtration in 1,000 to 2,000 kVp units. Inherent filtration above these tolerances reduces contrast, and hence, the sensitivity of radiographic inspection, especially on thin sections and light alloys. For this reason, during radiographic inspections using kilovoltage of 150 kVp or less, the tube head SHALL be configured so generated radiation will travel from the target through a beryllium window without passing through any media other than air or insulating gas.

6.2.4.4 Cooling Requirements. The product of mA and kV equals watts of electrical power in the electron beam striking the X-ray target. One watt of electrical power is equal to one volt-ampere. Therefore, in an X-ray tube operating at 10 mA (or 0.01 amperes) and 140 kV (140,000 volts), 1400 watts of electrical power are in the electron beam. Only a very small amount of the energy in the electron beam, about 0.05-percent at 30 kV to approximately 10-percent in the MeV energy range is converted into X-radiation. Most of the other electron beam energy is converted into heat. This heat in the X-ray tube target material is one of the limiting factors in the capabilities of the X-ray tube. Thus, it is necessary to remove this heat from the target as rapidly as possible. Various techniques are used for removal of this heat. In some instances, the target is comparatively thin, and requires a suitable oil to be circulated on the back surface to remove the heat. In other cases, (where the anode is being operated at ground potential) use a water-antifreeze mixture to conduct heat away from the target. Most X-ray targets are mounted in copper, which is used as a heat sink. Some units have no external method of heat removal, but depend upon heat dissipation into the atmosphere by the fins of a thermal radiator. Some totally enclosed tubes depend upon the heat storage capacity of the anode structure to absorb the heat generated during X-ray exposure. This heat is then dissipated after the unit is turned off. These units usually have a duty cycle limiting the operation. This duty cycle is dependent upon the heat storage capacity of the anode structure and the rate of heat dissipation by thermal radiation. The rate of heat removal from the X-ray target is the primary limiting factor in X-ray tube operation.

6.2.5 Intensity and Distribution of an X-ray Beam.

6.2.5.1 Heel Effect. For simplicity's sake, most literature states the intensity of radiation of the primary beam is constant, this is not quite correct. There is a variation in intensity due to the angle at which X-rays are emitted from the focal spot. This variation in intensity is called the heel effect (Figure 6-12).

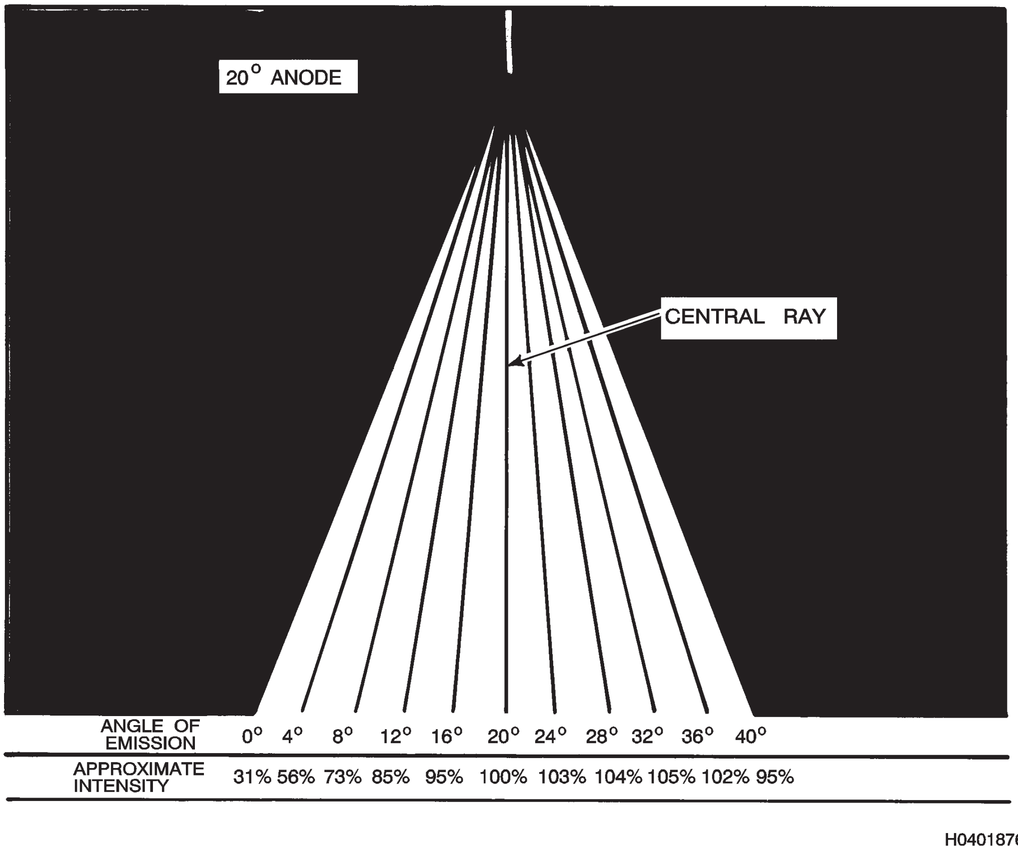


Figure 6-12. Variation of Intensity in the Primary Beam Due to the Heel Effect

6.2.5.1.1 The intensity of the beam diminishes rapidly from the central ray toward the anode side and increases slightly toward the cathode side. In general practice, the heel effect is not evident, provided the maximum lateral dimension of the object to be radiographed is less than half the source-to-film distance (SFD). In other words, coverage of a 14-inch by 17-inch film requires an SFD of approximately 36-inches to provide a field intensity of plus or minus 12-percent over the entire film. This is based upon using part of the radiation field within a cone having a 30-degree included angle. Remember, the source for an X-ray tube is the focal spot. For a single exposure of larger areas requiring multiple films, the SFD must be increased. A detailed example for figuring the heel effect is in (paragraph 6.7.9).

6.2.5.2 Beam Coverage. The greater the field size available from an X-ray unit, the greater its radiographic inspection capacity. Except at extremely high voltages, the X-ray beam has an angle of coverage that is a function of the X-ray target angle, the geometry of the focal spot, and the X-ray port size. As indicated in the discussion on "heel effect" in the previous paragraph, the physical size of the field of uniform intensity increases directly in proportion with the distance from the target to the film. However, the beam intensity decreases proportionally with the square of the distance. As a result, the exposure (product of amperage and time) must be increased to produce equivalent density on the radiograph. If a technique has been established but the situation requires a different SFD (Table 6-2), use these multiplication factors for calculating new exposure times to be used with the original kV and mA values.

NOTE

To change the SFD from any given distance to any desired distance, locate the given distance on top of the chart. Next, read down the left side of the table to the desired distance. Multiply the original exposure by the number common to both the distance in the given column and the distance in the desired row to get the new exposure. This chart MAY be used for distance changes providing the kV and mA levels are not changed.

Table 6-2. Exposure-Time Correction Factors for Different Source to Film Distances

Desired Distance (Feet)												Given Distance (Feet)								
↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	0.25	0.11	0.06	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
2	4	1	0.44	0.25	0.16	0.11	0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.0
3	9	2.3	1	0.56	0.36	0.25	0.18	0.14	0.11	0.09	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.02	0.02
4	16	4	1.8	1	0.64	0.44	0.33	0.25	0.20	0.16	0.13	0.11	0.09	0.08	0.07	0.06	0.06	0.05	0.04	0.04
5	25	6.3	2.8	1.6	1	0.69	0.57	0.4	0.31	0.25	0.21	0.17	0.15	0.13	0.11	0.10	0.09	0.08	0.07	0.06
6	36	9	4	2.3	1.4	1	0.73	0.56	0.44	0.36	0.30	0.25	0.21	0.18	0.16	0.14	0.12	0.11	0.10	0.09
7	49	12.3	5.4	3.1	2	1.4	1	0.77	0.60	0.49	0.40	0.34	0.29	0.25	0.22	0.19	0.17	0.15	0.14	0.12
8	64	16	7.1	4	2.6	1.8	1.3	1	0.80	0.64	0.53	0.44	0.38	0.33	0.28	0.25	0.22	0.20	0.18	0.16
9	81	20.3	9	5.1	3.2	2.2	1.7	1.3	1	0.81	0.67	0.56	0.48	0.41	0.36	0.32	0.28	0.25	0.22	0.20
10	100	25	11.1	6.3	4	2.8	2	1.6	1.2	1	0.83	0.69	0.59	0.57	0.44	0.39	0.35	0.31	0.28	0.25
11	121	30.2	13.4	7.6	4.8	3.4	2.5	1.9	1.5	1.2	1	0.84	0.72	0.62	0.54	0.47	0.42	0.37	0.34	0.30
12	144	36	16	9	5.8	4	2.9	2.3	1.8	1.4	1.2	1	0.85	0.73	0.64	0.56	0.50	0.44	0.40	0.36
13	169	42.2	18.8	10.6	6.8	4.7	3.4	2.6	2.1	1.7	1.4	1.2	1	0.86	0.75	0.66	0.58	0.52	0.47	0.42
14	196	49	21.7	12.3	7.8	5.4	4	3.1	2.5	2	1.6	1.4	1.2	1	0.87	0.77	0.68	0.61	0.54	0.50
15	225	56.2	25	14	9	6.3	4.6	3.5	2.8	2.2	1.9	1.6	1.3	1.1	1	0.88	0.78	0.69	0.62	0.56
16	256	64	28.4	16	10.2	7.1	5.2	4	3.2	2.6	2.1	1.8	1.5	1.3	1.1	1	0.89	0.79	0.71	0.64
17	289	72.2	32.1	18.1	11.6	8	5.9	4.5	3.6	2.9	2.4	2	1.7	1.5	1.3	1.1	1	0.89	0.80	0.72
18	324	81	36	20.2	13	9	6.6	5.1	4	3.2	2.7	2.3	1.9	1.6	1.4	1.3	1.1	1	0.89	0.81
19	361	90.2	40.1	22.6	14.4	10	7.4	5.6	4.5	3.6	3	2.1	1.8	1.6	1.4	1.2	1.1	1.1	1	0.90
20	400	100	44.4	25	16	11.1	8.2	6.3	4.9	4	3.3	2.8	2.4	2	1.8	1.6	1.4	1.2	1.1	1

6.2.6 Interaction of Radiation With Matter.

6.2.6.1 Absorption Mechanisms. Absorption of gamma or X-radiation by materials requires detailed consideration. These radiation photons are electromagnetic waves of energy, have no mass or electrical charge, and can penetrate the densest of materials. These waves are dimensionally so short they have wavelengths less than the electron spacing in the atoms and therefore have the capability of traveling through the atomic structure. The absorption of the photons is a result of the photon either striking an electron or entering the nuclear field of the atom. The energy lost by a radiation beam as it travels through matter is due to interactions of the photons with matter. In these interactions, the energy of the photon is transferred principally through three processes. These are “photoelectric absorption,” “Compton effect,” and “pair production” (Figure 6-13). At extremely high photon energies a small amount of absorption is due to the photodisintegration process, but this is of little consequence in radiographic applications. Most of the radiation absorption is due to interaction of the photons with electrons in the atoms of the absorbing material. Therefore, an absorber may be judged somewhat in relationship to the electron density of the absorber, or approximately the number of electrons in the radiation beam path. The parameters that contribute to this electron density are the atomic number, the density, and the thickness of the absorber. The atomic number is the number of protons in the nucleus of the particular atom, and material density (usually expressed as grams per cubic centimeter) is related to the number of atoms compacted in a given material volume. The thickness of the absorber can be mechanically measured. Atomic number, material density, and absorber thickness combine to present an absorber value to the radiation. The radiation photons interact with the atoms in the absorber in different manners, depending upon the energy or wavelength of the photon.

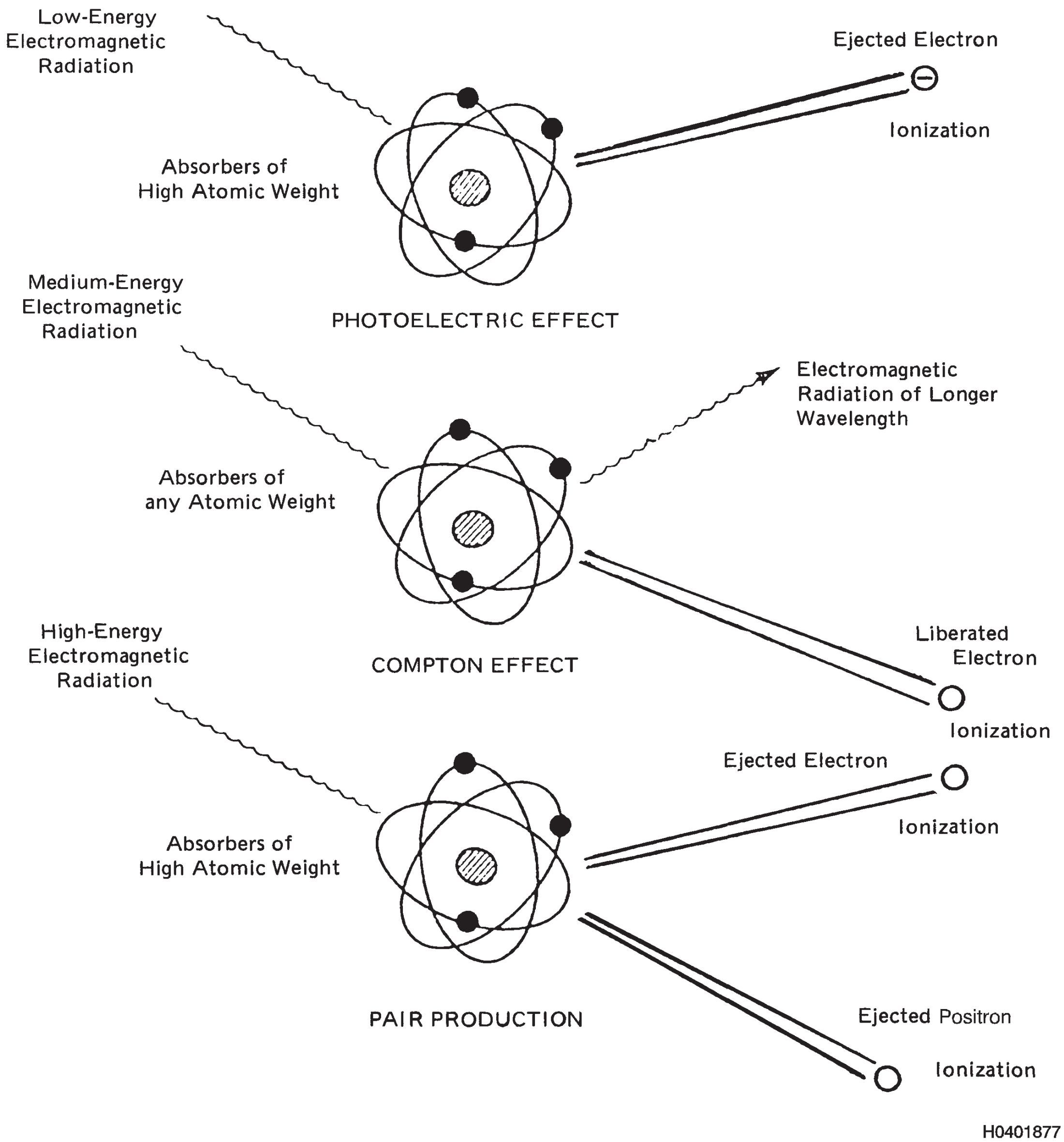


Figure 6-13. Illustration of Various Radiation Absorption Interactions

6.2.6.1.1 Photoelectric Absorption. When the photons have energies of 100 keV or less, they are readily absorbed by the electrons in the orbital shells of the atoms of the absorber. The energy of the photon is transferred to the electron; often dislodging it from its orbit and the remainder of the photons energy is used to give the electron kinetic energy or velocity. These ejected electrons are called "photoelectrons" and the process is known as "photoelectric absorption." The moving electrons lose their energy through Coulombic interactions and can produce ion pairs.

NOTE

During this process, the radiation photon has given up all of its energy and no longer exists. This mechanism of absorption has a very high probability for very low energy radiation and accounts for the major absorption of radiation when photon energies are 100 keV and less.

6.2.6.1.2 Compton Effect (Scattering). When the photon energies are in the 100 keV to 10 MeV range, all of the energy is not required to dislodge an orbital electron and accelerate it by induction of kinetic energy. In this case, photoabsorption can occur, but the photon continues at some different path and at a reduced energy level, due to the loss of energy to the electron. By this mechanism of absorption, the path of the photon is altered and its energy decreased. This mechanism of absorption is referred to as Compton Effect or Compton Scattering. Compton Effect accounts for the major absorption of radiation in the energy range between 100 keV and 10 MeV.

6.2.6.1.3 Pair Production. When photon energies exceed 1.02 MeV, their energy can cause pair production. In this event, the nuclear field surrounding the nucleus of the atom disintegrates the high-energy photon. The energy of the photon converts into an electron-positron pair. The positron has the same mass as an electron and is of equal, but opposite charge. It may be noted in this absorption mode, the energy of the massless photon is converted to mass. Einstein's equation states energy equals mass times the square of the velocity of light ($E = mc^2$). If this equation is used, it can be found the mass of an electron is equivalent in energy to a 0.51 MeV photon. This explains the requirements for a photon to have energy of at least 1.02 MeV before pair production can occur. Additional energy above the 1.02 MeV causes the pair of particles to have kinetic energy or velocity. The positron may cause ionization or it may combine with an electron, causing annihilation and emission of two gamma photons of 0.51 MeV per photon. These lower energy photons may subsequently interact by either the photoelectric or Compton Effect absorption modes.

6.2.6.2 Significance of Absorption Mechanisms. With three different absorption mechanisms, it is evident an absorber, when bombarded by photons of electromagnetic radiation, has absorption characteristics highly affected by photon energy. A graph illustrating the three major modes of absorption (Figure 6-14) is how they contribute to the total absorption in the element iron with its atomic number of 26. It should be noted from (Figure 6-14) nearly all of the absorption of radiation below 100 keV is due to the photoelectric effect. This absorption is highly dependent upon the atomic structure and the binding energies between the electrons and the nucleus. Therefore, the atomic number of the material will greatly affect radiation absorption by the photoelectric effect. When radiation energy is between 100 keV and about 10 MeV, absorption is almost entirely due to Compton Effect and atomic number is no longer the major criteria of absorption; instead, material density is the major controlling factor. In the energy range between 10 and 100 keV, radiation absorption is very sensitive to keV changes; a unit change in keV will cause three units of change in the atomic absorption coefficient. For energies between 200 keV and about 3 MeV a unit change in keV will only cause half a unit change in the atomic absorption coefficient, so the absorber is much less sensitive to changes in radiation energy. When the radiation energy is between 3 and 30 MeV, the atomic absorption coefficient is for practical purposes unchanged.

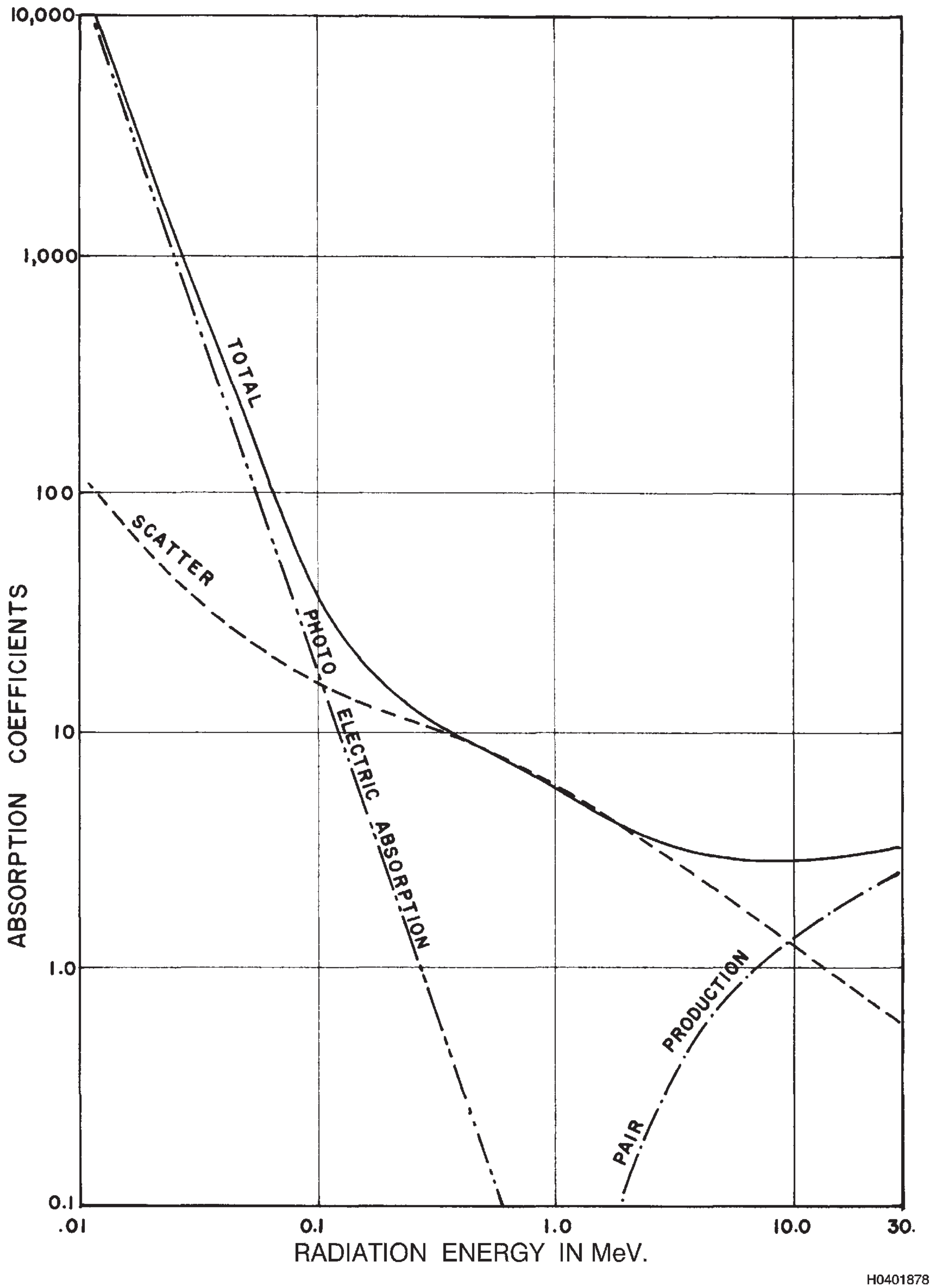


Figure 6-14. Absorption Coefficients for Different Modes of Absorption in Iron

6.2.6.3 Real Life Absorbers. In industrial applications, test specimens are being bombarded by the radiation photons, which are absorbed and scattered. In this process, electrons are ejected from the atoms of the test material. These absorbers are not ideal; they do not act as an ideal absorber in that they do not attenuate radiation in accordance with theoretical physics. Electrons, degenerated scattered photons, characteristic radiation from the test material, and some of the primary beam are all present on the film side of the test object simultaneously. The classical attenuation equation does not consider all these various components, so it is not strictly applicable in actual radiographic practices.

6.2.6.4 Diffraction Patterns. In the radiography of very coarse grain structure materials, such as inconel and cast irons, diffraction patterns are often revealed in the radiographic image. These patterns are due to the selective diffraction and absorption by the atoms of a definite pattern in the crystal structure. The definitive pattern of the atoms of a crystal can be aligned with the X-ray beam at a particular angle, so the radiation is altered in its direction of travel and concentrated upon the film as a linear indication. These crystalline diffraction patterns are superimposed upon the radiographic image and make interpretation very difficult. Often these dense, sharp lines caused by the crystal diffraction are interpreted as internal cracks. If uncertainty exists as to interpretation of a particular indication, a second radiograph can be made at a slightly different angle (less than 10 degrees difference). It is unlikely the crystal causing the diffraction pattern would be located in precisely the same relative position as to cause the diffracted line to strike the film in the same relative position. Changes in radiation energy will also affect diffraction patterns. Often by changing the operating kilovoltage, the problem of diffraction patterns can be reduced.

6.2.7 Radiation Energy.

6.2.7.1 White Radiation. Radiation generated by an X-ray tube contains various energies and therefore is referred to as white radiation (Figure 6-15). The X-rays are a continuous spectrum and the beam is selectively attenuated as it passes through an absorber. The low energy radiation is highly absorbed by the first few layers of the absorber medium and the spectral distribution is altered by this selective absorption. Thus, as an absorber is absorbing the white radiation, the attenuation rate more nearly approaches monochromatic radiation. Figure 6-15 shows a semi-logarithmic graph of the absorption of a monochromatic beam and a multienergy beam of white radiation. For approximate estimations of effective X-ray attenuation coefficients, it may be assumed the average energy of an X-ray beam is about 50-percent of the peak operating kilovoltage for glass window tubes and 30-percent for beryllium window X-ray tubes.

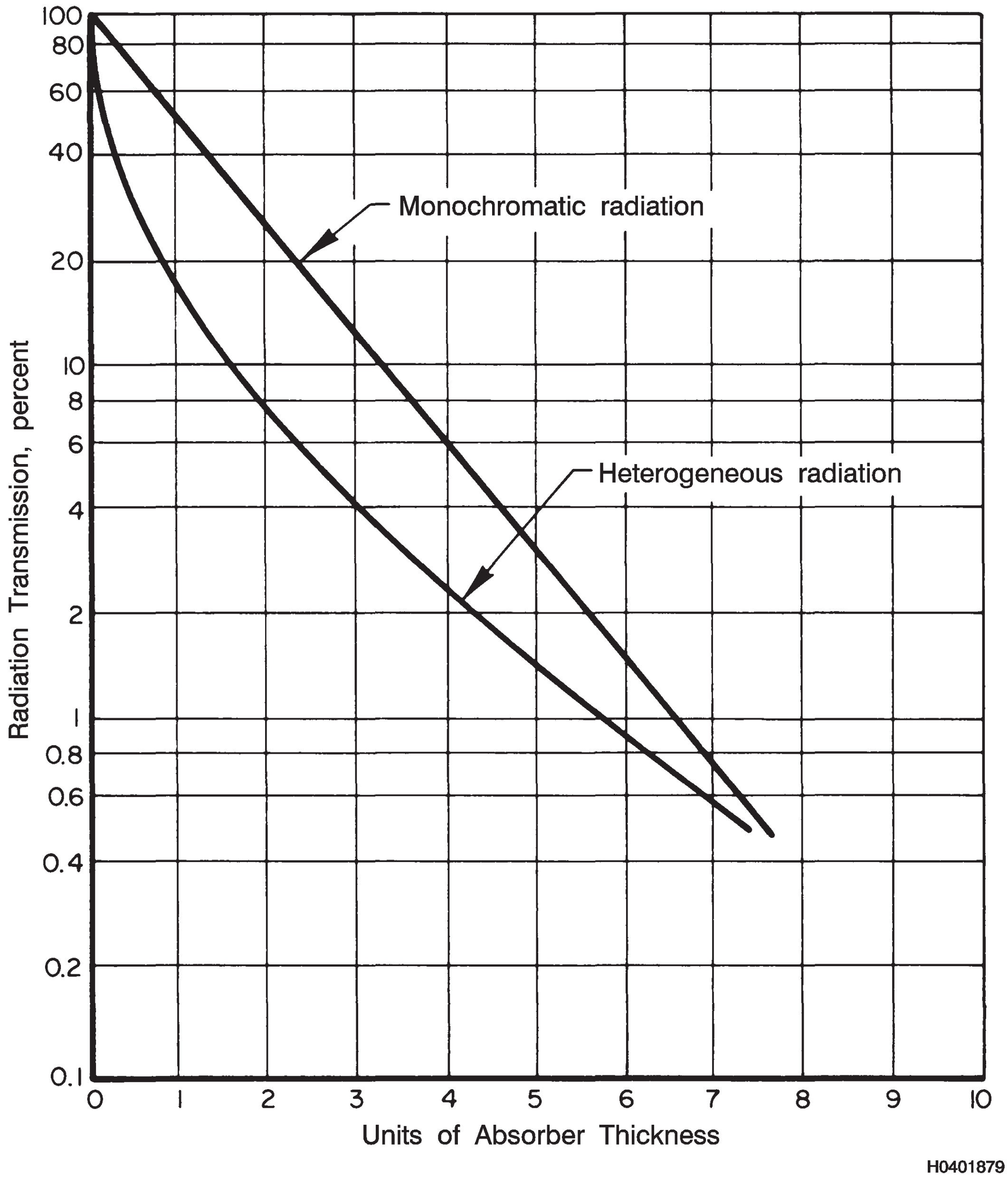


Figure 6-15. Absorption Curves of Monochromatic and Multi-Energy Radiation

6.2.8 Scatter Radiation.

6.2.8.1 Description of Scatter Radiation. When high-energy electromagnetic radiation bombards matter, some of the radiation photons are scattered by electrons. This process is called the Compton Effect. If the photon has a greater quantity of energy than necessary to eject an electron from its orbital path, it continues to travel with a loss of energy at some angle to its original path. The photon energy must be reduced to a very low value before complete annihilation is possible by photoelectric absorption. In low atomic number materials the photon direction is changed with little loss of energy and its energy must be reduced to a very low energy to be absorbed completely. Thus, a single photon might scatter many times, losing all semblance of its original path. If this scattered photon strikes the film, it reduces the image definition since it exposes the film at a spot other than directly under the point where it first entered the test material. High atomic number materials rob the photon of greater amounts of its original energy and also have much higher photoelectric absorption values. These more quickly reduce the photon energy to the point where the photon is completely absorbed. For these reasons, low atomic number materials transmit larger quantities of scattered radiation than high atomic number materials. More information on scatter radiation can be found in (paragraph 6.4.2.11).

NOTE

Low atomic number materials SHOULD be removed from the beam to the extent possible, to prevent scattering of the primary beam. Wood, concrete, or other low atomic number materials in the radiation beam SHOULD be covered with lead or a high atomic number material to reduce the scatter. In actual practice this means tables, floors, or walls behind/beside and close to the test part SHOULD be covered with lead.

6.2.8.2 Scatter Radiation Build Up. Scattering is due to photon collision with electrons in their path. As material thicknesses increase up to a critical thickness, the amount of scattered radiation emanating from the material increases. If additional thicknesses of material are added, the scattered radiation generated in these added layers has insufficient energy to penetrate the material between them and the film. The amount of scattered radiation emanating from the back of a part under inspection increases with part thickness up to a total, which varies with radiation energy. Since absorption due to the Compton Effect decreases with increasing radiation energy, less scattering occurs at higher radiation energy levels. Build-up scatter radiation can introduce contrast problems in the radiography of low atomic number materials such as graphite, plastics, and magnesium.

6.2.9 Material Contrast.

6.2.9.1 Material Contrast Factor. In consideration of the previous discussion on radiation absorption, the most important variable that can be controlled by the radiographer in industrial X-ray inspection is the kilovoltage. The amount of radiation absorbed by the part being inspected depends on the atomic number, density, and thickness of the material. The radiographer cannot change these factors, but can change the energy of radiation. In the attenuation equation, $1n(-\mu x) = I^{T}/I^{o}$, it can be visualized the linear attenuation coefficient (μ) can be changed by changing radiation energy. This in turn will change the ratio I^{T}/I^{0}, or the percent radiation transmitted through a part of thickness, x. In industrial radiographic applications, the difference in thickness (often due to discontinuities) is the actual parameter from which interpretation is made. Therefore, the greater the change in the radiation transmitted due to a particular change in material thickness, the more obvious is the thickness change revealed in the final image. This radiation difference due to material thickness change is called the material contrast. The material contrast is a function of the absorption characteristics of the part being inspected and the radiation energy level. When measurements have been made and a numerical value has been established, it is called the material contrast factor.

6.2.9.2 Percent Radiation Transmission. When monochromatic radiation is used, the percentage of radiation transmission can be calculated from the formal laws of attenuation. Since this condition seldom exists in actual practice, the percent of radiation transmitted must be empirically measured. When the proper recorder is used, the actual measurements will include the scattered radiation as well as the transmitted primary beam, both of which can be expected to expose a film or interact with any other recorder in a typical industrial radiographic set-up.

6.2.10 Understanding Radiographic Film.

6.2.10.1 Function of Radiographic Film. Films can be used as a recording medium because their emulsions are sensitive to the quantity and the energy of electromagnetic radiation over a wide spectral range. In the photographic process, the electromagnetic radiation of the visible spectrum is focused with a lens on the film surface to record the variations of light intensities and form an image. In radiographic applications, the radiation is of such high energies they cannot be focused by a lens. In radiography, recording the variations in radiation quantities caused by absorption and scattering by the test specimen forms a shadowgraph of the test object. After final processing, film exposed with X- or gamma rays is called a radiograph; film exposed by using a radioisotope might be called a gammagraph. Films are an excellent recording medium with a very high signal-to-noise ratio and high amplification. This section describes how films work, reviews how films respond to radiation, and discusses radiographic paper.

6.2.10.2 Structure of Industrial Radiographic Film. Industrial X-ray film consists of an emulsion and a blue tinted base of polyester. The schematic structure of radiographic films is below (Figure 6-16).

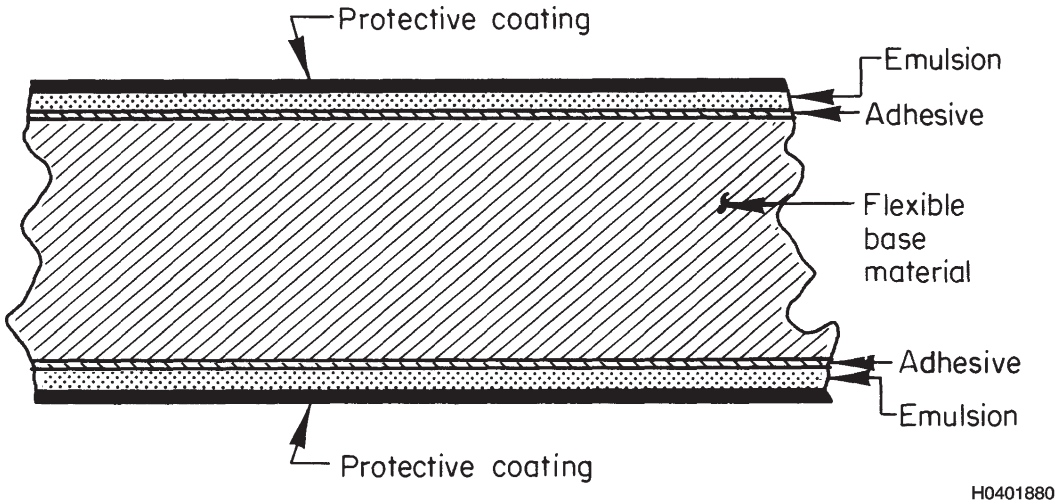


Figure 6-16. Sketch of Cross Section of X-ray Film

6.2.10.2.1 Adoption of a Polyester Base. It has been many years since flammable cellulose nitrate film base was replaced first with inflammable cellulose acetate then with polyester base materials. Polyester base materials have advantages because they provide flatness and great strength. Little expansion and contraction takes place and the material is not hygroscopic. These advances in a polyester film base are indispensable to rapid film transport in automatic processors.

6.2.10.2.1.1 Polyester Base. Most modern films have a polyester base which is either transparent or has a slightly blue tint. The polyester is very durable, does not absorb water or processing chemicals, is dimensionally stable, dries easily, and will not support combustion. The polyester base is approximately 175 µ thick.

6.2.10.2.2 Emulsion. The emulsion consists of silver halide crystals as photosensitive material, plus additives and gelatin. The silver halides form an image when exposed by X-rays, gamma rays, secondary electrons, or fluorescent light. The emulsion in films used for general photography is coated only on one side of the base, whereas it is coated on both sides of most industrial X-ray films. Since the thin support material offers very little absorption to the X-rays normally used for industrial applications, the double emulsions essentially reduce exposure requirements to one-half that required for a single emulsion, however, some films intended for radiography in which visibility of the smallest detail is required, have emulsion only on one side. The absorption of high energy X-rays or gamma rays is increased by using two emulsion layers so the photosensitive silver compound is utilized more effectively for the absorption of radiation and electrons. Furthermore, the two emulsion layers help to increase contrast and image density of the radiographs. Each layer of emulsion is approximately 10 to 15 µ thick.

6.2.10.2.3 Outer Protective Layer. The emulsion may be coated on one or both sides of the base in layers and protected on both sides with very thin outer protective layers. Each outer protective layer is approximately 1 µ thick.

6.2.10.3 Latent Image. The latent image is formed by interactions of the electromagnetic radiation with the silver bromide crystals. When solid silver bromide is formed in the manufacture of film, the silver atoms give up an orbital electron to a bromine atom. Since the silver atoms have given up an electron, they have a positive electrical charge and are silver ions (Ag^+). The bromine atoms have acquired this negative electron and have become bromide ions (Br^-). The silver bromide crystal is a cubical array of the silver and bromine ions. The cubical crystalline structure of the silver bromide crystal is not perfect; if it were, the photographic process could not exist. Within the crystal lattice structure are extra silver ions called interstitial ions; these do not occupy a lattice position in the crystal. There are also foreign molecules or dislocations (distortions) of the crystal array within the crystal, all of which form latent image sites.

6.2.10.3.1 The accepted theory of the formation of the latent image (an image which may be revealed by development) in a photosensitive emulsion is based upon the Gurney-Mott concept of exposure. It is theorized the formation is a two-step process. The electromagnetic radiation ejects an electron from the negatively charged bromine ion in the crystalline structure, thus converting the ion into a bromine atom. The free electron can travel within the crystal to a dislocation or other latent image site where it is trapped, establishing a negative electrical charge at that point. This negative electrical charge attracts one of the positively charged interstitial silver ions to the latent image site. When the silver ion reaches the image site, the negative electron counteracts its positive charge and it becomes neutralized and exists as a silver atom. The latent image site is now electrically neutral. This process MAY be repeated several times, adding silver atoms to the latent image site in the crystal. These few silver atoms act as a catalyst for reducing action of the developer, thus making the entire emulsion grain susceptible to conversion to metallic silver in development.

6.2.10.4 Films Reaction to Development. The developing agent selectively reduces those crystals containing latent images into black metallic silver, but has a much smaller effect on those crystals not exposed. The metallic silver is opaque and forms the radiographic image.

6.2.10.4.1 Theory of Film Developer. The purpose of the developing solution, or developer, is threefold. First, it blackens those parts of the emulsion exposed (e.g., when a crystal of the film's silver bromide emulsion has been exposed to X-ray radiation and is put into a developing solution, the developer takes the bromide away from the silver and leaves black metallic silver in the gelatin). Where full exposure has occurred, a maximum number of crystals are affected and almost all of them are reduced by the developing solution to metallic silver. Second, it produces various shades of gray where the film has been only partially exposed. These grays are the result of partial removal of bromide. The concentration of black metallic silver per unit area of the film is dependent upon the amount of exposure received, and determines the factor known as "film density". The image of the object radiographed consists of varying densities spread over the film, corresponding to the varying amounts of exposure received by the film. Third, is its effect on those parts of the film which have received no exposure. Since no crystals were affected, the developer SHOULD leave these parts unchanged. Thus, a developing solution SHOULD remove bromide from the film emulsion where exposure has occurred, but SHOULD NOT produce effect on unexposed areas of the film.

6.2.10.4.1.1 A very limited number of chemicals possess the ability to distinguish between exposed and unexposed crystals and therefore only a few are suitable for use in developers. No chemical known will leave an unexposed area indefinitely unchanged. All will begin to develop unexposed parts after a period of time, producing a condition called "chemical fog." All developing agents have a definite fogging time beyond which bromide will be freed in unexposed areas.

6.2.10.5 Image Quality. Microscopic variations in the response of film to the incident radiation produce effects of considerable practical significance. The number of sites where the silver atoms can respond to the radiation vary in location throughout the emulsion and are inversely proportional to the size of the silver bromide grains. Thus, after exposure to radiation, the density of the image will vary. The larger the number of sites activated by radiation, the larger the number of silver atoms per unit area, and, statistically, the smaller the density variations. The practical factors are:

6.2.10.5.1 Graininess. The graininess of the film is the visual impression of non-uniformity of density in a radiographic image. Graininess increases with increasing film speed and with increasing energy of the radiation. Apart from the visual appearance of graininess, the effect may be subjected to physical measurements. This measured property is referred to as "granularity." This term has been adopted as an expression for physical measurements of the statistical fluctuations of density over the area of a photographic emulsion. Obtain granularity measurements by scanning a sample of emulsion with a small spot of light (diameter of the order of 0.08 mm) and record the resulting irregular fluctuations of the transmitted light.

6.2.10.5.2 Signal-to-Noise Ratio. The accidental variation in image density makes it more difficult to identify the deliberate variation in image density resulting from use of the film. The relationship between the two density variations is known as the signal-to-noise ratio. The ratio for threshold visibility of detail SHALL be at least five.

6.2.10.6 Film Image Density. In photographic usage, density is a measure of the degree of blackening of the processed film caused by exposure to radiation. Film image density is the logarithm of the reciprocal of the fraction of light transmitted through the film with respect to the light incident on the film and is discussed further in (paragraph 6.7.5).

6.2.10.6.1 The relationship of light transmission and density are in (Table 6-3). A typical density used in practical radiography is 2.0 and represents 1-percent transmittance.

Table 6-3. Relationship of Light-Transmission to Film Density

Transmittance (I_T / I_0)	Percent Transmittance (I_T / I_0) x 100	Opacity (I_0 / I_T)	Film Density $Log_{10} (I_0 / I_T)$
1.00	100	1	0
0.50	50	2	0.3
0.25	25	4	0.6
0.10	10	10	1.0
0.01	1	100	2.0
0.001	0.1	1,000	3.0
0.0001	0.01	10,000	4.0

6.2.10.7 Characteristic Curve. The characteristic curve is the response of a type of film to radiation of a particular energy. It is obtained by plotting the correlation between the film-image density against the logarithm of relative exposure. Since density is a logarithm (paragraph 6.7.6), log-log scales are used for the plot. Log-log scales not only make interpretation of the graph easier, but also the important values of relative exposure can be derived easily by subtracting one logarithm value from another. At low exposures, a large change in exposure is needed to produce a significant change in density (Figure 6-17). As relative exposure increases, the film emulsion becomes more sensitive and the same exposure change produces a greater density difference. The gradient (slope) of the curve increases with increasing exposure Figure 6-17). At very high values, the gradient may start to decrease; that is, the film again becomes less sensitive, however, this effect is not often encountered in industrial radiography, though common with medical film. The term used to refer to the gradient of the characteristic curve is “film contrast.”

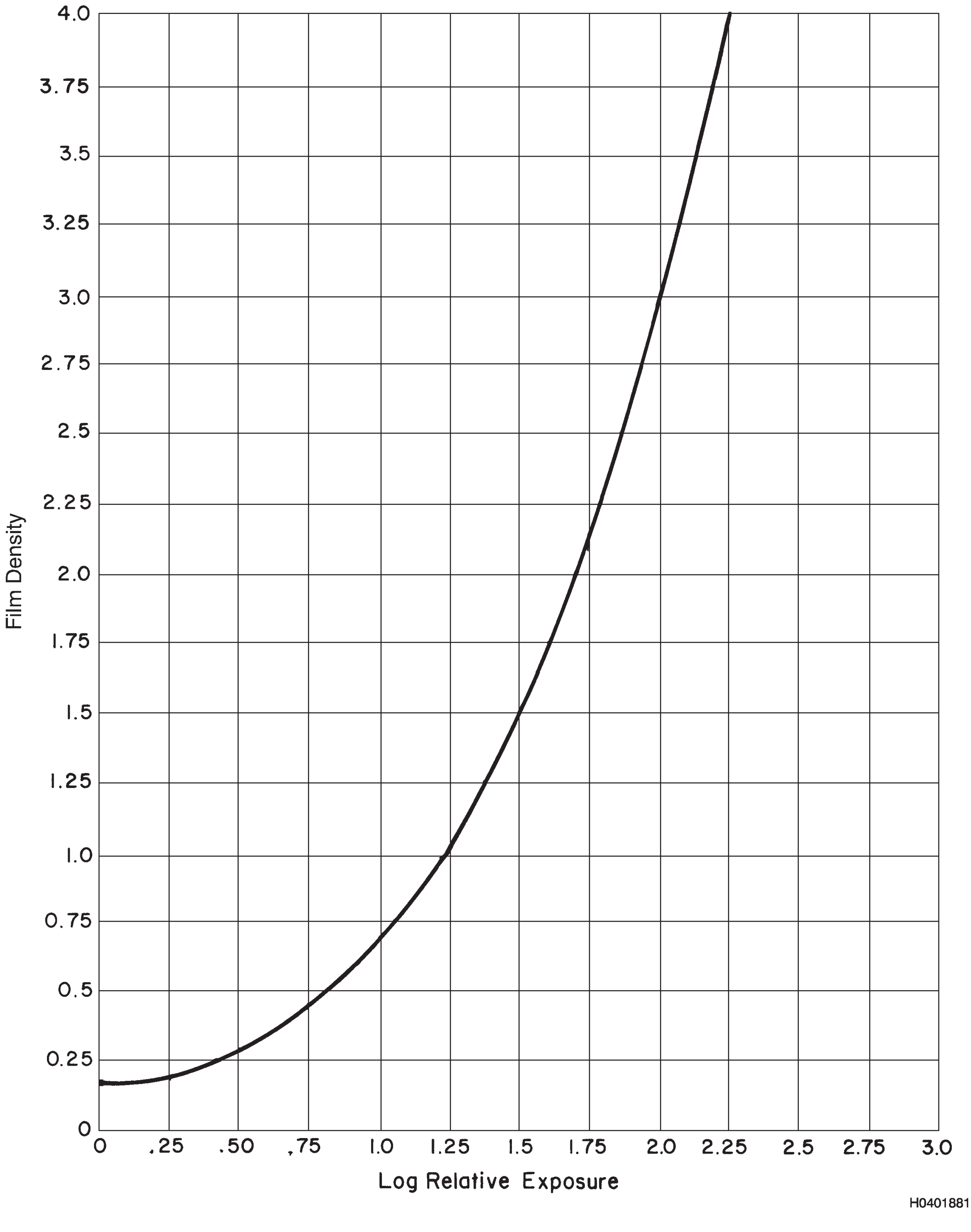


Figure 6-17. Typical Characteristic Curve

6.2.10.7.1 A characteristic curve provides information about speed, contrast (average gradient), and fog of X-ray film. The characteristic curve is significant because it demonstrates, within limits, that a dense film is more sensitive to small variations in exposure than a light film. Therefore, the dense film is better to show small changes in subject contrast due to discontinuities and geometric changes in the part. Characteristic curves can also be used to calculate exposure changes needed to optimize a technique when altering film type or desired density.

6.2.10.8 Film Speed. Film speed is a factor in determining the amount of radiation a film must receive to obtain a given density. Generally, film speed varies with film grain size. The larger grain film is faster and the smaller grain film is slower. While film speed is sometimes an important consideration for economy, normally the prime consideration is resolution of the details. High-speed films (e.g., films with low signal-to-noise ratios), SHOULD only be used when they are capable of meeting the resolution requirements of the inspection. Where high-detail resolution is required, the slower, higher signal-to noise ratio films SHOULD be used without exception.

6.2.10.9 Film Contrast. Film contrast is a measure of the difference in film density due to exposure to different amounts of radiation. When exposed beneath a step wedge, a film with low contrast would show only minor changes in image density between one step and another. A high-contrast film, exposed under identical conditions would show sharp graduated changes in image density between steps. The efficiency with which the emulsion responds to an increment in exposure varies with the absolute value of the exposure. If a radiograph has high contrast, small differences in light transmission are high and readily discerned by the eye. Thus, the image will reveal small discontinuities in the subject. As a result, a dense image on the film makes small discontinuities on the specimen more visible. Image densities of 2.0 or more are usually recommended or required for high sensitivity to discontinuities in critical areas of parts. This will be discussed further in a later section. Film contrast SHOULD be distinguished carefully from subject contrast (a flat sheet specimen will give negligible contrast with any film). Subject contrast is affected by X-ray kilovoltage or gamma-ray characteristics. In summary, the overall image contrast with any given specimen will depend upon:

- Kilovoltage of the X-ray beam or characteristics of gamma radiation.
- Type of screens used.
- Image density.
- Processing conditions.
- Film contrast.

6.2.10.10 Film Latitude. The film latitude is the reverse of film contrast, the higher the contrast, the smaller the latitude, the lower the contrast, the greater the latitude. Latitude is, therefore, the range of radiation intensities a film is capable of recording. Latitude is also the term used to indicate the range of material thicknesses that can be visualized in the final image. Often in the radiography of castings or circular rods, where it is necessary to visualize a large range of thicknesses, wide latitude is desirable.

6.2.11 Fundamentals of Digital Radiography.

6.2.11.1 Basic Image Types. Image types could be classified as continuous and discrete. Discrete (distinct from each other) values are digital images and the continuous (variables flow into the next) are considered to be similar to regular film images. These definitions are the basic definitions in any mathematics or scientific discipline. Continuous can be converted to discrete variables. Digitization of continuous variable is a common practice. Digital imaging techniques allow us to retrieve information electronically for easy and accurate manipulation or analysis by computer. Digital images vary from traditional images in the way the image information is represented.

6.2.11.2 Analog versus Digital Images. Traditional images, like the image that appears on an industrial radiographic film, are made up of continuous tones. We can get an electronic representation of the continuous tones with an analog waveform generated by some measuring device. Sampling discrete sections of the waveform and storing the sampled value as strings of ones and zeros (the only digits used in modem computing equipment) produce digital images.

6.2.11.2.1 There are two ways in which computers handle graphic information. The two methods are known as “Vector” and “Raster” graphics.

6.2.11.2.1.1 In vector graphics, any image created remains separate from others. Images are described mathematically and are not tracked in pixels. Vector graphics are the graphics created in drawing and illustration programs, like clipart in word processing packages. These graphics are stored as a collection of objects described mathematically using shape, line segments, and arcs. Vector graphics are also known as object-oriented graphics because of its use of an object model to describe the mathematical shapes that construct an image.

6.2.11.2.1.2 Raster graphics, also known as bit-mapped graphics, are created by scanners and digitizers. Raster images are comprised of a two dimensional array of discrete pixels (like a computer monitor screen). A bitmap is a file that indicates a color for each pixel along the horizontal and vertical axis. Raster and bitmap images are used interchangeably. They both refer to a color format where the image is composed of either black or white pixels. Working with raster images means working with pixels, not objects or shape. Each pixel in an image is stored in its own location within computer or storage memory as a number representing color and brightness (and sometimes transparency) or other levels. Because storing formulas for drawing shapes takes less memory in general than actually mapping out the individual pixels of the image, vector graphics tend to be much smaller in size than raster or bitmapped images.

6.2.11.3 Digital Image Quality. The quality of bit-mapped graphics is determined at capture or resampling time by two factors of resolution: "brightness resolution" and "spatial resolution."

6.2.11.3.1 Brightness Resolution. The brightness resolution is also referred to as the grayscale or color range of an individual pixel. Brightness resolution is defined in a digital image by the pixel it represents. The value can be made of one or more "bits." The more bits actually used to define the brightness levels in a digital image, the higher the brightness resolution (and hence the quality) of the image (paragraph 6.2.11.4). Brightness resolution is also known as pixel depth.

6.2.11.3.2 Spatial Resolution. Spatial resolution is the number of pixels horizontally and vertically in a digital image. Spatial resolution of a digital image determines the actual size of the pixel in real units, and thus is determined by the sampling interval of the original digitization operation. A longer interval produces lower spatial resolution images while a shorter interval produces higher spatial resolution. The term "resolution" when not preceded by spatial or brightness generally refers to spatial resolution.

6.2.11.4 Pixel Depth. Pixel depth, as already stated, is the measure of brightness resolution in a digital image. Here is the way in which it works for common pixel depths:

6.2.11.4.1 1-Bit Pixel - A 1-bit pixel depth image can be made up of, at the most, only two colors, generally black and white. Each pixel is represented in memory as either a one or a zero. Gray values are simulated by grouping black and white pixels over an area to make it appear brighter or darker. Fax machine printouts and even black and white newspaper photographs are examples of 1-bit images.

6.2.11.4.2 8-Bit Pixel - An 8-bit pixel image can display 256 colors or grayscale levels at the most. They are comprised of individual pixels made up of eight bit each, yielding 2 to the 8^{th} power brightness (or color) levels. Color images are represented by using the brightness information of the pixel as a value to use in a table of color values. Web based images with a "GIF" extension, and many grayscale computer displays are examples of 8-bit graphics.

6.2.11.4.3 12-Bit Pixels - 12-Bit images are almost always grayscale images. The value of the pixel is made up of 12 bits which equates to 4096 individual gray scale values.

6.2.11.4.4 24-Bit and higher - 24-Bit and higher color images (also known as "true-color" images) group three or more 8-bit bytes of brightness information together. Each byte represents a color channel (or an alpha transparency channel) of brightness. The effect is one of millions of colors, but with the same overall brightness resolution of an 8- bit, grayscale image. There is no difference in a 24-bit grayscale image and an 8-bit grayscale image as far as quality is concerned.

6.2.11.5 Capture. Digital radiographic images are "captured" in many different ways in industrial radiography. Some methods involve the use of standard radiographic film, "film based capture" or film designed with digitization in mind. Other methods bypass using film altogether and use direct or indirect capture methods, "filmless capture." All rely on taking an analog signal and converting it to a sampled digital form using solid state "charged coupled device (CCD)" sensors, photovoltaic cells, or photo-multiplier tubes for the analog signal.

6.2.11.5.1 Film Based Capture. Three methods generally used for the digitization of radiographic film. "Laser scanners" (considered the most accurate for brightness of resolution), "CCD scanners" (which although they do not perform as well for brightness of resolution, are available for higher spatial resolution than laser scanners), and the "CCD camera" aimed at a lightbox. Film scanners can convert the analog image of film into a digital image that can be shared, manipulated, and annotated electronically.

6.2.11.5.1.1 Laser Scanners. Laser scanners utilize a laser beam that passes through the film and the resulting light is converted to a voltage signal by a photomultiplier tube. The voltage values are sampled over time to produce a digital image with brightness values calibrated to optical density values.

6.2.11.5.1.2 CCD Scanners. CCD scanners use a charge-coupled device as a detector. For digital radiography purposes, the CCD is generally in array of thousands of tiny photocells that create pixels for a line of the scanned radiograph as the image is passed over it, illuminated by a fluorescent lamp. Home and desktop photographic scanners are much like the CCD scanners, except home scanners are generally not set up to handle transparency data as in a radiographic film.

6.2.11.5.1.3 CCD Camera. The least expensive of systems are generally composed of a digital camera focused on an area of a lightbox with a radiographic film placed upon it. The camera takes a digital picture using a two dimensional, CCD array of the area of the radiograph focused upon. These systems can be difficult to calibrate and depending upon the limitations of the camera CCD size, often can be used to take quality digital images of only small portions of the radiograph at a time.

6.2.11.5.2 Filmless Capture. Radiographic film is not always needed or desired for digital radiography. Several alternatives to film are available today. Let us briefly discuss the two methods ("indirect" and "direct") of capture, and the devices used for filmless capture.

6.2.11.5.2.1 Indirect Capture. Indirect capture may be the most popular form of filmless digital radiography; this may be due to it being the easiest form to implement, and also due to a wide availability of indirect capture hardware. Indirect capture utilizes a means of converting X-ray light into visible or near visible light that can be detected and measured by photomultiplier tubes, CCD or other photo cells. Computed radiography, a photo luminescence method, is a two step radiographic imaging process. A storage phosphor imaging plate is exposed to penetrating radiation and the luminescence from the plate's photostimulated luminescent phosphor is detected, digitized, and presented via monitor or hard copy. The following are some devices used for indirect capture of images:

6.2.11.5.2.1.1 Phosphor Screens. – Phosphor screen based systems are the most like traditional film based radiography. A special capture system X-ray sensitive plate or screen captures radiographic information and is then placed in a digitizer or reader to convert the information into a digital image. The plates can be either rigid or flexible, depending upon the hardware used, and are reusable. Phosphor filmless imaging is a very popular method of digital radiography because of the ease of use, and film like nature of the process.

6.2.11.5.2.1.2 Amorphous Silicon Plates. – These devices are sometimes called "direct capture" devices because they seem to work by directly capturing X-ray data and at first glance are indistinguishable from true direct capture devices, but in truth, they are indirect capture devices because they use a scintillating crystal to convert X-ray light into visible light, which is sampled by the photovoltaic array they contain. Amorphous silicon plates generally require the use of a lab environment, as they are directly connected to the computer for digitization. They are available in real time and near real time models. An advantage of amorphous silicon systems is an overall reduction of time to acquire an image contrasted against traditional radiography. These systems are very delicate and are not recommended for field environments.

6.2.11.5.2.1.3 Digital Cameras. – Like the amorphous plates, they can produce real time images and incorporate the use of a scintillating crystal to convert X-ray light into visible light for capture. They tend to have much smaller CCD arrays compared to amorphous silicon systems, but can focus on smaller areas of a part in real time. Digital camera based, CCD, or image intensifier all use the light that is generated off another medium, that is, light emitting phosphor screen. This image is then digitized and displayed. This process can either be real-time or still images.

6.2.11.5.2.2 Direct Capture. Direct capture systems use selenium or some other material that produces a voltage when exposed to high energy radiation. Aside from this, they work in basically the same manner as an amorphous silicon plate. Selenium based systems can sometimes be overly responsive to external factors. These factors, such as ambient heat and high radiation can sometimes damage the device. These systems require indoor lab use with controlled conditions.

6.2.11.6 Digital Image Quality Factors. Image quality of a scanned or digitized image is dependent upon pixel size, spatial resolution, and the pixel depth (brightness resolution). The sampling time for a given area is generally proportional to the spatial resolution (number of pixels per square inch or square millimeter) and to the brightness resolution (bits per pixel). Generally, digital capture systems and scanners allow you to set these values up to the limit of the hardware. It is not always necessary to do so for all shots. Entrapped water detection, for example, would benefit from the highest brightness resolution, but would not require the highest spatial resolution. Also, the size of the stored image in bytes is directly proportional to the image spatial resolution – so it does not make sense to perform every capture at the highest possible quality. The procedure and part SHOULD dictate the resolution settings to use for digital capture. In addition to the brightness and spatial resolution of digital images, there are other factors that affect the quality of a captured digital image introduced as part "noise," of the capture process itself. Other factors are "dynamic range," and "artifacts."

6.2.11.6.1 Noise. Noise is defined by ASTM as the data present in a radiological measurement which is not directly correlated with the degree of radiation attenuation by the object being examined. Scatter within the image, variations in the phosphor plate and electronic induced noise all contribute to the degradation of the image. Noise creeps into a digital radiograph in a couple of ways. There is the noise inherent in radiography, and can generally be kept to a minimum by using the proper and prescribed techniques. There is also the noise in the digital capture hardware. The modular transfer function (MTF) is used to measure the signal-to-noise ratio. This SHOULD be considered a factor when deciding upon a digital capture system for your particular application.

6.2.11.6.2 Dynamic Range. Dynamic range is the effectiveness of the scanner or capture hardware in differentiating between differing shades of gray or brightness. It is a measurement of the number of bits used to represent each pixel in a digital image. Phosphor plate capturing systems tend to excel in the dynamic range department while film digitizers tend to have a breakdown level toward the higher densities. The greater the dynamic range, the higher the contrast and color/grayscale bit depth.

6.2.11.6.3 Artifacts. Artifacts are unwanted images caused by input or output process, that is, hardware or software. Images like films are subject to artifacts created during image capture. Artifacts, such as dust and fingerprints, can also harm the quality of a digital image. Many times, artifacts are hard to distinguish from actual indications on an image because of the nature of digital imaging. It is important to keep the capturing hardware clean and to cover digitizers and scanners when they are not in use to minimize artifacts.

SECTION III RADIOGRAPHIC EQUIPMENT

6.3 RADIOGRAPHIC INSPECTION EQUIPMENT.

6.3.1 Types of X-ray Generators.

6.3.1.1 Tank Type Generators. Tank-type units are usually small and light in weight for ease of portability. The entire high voltage circuit is housed in a single housing, which is commonly known as the tube head in portable X-ray units. This arrangement avoids having to transmit high voltage from the high voltage transformer to the X-ray tube by means of insulated conductors. The housing contains the X-ray tube, the high voltage transformer, and the filament transformer. Electrical insulation is usually by transformer oil or compressed insulating gas. The control box is a separate unit that can be positioned at some remote distance to protect the operator from radiation. Different circuit designs are used in various tank-type generators.

6.3.1.2 Separate Component Generators. Separate component units are those units where the transformers are separated from the X-ray tube. The high voltage and filament connections are made between the transformers and the X-ray tube through insulated cables. These units offer the advantage of ease of positioning the X-ray tube. The tube is contained in a protective housing with adequate insulation for the high voltages to be applied to the tube. These separate component units are usually fixed installations and parts to be inspected are transported to the X-ray equipment. Size or weight of this equipment is not of importance because they are usually intended for radiography in a shielded facility.

6.3.2 Types of X-ray Tubes.

6.3.2.1 Directional Tubes. In directional X-ray tubes, the anode is set at an angle to the electron beam. When the high-speed electrons strike the target, X-radiation is generated in a solid spherical pattern. The massive anode functions as an absorber for the radiation traveling into the anode. In most X-ray tubes, lead-absorbing materials are used to restrict the exiting radiation to a cone-shaped field passing through a window. The shielding reduces the leakage radiation hazard to personnel, and prevents additional scattered radiation from surrounding materials and areas. In some portable equipment, shielding of the X-ray tube has been omitted for the advantage of saving on weight. In some very high-energy units, such as betatrons and linear accelerators, the target is comparatively thin and offers little absorption to the very high-energy radiation being generated. The radiation beam from the front of the target is shielded to provide a directional pattern, conical in shape.

6.3.2.2 Rod Anode X-ray Tubes. These tubes are designed to produce a radiation beam in a circular pattern. These tubes are used for circumferential radiography, particularly pipe welds. By use of an absorbing sleeve (usually lead), the circular radiation pattern can be reduced to a directional beam.

6.3.3 Considerations in Choosing Equipment.

6.3.3.1 Choice of Radiation Energy. The relation of X-ray voltage to the penetration for steel or other common materials depends upon the density of the material and the absorption characteristics of the material in the X-ray beam. For more information, (Table 6-4) can be used as a guide for applying X-rays to inspection problems, assuming average radiographic results are expected. It is necessary to establish lower limits as well as upper limits on material thickness because using voltages higher than required to penetrate a given thickness will reduce the radiographic contrast.

Table 6-4. Appropriate Radiation Energies for Radiography of Steel

Kilovoltage Range	Material Thickness
5-50 kV [1]	Extremely thin, such as foil up to 1/8 in.
50-150 kV	1/8 to 3/4 in. steel
100-200 kV	1/4 to 2 in. steel
200-400 kV	3/4 to 3 in. steel
1000 kV	1 to 5 in. steel
2000-6000 kV	2 to 8 in. steel
15-24 MeV	3 to 18 in. steel

[1] This energy range is also useful for composite structures. Note that for X-ray energies of 15 kV or less, scatter in the air path may be a problem.

6.3.3.2 Choice of Equipment. Equipment choice SHOULD depend upon the circumstance under which radiographic inspection is to be conducted and the technique requirements. Some factors are "tube head type," "window," and "focal spot size."

6.3.3.2.1 Tube Type. The choice of a directional or a rod anode tube type SHOULD depend upon the type of radiographic inspection conducted. Circumferential specimens, such as pipe welds, are compatible with the rod anode radiation. The directional X-ray tubes restrict the radiation to a smaller area and have a comparatively smaller focal spot resulting in better quality radiographic images.

NOTE

The scattered radiation is greater with the rod anode and additional personnel protection is often necessary.

6.3.3.2.2 Window. When the X-ray absorption of a test object is low, lower energy radiation is required. To take advantage of the higher contrast provided at lower energies, an X-ray tube with a beryllium window SHOULD be used since beryllium transmits the low energy radiation. The beryllium window offers advantages up to 150 kVp and, therefore, radiographic inspections requiring 150 kVp or less SHALL use a beryllium window X-ray tube. A typical glass window SHOULD prove satisfactory for energies above 150 kVp. The beryllium window and the resultant soft (low energy) spectrum SHALL also be used for the inspection of composite laminates. For example, a graphite-epoxy composite laminate 0.100- inch thick might require the use of X-ray energy in the order of 10-20 kV for optimum sensitivity. Reasonable exposures with standard portable X-ray equipment are often difficult below 25-30 kV. X-ray energies of 15 kV or less, the air between the source and object would scatter the X-rays. If the X-ray equipment will operate that low, one way to displace the air is to stuff a helium-filled plastic bag between source and object.

6.3.3.2.3 Focal Spot Size. X-ray tubes are available with different focal spot sizes. The focal spot in an X-ray tube is the area of the target that produces the primary X-ray energy (Figure 6-11). The actual size of the focal spot is determined by the electron bombardment pattern on the target. The minimum size of this area is limited by the melting point of the target material and the concentration of the bombarding electrons per unit area. Tungsten (W) is most often used as target material because of its high melting point of 6170°F and high efficiency of X-ray production. An effort is made in X-ray tube design to achieve the smallest possible focal spot consistent with voltage, current required, melting temperature of the target material, and the field coverage needed. The smaller the focal spot size, the sharper the radiographic image. It is normal to expect a focal spot size of 2 to 10 mm (millimeters) in the voltage range of 100 to 2,000 kVp. For special applications, equipment with focal spots less than 1 mm in diameter is available. X-ray tubes with dual focal spots are often used so the operator can choose the focal spot size and operational conditions compatible with the demands of inspection quality. New X-ray machines are also available with focal spots called mini-focus (spot size in the range of 0.2 to 1 mm) and micro-focus (spot size in the range of 0.002 to 0.025 mm). These new small focal spot X-ray units provide excellent image sharpness and can also be used to enlarge the X-ray image geometrically.

6.3.3.3 Equipment Protective Devices. X-ray generators SHALL be not only safe to use, but also SHALL be protected against damage from inadvertent misuse. To accomplish this objective, X-ray equipment SHALL have protective devices as discussed in the following paragraphs.

6.3.3.3.1 Overload Thermal Circuit Breaker. The overload thermal circuit breaker (usually incorporated in the main line switch) provides protection to the equipment SHOULD a component failure be encountered. This protection assures the thermal circuit breaker will disconnect the unit from the power supply before extensive damage is done to the control box assembly or tube X-ray tube head.

6.3.3.3.2 Over-Voltage Protection Circuit. The over-voltage protection circuit works by either setting spark gaps to arc at the over-voltage point or by a voltage sensitive relay in the control circuit of the high voltage section. Sometimes both methods are used since it is possible under extreme conditions of surges, the over-voltage relay circuit MAY NOT react. This eliminates the possibilities of voltage damage due to operator carelessness or component failure.

6.3.3.3.3 Inverse Voltage Suppressor. There is also the possibility of inverse voltage damage in a high voltage X-ray circuit. This becomes a problem when the line voltage conditions vary widely (e.g., when using X-ray equipment in the lab on constant power or in the field on a portable generator). A circuit called the inverse voltage suppressor, consisting of a resistor and rectifier network in the primary winding of the transformer is used to protect X-ray equipment under these conditions.

6.3.3.3.4 Over-Current Fuse. An over-current fuse is used in the control circuit of the filament supply to prevent damage to the tube head due to incorrect usage of the equipment or component failure. The alternative is to design components in which the combination of variables will not result in damage to the unit. This is not desirable when attempting to achieve maximum utility in a design.

6.3.3.3.5 Over-Temperature Thermostat. To achieve the maximum safe working temperature of materials such as oil and solid insulation used in high voltage X-ray circuits, it is necessary to prevent over-temperature of the materials. To accomplish this, an over-temperature thermostat is installed in the X-ray tube head to prevent damage to those materials.

6.3.3.3.6 Flow Switches and Pressurestats. When using gas as insulation material, it is necessary to provide pressurestats in the X-ray tube head. Pressurestats prevent operation and consequent damage to the equipment SHOULD the gas pressure fall below the safe operating level for insulation of the high voltage parts. Flow switches and pressurestats in the oil and water circulators are also used to prevent operation of the X-ray unit when the unit is not being properly cooled. The type of protection provided in the unit will determine the degree of dependability of the equipment.

6.3.4 Considerations When Operating X-ray Equipment.

6.3.4.1 Effect of Focal Spot Size. The size of the focal spot bombarded by the electrons affects the heat dissipation capabilities of the anode. This limits the tube rating, or the milliamperes at which the tube MAY be safely operated. Additional effects are:

6.3.4.1.1 Heat Dissipation. The method of removing heat from the X-ray tube anode affects the tube ratings. An X-ray tube dependent upon convection cooling has a lower limit of operation than the same tube where water or some other coolant is used to conduct heat away from the focal spot.

6.3.4.1.2 Operational Considerations.

CAUTION

Follow manufacturer's guidance for warming up X-ray equipment.

When a new X-ray tube is put into operation, it requires a warm-up period. A tube head, new or used may have been stored for a period of time, and a very small amount of gas may have been released into the vacuum by the metallic parts within the tube. These gases can be driven back into the metal components by operating the tube at a low kilovoltage and slowly heating the anode to high temperatures. Therefore, an X-ray tube head, which has not been operated for a specified period of time, SHALL be energized at a low kilovoltage, and the kilovoltage slowly increased until maximum rating has been obtained. The same procedure SHALL be used when a unit has not been operated for 30-days or more.

6.3.4.2 Component Substitution Rules. The Department of Defense has spent many thousands of dollars on repair, replacement, and shipping costs for X-ray equipment. The following information is a guide that will assist NDI personnel when troubleshooting X-ray equipment.

a. The most likely cause of a system malfunction could be a defective tube head cable. The cable alone may be defective or the defective cable could damage other system components.

(1) The first step in troubleshooting X-ray equipment is to substitute a known-good tube head control cable with the malfunctioning equipment.

CAUTION

Never substitute a good control box or tube head without first doing this step because a bad cable may damage the known good system too.

(2) If the system still does not work after substituting the good cable, do not then assume the original cable is good; set it aside.

b. After ensuring a good cable is installed, the next component to substitute is a known-good tube head for the questionable one.

(1) When testing the system after substituting the known-good tube head, always start in the “Operate Mode” with a 0 kV and 0 mA on the set line. After pressing the “X-ray ON,” advance the mA to 5.0 mA, and then the kV one kV at a time, the mA SHOULD be flowing at 5.0 mA by the time 25 kV is reached. Continue to advance the kV up to 100 kV. If no problems are encountered up to 100 kV, slowly warm the tube head up as if the tube head was not used for the previous 30-days. If problems occur at low kV, do not advance the kV.

(2) If no problems are noted, do not assume the original tube head is good or bad.

c. If malfunctions still occur, substitute a good control box. Start in the “Operate Mode” and advance mA and kV as in Step b.1.

d. The system SHOULD be operating properly now if all of the components used for substitution were good.

(1) Now check out the original tube head by putting it back on the system. Again start testing in the “Operate Mode” with 0 kV and 0 mA set on the control unit. After pressing the “X-ray ON,” advance the mA to 5 mA and the kV one kV at a time. The mA SHOULD be flowing at 5.0 mA when 25 kV is reached. Continue to advance the kV up to 100 kV. If problems occur at low kV, do not advance the kV. If no problems are encountered up to 100 kV, auto-warm the tube head as if the tube head had not been used for the previous 30-days.

e. Continuity test the cables pin on one end, to corresponding pin on other end, and from each pin to all the other pins, and the shell on the same end of the cable. Always make sure cable connectors are fully inserted.

NOTE

A cable may be good lying in one position, but defective in another position. It is also possible to identify a bad cable by simply X-raying it with a good instrument. Broken wires are commonly found within one-foot from the end connectors.

6.3.4.3 Tube Head Rating. Several variables affect the maximum rating of an X-ray tube head. These SHALL be carefully observed to ensure the X-ray tube head rating is not exceeded. Some of the more important variables to be considered are listed below.

6.3.4.3.1 Focal Spot Size. The size of the focal spot dictates the milliamperes that can safely be conducted across the X-ray tube.

6.3.4.3.2 Method of Cooling. The method used to remove heat from the anode affects the length of time the tube head MAY be operated under a standard operating condition. The operation is extended by the use of external coolant.

6.3.4.3.3 Type of Circuit. The type of circuit design used in the X-ray generator affects the tube head rating. When self-rectified circuitry is used, the inverse voltage applied to the X-ray anode limits the operation of the tube head. Usually, the maximum operating conditions are much greater where full wave circuitry is used in comparison to self-rectified generators.

6.3.5 Standard Industrial X-ray Equipment in the DoD.

6.3.5.1 Lorad LPX-160A Portable Industrial X-ray Unit. The LPX-160A is an air or water-cooled X-ray unit with an operating potential of up to 160 kV and a tube current of up to 5 milliamperes (mA). The tube head is insulated with sulfur hexafluoride gas, pressurized to 50 psig @ 70°F, is end grounded and has a 0.063-inch thick beryllium window (for beam filtration) located approximately 2-inches from the end of the tube. At 0.5-meter from the window, the dose rate in the primary beam is about 240 R/min (2.4 Sv/min) and 14 R/min (0.14 Sv/min), unfiltered and filtered respectively through 0.5-inches of aluminum. The unit has a cone shaped radiation field (full angle = 40°). Leakage radiation as measured one meter from the tube head, with the main beam being absorbed by 25 half-value layers of lead, ranged from 12.7 mR/hr (0.127 mSv/hr) to 385 mR/hr (3.85 mSv/hr). The measured half-value layer (HVL) of 0.41 inches corresponds to an average X-ray energy of about 83 keV.

6.3.5.2 Magnaflux GXR7.6B/GXR7.6C 150-KVP X-ray Unit. Unit output is approximately 49 R/min (0.49 Sv/min) at one-meter from the tube target with the tube operating at 150 kVp and 7 mA. The tube head assembly contains an end-anode ceramic-enveloped X-ray tube with a 0.03-inch (0.75-mm) beryllium window for beam filtration. The unit has a cone shaped radiation field (full angle = 40°). Maximum leakage radiation is approximately 1.3 R/hr (0.013 Sv/hr) at 1-meter with the tube head placed in a horizontal position and with the beam port down and blocked by a 1/4-inch lead sheet.

6.3.5.3 Sperry SPX 160-KVP X-ray Unit. The output of this unit is approximately 60 R/min (0.6 Sv/min) at one meter from the tube target with the tube operating at 160 kVp and 5 mA. The only filtration in the primary X-ray beam is provided by the 0.092 inch (2.3 mm) beryllium window. The unit has a cone shaped radiation field (full angle = 40°). The duty cycle is continuous with external cooling. The end-anode type of X-ray tube is shielded with a 1/8-inch lead collar with a circular aperture for the primary beam. Typical tube housing leakage radiation exposure rates range from 300 to 600 mR/hr (3 to 6 mSv/hr) at one-meter from the tube target. However, a cone of leakage radiation, ranging from 1 to 4 R/hr (0.01 to 0.04 Sv/hr) at one-meter and emanating from the high-voltage-input end of the tube housing at an angle of approximately 10° - 18° with the major axis, MAY be detected with some units.

6.3.5.4 Sperry 275-KVP X-ray Unit. The maximum output of a typical 275-kVp X-ray unit is 150 R/min (1.5 Sv/min) at one-meter from the tube target with the tube operating at 275 kVp and 10 mA. The beryllium window provides an inherent filtration approximately equivalent to 0.1 mm aluminum. The unit has a cone shaped radiation field (full angle = 35°). The duty cycle is continuous with external cooling. The end-anode part of X-ray tube is shielded with a 1-inch lead collar with a circular aperture for the primary beam. Typical tube housing leakage radiation exposure rates range from 500 to 1000 mR/hr (5 to 10 mSv/hr) at one-meter from the X-ray tube head. The 1000 mR/hr (10 mSv/hr) exposure rates generally occur at 90° to the major tube axis at the high-voltage-input end of the tube housing.

6.3.5.5 Sperry 300-KVP X-ray Unit. The maximum output of the 300 kVp unit is about 117 R/min (1.17 Sv/min) in the beam at 1-meter from the tube target with the tube operating at 300 kVp and 10 mA. Filtration of the primary X-ray beam is 2.36 mm beryllium for the 35° tube heads and 0.5 mm nickel for the 360° tube heads.

6.3.5.6 Golden Engineering XR-200 Digital X-ray Unit. The Digital Radiograph System (DRS)™ model XR-200 is a pulsed X-ray unit manufactured by Science Application International Corporation. The DRS (or Golden Source as commonly referred to) contains an X-ray tube head that is air cooled and is manufactured by Golden Engineering. The tube operating potential is 150 kV and with a 0.5-milliamperes (mA) fixed current. The maximum output of the digital X-ray unit is 3 to 3.2 mrem/pulse (0.03 to 0.032 mSv/pulse) in the primary beam at 1-foot from the tube-head target. The unit can be set at 1 to 99 pulses. The pulse rate is 25 pulses-per-second with a pulse width of 50-nanoseconds.

NOTE

The pulse rate can vary slightly according to the battery charge. The unit has a cone shaped radiation field (full angle = 40°).

6.3.6 Isotope Source Equipment.

6.3.6.1 Energy Spectra. Radioactive nuclei emit gamma rays with discrete energy levels and a spectrum consists of a series of very sharply defined energies. As the atomic nucleus of a particular radioactive isotope disintegrates, well-defined decay schemes are followed. Further, it is important to be able to express the source strength and rate of decay.

6.3.6.2 Isotope Source Strength. A new international unit for source strength is the becquerel (Bq). The becquerel is defined as "one-disintegration per second." Therefore, 1 curie (Ci) = 3.7 x 10^{10} Bq. The unit becquerel has no relationship to the source volume or the quantity or type of energy of the radiation emitted. This term only has meaning when the particular radioactive isotope is known. For example, five becquerels of cobalt-60 are not equivalent to five becquerels of iridium-192 because of different energy levels and decay schemes.

6.3.6.3 Isotope Source Focal Spot Size. For isotopes, the physical size of the radioactive source can be thought of as the "focal spot." Since the becquerel only relates the number of disintegrations per second, this unit has no relationship to the volume of mass or size of the radioactive source. The term "specific activity" is used to define the quantity of radioactivity of one gram of the substance and is expressed as becquerels per gram. Specific activity is expressed as the number of curies or becquerels per unit mass or volume. The shorter the half-life, the less amount of material required to produce a given activity or becquerels. The higher specific activity of Iridium results in physically smaller sources. For radiographic applications, a small source size is desirable to produce images with good resolution or sharpness, just as a small focal spot in an X-ray tube is required for high-resolution radiographs. Large sources produce geometric distortion resulting in radiographs with poor definition. Effort is constantly being devoted to producing radioactive isotope sources with high becquerel strengths in small volumes of material. Some special sources are stated as high specific activity, indicating a high radiation output relative to the source size. Nevertheless, in most isotopes, the source size exceeds the focal spot size in X-ray tubes.

6.3.6.4 Isotope Source Decay Characteristics. As radioactive material decays, there are a fewer number of unstable atoms left to decay. As time passes, the radioactive material is becoming less and less radioactive. Different isotopes have different decay rates. If a single atom of an isotope existed, it would be impossible to predict at what moment in time it might disintegrate. But if large numbers of atoms exist, it is possible to measure the lapse of time required for one atom out of every two to disintegrate, this is called the half-life of an isotope. The half-life is defined, as the time required for an isotope to decay to one-half of its original radioactivity.

6.3.6.5 Isotope Source Sensitivity.

WARNING

The radiation levels at the surface of the shielded container are hazardous to personnel over prolonged periods of contact.

CAUTION

Undeveloped film SHALL NOT be stored in the immediate area of the shielded container.

Radiographic definition obtained with isotope sources is usually of lower quality than obtained with X-rays because of:

6.3.6.5.1 Focal Spot Size. Usually isotope sources have a larger focal spot size than X-ray tubes in order to have a sufficient quantity of radiation to prevent very long exposure times.

6.3.6.5.2 Fixed Radiation Energy. Isotopes emit radiation with an energy characteristic of that particular radioactive material. Therefore, the operator has no choice of radiation energy, and it is not always possible to select the radiation energy compatible with the absorption characteristics of the part being inspected.

6.3.6.5.3 Exposure Techniques. Exposure times are important, and often isotopes are weak in radiation output. Consequently, source-to-film distances must be decreased to reduce exposure times. This leads to poor definition of the radiograph.

6.3.6.6 Isotope Source Cameras. Isotopes emit radiation continuously; they cannot be turned off like an X-ray generator. Isotopes are stored in radiation-shielded containers, which reduce the radiation to a safe level for personnel not making radiographic exposures. The shielded container is designed so the radioactive isotope can be remotely positioned for a radiographic exposure. Many schemes have been devised for remote handling of isotopes. Source holders, commonly called isotope cameras, generally are of two typical designs.

6.3.6.6.1 The simplest cameras are designed for direct beam radiography. The source is only allowed to produce a restricted conical direct beam. The container itself is used to absorb radiation not emanating from the window or port. Some units are designed so the window can be opened and closed from a remote distance.

6.3.6.6.2 The other type of isotope camera is normally used for circumferential radiography. These are devised to move the source from its shielded container to a point some distance away, and then upon completion of exposure, return the source to its container. In this type of camera the radiation is being emitted in all directions.

6.3.6.7 Acquisition and Maintenance of Isotope Source.

NOTE

In the event of any malfunction, the appropriate equipment service manual SHALL be consulted.

All man-made radioactive isotopes are under the jurisdiction of the Nuclear Regulatory Commission (NRC). A license is required to purchase and use these isotopes. The Air Force possesses a Master Materials License from the NRC. In order to obtain sources at base level, contact the base Radiation Safety Officer (RSO), normally the base RSO is the Bioenvironmental Engineer (BEE). The base RSO will help obtain a permit from the USAF Isotope Committee, which is the regulatory body within the Air Force. Each permit will give specific requirements for any radioactive isotope used for radiography.

6.3.7 Radiographic Film.

6.3.7.1 Classification of Radiographic Film.

6.3.7.1.1 Classification by Signal-to-Noise Ratio. The effect of signal-to-noise ratio caused by film grain size is shown with a microdensitometer trace across the radiographic images of a series of small wires made through one inch of aluminum (Figure 6-18). All exposure parameters were a constant except exposure time, which was varied to compensate for the three different film speeds. The ratios between the trace amplitudes for the wires and the respective backgrounds indicate the signal-to-noise ratios for Class 1, Class 2, and Class 4 radiographic films. Notice the higher frequency content of the Class 1 film, indicating its greater detail resolution capability.

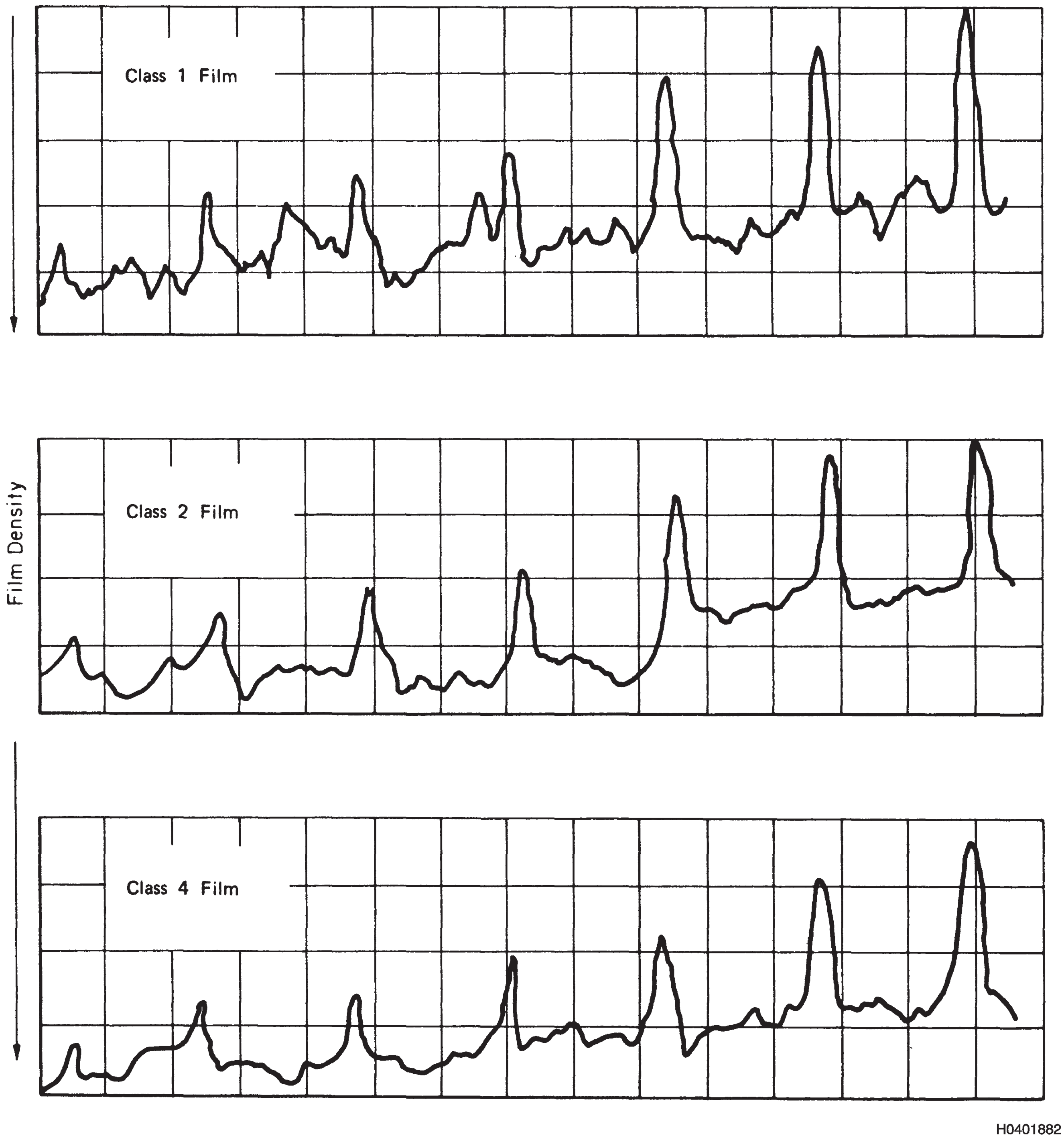


Figure 6-18. Microdensitometer Tracings of Images of DIN Wire Penetrameters

6.3.7.1.2 Classification by Film Speed. Another way to classify film is according to film speed. The approximate relative speeds of radiographic film exposed to radiation energy between 100 and 150 keV are as follows (Table 6-5).

Table 6-5. Relative Speeds of X-ray Films Exposed at 100 kVp

Film Designation	Relative Film Speed [1]
Agfa	
D8	3.7
D7	2.7
D6R	1.5
D5	1.7
D4	1.0
D3	0.75
D3 (single coat)	0.28
D2	0.28
Kodak	
AA	3.1
T	2.07
B	2.0
M	1.0
R	0.4
R (single coat)	0.2
Fuji	
1X150	3.6
1X100	2.0
1X80	1.0
1X59	.8
1X50	0.5
1X29	0.4
1X25	0.36

[1] Film speed numbers should be compared only within a single manufacturer.

6.3.7.2 Classes of Radiographic Film. Film is available that varies in signal-to-noise ratio, speed of response to radiation, and graininess. It is most appropriate to classify X-ray film in relation to the signal-to-noise ratios. Very fine-grain films with a very high signal-to-noise ratio require comparatively large quantities of radiation for exposure and produce images with excellent resolution of detail. In the choice of a particular film, a trade-off must be made between resolution and speed of exposure. The criticality of an inspection will determine this tradeoff. Some commonly used X-ray films are classified as follows:

- Class 1: This class has the highest signal-to-noise ratio and includes such films as: Agfa D2, Kodak Type R, and Fuji IX 25. These are considered high detail resolution films and SHOULD be employed when the most sensitive radiograph is desired.
- Class 2: This class is considered as high in signal-to-noise ratio and includes such films as: Agfa D4, Kodak Type M, and Fuji IX 50.
- Class 3: These films have a moderate signal-to-noise ratio and include: Agfa D5, Kodak Type T, and Fuji IX 59 with screen.
- Class 4: These high-speed films, by comparison, are considered to have a low signal-to-noise ratio and include: Agfa D7, Kodak Type AA, and Fuji IX 100.

6.3.7.2.1 The previous classifications differ from others because they are based upon signal-to-noise ratio rather than film speed. We show a bar chart (Figure 6-19) reflecting the relationships of signal-to-noise ratios, film speed, and detail resolution capabilities of different film classes. We also have a more detailed guide to film classification (Table 6-6) and

(Table 6-7). These tables are not inclusive of all film types or manufacturers which MAY be authorized for use, since manufacturers introduce new films or take existing films off the market from time to time. Specific inspection instructions MAY specify film other than what is listed. Each manufacturer has a particular designation for films. Small variations may be noted in film speed and contrast of the films made by the different manufacturers within a particular class.

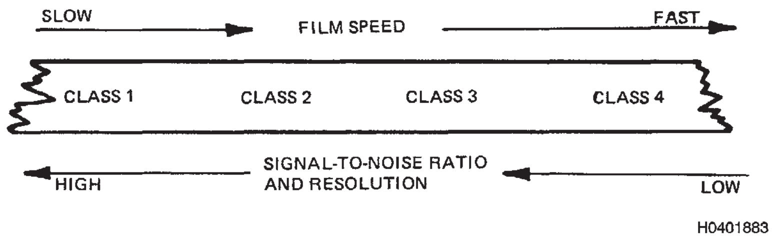


Figure 6-19. Relationship Between Signal-to-Noise Ratios and Speeds of Film

NOTE

The following classifications are based on film system rather than signal-to-noise ratio. The film plus the associated film-processing requirements are based according to the criteria established by the manufacturers of the film and processing chemicals. The classifications previously listed in this manual approximately corresponds to the new film system classifications, as follows:

- Class 1 is considered equivalent to ASTM Class Special
- Class 2 is considered equivalent to ASTM Class I
- Class 3 is considered equivalent to ASTM Class II
- Class 4 is considered equivalent to ASTM Class III
- Exceptions include films followed by an arrow; they are the equivalent of one class higher in the new system classification compared to the previous classification.

Table 6-6. Film Classes

Manufacturer	System Class			
	Special	I	II	III
Agfa	D2	D3 D4 D5	D7 (á)	D8
Fuji	IX25	IX 20 IX 50 IX 80	IX 100	IX 150
Kodak	DR	M MX 125 T	AA400 (á)	CX
The following table includes the ISO speed and signal-to-noise ratio for each film type.				

Table 6-7. Speed and Signal-to-Noise Ratio

Mftr	Class											
	Special			I			II			III		
	Type	Speed	S/N	Type	Speed	S/N	Type	Speed	S/N	Type	Speed	S/N
Agfa	D2	40	371	D3	64	294	D7(á)	320	142	D8	400	114
				D4	100	232						
				D5(á)	200	169						
Fuji	IX25	50		IX 20	25		IX 100	320		IX 150	500	
				IX 50	100							
				IX 80	200							
Ko-dak	DR	32	378	M	80	320	AA400(á)	320	140	CX	400	124
				MX 125	125	220						
				T(á)	200	209						

6.3.7.3 Storage of Unexposed Film.

CAUTION

Any films in containers sealed by the manufacturer and not opened SHALL be stored with the film on edge to avoid container damage and possible film damage. Storage temperature should be between 40 and 75°F at a relative humidity range of 30 to 60%. When storage temperatures exceed 90°F for 30 days or more, a fog test SHALL be performed with a limit of 0.30 density units total for base density. Regardless of storage temperatures, films SHALL be allowed to stabilize at room temperature before opening containers.

X-ray film is sensitive to the cosmic radiation that exists everywhere. This radiation will cause fogging. Fog is the darkening of the radiograph by scattered radiation, exposure to light, or pre-exposure to radiation. It can also be caused by over-development or aging. It SHOULD be noted fog brings no information to the film and merely creates a high background that reduces contrast and image visibility. The very high-speed films, being more sensitive to exposure, are more susceptible to fogging than the slower emulsions.

6.3.7.4 Film Expiration Date. The expiration date is marked on the film box at the time of manufacture. To prevent exceeding the expiration date, film SHOULD be ordered in quantities, so long-term storage is not necessary. The inventory of film SHOULD be rotated to use the older film first. Film that exceeds its "shelf life" date SHOULD NOT be put in salvage, the usability will be verified by: 1) processing an unexposed sheet to determine clearing and fog level, the density should not exceed 0.30, 2) if the clearing and fog level are satisfactory, make a radiograph of a step-wedge and penetrameters to determine the sensitivity and contrast of the film in question, a 1.4% sensitivity (2-1T) is recommended, 3) if these limits are acceptable, extend the shelf life by six months and continue using the film. Document the verification results on a DD Form 2477. At the end of the extended period reverify the film using the aforementioned procedure. If the film does not meet acceptable quality levels use the film for training, for clearing the automatic film processor, for detection of foreign objects, or if the quantity is so great to warrant, ship the film to the NDI Technical Training School, Air Education and Training Command (AETC) at NAS Pensacola. The Navy and Marine Corps can send film to NAVAL AIR Technical Training Center (NATTC) ATTN: NDI School, 230 Chevalier Field AVE, Pensacola, FL 32508. If the film is one-year past its original shelf life, the film SHALL NOT be used for crack detection and SHALL be utilized for one of the alternate purposes mentioned earlier. X-ray films present no greater fire hazard in storage in the X-ray laboratory and filing room than an equal quantity of paper records. There is no necessity for expensive vaults equipped with elaborate fire protection devices. Film storage area SHALL be kept clean.

6.3.7.5 Film Identification Methods. To properly apply information obtained through radiography, the material inspected must also be accurately identified with respect to the object radiographed. In the absence of engineering direction in a specific weapons system technical order, the required method of film identification is lead numbers and letters, lead tape, or lead labels. The Laboratory Supervisor can approve use of perforation methods for their specific laboratory. The required identification information SHALL be: Aircraft tail numbers or part name/serial number if not an aircraft item, julian date, inspection procedure, shot number, employee number of radiographer-in-charge, and organization. The inspection procedure may be abbreviated or shortened but must be clearly understood. The organization should include the wing designation number and the laboratory office symbol (e.g., 36 MXMFN). When film size does not allow identification on the film, it will be placed in an acceptable film file pouch and the information typed or written legibly on the film file. When the x-ray film interpreter is not the radiographer-in-charge the interpreter's employee number will be written on the x-ray film with an appropriate marker (e.g., grease pencil) or on the film pouch when film size is an issue.

6.3.8 Film Holders, Film Cassettes, and Radiographic Screens.

NOTE

Due to interaction between film and lead screens, film SHALL NOT be left in cassettes or film holders more than 24-hours.

Film holders and film cassettes are used to protect the film from light exposure while the film is being transported and while it is being exposed. These film holders are of various designs made to hold the various film sizes. Screens increase the imaging radiation being impinged upon the film and/or decrease the scatter radiation reaching the film.

6.3.8.1 Film Holders.

6.3.8.1.1 Flexible Film Holders. Flexible film holders are used where it is necessary to contour the film to achieve good film-to-test-object contact, however, sharp bends SHOULD be avoided. These holders are made of a lightproof flexible material. Lead screens with a rubber or vinyl backing are available to permit contouring and flexible positioning of the film for exposure.

6.3.8.1.2 Cardboard Film Holders. Cardboard film holders are used extensively in industrial radiography. They are simply a heavy, kraft paper envelope between hinged cardboard covers. The back has a lead foil lining to absorb back- scattered radiation. Always place the holder with the "tube side" mark toward the tube head or radiation source. If the holder position is reversed, the radiation is filtered by the lead foil backing and will result in images of lower density. The cardboard holders are economical and durable. Lead screens can be inserted into the envelope with the film for making lead screen radiographs. Intimate film-screen contact is normally accomplished by placing the object to be inspected on the cardboard holder.

6.3.8.1.3 Rigid Film Holders/Film Cassettes. The term cassette is usually applied to rigid film holders. Cassettes have a "bakelite" or "magnesium" front to allow transmission of X-rays. The back contains a lead foil lining to absorb the back-scattered radiation. Cassettes are normally used with calcium tungstate or lead screens. Cassettes provide uniform compression on the film and screens to assure good physical contact between the film and screen for ultimate image sharpness. Cassettes are comparatively heavy and somewhat difficult to handle.

6.3.8.2 Vacuum Cassettes. Vacuum cassettes are especially useful when utilized in conjunction with lead or fluorescent screens. The air is pumped out of the cassette, ensuring intimate film-screen contact. They are very flexible, allowing the film to be positioned in a confined space.

6.3.8.3 Using Film Holders and Film Cassettes. Film cassettes give better film-to-screen contact and are often used without a screen. Lead screens can be used with film holders, but care SHALL be taken to maintain even film-to-screen contact. In any critical exposure, the use of cassettes are recommended. Film holders are generally used to radiograph thin sections of materials at low kilovoltage, 150 kVp or lower. The sensitivity is reduced when using film holders on thick sections due to backscatter. Using film holders with a lead sheet backing will reduce the backscatter. At lower than 30 kVp, standard film holders cannot be used because the cardboard will show on the radiograph. For lower kilovoltage, holders can be made from vinyl or Mylar materials. A lead sheet can be taped to the back to reduce backscatter. Film holders can be taped in place or secured in any way that will not affect the radiograph adversely.

6.3.8.4 Labeling Film Holders and Film Cassettes. Ballpoint pen or other sharply pointed writing instrument SHALL NOT be used to write information on the surface of any cassette or film holder. Film artifacts may be produced which will affect radiographic interpretation. If identification is required use marking techniques, that the necessary information can be recorded on before applying to the cassette.

6.3.8.5 Bending or Kinking Film Holders/Cassettes. Care SHALL be taken not to bend or kink film holders unless absolutely necessary for placement of film for exposures. Artifacts may be produced, which could impair interpretation of the radiograph. An alternative includes the use of smaller or custom shaped film for better fit to part, if required.

6.3.8.6 Preparation of Film Holders/Cassettes.

CAUTION

Loading of film cassettes and film holders SHALL be accomplished under safe light.

a. Remove all unnecessary materials from the workspace.

b. Before loading the film cassette/holder, open it and examine for cleanliness and light leaks. Discard any film holders physically damaged beyond repair. Some light leaks MAY be repaired with black photographic tape. Remove any lint or dust with a clean cloth. Dust SHALL NOT be blown out since moisture may lodge on the holder and be transferred to the film.

c. Place the film, film cassette/holder, and if used, screens in a convenient location in the darkroom to simplify loading of the film cassette/holder.

d. If a screen is used, place it in the film holder face upwards so it will contact the film.

6.3.8.7 Loading the Film Holder/Cassette.

NOTE

Film SHALL NOT be allowed to slide into the cassette/holder pocket. Scratches from the cassette/holder or screen may result.

The procedure that follows covers only one type of film holder. Film holders vary in methods of locking and opening but the same procedure will apply except for these details.

a. Open the inner folded cover all the way.

b. Withdraw the film from the film box with paper cover in place. Handle the film only at the edges with light finger pressure.

c. Grasp one side of the paper cover to open it. Place the film so the free end is against the rear edge of the holder. Lower the film slowly and allow the film to fall gently into the holder and remove the paper.

d. Refold the inner paper cover.

e. Close the holder cover taking care the lead screen on the cover enters the holder pocket without binding. Some holders MAY NOT have a lead screen on the cover. In this case, when the use of the screen is desired, place it in the holder pocket face down.

f. Lower the holders cover and fasten the locking device. If the holder has a spring back, turn the latch to lock the holder.

6.3.8.8 Prepackaged Film. X-ray film suppliers offer X-ray film in prepackaged, flexible envelopes or in rolls. The prepackaged film eliminates the film loading operation in the darkroom. Packaged film is available, double-loaded with films of differing speeds, or placed between two intensifying screens incorporated in the package. This film is convenient to use and is preferred for many industrial applications. Prepackaged film is the most widely used film due to its convenience for field inspection.

6.3.8.9 Radiographic Intensifying Screens.

6.3.8.9.1 Purpose of Radiographic Screens. X- and gamma radiation has such a great penetrating power that less than 1-percent of the energy is absorbed when striking film. Materials that emit less penetrating radiation in the form of secondary electrons or fluorescent light utilize the emitted radiation more fully. A radiographic intensifying screen is a layer of material that intensifies the imaging radiation being impinged on the film, decreasing the scatter radiation reaching the film. In industrial radiography, these are often used in direct contact with the X-ray film. There are three types of screens used to intensify an image: lead, fluorescent, and fluorometallic.

6.3.8.9.2 Types of Radiographic Screens.

6.3.8.9.2.1 Lead Screens. Certain materials emit electrons when struck by high energy X-rays or gamma rays; these electrons are called secondary electrons. X-ray film is not only sensitive to light, but to these secondary electrons. The material of choice is lead foil usually 0.001-inch to 0.040-inch thick, bonded to a flexible support. Lead screens in direct contact with film have two effects:

- Intensify Incident Radiation. Incident radiation with energies above 88 keV eject photoelectrons from the atoms of the lead. These photoelectrons act on the emulsion in the same way as the primary radiation beam.
- Improve Clarity. They improve clarity by absorbing scattered radiation of longer wavelengths.

6.3.8.9.2.1.1 When to Use Lead Screens. Lead screens SHOULD be used whenever they improve radiographic quality. Because of the resulting improvement, they are generally preferred to calcium tungstate screens. Whenever there is a need to perform a radiographic inspection using a combination of screens and film, they SHALL be of the same plane dimensions and in close contact with each other during exposure.

6.3.8.9.2.1.2 Selection of Lead Screens. Lead screens are available in various thicknesses and SHOULD be chosen relative to the radiation energy being used. The energy level threshold for lead screens is approximately 100 kVp. Any secondary electrons generated below this level have little effect towards intensification. Above 100 kVp, the general rule for lead screen selection is: For 100 - 400 kVp, use a front screen of 0.001 to 0.005-inch and a back screen between 0.005 to 0.010-inches. For isotopes (Iridium 192 and Cobalt 60), use a front screen of 0.005 to 0.010-inch and a 0.010-inch back screen. Supervoltages above 1.0 MeV require a front screen of 0.010 to 0.060-inch and a back screen between 0.010 to 0.040-inches. When used properly, they intensify the image by improving the image contrast and final radiographic sensitivity. Sample results are shown in (Table 6-8) however, the quality of the image is improved at all kVp settings.

Table 6-8. Sample Result

Source Power	Relative Exposure Times for Equivalent Density Under Standard Conditions	
	Without Screens	With Lead Screens
120 kVp	1.0	1.0
150 kVp	1.0	0.7
200 kVp	1.0	0.5
Iridium 192	1.0	0.25
Cobalt 60	1.0	0.50

NOTE

The results were obtained with a 0.004-inch front screen and a 0.006-inch back screen.

CAUTION

Hydrogen peroxide or other common cleaning agents SHALL NOT be used for this purpose because their chemical composition will cause fogging of the sensitive film emulsions.

6.3.8.9.2.1.3 Care of Lead Screens. X-ray screens are given a special waterproof protection coating to both sides. Due to the high electron absorption in light materials and the intensifying action on lead foil screens caused by the electrons emitted under radiographic excitation, the surface SHALL be kept free from dust, dirt, and lint. These conditions will produce light densities on the radiograph. Sensitive surfaces of the screens SHALL NOT be touched because fingerprints may show up and interfere with accurate interpretation on the radiograph. If cleaning of the surface is required, wash with mild soap and water and dry thoroughly with a soft cloth. Remove grease and lint from the surface of lead foil screens with a solvent such as Isopropyl Alcohol. If more thorough cleaning is necessary, rub screens gently with the finest grade of steel wool. Film may be fogged if left between lead screens longer than is reasonably necessary, particularly under conditions of high temperature and humidity. When screens have been freshly cleaned with an abrasive, this effect will be increased. It is best to delay the use of freshly cleaned screens at least 24-hours.

6.3.8.9.2.1.4 Precautions When Using Lead Screens. Lead screens SHALL be used with great care. Common problems are:

- A fuzzy image resulting from lack of intimate contact between the screens and film.
- Dark lines on the image resulting from scratches on the screens.

6.3.8.9.2.2 Fluorescent Screens. Some materials fluorescence (emit light) when struck by X- or gamma radiation. Each fluorescent material normally referred to as phosphor, has its own fluorescent light spectral region. Intensification factors of 5 to 200 can be obtained by appropriate choice of phosphors relative to the spectral sensitivity of X-ray film. Due to the visible light dispersion from phosphor crystals to radiographic film, fluorescent screens render images less sharp than those obtained with direct exposure. Fluorescent screens produce radiographic images of inferior quality; therefore they are used selectively in industrial radiography for applications where they are allowed by code, and where the desired image quality requirements are met. For this reason, their use is normally limited to those situations where exposure speed is more important than image quality, or where the radiation quantity available is inadequate to perform the task. Fluorescent screens consist of a phosphor like calcium tungstate coated on a flexible support. Whenever there is a need to perform a radiographic inspection using a combination of screens and film, they SHALL be of the same plane dimensions and in close contact with each other during exposure.

6.3.8.9.2.2.1 Care of Fluorescent Screens. Fluorescent light from intensifying screens obeys all of the laws of visible light, and cannot pass through opaque bodies as X-rays do. Make every effort to keep the screens clean. To avoid extraneous shadows caused by absorption of the fluorescent light by foreign matter during exposure, dust and dirt particles SHALL NOT be allowed to collect between the film and screen surfaces. Stains upon the screens SHALL also be avoided. Calcium tungstate screens MAY be stored in the processing room but away from chemicals and other sources of contamination.

6.3.8.9.2.3 Fluorometallic Screens. Fluorometallic screens consist of calcium tungstate phosphor coated on lead foil, which in turn is coated on a suitable, flexible support. When used in appropriate applications, the combination of fluorescent phosphor and lead foil, results in substantial intensification with radiographic images having improved contrast. Intensification factors ranging from 5 to 30 can be obtained when these screens are exposed with appropriate industrial X-ray films, while factors of 30 to 150 can be realized when the screens are used with medical type films.

6.3.9 Quality Indicators.

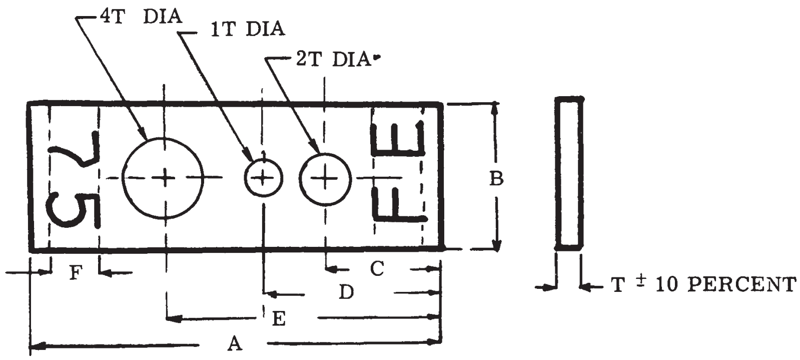
6.3.9.1 Penetrameters/Image Quality Indicators (IQI).

NOTE

Use of IQIs are specified within a given technique. If the IQI identified in the technique is not available, consult with the appropriate Air Logistics Center's NDI Level III for instructions. Penetrameters SHOULD be used during crack detection inspections.

Penetrameters or image quality indicators (IQI) are devices whose image is used on a radiograph to determine radiographic quality level (sensitivity). They are not intended for use in judging the size of, or in establishing acceptance limits of discontinuities. Instead, they are used to determine the acceptance level for the particular radiographic technique used to make the radiograph. The penetrameter is a test piece whose composition is similar to the material of the subject being tested. It generally is located in an appropriate location on, or adjacent to, the subject being radiographed. When it is specified by code, or when it is not practical to place the penetrameter on the subject, the penetrameter is located adjacent to the subject on a rectangular block of material similar to the penetrameter and having a thickness close to the subject.

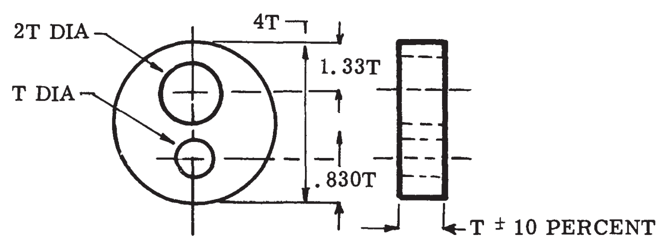
6.3.9.2 Description of Penetrameters/Image Quality Indicators (IQI). A wide range of penetrameters is specified for use by various industries. Wire penetrameters are particularly useful for weld inspection. A common form of penetrameters is a small plaque, fabricated of the same material being radiographed. The thickness of the penetrameter is a known percent of the test object thickness. Holes in the penetrameter are of diameters 1T, 2T, and 4T, where the T equals penetrameter thickness. Thickness visualization of these holes can be related to the sensitivity of the radiographic image. A typical penetrameter is shown in (Figure 6-20).



T	INCREMENTS	A	B	C	D	E	F
.005-.020 INCL.	.0025	2.000	.500	.520	.800	1.150	.250
.025-.050 INCL.	.005	2.000	.500	.520	.800	1.150	.250
.060-.160 INCL.	.010	2.850	1.000	.800	1.250	1.900	.375

MIN PENETRAMETER THICKNESS .005 ± 10 PERCENT
MIN DIAMETER FOR 1T HOLE .010 ± 10 PERCENT
MIN DIAMETER FOR 2T HOLE .020 ± 10 PERCENT
MIN DIAMETER FOR 4T HOLE .040 ± 10 PERCENT

DESIGN FOR PENETRAMETER THICKNESSES UP TO AND INCLUDING 0.160



DESIGN FOR PENETRAMETER THICKNESSES OF 0.180 AND OVER MADE IN .020 INCREMENTS

SYMBOL	MATERIALS (SEE 4.2.2.2.3)
SS	STAINLESS STEEL
AL	ALUMINUM
FE	STEEL
MG	MAGNESIUM
CU	COPPER
TI	TITANIUM

ALL DIMENSIONS IN INCHES.
HOLES SHALL BE TRUE AND NORMAL TO THE SURFACE OF THE PENETRAMETER. DO NOT CHAMFER.
TOLERANCES ON PENETRAMETER THICKNESSES AND HOLE DIAMETERS SHALL BE ± 10 PERCENT OR 1/2 OF THE THICKNESS INCREMENT BETWEEN PENETRAMETER SIZES, WHICHEVER IS SMALLER.

H0401884

Figure 6-20. Penetrameter Information

6.3.9.2.1 The penetrameter has lead numbers permanently attached to the plaque that indicates the material thickness on which the penetrameter is to be used. In Figure 6-20), the ID number indicates the penetrameter is for use on a 0.750- inch test object. The thickness (T) of the penetrameter is normally made to be 2-percent of the test object thickness. Therefore the penetrameter with an ID of 6.0-inches would be 0.120-inch thick. Except in special instances, plaque penetrameters less than 0.005-inch in thickness are not available, therefore, in normal operation, the 0.005-inch penetrameter is used on test objects when the thickness MAY be 0.25-inch or less. The use of IQIs is discussed further (paragraph 6.4.4).

6.3.10 Radiation Monitoring Devices and Instruments.

NOTE

Calibration of both DIRECT READING dosimeters and alarming rate meters SHOULD be scheduled so sufficient quantities remain on hand to support continuing radiography operations. Additionally, except in cases of emergency, TLD badges SHALL NOT be submitted until replacement badges have been received.

6.3.10.2 Personnel Monitoring Devices. TLDs are the primary dosimetry device and have generally replaced film badges as the legal record of radiation exposure in the Army and Air Force. Thermo Fisher Scientific Mark 2 Electronic Personal Dosimeters (EPD) are the approved direct reading digital dosimeters approved for NDI operations. For more safety-related information, see Section VIII for Air Force, and Section IX for Army.

CAUTION

Each personal alarming dosimeter/alarm rate-meter SHALL:

- Be checked to ensure that alarm functions (sounds) at the start of each shift.
- Be set to give alarm signals a preset dose rate of not more than 500 mR/hr (5 mSv/hr).
- Require special means to change the preset alarm function.

6.3.10.2.1 Thermoluminescent Dosimeter (TLD).

6.3.10.2.1.1 Theory of Operation. TLDs are well suited for personnel and environmental monitoring of X-ray and gamma radiation. TLDs are special materials which, when exposed to ionizing radiation, results in raising the electrons of the detector material to temporary higher energy states. When these materials are later heated, the electrons fall back to their normal energy states and in the process emit light. The amount of light emitted is directly related to the amount of radiation dose the TLD received. By measuring this light, the dose received by the individual wearing the dosimeter can be assessed. Although a number of materials can be used as TLDs, "lithium fluoride," "lithium borate," and "calcium sulfate" are the most common material used for personnel dosimetry.

6.3.10.2.1.2 The Control Device (TLD). To accurately measure personnel dose, each radiography area will have at least one device designated as a "Control Device" (TLD). It is used to measure radiation exposure received by personnel monitoring devices (primarily from naturally occurring background radiation) while badges are in storage and transit.

a. The control device SHALL be stored in the same area as the personnel TLD, away from sources of radiation in a temperature and humidity controlled area. The control device SHALL NOT be removed from this area.

b. The control device SHALL NOT be worn by any individual.

6.3.10.2.1.3 Dosimetry Services (TLD). Dosimetry service for Air Force installations is provided by USAFSAM/OEHHD, 365 Third Street Bldg 674-C, Wright-Patterson AFB, OH 45433, through the Installation RSO, in accordance with the provisions of AFMAN 48-125, *Personnel Ionizing Radiation Dosimetry*. Bioenvironmental Engineering is responsible for the dosimeter program at base level and will receive all routine reports issued by the USAFSAM/OEHHD. The Installation Radiation Safety Officer SHALL investigate all dose reports which exceed predetermined action levels, and ensures all records of radiation dosage are properly maintained for each individual on the program.

6.3.10.2.2 Electronic Personnel Dosimeter (EPD). Although approved in ANSI-N13.11 as a dosimeter of record in lieu of a TLD, the EPD is currently used within DoD for instant readout of dose and dose rate. It measures gamma and X-ray radiation over the range of 20 keV to 6 MeV and beta radiation from 250 keV to 1.5 MeV, and it provides readout of both skin (7 mg/cm^2) and deep dose equivalent (1000 mg/cm ^{2}). The readout provides a dose equivalent range of 0.1 to 1000 rem. The radiation is detected by three silicon diode detectors, which save data to secure memory every few minutes and provide visible and audible alarms if either the accumulated dose or dose rates exceed specified levels. Doses SHOULD be checked periodically throughout the day when performing radiography and SHALL be recorded in the dosimetry log at the beginning and end of each operation for future comparison with TLD results. When EPDs are submitted for calibration long-term dose memory is reset to zero. They are worn in the same manner as TLDs.

6.3.10.2.2.1 The Thermo-Fisher Scientific EPD model -Mark2 is a direct reading electronic dosimeter that is sensitive to X-ray, y (gamma) radiation, and ß (beta) particles. The Air Force Personnel Ionizing Radiation Dosimetry Program uses this dosimeter solely to detect and measure exposures to high energy photon *y* radiation. The principal application of this dosimeter is in support of emergency response operations and Nondestructive Inspection (NDI). The EPD-2 detects radiation by use of multiple diode detectors, giving direct readout of dose equivalents Hp(10) (deep/whole body) and Hp(07) (shallow/skin) in units of Sv and rem. Display range is auto ranging from 0 mrem to >1600 rem. Dose rate display ranges from 0 to 400 rem/hour auto ranging, with resolution to the 2 most significant digits. The dosimeter is linear to ±10% at dose rates <50 rem/hour; ±20% from 50 - 100 rem/hr; ±30% from 100 -200 rem/hr; and ±50% from 200 - 400 rem/hour. Energy response relative to Cs-137 is certified by the manufacturer to be linear to ±50% from 15 - 17 keV; ±20% from 17 keV -1.5 MeV; ±30% from 1.5 MeV - 6 MeV; and ±50% from 6 MeV to 10 MeV. Dosimeter accuracy is certified by the manufacturer to be ±10% for Cs-137. The dosimeter includes a number of audible and visual alarms for dose, dose rate, and other parameters that are user configurable via an infrared interface and associated software.

6.3.10.2.2.2 Digital/Personal Alarm Dosimeter (DAD/PAD).

CAUTION

- Geiger Mueller tubes will saturate at high dose rates (R/hr). They are never to be used in areas where dose rates can reach these levels. The DAD/PAD is a solid-state dosimeter that uses a halogen-quenched, filtered Geiger-Mueller (GM) tube for detecting and measuring radioactivity. The GM tube converts the radiation detected into pulses, which are fed to an amplifier and then to a pulse-division circuit which produces an output to the digital display counter whenever pulses equivalent to one dose increment have been accrued. At the same time, the division circuit output actuates the audible system and emits a “chirp” for each dose increment. The radiation is recorded normally in dose increments of 0.25 mR to 1 mR units.
- The DAD/PAD is a direct reading dosimeter that is approximately the size and shape of a typical telephone-paging unit. It provides both a visual and audible indication in direct proportion to radiation-intensity/dose-rate. The term “chirper” is also used as a common name for this type of dosimeter because of the audible sound emitted when operated in the presence of radiation. The DAD/PAD SHALL be worn between the neck and waist on an outer garment. It MAY also be worn on a belt provided the DAD/PAD’s securing clip is designed for attachment to a belt.

6.3.10.2.2.3 Some units of this type are equipped with a chirp rate switch allowing the user to select a low or high chirp rate. In the low position, each dose increment produces one chirp; in the high position, each increment produces about 40-chirps, giving a more immediate audible warning at relatively low exposure rates. For example, at an exposure rate of 10 mR/hr, the unit will chirp about every 6-minutes in low position and about every 10-seconds in the high position.

6.3.10.2.2.4 The alarm dosimeter has a case usually constructed from aluminum or high impact plastic. The DAD/PAD is lightweight (8-ounces or less), has a corrosion-resistant surface coating and operates on a 9-volt alkaline battery for up to 6-months of normal use.

6.3.10.2.2.5 Operation is very simple: turn the unit on. Some units reset the display each time the unit is turned on; others require resetting the display with a reset switch or button. A memory is available on some models, which allows the unit to be turned off without losing the stored dose. This feature permits a single daily recording of the wearer’s exposure dose because the dosimeter will continue to monitor exposure to the radiation without having to record each exposure dose if operations are stopped and resumed several times in a day’s operation.

NOTE

Dosimeter reading for each individual SHALL be entered on the utilization log at the beginning and end of the workday.

6.3.10.2.2.6 Any time a DAD/PAD is used by a different radiographer, it SHALL be reset to zero prior to use. Each radiographer SHALL wear a single DAD/PAD, which has been reset to zero prior to the start of each day's operation and calibrated in accordance with specific equipment technical data. A reading MAY be obtained at any time while working in a radiation area by simply pushing a read button to view the accumulated dose on the readout display.

6.3.10.2.3 Victoreen Model 885 PAD. This is another example of the alarm dosimeter. It detects gamma and X-rays over a range of 0-999 mR (0-10 mSv) by integrating radiation exposures. It provides both a visual and audible indication and "chirps" in direct proportion to radiation intensity/dose rate with "chirps" at the rate of one chirp per 0.025 mR. Using one 9V alkaline battery, the PAD will operate for 30-days continuously or for 120-days at 8-hours per day. (Low battery indicator denotes when battery life drops below 100-hours.)

NOTE

The Model 885 PAD SHALL be worn under outer garments when conducting operations during cold weather as it is designed to function properly only when the lower operating temperature is above 32°F (0°C).

6.3.10.3 Survey Instruments. Radiation exposure, at the energies used for industrial radiography, is most accurately measured with ionization chamber type survey instruments. These detectors use an air filled chamber across which an electric field is applied. When X-ray or gamma radiation interacts with the air in the chamber, it creates positive and negative ions that drift apart under the influence of the electric field. As the ions are collected on the electrodes within the chamber, a small current is generated which is measured by the instrument and directly related to the radiation exposure rate in air. For additional safety-related information, see Section VIII for Air Force, and Section IX for Army.

6.3.10.3.1 Characteristics. Radiation exposure measurement instrumentation SHALL have a range suitable for the conditions of use. Accordingly, all survey instruments used for industrial radiography "SHALL be capable of measuring a range from 2 mrem/hr (0.02 mSv/hr) through 1 rem/hr (0.01 Sv/hr), as a minimum" (10 CFR 34.25).

6.3.10.3.2 Environmental Interference. Portable survey instruments are affected by such factors as ambient temperature, configuration of radiation source (e.g., round, square, rectangular, etc.), isotope source, atmospheric pressure and relative humidity, direction of radiation beam, radiation quality (effective energy or radiation spectra), and instrument susceptibility to radio frequency radiation (RFR). Instrument response variations due to temperature and pressure usually do not exceed ±5% for survey instruments. Instrument directional dependence is negligible when the instrument's sensitive volume is pointed in the direction of the radiation origin. Instrument susceptibility to RFR MAY significantly affect ionizing radiation measurements in the presence of RFR. If RFR interference is suspected, it can often be confirmed by placing a piece of leaded (Pb) rubber or similar shielding material over the ionization chamber of the instrument to filter out the gamma or X-ray, while observing the instrument reading. If no change is noticed in the instrument response when the lead is placed over the chamber, the previous instrument response can be primarily attributed to RFR interference.

6.3.10.3.3 Survey Meter Response to a Spectrum of Energies. An X-ray machine operating at a given tube potential (kVp), produces a spectrum of X-ray energies. Since industrial X-ray machines do not contain primary beam filtration (except the X-ray tube window), the X-ray spectrum contains a relatively large portion of low energy X-rays (below 50 keV) regardless of the tube potential (kVp) setting employed. Therefore, it is important that the survey instrument used in determining the exposure rate produced by such X-ray machines be energy independent or, in other words, capable of accurately measuring the exposure rate over a wide range of X-ray energies.

6.3.10.3.4 Descriptions and Operating Characteristics of Specific Instruments.

NOTE

The Nuclear Research Corporation SM-400 end cap contains a lever-operated alpha/beta check source to verify instrument operation each time it is used.

6.3.10.3.4.1 The 440, 450B, 450P, SM-400, and the VR-10 are similar in size, appearance, and specifications. All are authorized for use during NDI radiographic operations.

6.3.10.3.4.2 These instruments are, for practical purposes, energy independent from 15 keV to 1.2 MeV with their front caps removed.

6.3.10.3.4.3 The batteries for the 440 and VR-10 consist of four "D" flashlight cells. Each instrument weighs approximately 5- 1/2-pounds and its overall dimensions are 10-inches long, 4-inches wide, and 7-inches high. The SM 400 uses two "D" flashlight cells and weighs approximately 5-pounds. Its overall dimensions are 10-inches long, 4.5-inches wide, and 7-inches high.

6.3.10.3.5 Recommended Instruments. The Victoreen Model 440, Nuclear Research Corporation SM400, and the Heat Pipe Model VR-10 survey meters have been standard instruments authorized for use in the Air Force as noted in AS-455 for industrial radiography. Suitable replacement instruments include Victoreen models 440RF/D, 450, 450B, and 450-CHP; ThermoEberline models SHP-400 and RPO-20; Inovision Radiation Measurements models 451B and 451P survey meters. Other survey instruments (Ion chambers) MAY also be considered providing they have been approved by the local Base RSO and USAFSAM/OEHHH(Air Force). For additional safety-related information, see Section VIII for Air Force, and Section IX for Army.

6.3.10.3.5.1 Victoreen Model 450P Survey Meter. The Model 450P is a lightweight portable survey meter designed to measure X-ray above 25 keV. It has a five-decade operating range from 0-5 mR/hr (0-0.05 Sv/hr) on the lowest scale to 0-5 R/hr (0-50 mSv/hr) on the highest scale and has a programmable “flash alarm” which causes the display to pulsate at a rate of once per second when the measured dose rate exceeds a preset limit. The detector is a 300-cc ionization chamber pressurized to 6 atmospheres. The Model 450P measures exposure, exposure rate, and can be used to “freeze” the maximum exposure rate encountered and displays results on an illuminated analog/digital display. For maximum sensitivity, the Model 450P survey meter SHOULD be perpendicular to the ground plane when making measurements rather than being parallel to the ground. The Model 450P is considered Hazardous Material for shipping purposes because of the pressurized ion chamber and must be shipped to TMDE accordingly.

6.3.10.3.5.2 Victoreen Model 450B and 450-CHP Survey Meters. The Model 450B and 450-CHP survey meters are similar instruments that detect gamma and X-ray radiation above 7 keV. Both have a five-decade operating range measuring from 0-5 mR/hr (0-0.05 mSv/hr) to 0-50 R/hr (0-0.5 Sv/hr). The detector for both instruments is a 349-cc air ionization chamber that has a 200 mg/cm^2 bakelight wall and a 1.7 mg/cm^2 mylar window. They operate continuously for about 200 hours on a set of two new 9-volt batteries. The Models 450B and 450-CHP SHOULD always be used with the cap off when measuring X-ray and gamma radiation with energies below 200 keV due to energy response variation.

6.3.10.3.5.3 Victoreen Model RPO-50 Survey Meter. The Model RPO-50 has similar controls compared to the SM- 400, and Victoreen 440, but has significantly improved performance characteristics. It detects gamma and X-ray radiation above 7 keV. The Model RPO-50 has four operating ranges, measuring from 0-5 mR/hr (0-0-50 mSv/hr) to 0-5 R/hr (0-0.05 Sv/hr). The detector is a 349-cc air ionization chamber that has a 493-mg/cm ^{2}bakelight wall and a 3.5 mg/cm ^{2}window. It operates continuously for about 3000-hours on a set of four new 9-volt batteries. It is environmentally sealed and has limited RF shielding, permitting its use in demanding environments.

NOTE

The Model RPO-50 SHOULD always be used with the cap off when measuring X-ray and gamma radiation with energies below 200 keV due to energy response variations.

6.3.10.3.6 Recommended Survey Instruments for Use in RF Fields.

6.3.10.3.6.1 Victoreen Model 440 RF/D Survey Meter. The Model 440 RF/D survey meter is specially designed to be used in strong radiofrequency radiation fields up to 20 mW/cm^2. It detects gamma and X-ray radiation above 12 keV. The Model 440 RF/D has 5 operating ranges, measuring from 0-1 mR/hr (0-0.01 mSv/hr) to 0-100 mR/hr (0-1 mSv/hr). The detector is a cylindrical 3.56 cm diameter, 10-cm^2 cross-section air ionization chamber that has a 1.5 mg/cm^2 mylar window and a 13 mg/cm^2 magnesium window. It operates continuously for about 200-hours on a set of five new 9-volt batteries. The model 440 RF/D includes an internal check source to verify correct system operation. The instrument does have a significant variation in energy response, requiring the instrument reading to be corrected dependent on the kVp of the X-ray system being surveyed.

Table 6-9. Recommended Survey Instruments and Relative Energy Response

Instrument	Percent Relative Response					
Effective Energy (keV)	22	32	70	120	170	663 [1]
Nuclear Research Corp. Model SM400 Cap off	100	105	108	108	107	96
Nuclear Research Corp. Model SM400 Cap off	100	105	108	108	107	96
Victoreen Model 450B (Bottom cap off)	93	98	106	108	105	–
(Bottom cap on)	58	80	112	112	106	93
Victoreen Model 450P	55	88	106	104	103	103
Victoreen Model 440	94	104	116	118	116	100

NOTE

When monitoring radiation fields using instruments with caps, the caps SHOULD be removed. The caps SHOULD be replaced after use. The thin mylar cover at the end of the ionization chamber is easily punctured. If it is punctured, the instrument is inoperative and SHALL be repaired or replaced.

[1] 663 keV represents Cs-137, which is commonly used for calibration.

6.3.11 Radiographic Processing Equipment. Radiographic processing involves two basic modes, “manual” and “automatic” processing. A third mode, “digital” will be discussed later.

6.3.11.1 Manual Processing. In the case of manual processing, chemistry is placed in tanks of a suitable material. Films are affixed to corrosion resistant metal hangers, which are submerged in the chemistry during processing. Chemistry temperature needs to be controlled, and in some instances, is accomplished with an incoming water mixing valve. A separate electrical dryer unit is generally employed to dry the processed film.

6.3.11.2 Automatic Processor. Automatic dry-to-dry machine processing is in wide use today because it affords increased processing stability and results in significantly shorter total processing time. Most automatic processors incorporate mutually or simultaneously driven transport rollers. All of the rollers in the four processing stages of development, fix, wash, and dry are driven at the same speed and therefore turn together as the film is being transported between them.

6.3.11.2.1 Various sub-assemblies incorporated in automatic processors include developer, and in some instances fixer temperature control units, a dryer heater fan, and automatic chemistry replenishment pumps.

6.3.11.2.2 Maintenance of Automatic Processors. Periodic inspection, maintenance, and lubrication of radiographic film processing equipment is required by the technical manual governing its operation. It is imperative the prescribed daily, bi-weekly, and monthly requirements be strictly followed to ensure proper operation of equipment and to support quality radiographic inspection results. With appropriate maintenance, automatic processors SHOULD give reliable and repeatable service for long periods of time.

6.3.12 Film Evaluation Equipment.

6.3.12.1 Densitometer. Measurement of radiographic density SHALL be done with electronic direct-reading type densitometers. The electronic direct-reading type densitometer is more accurate than the visual type. This densitometer SHALL be capable of measuring the light transmitted through a radiograph with a film density up to 4.0 with a density unit resolution of 0.02. When film densities greater than 4.0 are required to perform a radiographic inspection a densitometer applicable to film densities up to maximum density is necessary.

6.3.12.1.1 Film Density Reference Strip. A photographic or radiographic-calibrated reference density strip, traceable to the National Institute of Standards and Technology (NIST), SHALL be used to calibrate the densitometer prior to determining the density of a radiograph. These calibrated density strips SHALL be replaced whenever they are physically damaged (e.g., scratched, crimped, or become wet by any fluid) to such an extent it may influence their effectiveness.

6.3.12.2 Illuminators/Viewers. For information (paragraph 6.5.10.6).

6.3.13 Digital Radiographic Viewing, Storage, Archival, and Printing Systems.

6.3.13.1 Viewing Systems. Digital radiographs are viewed on systems primarily designed for digital radiography. The systems differ from ordinary image processing systems for home and photographic use in that they are tailored specifically for radiography. Systems SHOULD provide at least all the functionality discussed in this section to allow you to be an effective digital radiographer. Hardware for digital radiography is designed with radiography in mind, the computer for running the software and the interfaces to the acquisition hardware are all specialized pieces of equipment designed to handle large radiographic images with little chance of data corruption or image alteration.

6.3.13.1.1 Generally, grayscale monitors are used for digital radiography with a portrait oriented large screen and a high dynamic range to display radiographic data in the most meaningful way. High resolution and bright color monitors are also in use and add the capability to use color processing techniques to visualize the radiographic data as well as provide support for text and vector graphic color annotations on images. Ten bit monochrome monitors provide significantly more shades of gray to produce a smoother image and greater appearance of sharpness. 10 bits in a 2048 x 1536 is considered a 3 mega pixel monitor.

6.3.13.2 Storage Systems. Storage for the digital radiographs range from hard drives to magnetic tape systems. Currently CDs are the media of choice, but these are quickly being replaced by DVDs, which hold much more data than a CD. Most digital radiographs opt not to compress their images at all and store the original raw data. It is always recommended a backup copy of digital data is kept at all times.

6.3.13.3 Archival Systems. Archival and retrieval systems are gaining popularity for radiographers that generate large amounts of digital radiographs. These systems are usually comprised of a database and storage mechanism connected over a network. They make searching for an image easy through database commands at the workstation and deliver the image to the viewer upon request with the actual storage media used unknown at times to the radiographer so he or she need never worry about disk space, etc.

6.3.13.4 DICONDE. An emerging standard for industrial digital radiography (and other digital images for nondestructive testing) is known as “DICONDE” -Digital Image Communication for Nondestructive Engineering, and is based upon the already well established DICOM protocol. This standard defines the manner in which image acquisition hardware, software, databases and archival system and printers SHOULD communicate. It also sets standards for data associated with a digital image and a universal file format and protocol so equipment by varying vendors will work with each other.

6.3.13.5 Printing. Digital images allow for the easy replication of hardcopy data either on film or paper. There are several digital film printers available at varying prices so you can produce a hardcopy film from a purely digital image. Some systems use chemicals similar to standard film processors, but more common are the systems which use either dye sublimation or thermal films for the hardcopy output of digital radiographs. Most digital radiographers forego the use of a film printer as in most cases, it is unnecessary in modern digital radiographic labs.