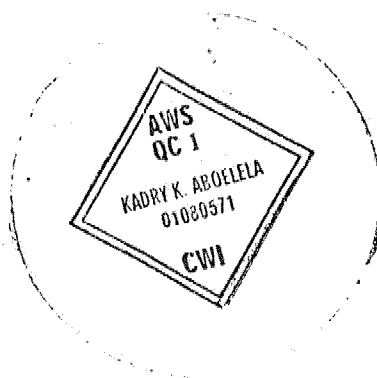


ASNT Level III Study Guide Radiographic Testing Method

second edition

by Timothy Kinsella



The American Society for Nondestructive Testing, Inc.

ASNT Level III Study Guide: Radiographic Testing Method

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Foreword

The American Society for Nondestructive Testing, Inc. (ASNT) has prepared a series of *Level III Study Guides* which are intended to present the major areas in each nondestructive testing method. They can be used to prepare for taking ASNT NDT Level III tests or an employer's inhouse Level III tests. The Level III candidate should use this *Study Guide* as a preparation tool, even though it does not contain all of the information an ASNT NDT Level III is expected to know.

Since the last printing of this *Study Guide*, there have been significant advances in radiography. These advances are found primarily in the area of digital methods that are experiencing increasing widespread usage. The same depth of understanding is required for these processes as for the corresponding film processes including image acquisition (either latent or direct), display of the image (corresponding to film development), and viewing and interpreting images and image quality.

The material in this *Study Guide* provides a review of the body of knowledge for the radiographic testing method. Because this guide provides only an overview of the subject matter, the Level III candidate should use it as one of several preparation tools. To be most effective this *Study Guide* should be coordinated with the Level III Topical Outline for the Radiographic Testing Method in the most recent edition of *Recommended Practice No. SNT-TC-1A*. It should also be used in combination with *Nondestructive Testing Handbook*, third edition: Volume 4, *Radiographic Testing, Supplement to Recommended Practice No. SNT-TC-1A (Q&A Book): Radiographic Testing Method* and the other references listed on page ix.

Because the preparation of this *Study Guide* was not coordinated with the actual exams, it should be noted that there may be questions on the exams that cover material not included in this publication, and there may be material in this guide that does not appear on the exams.

In using this *Study Guide*, specific references are cited where detailed information can be obtained. The source documents used in this *Study Guide* are listed in *References* on page ix. Typical Level III questions at the end of each section serve as a benchmark for determining a candidate's comprehension of the material.

A typical use of this *Study Guide* might include the following steps:

1. Review the questions at the end of each section to assess your comprehension of the radiographic testing method.
2. If the questions in a certain section are found to be difficult, carefully study the information presented in that section as well as the cited reference material. This review of the information in the *Study Guide* will refresh your memory of theory and facts long forgotten.

ASNT is an International System of Units (SI) publisher. Units of measure throughout this book are provided in SI units followed by cgs units in parentheses. A typical conversion would be 5 cm (2 in.). To accommodate equations in this *Study Guide*, some conversions have been made with differing significant figures. For example, 5 cm may be converted to 1.97 in. and 16.65 cm may be converted to 6.56 in.

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Chapter 1

Basic Physics of Radiography

Elementary Particles

The Electron

The *electron* is an elementary particle that is present in all atoms in groupings called *shells* around the nucleus. When they detach from the nucleus they are called *free electrons*. The antiparticle of the electron is the *positron*. An *antiparticle* is a subatomic particle that has the same mass number as another particle and equal but opposite values of some other property or properties. For example, the antiparticle of the electron is the positron, which has a positive charge equal in magnitude to the electron's negative charge.

The Proton

The *proton* is an elementary particle that is stable and bears a positive charge equal in magnitude to that of the electron. The proton occurs in all atomic nuclei (the hydrogen atom contains a single proton).

The Neutron

The *neutron* is a neutral particle that is stable in the atomic nucleus but decays into a proton and electron, and an antineutrino with a mean life of 12 minutes outside the nucleus. Neutrons occur in all atomic nuclei except normal hydrogen.

Atomic Structure

An *atom* is the smallest part of an element that can exist and consists of a small dense nucleus of protons and neutrons surrounded by moving electrons. The number of electrons equals the number of protons so the overall charge is 0. Electrons may be thought of as moving in circular or elliptical orbits or, more accurately, in regions of space around the nucleus. Electrons are arranged in shells at various distances from the nucleus according to how much energy they

have. These shells are identified by the letters K, L, M, N, O, P and Q with K being the closest to the nucleus. Each shell can hold only a certain maximum number of electrons; the K shell can hold no more than 2, the L shell no more than 8, shell M no more than 18, shell N no more than 32, shell O no more than 50, shell P no more than 72 and shell Q no more than 98.

Atomic Number

The *atomic number* is the number of protons in the nucleus of an atom. The atomic number is equal to the number of electrons orbiting the nucleus in a neutral atom. The symbol for atomic number is Z.

Mass Number

The *mass number* is the sum of the protons and neutrons in an atom. Although all atoms of an element have the same number of protons, they may have different numbers of neutrons. Atoms that have the same number of protons but different numbers of neutrons are called *isotopes*.

Atomic Weight

The *atomic weight* is the weight of an atom expressed in *atomic mass units* (amu). One atomic mass unit equals 1/12 the weight of an atom of C-12. For most atoms the weight in atomic mass units is extremely close to the mass number.

Isotope

An *isotope* is an atom with a specific atomic number and mass number. Each atomic number element may exist with different mass number and these are *isotopes*. For example, hydrogen (1 proton, no neutrons), deuterium (1 proton, 1 neutron), and tritium (1 proton, 2 neutrons) are isotopes of hydrogen. Some isotopes are stable while others are unstable and change state by radioactive decay.

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Electromagnetic Radiation

The Photon

Electromagnetic radiation occurs in the form of individual packets of energy called *photons*. When photons travel through space, they appear as continuous electromagnetic waves. However, when photons of radiation strike a substance, they behave as if they were separate particles of energy instead of a continuous wave. Each photon has a certain amount of energy that is proportional to its frequency.

X-rays

X-rays are produced whenever high energy electrons suddenly give up energy. This can be done either by accelerating electrons to a high speed and then stopping them suddenly, or by these high speed electrons striking others and knocking them out of their normal positions. When these dislodged electrons fall back into place, they give off X-rays. The position of X-rays in the electromagnetic spectrum is shown in Figure 1.1.

Gamma Rays

Gamma rays are similar to X-rays except that they have a much shorter wavelength and differ in their origin. Gamma rays are emitted from the nucleus itself during the process of radioactivity. The position of gamma rays in the electromagnetic spectrum is shown in Figure 1.1.

Radioactivity

In some atoms, the nucleus changes naturally. The change may be only in the arrangement of the protons and neutrons, or the actual number of protons and neutrons may change. These changes

give off radiation that consists of alpha or beta particles or gamma rays. The type of radiation given off depends on the way the nucleus changes. Gamma rays are given off if only the arrangement of the protons and neutrons changes. Alpha and beta particles may also be given off if the number of protons and neutrons changes.

Alpha Particles

An *alpha particle* is a He-4 nucleus emitted by a larger nucleus during the type of radioactive decay known as *alpha decay*. Because a He-4 nucleus consists of two protons and two neutrons bound together as a stable entity, the loss of an alpha particle from a larger nucleus involves the decrease in nucleon (protons and neutrons) of 4 and a decrease of 2 in the atomic number. For example, a U-238 nucleus decays into a Th-234 nucleus.

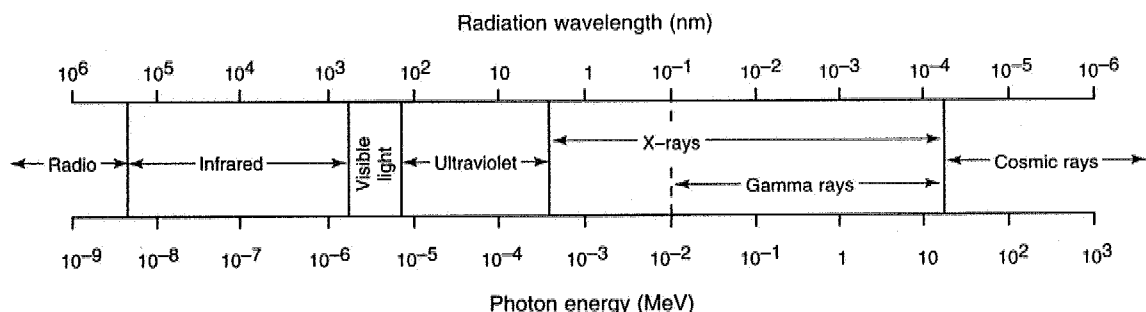
Beta Particles

Beta particles are the electrons or positrons emitted during *beta decay*, in which an unstable nucleus changes into a nucleus of the same mass number, but different proton number. The change involves the conversion of a neutron into a proton with the emission of an electron and an antineutrino ($n \rightarrow p + e^- + \bar{\nu}_e$) or of a proton into a neutron with the emission of a positron and a neutrino ($p \rightarrow n + e^+ + \nu_e$). An example is the decay of C-14.

Radioactive Decay

This is the spontaneous transformation of one radioactive material into another with the emission of one or more particles or photons. The resulting material may or may not be radioactive. The time required for half the original material to

Figure 1.1: Electromagnetic spectrum.



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Chapter 1: Basic Physics of Radiography

decay is called the *half life*. For example half of a given quantity of Co-60 is converted to stable Ni-60 in 5.26 years. In another half life (5.26 years), one quarter of the original Co-60 remains and three quarters of the original quantity is now Ni-60. This can be described mathematically as follows:

$$N_t = N_0 e^{-\lambda t}$$

Equation 1

where:

N_t = quantity at time t ,
 N_0 = original quantity,
 λ = decay constant,
 t = decay time.

Because the decay constant is equal to $0.693/T$ when the quantity has decreased to $1/2$ the original amount, the half life of a radioactive isotope is defined as:

$$T_{1/2} = \frac{0.693}{\lambda}$$

The decay equation may then be written as:

$$N_t = N_0 e^{-0.693t/T}$$

Equation 2

Other half lives of particular interest to radiography are 74 days for Ir-192 and 30.1 years for Cs-137.

Activity

Activity is the number of atoms of a radioactive substance that disintegrate per unit time, the specific activity of the activity per unit mass of a pure radioisotope. The becquerel (Bq), the SI unit of activity, represents one spontaneous transition per second.

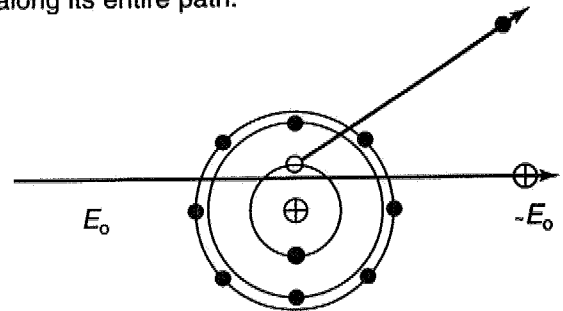
Thus $1 \text{ Bq} = 1 \text{ s}^{-1}$. The former unit, the curie (Ci), is equal to $3.7 \times 10^{10} \text{ Bq}$.

Radiation Interaction with Matter

Ionization

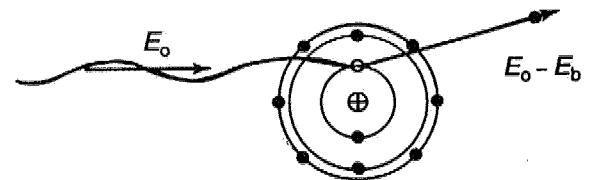
An *ion* is an atom that has either lost one or more electrons, making it positively charged, or gained one or more electrons, making it negatively charged. In the context of radiography, *ionization* occurs when an atom or molecule loses one or more electrons as a result of energy gained

Figure 1.2: Ionization by an alpha particle that ejects an orbital electron from the atom. Specific ionization is the number of ion pairs generated by particle per unit path. Total ionization designates the number of ion pairs produced by a particle along its entire path.



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Figure 1.3: Photoelectric interaction of an incident photon with an orbital electron.



Legend

E_b = energy binding electron to atom
 E_0 = original energy of photon

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in a collision with another particle or quantum of radiation. See Figure 1.2.

Photoelectric Effect

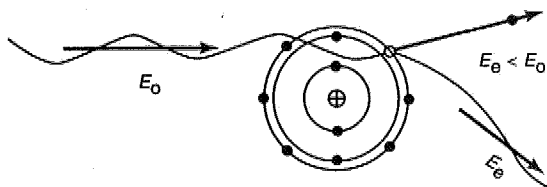
The *photoelectric effect* is the liberation of electrons from a substance exposed to electromagnetic radiation. The number of electrons emitted depends on the intensity of the radiation. The kinetic energy of the electrons emitted depends on the frequency of the radiation. The photoelectric effect usually occurs at photon energies below about 0.3 MeV. See Figure 1.3.

Compton Effect

Compton scattering is a process in which moderate energy photons (about 0.3 to 3.0 MeV) lose part of their energy to an electron. This

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Figure 1.4: Compton scattering. Incident photon ejects an electron and ejects a lower energy scattered photon.

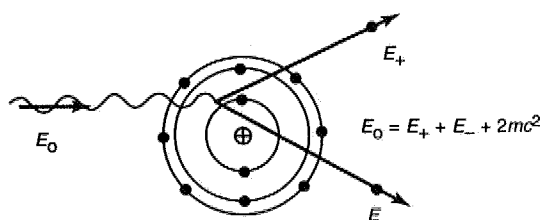


Legend

E_e = lower energy of scattered photon
 E_0 = original energy of photon

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Figure 1.5: Pair production of an electron and a positron from an incident photon.



Legend

c = speed of light
 E = energy of incident photon
 E_+ = energy of positron
 E_- = energy of negative electron
 m = electron mass

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process results in an ejected electron and a lower energy photon as shown in Figure 1.4. The photon may leave the atom in any direction relative to its incident direction, hence the term scatter. The lower energy photon leaving the Compton interaction may experience another Compton or photoelectric interaction, depending on its energy.

Pair Production

Pair production is the creation of an electron and a positron resulting from the interaction of a high energy photon (greater than 1.02 MeV) and a nucleus as shown in Figure 1.5. The creation of the two particles requires 1.02 MeV, which is then the threshold energy for the conversion. Any energy above this amount is shared by the two particles as kinetic energy.

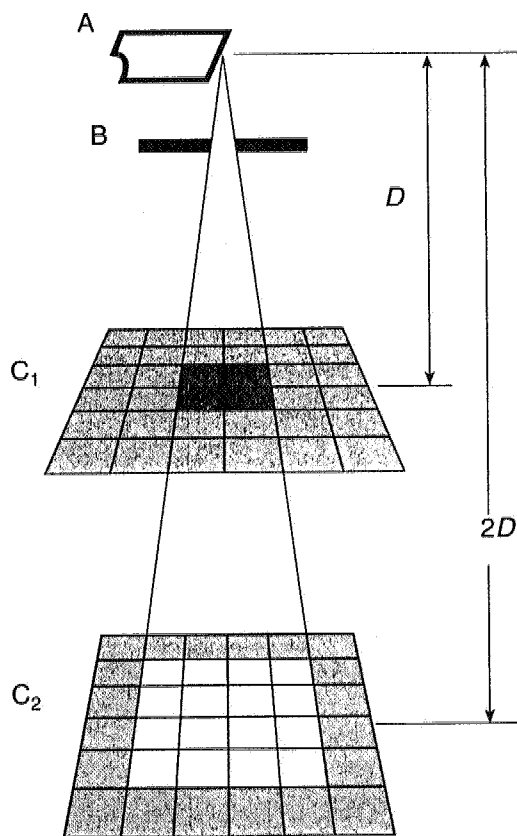
Rayleigh Scattering

In this type of scattering incident photons are deflected by the atoms and molecules without any change of energy. This *rayleigh*, or *coherent*, scattering is important for low energy radiation. Coherent scatter may remove as much as 20% of the incident photons from a beam.

Attenuation

The processes listed above, as well as a few others of general less importance, produce attenuation of the radiation. The *attenuation* of beta particles, neutrons, X-ray photons and gamma photons can be described by similar mathematical expressions of the form:

Figure 1.6: Schematic diagram illustrating the inverse square law.



Legend

A = radiation source
B = focal point
C₁ = first film plane
C₂ = second film plane
D = source-to-film distance

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$$I = I_0 e^{-kd}$$

Equation 3

Inverse Square Law

The *inverse square law* describes the reduction in radiation intensity with distance, when no absorber is present and the source of radiation approximates a point. In such a case, the radiation intensity decreases as the square of the distance from the source; i.e., inversely with the square of the distance. This principle is illustrated in Figure 1.6. The inverse square law is expressed mathematically as

$$\frac{I_1}{I_2} = \left(\frac{D_2}{D_1} \right)^2$$

Equation 4

where the subscripts 1 and 2 refer to different points along a line radiating from the source. Because of this inherent characteristic of radiation, if the radiation has a certain intensity at 1 m from the source, it will have four times that intensity at 0.5 m, but only one quarter that intensity at 2 m and only one ninth that intensity at 3 m.

Chapter 1 Review Questions

- 1.1 In the SI system, the distinction between upper and lower case letters is meaningful and should be observed. For example, the meanings of the prefix m (milli) and the prefix M (mega) differ by how many orders of magnitude?
- 3
 - 6
 - 9
 - 12
- 1.2 Which of the following formulas describes the inverse square law?
- $\frac{I^1}{D^1} = \frac{I^2}{D^2}$
 - $\frac{I_1}{D_1^2} = \frac{I_2}{D_2^2}$
 - $\frac{I_2^1}{D^1} = \frac{I_2^2}{D^2}$
 - $(I^1 D^1)^2 = (I^2 D^2)^2$
- 1.3 If one eighth of a sample of radioisotope remains after 24 years, what is the half life of the radioisotope?
- 3 years
 - 4 years
 - 6 years
 - 8 years
 - 12 years
- 1.4 A positively charged particle with a mass equal to the electron is the:
- proton.
 - positron.
 - meson.
 - deuteron.
- 1.5 The number of protons in the nucleus is called the:
- atomic mass.
 - atomic weight.
 - atomic number.
 - relative atomic mass.
- 1.6 What particle is identical to the electron in rest mass and rest energy, with a positive charge numerically equal to the electron's negative charge?
- positron
 - neutrino
 - quark
 - lepton
- 1.7 Emission of an alpha particle decreases the mass of the nucleus by ____ and the atomic number by ____.
- 4, 4
 - 4, 2
 - 2, 2
 - 2, 4
 - 2, 1
- 1.8 After 4 half lives, what percentage of a radioisotope's life remains?
- 25%
 - 12.5%
 - 6.25%
 - 3.12%
- 1.9 The reduction in the energy of photons when they are scattered by free electrons which thereby gain energy is called:
- the photoelectric effect.
 - compton scattering.
 - pair production.
 - None of the above.

Chapter 1: Basic Physics of Radiography

- 1.10 Beta particles are identical to high speed electrons with the following exception that:
- they may be either positively or negatively charged.
 - they have twice the rest mass.
 - they have opposite spin and magnetic moment.
 - they have twice the Compton wavelength.
- 1.11 Which of the following is not one of the three major photon attenuation processes?
- Compton scattering
 - photoelectric effect
 - pair production
 - electron capture
- 1.12 In the SI system, the unit of energy is the:
- joule.
 - pascal.
 - newton.
 - watt.
- 1.13 An alpha particle is:
- one particle in the class of particles called *leptons*.
 - identical to a helium nucleus.
 - a type of quark.
 - very small compared to other particles.
- 1.14 A semilogarithmic plot of the percent of radioactive material remaining versus time results in:
- an ellipse.
 - a hyperbolic curve.
 - a quadratic curve.
 - a straight line.
- 1.15 The creation of a positron and an electron from the interaction of a photon with an energy of at least 1.02 MeV, and a strong electric field such as that surrounding an atomic nucleus, is called:
- the photoelectric effect.
 - Compton scattering.
 - pair production.
 - None of the above.
- 1.16 Emission of a beta particle changes the mass of the nucleus by ____ and the atomic number by ____.
- 0, 1
 - +1, 1
 - 1, 1
 - 1, 0
- 1.17 A particle with no rest mass, no charge and no magnetic moment is a:
- photon.
 - deuteron.
 - neutrino.
 - meson.
- 1.18 ANSI, ASNT, ASTM, IEEE, ISO and NIST all support the replacement of the older English units of radiation measurement with SI units. The new units that replace the curie, roentgen, rad and rem are:
- joule, newtons per kilogram, gray and sievert.
 - becquerel, newton-meter, coulomb and sievert.
 - joule, becquerel, coulomb and sievert.
 - becquerel, coulomb per kilogram, gray and sievert.
- 1.19 What is meant by the dual nature of the photon?
- It has both charge and mass.
 - It behaves as both a particle and a wave.
 - It has both spin and charge.
 - It can produce both ionization and decay.
- 1.20 The atomic mass is:
- the number of protons and neutrons in the nucleus.
 - the cumulative weight of nucleons and electrons in an atom.
 - the rest mass of all particles that an atom consists of.
 - None of the above.

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- 1.21 The liberation of electrons from a substance exposed to electromagnetic radiation is called:
- a. the photoelectric effect.
 - b. compton scattering.
 - c. pair production.
 - d. None of the above.
- 1.22 Which of the following is not one of the five primary modes by which atoms disintegrate?
- a. emission of an alpha particle
 - b. emission of a beta particle
 - c. quantum scintillation
 - d. spontaneous fission

Chapter 2

Shielding and Facility Design

Most national regulations on radiological protection have a number of safety requirements. The main points are summarized below, but it is emphasized that for full details of the necessary procedures, particularly the certifications required, the formal legal documents and codes for each location or country must be studied.

Radiation Attenuation

The attenuation of alpha and beta radiation of less than 2 to 5 MeV is relatively straightforward and is treated extensively in the references. This discussion of radiation attenuation will be directed toward penetrating photon radiation.

The absorption of X-radiation and gamma radiation is the consequence of a series of single events. During each such event a photon is removed from the beam after undergoing an interaction with an atomic nucleus or an orbital electron. The primary interactions that occur are photoelectric absorption, Compton scattering and pair production. The probability for absorption or scattering for any particular radiation type and energy with a specific element is referred to as the *cross section*.

Although there are three forms in which attenuation coefficients are expressed, atomic attenuation coefficient, mass attenuation coefficient and linear attenuation coefficient, only the last is used extensively in practical shielding calculations. The *linear attenuation coefficient* is the probability per unit path length that a photon will be removed from the beam. The linear attenuation coefficient is usually expressed in reciprocal centimeters (cm^{-1}) and in equations represented by the symbol μ . The linear attenuation coefficient can be determined from the mass attenuation coefficient by multiplying by the density of the material.

Half-Value and Tenth-Value Layers

A convenient practical measure of radiation attenuation is the half-value layer (HVL). The half-value layer of any specific material is that thickness that will reduce the radiation intensity to one half its initial value. Half-value layer is related to the linear absorption coefficient by

$$\text{HVL} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$$

Equation 5

Similarly, a tenth-value layer (TVL) is that thickness of material that will reduce the radiation intensity to one tenth its initial value. Half-value layer and tenth-value layer are related as follows:

$$3.33 \text{ HVL} = 1 \text{ TVL}$$

Equation 6

Therefore if the half-value layer for a particular material were 5.00 cm (1.97 in.) the corresponding tenth-value layer would be 16.65 cm (6.56 in.).

Tables of half-value and tenth-value layer thicknesses for common materials and radiation sources such as cobalt, iridium and X-rays of various energies are available in references 1, 2 and 3.

Attenuation Equation and the Buildup Factor

The attenuation of penetrating photon radiation is exponential and the intensity I transmitted through an absorber (shield) can be expressed as

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

Equation 7

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where:

I_0 = the initial intensity,
 μ = the linear absorption coefficient, and
 t = the absorber thickness.

A useful manipulation of the attenuation equation that will allow straightforward calculation of the absorber thickness, is

$$\ln \frac{I_0}{I} = \mu t$$

Equation 8

This attenuation equation is based on narrow beam measurements, which assume that the only radiation reaching the detector has been scattered through an angle of less than 0.01 steradian. In actual practice, broad beam conditions exist and, as a result, much more scatter reaches the detector.

To correct the attenuation equation for broad beam conditions, a simple multiplicative correction factor is used. This correction is referred to as the buildup factor B and the resulting equation is expressed as

$$I = I_0 B e^{-\mu t}$$

Equation 9

The buildup factors for specific materials and photon energies may be found in the literature and can be approximated by

$$B = 1 + \mu t$$

Equation 10

The buildup factor is dependent on the atomic number Z of the absorber and the energy of the initial photon.

Facility Design Considerations

Reference 1 has radiation transmission tables and graphs for various commonly used X-ray energies, radioisotopes and specific shielding materials such as lead, concrete and steel.

Workload

Radiography facility workload is defined as the number of milliamperere minutes per week for X-ray devices and the number of becquerel minutes (curie minutes) per week for

radioisotope devices. Examples of workload determination are as follows.

Example A:

- Estimated 400 exposures per week at 300 kV.
- Average 50 mA-min per exposure.

Therefore the projected workload is
20 000 mA-min per week.

Example B:

- Estimated 400 exposures per week with Ir-192.
- Average 48.15 GBq-min (4 Ci-min) per exposure.

Therefore the projected workload is
19 260 GBq-min (1600 Ci-min) per week.

Occupancy and Use Factors

Estimated use and occupancy factors should be supplied to the facility designer by the Level III. The *use factor* is that percentage of the time that the direct or scatter beam will be directed toward any particular wall, ceiling or floor of the radiography exposure cell.

If the radiation producing equipment is installed in such a manner that the direct beam is physically restricted from impinging on that wall, then that wall may be classified as a *scatter wall*, which will greatly reduce the amount of required shielding.

If the exposure cell is to be used for panoramic exposures or if complete freedom to direct the beam at any wall is desired, then all walls should be considered as *direct beam walls*. This choice, although offering the ultimate in facility versatility, could easily cause the shield cost to increase by 400% to 500%.

Typical use factors vary from 1/5 to 1, depending on the intended portion of the workload to be directed toward a particular shield.

Occupancy factors are equally important because they cause the shield thickness to be greatly increased or reduced. If an area adjacent to the exposure cell is a normal work station, then the occupancy factor would probably be considered as 1, whereas an unattended parking lot would be classed as 1/4 and a sidewalk as 1/16.

Equipment Considerations

Knowledge of radiation producing equipment, including its mechanical and

Chapter 2: Shielding and Facility Design

electrical operating characteristics, is required to select and provide proper facilities. A knowledge of appropriate source-to-film distances, needs for fixturing of radiographic subjects, and determinations of the types of radiographic techniques that will probably be used is also needed. In addition, to ensure safety, establish operating instructions and obtain regulatory approval, provisions must be made for beam collimation, shutter mechanisms, high radiation interlocks and alarm systems.

The leakage radiation characteristics of X-ray tube housings and gamma ray exposure devices need to be known to ensure adequate protection of personnel when the source is shielded. *Leakage radiation* is defined as all radiation, except the useful or direct beam that emanates from the tube or source housing.

Whenever feasible, the direct beam should be collimated to as small an area as possible. Collimation achieves two objectives. It reduces the hazard of personnel exposure to radiation and greatly reduces the amount of scatter radiation reaching the film being exposed.

Determination of Shield Thickness

Facility shielding estimates can be performed by direct calculations using the attenuation equation or an equation developed for the transmission tables of reference 14.

The following equation may be used for both gamma and X-ray shielding:

$$B = 0.1 \frac{Pd^2}{WUT}$$

Equation 11

where:

- P = the permissible average weekly exposure for design purposes —normally 25.8 $\mu\text{C/kg}$ (0.1 R) for controlled areas and 2.58 $\mu\text{C/kg}$ (0.01 R) for environs or uncontrolled areas,
- d = the distance from the source to the position in question in meters (feet),
- T = the occupancy factor,
- U = the use factor,
- B = the permissible transmission of gamma radiation, and
- W = the workload (GBq per week).

Once B is determined, the specific semilog plot of transmission versus specific material

shield thickness may be used to determine the required thickness.

General Guidelines for Laboratories

If any door of a radiographic enclosure can be opened, means must be provided so that the equipment is automatically switched off and cannot be switched on while the door is open.

In a large radiographic enclosure there should be an emergency exit and it is mandatory to provide an emergency switch inside the enclosure to switch off the equipment.

Audible warnings or visible lights are required to give warning that equipment is about to be energized or a source exposed.

There should be a separate warning light to show when the source is emitting radiation. It is good practice to duplicate this light in all places where workers may have access around the enclosure.

Suitable warning notices of ionizing radiation, such as signs or barriers, are also required.

Safety Monitoring

On any radiation enclosure, however detailed the design, a radiation survey must be undertaken before use or after any alterations. This should be done with the source operating at its maximum output and pointing in all directions in which it is likely to be used.

With very high energy (megavoltage) equipment, short life radioactivity can be induced in some materials. After long exposure at such energies it is desirable to monitor the level of any activity before handling the specimens. For example, the thresholds for inducing radioactivity are 5.0 MeV for iron, 6.1 MeV for aluminum, 11 MeV for copper and 1.8 MeV for phosphorous.

High energy X-ray equipment, particularly in the megavolt range, produces side lobes of radiation outside the main direct beam. Because this radiation has significant penetrating power, it can travel large distances in air. In some machines this unwanted radiation is absorbed close to the target, but in many machines it can travel upward and outward, and can spread outside if the laboratory has a relatively thin roof. It is usually not feasible to build a roof of the same thickness as the walls, so the radiation extending into the air above and scattered back to areas at ground level must be taken into account.

Chapter 2 Review Questions

- 2.1 The probability of absorption of any particular radiation type and energy by a specific element is referred to as the:
- attenuation.
 - buildup factor.
 - cross section.
 - atomic coefficient.
 - probability index.
- 2.2 Which of the following is not a form for expressing attenuation coefficients?
- atomic
 - rayleigh
 - linear
 - mass
- 2.3 A material with a 9.83 in. tenth-value layer has a half-value layer of:
- 2.50 cm (0.983 in.)
 - 7.49 cm (2.95 in.)
 - 12.48 cm (4.92 in.)
 - 8.23 cm (3.24 in.)
 - 4.06 cm (1.60 in.)
- Because Review Questions 2.4 and 2.5 are not linear conversions, the attenuation coefficients will not include both cgs and SI units.
- 2.4 If a specific material had a linear attenuation coefficient of 0.20 cm^{-1} what would the half-value layer be in that material?
- 1.42 cm
 - 3.45 cm
 - 3.66 cm
 - 8.76 cm
 - 6.73 cm
- 2.5 If the intensity of a radiation source was initially 25.8 mC/kg per hour (100 R per hour) and it was desired to reduce this intensity to $2.58 \text{ } \mu\text{C/kg}$ per hour (10 mR per hour), what thickness of shield would be required? Assume that the linear attenuation coefficient for the specific energy is 0.90 cm^{-1} .
- 9.6 cm
 - 0.2 cm
 - 2.55 cm
 - 8.28 cm
 - 2.22 cm
- 2.6 What would be the facility workload for a busy exposure cell with the following average techniques: 110 exposures per week at 10 mA·min; 500 exposures per week at 22 mA·min; 1150 exposures per week at 5 mA·min.
- 34.600 mA·min per week
 - 7.850 mA·min per week
 - 17.850 mA·min per week
 - 2.550 mA·min per day
 - 71.400 mA·min per month
- 2.7 An occupancy factor commonly used for design purposes of uncontrolled sidewalk areas is:
- $1/4$.
 - $1/5$.
 - $1/16$.
 - 1.
 - $1/10$.

Chapter 3

Radiation Sources

X-ray Generators

X-rays are produced whenever electrons are suddenly brought to rest by colliding with matter. It is necessary therefore to have the following:

1. a means of producing and sustaining a stream of electrons,
2. a means of accelerating the electrons to a high velocity,
3. a target for the electrons to strike.

To acquire the energies necessary for industrial radiography, the electrons must experience an accelerating voltage from about 30 kV to 30 MV. There are two main methods for achieving this.

1. By direct application of a potential between the source of electrons (cathode) and the target (anode). This method is used in X-ray tubes and may be used to generate up to 2 MeV.
2. By application of a relatively small accelerating potential to the electron and arranging for this to be repeatedly applied until the electrons have acquired the desired energy, when they are diverted on to the target. These are known as *accelerators*.

X-ray Tubes

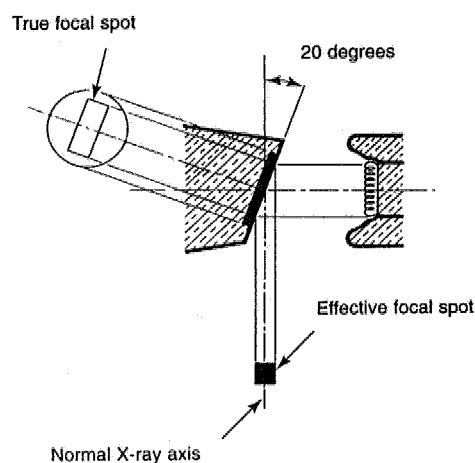
A medium voltage X-ray tube usually consists of an insulating, vacuum-tight envelope (generally of glass) containing the cathode and anode. The cathode will consist of a tungsten filament, usually wound spirally, surrounded by a focusing cup that is shaped like a metal electrode. This cup acts as an electrostatic lens and controls the shape of the electron beam emitted by the filament. The size of the focal spot depends on the dimensions and location of this cup in relation to the cathode assembly. The anode consists of a metal electrode of high thermal conductivity containing the target. The

copper anode has a copper extension through the envelope of the X-ray tube and various arrangements are used to dissipate the heat generated.

The face of the target facing the filament is at an angle to the axis of the tube. By this means the energy of the electron beam is dissipated over a considerable area of the target, but seen from the central axis of the X-ray beam, the effective size of the target (the focal spot size) is much smaller than the real size of the target as shown in Figure 3.1. By this means a high output of X-rays can be obtained from a comparatively small focal spot, without danger of melting the target material.

X-ray tubes are designed to carry the maximum current possible without melting the target. Consequently, the cooling system and its efficiency are of paramount importance. The

Figure 3.1: Schematic diagram of effective (or projected) focal spot of X-ray tube.



Reprinted from *Nondestructive Testing Handbook*, third edition: Volume 4, *Radiographic Testing*.

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maximum operating voltage of an X-ray tube depends on the possibility of sparking between either cathode and anode, or surface sparking on the glass. This has driven the development of ceramic tubes and various grounding schemes.

Tubes with specially shaped anodes have been developed that provide a panoramic beam to aid the inspection of pipes. There are two general types. In one the anode is conical and the electron beam strikes the curved surface of the cone so that a panoramic 360 degree beam of X-rays is emitted. In the other type, a flat faced anode is used that again gives a panoramic beam of X-rays, but it is thrown in front of the tube.

It is possible to use a special electron focusing system between the filament and anode to reduce the effective focal spot size to a few micrometers; these are *microfocus tubes*. The purpose of these tubes is twofold.

1. Magnified images can be obtained without loss of image sharpness.
2. Very short source-to-film distances can be used.

Owing to the dangers of pitting from heating on the target face, provision is made either to move the anode to provide a new target area, or to deflect the electron beam to a new area of the anode. Because of cooling limitations on the target, the X-ray output of microfocus tubes is necessarily very small and varies with the focal spot size.

Electronic Radiation Sources

X-ray Sources (Electron Accelerators)

Betatron

The *betatron* is basically a combination of an electromagnet and a transformer designed to guide and accelerate electrons in a circular orbit to very high energies.

The toroidal type of hot cathode high vacuum X-ray tube commonly used in a betatron is capable of injecting and energizing electrons to many millions of volts before striking the target to produce X-rays.

Betatrons of this type have been constructed to generate X-rays at energies ranging from 15 to 100 MeV. The average beam current is on the order of 1 to 3 μA . The focal spot of the target is usually less than 1 mm (0.04 in.) in diameter.

Commercially available betatrons are capable of radiographing steel (or equivalent) in the range of 5 to 41 cm (2 to 16 in.).

Van de Graaff Generators

The van de graaff X-ray generator is unlike conventional X-ray machines that obtain kilovoltages from a transformer. The high tension generator in a van de graaff system operates on electrostatic principles. The van de graaff X-ray system consists of two major components — the generator and the acceleration tube.

The electrodes in the generator are insulated by a nonconductive gas and comprise a system of a certain capacitance. The system is charged by a belt of insulating material traveling typically at 1500 m/min (5000 ft/min). The electrode contacting the bottom of the belt is earth ground, whereas the high tension (voltage) electrode is mounted on a series of insulating plates.

The belt is charged negatively at the bottom of the belt, with the negative charge removed through an array of needle points at the top of the belt, accumulating the charge on the high voltage terminal. The charge Q on the belt is given by the formula:

$$Q = CV$$

Equation 12

where:

C = capacitance, and
 V = voltage.

The charge carried by the belt increases with the value of the capacitance but the voltage between electrodes on the belt remains constant. This negative charge carried by the belt discharges through the comb (needle points) at the top of the belt. The smaller the capacitance of the system of needle points and belt, the greater the voltage between the high voltage terminal and the belt. In fact, if Q is constant, the value of V will be inversely proportional to that of C .

The components that make up the accelerator tube are the accelerating tube (with resistors between accelerating plates), electron gun and anode.

The accelerator tube contains a flat, small (0.075 mm² or 0.0001 in.²) tungsten cathode that is connected to the high tension electrode. The cathode emits electrons and, in the vacuum of the accelerator tube, these electrons are accelerated to a high speed because of the difference in potential between the cathode (at a high negative potential) and the anode, which is ground. The sudden deceleration of electrons upon striking the anode produces the X-radiation.

Chapter 3: Radiation Sources

The van de graaff system is designed to radiograph up to about 30 cm (12 in.) of steel or equivalent at energy levels up to 3.5 MeV. The intensity of the electron beam varies from a few microamperes to several hundred microamperes.

Linear Accelerator

The linear accelerator is an apparatus for generating energies to 30 MeV. The high radiation outputs of industrial linear accelerators have made it possible to radiograph up to about 66 cm (26 in.) of steel.

The major components of a linear accelerator are:

1. filament,
2. transmission target,
3. focus coils,
4. pulse modulator,
5. waveguide,
6. magnetron or klystron.

The acceleration of the electrons in a linear accelerator occurs in a straight tube called the *waveguide*. The electrons are carried along the tube by electromagnetic waves generated by the magnetron or klystron. These high frequency waves of energy are in the S-band frequency spectrum (about 3 GHz) for magnetrons and the L-band for klystrons (about 13 GHz).

The velocity of this high frequency wave along the waveguide is controlled by the spacing of the coaxial irises. Pulses of electrons are injected at one end of the waveguide in correct phase with the electromagnetic wave: at the other end of the waveguide the electrons strike a target (usually less than 2 mm² or 0.003 in.²) and generate X-radiation. Typical waveguides are 0.9 to 1.5 m (3 to 5 ft) long.

In the first section of the guide (the *buncher section*), the electrons are bunched into pulses and the electron velocity increases from 0.4 c to almost c (the velocity of light).

Further transfer of energy to the electron can occur by relativistic increase in mass along the second section of the waveguide. The groups, or bunches, of electrons in linear accelerators produce pulses of X-rays, usually at pulse frequencies between 100 and 500 pps (pulses per second), with pulse lengths of 1 to 2 μ s.

Industrial linear accelerators cover a wide range of electron energies from 2 to 30 MeV and, as they can produce large beam currents, high X-ray outputs are obtained — typically 20 times to 100 times the output of a betatron at the same energy level.

High Voltage and Low Voltage Generators

Line voltages in the 100 to 250 V range are used to produce X-rays from 5 to 420 kV using high tension rectifying power supplies.

The conventional X-ray generator consists of three major components: the X-ray tube, the high voltage source and the control unit.

The delicate interior components of the X-ray tube are maintained under a vacuum by a glass or metal ceramic enclosure. The vacuum improves efficiency by allowing more electrons to reach the target. The enclosure is then protected from physical damage by an outer housing, usually of sturdy metal construction. The major interior components are the focusing cup, filament (cathode), target mounting structure and the target (anode).

The filament, which is heated by resistance, provides the electrons to be accelerated: the current in the filament circuit is normally in the range of 1 to 10 A. Filament current should not be confused with tube current, which is the electron flow between the cathode and the anode. The tube current can vary from several hundred microamperes up to 20 mA for conventional X-ray units.

The focusing cup is a recess in the cathode in which the filament is housed. Its purpose is to surround the emerging beam of electrons with a negative field that repels the electrons from the cup wall and tends to focus them, allowing for better control of how the electrons will impinge on the target.

The target, or anode, is usually composed of a large heat sink in which the target is intimately bonded. The anode is the positively charged electrode that attracts the electrons from the filament and also dissipates the heat generated during the production of X-rays. The actual target is small in relation to the overall anode and is made of tungsten (high melting point) or other suitable high-Z material.

The circuit of an X-ray generator can be designed to produce X-rays of varying intensity and energy (quality). Obviously, the higher the output energy and intensity, the more costly and vice versa.

Most portable units use self rectified, half wave circuits and are used to produce X-rays in the 50 to 200 kV peak range, with tube currents from 2 to 8 mA. These circuits fit into three major categories: cathode grounded, center grounded and anode grounded, each with its own advantages and disadvantages. For tube outputs exceeding 200 kV peak and reaching 420 kV peak or greater, the following three circuit types, or a

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variation of them, have been used: villard circuit, graetz circuit and greinacher circuit.

These have now largely been replaced by more modern electronics using multipliers, inverters, etc. In many cases, high frequency is used (12 kHz). Such circuits are better at maintaining a stable output from a changing input voltage and are physically smaller.

Target Materials and Characteristics

Target material in currently available X-ray generating equipment is tungsten. Tungsten is extremely well suited for use as a target because of its high melting point (3410 °C or 6170 °F) and high atomic, or Z, number (74). It is essential to use a material with a high melting point because of the amount of heat generated when X-rays are produced.

Heat generated during the production of X-rays is high in comparison to the amount of X-rays produced, for example:

- 99.9% heat, 0.1% X-rays at 50 keV,
- 97% heat, 3.0% X-rays at 300 keV,
- 60% heat, 40.0% X-rays at 40 MeV.

High atomic number is important because the higher the atomic number, the higher the conversion of the electron's kinetic energy to X-rays. The greater the number of electrons striking the anode, the greater the number of X-rays generated.

The efficiency of the target material in the production of X-rays is directly proportional to its atomic number and the accelerating voltage. Platinum and gold have been used for selected applications as target material, but special heat removal methods are required. Copper, iron and cobalt have been used in some units to take advantage of characteristic X-rays generated.

Characteristic X-ray Spectra

In any discussion of the X-ray spectrum, it is necessary to identify both of the key portions of electromagnetic radiation spectra encountered, continuous and characteristic X-rays. In addition to the bremsstrahlung, there are intensity peaks characteristic of the target material. These peaks, or spikes, are caused by interaction between the impinging stream of high speed electrons and the electrons that are bound tightly to the nuclei of the target material.

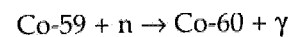
A typical X-ray spectrum illustrating the continuous radiation and the characteristic peaks is shown in Figure 3.2.

Radioisotope Sources

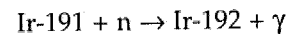
Neutron Activation

Elements such as cobalt and iridium may be exposed to neutron bombardment in nuclear reactors to produce useful radioisotopes for radiography. Nuclear reactors (research or isotope production reactors, not those used for electrical power) are sources of the large number of neutrons necessary to produce radiographic quality radioisotopes. Other neutron sources generally cannot compete for the production of radiographic sources.

The neutron reaction used involves the absorption of a thermal neutron in the nucleus of the target atom with the loss of a gamma photon. The thermal neutron is a neutron that has been slowed down to a kinetic energy of about 0.026 eV. At this low energy, the probability of absorption in the atom's nucleus is high (this probability is called *cross section*). The reactions may be represented as:

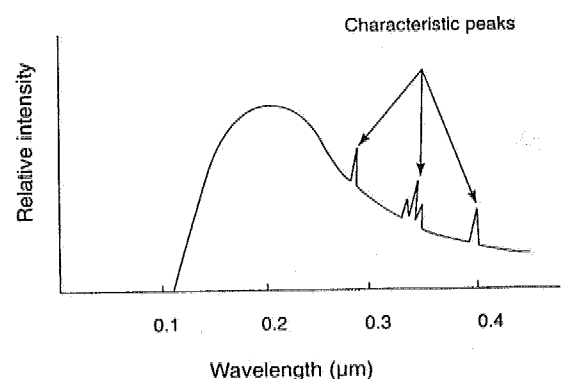


and



The target materials, Co-59 and Ir-191, exist in nature. Normally, the metallic forms of these elements are made into small pellets that are placed into a nuclear reactor for activation.

Figure 3.2: Typical X-ray spectrum.



Reprinted from *Nondestructive Testing Handbook*, third edition: Volume 4, *Radiographic Testing*.

Chapter 3: Radiation Sources

Fission Fragments

Some radiographic sources are obtained from the fragments of the uranium (U-235) atom after fission, when the U-235 splits into two slightly unequal sized smaller atoms. Two of the fission fragments that have been used for radiography are Cs-137 and Tm-170. The fission fragments are separated by dissolving the used nuclear fuel from a nuclear reactor in acids and performing extractions, precipitations and other chemical processing to isolate the desired materials.

Fabrication and Design of Sources

Chemical Form

The radioactive material is in the form of metal pellets whenever possible. This is particularly true for cobalt and iridium. The metallic form of these elements is relatively stable in air, easy to obtain and machinable. Cobalt metal is often formed into pellets about 2 mm (0.08 in.) in diameter and thickness.

Each pellet produces about 185 GBq (5 Ci) after neutron bombardment. Iridium is irradiated in 1 mm (0.04 in.) thick pellets 2 or 3 mm (0.08 or 0.12 in.) in diameter, which produce about 925 and 1850 GBq (25 and 50 Ci), respectively, after neutron bombardment. Cesium is usually incorporated into either glass or ceramic material because the metal is chemically active and the oxide and salts are powders that are difficult to handle. Thulium is most often handled as a ceramic pellet or as thulium oxide.

Encapsulation

To prevent the loss of radioactive material to the working environment, the radioactive material is encapsulated. The radioactive source is placed into a cavity in a stainless steel cylinder and covered with a stainless steel lid that is welded in place.

Cesium sources are usually doubly encapsulated, sealed inside a stainless steel capsule, that is sealed inside another stainless steel capsule. Iridium and cobalt may also be doubly encapsulated, although many manufacturers only single encapsulate. The outer stainless steel cylinder is attached (before source fabrication) to a flexible cable having a coupling on the opposite end. The coupling allows a long cable to be attached to the source so that it may be manipulated remotely.

Exposure Devices

Exposure devices permit remote operation of the radioactive source to reduce radiation exposure to the radiographer. One type has the source capsule installed in the edge of a cylinder of shielding material that rotates inside a larger cylinder of shielding material. Rotation of the small cylinder to expose the source can be done remotely. A second type of exposure device allows long flexible cables to be attached to the source while it is stored in the center of a shield.

When the cable is moved by turning a crank, the source moves out of the shield through a guide tube to a position where the radiographic exposure is made. Collimators may be attached to the end of the guide tube to provide radiation exposure in a limited area. Collimators are made of either tungsten or depleted uranium (uranium with most of the U-235 removed). A third type moves the source into the exposed position within the exposure device by means of a vacuum.

Depleted uranium is most often used for the shielding of radiographic sources. Lead shielding is still in use but does not provide the structural durability and fire resistance of uranium and requires more mass to provide the same shielding as the lighter uranium. Depleted uranium is itself radioactive. Therefore, modern exposure devices exhibit very low levels of radiation even when no radiographic source is present.

Tungsten is also used as shielding material for exposure devices and collimators. Tungsten can be precisely machined, is very durable and is not radioactive. It is a desirable shielding material but is very expensive.

Excellent treatment of radiation sources can be found in reference 1, Sections 2, 3 and 6 and reference 3.

Chapter 3 Review Questions

- 3.1 X-rays may be produced when high speed _____ are stopped by a high atomic number target.
- electrons
 - protons
 - hydrogen ions
 - helium ions
 - All of the above.
- 3.2 What naturally occurring radioisotope has been used for radiography?
- Co-60
 - Cs-137
 - Ir-192
 - Ra-226
 - All of the above.
- 3.3 Neutron activation produces radioisotopes by:
- excitation of the nuclei of the target atoms by neutrons.
 - loss of electrons, caused by neutron bombardment, from the target atoms.
 - capture of a neutron by the target atoms.
 - loss of a neutron by the target atoms.
 - rapid acceleration of the neutron to release gamma rays.
- 3.4 Which of the following may be produced by neutron activation?
- Co-60
 - Cs-137
 - Ir-192
 - a and b above
 - a and c above
- 3.5 Which of the following may be produced as a product of fission?
- Co-60
 - Cs-137
 - Ir-192
 - Ra-116
 - b and d above
- 3.6 Which of the following produces the most penetrating gamma rays?
- Co-60
 - Cs-137
 - Ir-192
 - Tm-170
 - U-235
- 3.7 Radiographic sources are encapsulated to
- improve the gamma ray output.
 - harden the radiation beam.
 - increase the cost of the sources.
 - prevent loss of the radioactive material.
 - collimate the gamma ray beam.
- 3.8 An acceptable modern radiographic exposure device may be:
- a radiographic source suspended from a pole by a string.
 - a radiographic source on a cylinder of shielding material rotating in a larger cylinder of shielding material.
 - a radiographic source on a flexible cable that may be driven out of a shield through a guide tube to a remote location.
 - a radiographic source that may be removed from a shield by long tongs or pliers so that it can be placed for exposure.
 - b and c only.
- 3.9 An acceptable modern radiographic exposure device uses _____ as the shielding material.
- lead
 - depleted uranium
 - steel
 - tungsten
 - aluminum

Chapter 3: Radiation Sources

3.10 In the doughnut shaped tube of a betatron, electrons are accelerated to high speeds by:

- a. RF power phasing.
- b. uniform voltage distribution.
- c. magnetic induction.
- d. an insulated charging belt.

3.11 Electrostatic generators (van de graaff) for radiography operate in the range of:

- a. 1 to 2 MeV.
- b. 5 to 10 MeV.
- c. 10 to 15 MeV.
- d. 15 to 25 MeV.

3.12 The high frequency waves of energy generated by the magnetron in a linear accelerator are in which band of the frequency spectrum?

- a. L-band
- b. M-band
- c. K-band
- d. S-band

3.13 The efficiency of target material in the production of X-rays is _____ to its atomic number.

- a. equal
- b. proportional
- c. indirectly proportional
- d. conversely equal

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Chapter 4

Personnel Safety and Radiation Protection

Radiation Measurement Units

Activity

Activity is the rate of decay (disintegrations per unit time) of a given amount of radioactive material. The unit of activity is the *becquerel* (*curie* in the cgs system) and is defined as one disintegration per second. *Specific activity* is the total activity of a given radioactive isotope per unit mass or volume. The units are becquerels per gram. A high specific activity indicates that a source of a given strength will be of smaller physical size. (Table 4.1)

Exposure

Exposure is the measure of X-radiation or gamma radiation based on the ionization produced in air by the X-rays or gamma rays. *Coulomb per kilogram* is used for measuring exposure. In the cgs system, the unit of exposure is the *roentgen*. It is the quantity of X-radiation or gamma radiation that will produce one electrostatic unit (esu) of charge in 1 cm³ of dry air at standard temperature and pressure (0 °C and 760 mm Hg).

Dose

Dose is the measure of energy deposited by radiation in a material, or of the relative biological damage produced by that amount of energy given the nature of the radiation. *Absorbed dose* is the mean energy imparted to matter by ionizing radiation per unit mass of irradiated material. The unit of absorbed dose is the *gray* (*rad* or radiation absorbed dose in the cgs system). One gray equals 100 rad. The gray or rad can be used for any radiation, but do not describe the biological effects of the

different radiations. *Dose equivalent* is a quantity used for radiation protection purposes. Not all radiation has the same biological effect, even for the same amount of absorbed dose. The amount of energy required to produce an ion pair in animal tissue differs from the energy needed to produce an ion pair in air. Dose equivalent is defined as the product of the absorbed dose (*D*) and the *quality factor* (*QF*). The quality factor corrects for the dependence of biological factor on the energy and type of radiation. For practical purposes the conservative quality factors in Table 4.2 can be used.

For example, consider an absorbed dose of 1 mGy (0.1 rad) from 2 MeV neutrons. The dose equivalent is as follows:

$$DE = D(QF)$$

$$SV = Gy(QF)$$

$$DE = 1 \text{ mGy} \times 10 = 10 \text{ mSv}$$

or

$$(DE = 0.1 \text{ rad} \times 10 = 1 \text{ rem})$$

Equation 13

The *sievert* (*rem* or *roentgen equivalent man* in the cgs system) is the unit of absorbed radiation dose in biological matter (dose equivalent). *Dose rate* is the quantity of radiation occurring per unit

Table 4.1: Radiation measurement units.

	SI System	cgs System
Activity	becquerel (Bq)	curie (Ci)
Specific Activity	becquerel per gram (Bq/gm)	curie per gram (Ci/gm)
Exposure	coulomb per kilogram (C/kg)	roentgen (R)
Absorbed Dose	gray (Gy)	rad
Dose Equivalent	sievert (Sv)	rem
Dose Rate	sievert per hour (Sv/h)	rem/h

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of time. Dose rate is commonly expressed in sieverts per minute (rem per hour).

Table 4.2: Quality factors of radiation.

Radiation Type	Quality Factor
X-rays, gamma rays, electrons and beta	1
Neutrons, energy < 10 keV	3
Neutrons, energy > 10 keV	10
Protons	10
Alpha particles	20
Fission fragments, recoil nuclei	20

Biological Effects of Radiation

Natural and Manufactured Background Radiation Exposure

Humans are constantly being irradiated by natural and manufactured radiation occurring in the environment. All types of radiation sources make up this background level of exposure. Alpha and beta radiation, as well as gamma rays, are emitted from radioisotopes that are in our food or found in items we handle daily. Cosmic rays and high energy neutrons constantly bombard us from sources outside the earth's atmosphere.

Radium, potassium, thorium and uranium make up the bulk of natural background exposure. These elements occur in nature all over the world and many building materials, such as sand, stone, brick, concrete, etc., contain measurable quantities. Other radioactive elements commonly found in nature are C-14 and H-3 (tritium). The National Committee on Radiation Protection estimates total per capita natural exposure to be about 0.83 mSv per year (83 mrem per year).

In addition to naturally occurring sources of radiation, people are also exposed to manufactured sources that contribute to the background exposure. Included are medical and dental X-rays (about 0.9 mSv per year or 90 mrem per year), fallout from nuclear weapons (0.05 mSv per year or 5 mrem per year), and exposure from consumer products such as color television X-radiation (0.01 mSv per year or 1 mrem per year). The National Committee on Radiation Protection estimates per capita

manufactured exposure at 0.003 mSv per year (0.3 mrem per year).

Total natural and manufactured background radiation exposure is estimated at 1.793 mSv per year (179.3 mrem per year), typically rounded up to about 2 mSv per year (200 mrem per year).

Human Organ Radiosensitivity

Tissues and organs of the body differ in their response to radiation exposure. This response is called *radiosensitivity*.

The radiosensitivity of an organ or tissue is proportional to the reproductive capacity of the cells that compose that particular organ or tissue type. Generally those cells that are most active in reproducing themselves and cells that are not fully mature are most sensitive to radiation. It can be easily seen that certain organs will receive more damage than others, and that children will generally receive greater injury than adults for the same exposure.

Lymphocytes, white blood cells formed by the spleen and lymph nodes, are the most sensitive to radiation exposure. Granulocytes, white blood cells formed in the bone marrow, are also highly radiosensitive.

Basal cells, so named because they are the originators for the more complex specialized cells of the gonads, bone marrow, skin and alimentary canal, rank very high in their degree of radiosensitivity.

Alveolar cells, lung cells that absorb oxygen from the air, are fairly radiosensitive.

Bile cells, which line the digestive system walls, have intermediate radiosensitivity. A very large exposure is required before enough bile cells are damaged that the digestive system will fail to function properly.

Kidney tubule cells are affected rather quickly by radiation exposure; at high levels, this can cause severe symptoms in the exposed individual.

Endothelial cells, which line the closed cavities of the body, such as the heart and blood vessels, are only moderately radiosensitive.

Connective tissue cells, which support organs, are fairly resistant to radiation exposure. The muscle tissue cells rank very high in their radiation resistance, whereas bone and nerve cells have the highest resistance and are referred to as being the least radiosensitive.

Symptoms of Radiation Injury

If proper safety precautions are maintained, personnel working in radiography should never experience the effects of radiation injury.

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Radiation injury falls into two general categories: prompt effects and delayed effects. As the term suggests, *prompt effects* are those that will be experienced a short time after receiving the radiation exposure.

Listed below are some of the prompt symptoms associated with overexposure to radiation.

1. Experiencing a heated feeling or tingling similar to that felt when your hand goes to sleep. There is a possibility that you may have received a high exposure if you have these sensations after your dosimeter goes off scale or if you suspect that you may have come in close contact with a radiography source.
2. Normally, if an acute exposure has occurred, the area exposed will blister within a matter of days.
3. If the exposure is very high the exposed area may become very red and chafed. This is known as an *erythema dose* when reddening occurs. An exposure of greater than 258 mC/kg (1000 R) is required to cause reddening.

If a high exposure is received to the whole body, vomiting may result, followed by severe diarrhea. Medical attention should be obtained immediately if any of these symptoms is noted.

The potential *delayed effects* of radiation exposure include genetic defects in offspring of exposed persons and increased risk to certain types of cancer. Unless significantly large exposures are received, these risks are no greater and, in fact, are much less than other risks experienced in our personal and business lives.

Table 4.3 is a summary of the possible effects for various exposure levels.

Radiation Damage, Repair Concepts

Radiation exposure primarily causes injury to living tissue through ionization. Ionization involves changing the molecular structure and producing positive and negative ions. The charged atoms that make up complex molecules may cause the molecule to split or break into parts, some of which will be charged. The charged components may react with adjacent atoms and molecules, producing new substances or compounds.

Because living cells are mostly water, radiation passing through such a cell has a good possibility of striking water molecules (H_2O). When this occurs, the hydrogen and oxygen atoms may release their bonds in the water molecule and become ions. These ions may recombine as HO_2 (hydrogen dioxide) and H_2O_2 (hydrogen peroxide). Both of these compounds are powerful oxidizing agents and will easily break down the highly complex protein molecules in body cells. When a cell is attacked by these and other chemical agents, various effects can occur, including:

1. abnormal cell growth,
2. alteration of DNA cells,
3. cell death, and
4. cell failure to reproduce.

In general, radiation damage to humans occurs on a cellular level and is chemical in nature.

Radiation from background sources constantly irradiates the human body and a small

Table 4.3: Summary of possible effects from various exposure levels.

Radiation Exposure	Effects on Personnel
0-0.25 Sv (0-25 rem)	No obvious injury.
0.25-1 Sv (25-100 rem)	Possible minor blood count effects, usually temporary in nature.
1-2 Sv (100-200 rem)	Noticeable physical effects and potential permanent injury; possible transient nausea and vomiting; noticeable blood count change.
2-4 Sv (200-400 rem)	Injury and possible permanent disability; severe blood count changes; gastrointestinal damage in upper dose range, producing diarrhea and vomiting.
4 Sv (400 rem)	Fatal to 50% of the individuals exposed if no treatment is received; severe blood changes; severe gastrointestinal damage and related symptoms.
8 Sv (800 rem)	Fatal to 95% of the individuals so exposed if no treatment is received.
10 Sv (1000 rem)	Fatal to 100% of the individuals so exposed; neurological damage and quick shock symptoms overcome the patient; death certain within days.

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number of cells are continually being destroyed or mutilated. As long as the number remains small, the body can, through its natural repair mechanisms, discard the damaged cell and replace it with a new cell. This repair mechanism allows us to receive a limited amount of radiation exposure without noticeable effects. Our repair mechanism for radiation exposure is similar to the way the body repairs cuts, burns, bruises or fractures. If the cut is too large or the burn area too extensive, there may be permanent damage or even death. The same holds true for body injury caused by radiation.

Acute Radiation Exposure

Living organisms usually begin repair processes as soon as some damage has been detected by living cells. Up to a point, the body can keep up with the damage and continue repairing, even on a continuous basis. For this reason, an individual can be exposed to considerable amounts of radiation exposure over a relatively long period of time without noticeable effects. However, if the same total amount of exposure were given in a very short time (minutes to hours), severe symptoms would be produced. Therefore, the rate of exposure is a major factor in determining if acute exposure has occurred.

An acute exposure will give traumatic results in a relatively short period of time. A whole body exposure is more harmful than localized exposure of an extremity because all areas are irradiated and the repair mechanisms of the body have limitations. Radiation injury and effects for the same dose vary significantly among individuals.

Acute and/or prompt effects can be expected from whole body exposures experienced over a short period of time. Although the potential whole body acute effects are grave, significant carelessness would be necessary to bring about such an exposure.

Acute exposures to body extremities, fingers, hands, and arms are a greater possibility, owing to the potential for physically contacting the sealed radiography source when connecting and disconnecting source assemblies if those procedures are improperly performed.

Localized exposures of 6 Sv (600 rem) may cause reddening and a burning sensation similar to that of a first degree burn in the contact area. At exposures of 10 Sv (1000 rem), serious tissue damage can occur, and reddening immediately and blistering of the area within one to three weeks can be expected. At exposures of

20 to 30 Sv (2000 to 3000 rem) to a localized area, pain and swelling will occur within hours, and the area will become red and produce blistering within the same time interval.

Permissible or Allowable Personnel Dose

Personnel monitoring techniques are used to measure the accumulated exposure dose of personnel working with ionizing radiation. For practical purposes, the assumption is made that radiation exposure has a threshold value below which no particular effect is experienced. The National Council on Radiation Protection defines permissible radiation dose as "the dose of ionizing radiation, that in the light of present knowledge is not expected to cause appreciable bodily injury to a person at any time during his lifetime." The National Council on Radiation Protection defines the maximum permissible dose equivalent man values for personnel exposure in Table 4.4.

The same values are adopted in both federal and state regulations. Personnel employed in industrial radiography, using modern equipment and safe practices under normal workload conditions, should be able to maintain weekly whole body exposures well below 1 mSv (100 mrem) per week, 12.5 mSv (1.250 mrem) per calendar quarter and 50 mSv (5 rem) per calendar year.

In addition to evaluating and developing recommended weekly, quarterly and yearly exposure doses, the National Council on Radiation Protection developed a whole body long term accumulated dose formula. This formula allows exposure dose to exceed 50 mSv per year (5 rem per year) as long as the lifetime allowable dose for the individual's age has not been exceeded. The National Council on Radiation Protection states "Long term accumulated whole body dose equivalent shall not exceed [50 mSv] 5 rem multiplied by the number of years beyond 18, i.e., maximum accumulated dose equivalent = $(N - 18) \times 5 \text{ rem}$, where N is the age in years and is greater than 18." This formula may be used if an individual has exceeded the yearly allowable dose and it is desired to allow him to continue working with sources of ionizing radiation. This concept is commonly referred to as the *radiation banking concept*, in which for each year over age 18 the individual is credited with 50 mSv (5 rem) of maximum permissible exposure dose.

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ALARA

ALARA is the acronym for *As Low As Reasonably Achievable* and is the principle that radiation doses should be kept as low as reasonably achievable, taking into account economic and social factors.

Radiation Detectors and Personnel Monitoring

The various types of nonimaging radiation detectors have one common characteristic. In one form or another, they depend on detection of the ionization produced when radiation interacts with matter. Among the detector types commonly used in radiography are gas filled radiation detectors, scintillation detectors, semiconductor detectors, thermoluminescent detectors and film badges.

Gas Filled Radiation Detectors — General

Gas filled detectors fall into three types: ionization chambers, geiger-mueller tubes and proportional counter chambers. Each of these methods uses a gas filled chamber and a central electrode insulated from the chamber walls. A voltage is typically applied between the wall and the central electrode. The principle for all three

with regard to detection is the same, radiation ionizes the gas. The number of ion pairs produced per unit of path length is referred to as the *specific ionization*. The energy of the radiation to be detected and the type of gas used in the detector will affect the specific ionization. To create an ion pair in most gases requires about 34 eV. A single 1 MeV photon has the potential of creating 30 000 ion pairs in the process of dissipating its energy. The critical difference between the detectors is the applied voltage.

Ionization Chamber Devices

Direct reading pocket chambers or dosimeters are required safety equipment for personnel working in industrial radiography. These chambers are small, 13 mm (0.5 in.) diameter by 100 mm (4 in.) length. They are convenient to use as integrating dosimeters capable of being read during field use.

A typical ionization chamber consists of a cylindrical form with a central conductor located on the cylinder's axis and insulated from the outer walls. Photons, or charged particles, ionize the air. The negative ions are attracted to the positively charged center electrode and produce a minute current path between the outer wall and the center electrode. When this type chamber is operated in the ion saturation region, the current

produced is an accurate measurement of the rate at which ion pairs are formed within the gas. Measurement of this current is the principle behind the DC ion chamber.

Chamber wall materials are important design considerations because the radiation to be detected must penetrate the wall to ionize the gas. The wall material will affect the energy response at energies typically below 100 keV; therefore this should be a particular consideration in low energy radiographic applications. An energy response curve should be reviewed for each

Table 4.4: Maximum permissible dose (MPD) values.

	Maximum 13 week Dose	Maximum Yearly Dose	Maximum Accumulated Dose
Controlled areas	Sieverts (rem) ^a	Sieverts (rem) ^a	Sieverts (rem) ^a
Whole body, gonads, lens of eye, red bone marrow	0.03 (3)	0.05 (5)	0.05(N-18) [5(N-18) ^b]
Skin (other than hands and forearms)		0.15 (15)	
Hands	0.25 (25)	0.75 (75)	
Forearms	0.10 (10)	0.30 (30)	
Other organs	0.05 (5)	0.15 (15)	
Noncontrolled areas		0.005 (0.5)	

^a The numerical value of the dose equivalent in rem may be assumed to be equal to the numerical value of the exposure in roentgen for the purpose of this report.

^b N = Age in years and is greater than 18. When the previous occupational history of an individual is not definitely known, it shall be assumed that he has already received the MPD permitted by the formula 5(N-18).

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type of ion chamber as a standard practice before specifying its use for routine radiographic applications to ensure it is adequate.

These instruments typically use an aluminum or steel outer shell that protects the delicate internal components but is thin enough to avoid significant attenuation in the walls and enhance electronic equilibrium. The pocket chamber is initially charged using an external dosimeter charger. The resulting drop in chamber voltage when exposed to radiation is used as the measure of total integrated ionization charge.

The direct reading pocket dosimeter has an internal quartz fiber electroscope, which can be read on an internal scale by holding it up to a light source and viewing the scale through the magnifier lens. Pocket dosimeters capable of reading up to 2 mSv (200 mrem) of exposure are required for personnel working in industrial radiography.

Because of the fragility of the device, it is easy to destroy the electroscope by dropping the dosimeter; therefore consistent methods for securing pocket dosimeters are required. In addition, if the charging electrode is not covered with a cap during use, moisture and humidity can provide a leakage path and discharge the dosimeter, causing the hairline to go off scale.

Geiger-mueller Tube Devices

Sealed, gas filled detector tubes operating in the geiger-mueller voltage region above 1000 V are referred to as geiger-mueller detectors. This type of detector can be used to detect any radiation that will produce ionization within the chamber. The production of only one ion pair within the tube will produce a discharge and, therefore, a pulse, if the discriminator of the measuring device is set low enough. Because of this characteristic, the geiger-mueller device is more sensitive and is capable of measuring lower radiation levels than the typical ionization chamber.

The geiger-mueller tube consists of an envelope of metal or glass (the cathode), a center electrode (anode), usually tungsten wire 0.08 to 0.10 mm (0.003 to 0.004 in.) in diameter, and a fill gas. Noble gases, particularly argon, helium and neon, are commonly used for fill gases, with the addition of small amounts of gases such as alcohol, bromine or chlorine for quenching purposes.

When an ion pair initiates a discharge in the geiger-mueller voltage region, an avalanche of positive ions is created along the entire anode wire through gas amplification. Once a given ion

amplification reaches a predetermined density of charge, a discharge occurs, producing an output pulse. Each discharge, regardless of the number of original ion pairs, is terminated after developing the same total charge. Therefore, all output pulses are about the same size. Usually these pulses are 0.25 to 10 V and therefore do not require sophisticated electronic amplification circuitry. These factors allow geiger-mueller instruments to be small, less costly, rugged and generally dependable.

Geiger-mueller tubes are manufactured in many shapes to accomplish specific detection tasks. Those geiger-mueller tubes used in radiography survey instruments are typically cylindrical and most are of the miniature variety. Typical sizes are 19 to 38 mm (0.75 to 1.5 in.) in length and 6.4 to 12.7 (0.25 to 0.50 in.) in diameter. Geiger-mueller tubes use energy compensation filters.

Scintillation Detectors

One of the oldest known methods for detection of ionizing radiation is light scintillation. Certain materials emit visible light photons after ionizing radiation interacts with them; these materials are said to *scintillate*. Scintillators may be in the solid or liquid state. For applications in radiography, solid organic or inorganic scintillators are used. The use of a solid detection medium has a great advantage.

In the measurement of high energy photons, detector dimensions can be kept much smaller than an equivalent gas filled detector because solids are so much more dense than most gases. Scintillators are used in highly sensitive survey instruments and also as the detecting medium for the radiographic process. Scintillation detectors are widely used in real time radiography and computerized tomography. For use in detecting gamma photons, scintillators have detection efficiencies 10⁹ times greater than typical gas ionization chambers.

Commonly used inorganic solid scintillators and their activator impurities include:

1. gadollineum
2. sodium iodide: NaI(Tl),
3. lithium iodide: LiI(Eu),
4. cesium iodide: CsI(Na),
5. zinc sulfide: ZnS(Ag).

Another commonly used scintillator is the plastic scintillator. These materials have several advantages, the principal one of which is they are commonly available in the form of rods, cylinders

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and flat sheets. In addition, they are relatively inexpensive.

For a scintillator to be used as a radiation detector, it has to be coupled to a device that will count or integrate the light pulses from the scintillator. This is commonly accomplished by using photomultiplier tubes. The photomultiplier tube is composed of a photosensitive layer, the photocathode, coupled to an electron multiplier structure. The photocathode converts incident light photons from the scintillator into low energy electrons via the photoelectric effect.

Because the number of photoelectrons involved in a single pulse from the scintillator may be too small to produce a significant charge, the signal requires amplification. The dynode structure of the photomultiplier tube accomplishes this by *avalanching*; that is, multiplying the number of electrons. After such amplification through a photomultiplier tube, a typical pulse from the scintillator will produce 10^7 to 10^{10} electrons. This amplification produces a charge at the anode large enough to be easily counted electronically.

The output pulses from photomultiplier tubes can simply be counted or the output pulse can be amplified and the pulse height analyzed. The charge amplification from a photomultiplier tube is very linear; therefore the output pulse is proportional to the original number of photoelectrons or the energy deposited within the scintillator. This fact allows the output to be calibrated against a photon source of known energy. Electronic discrimination of unwanted low energy signals is possible. The high voltage supply for the photomultiplier tube is in the neighborhood of 1000 V.

Semiconductor Detectors

The advantages of using solid medium detectors were discussed briefly in the section on scintillation detectors. Scintillation detectors have several limitations; the major one is their relatively poor energy resolution. In addition, the number of events that must occur to convert the incident radiation to light and then eventually to an electrical signal involves many inefficient steps. Semiconductor detectors offer the advantage of the solid detecting medium and enhance the energy resolution of the system. Spectroscopic applications, from an energy resolution standpoint, are greatly improved with the use of semiconductor detectors. Photodiodes are used in lieu of scintillation detectors in some real time and tomography equipment designs.

The most widely used semiconductors for radiation detection are the diffused *p-n* junction, surface barrier, lithium drifted silicon or germanium and intrinsic germanium detectors.

Thermoluminescent Detectors

Another category of inorganic crystals, known as *thermoluminescent materials*, can be used to detect ionizing radiation. Thermoluminescence is the emission of light from materials when the materials are heated. If the material has been exposed to ionizing radiation above a certain minimum threshold, a measurable amount of light will be emitted from the material when it is heated to the appropriate temperature in a controlled manner.

The amount of light emitted is proportional to the amount of radiation to which the thermoluminescent material was subjected. This light emission typically will not occur at room temperature for most thermoluminescent materials, and herein lies the advantage of these materials as radiation detectors. Crystals of thermoluminescent material function as integrating radiation detectors and will release the exposure information only when heated. The most common use of thermoluminescent material is as a thermoluminescent dosimeter (TLD) for personnel monitoring.

The materials most often used as thermoluminescent dosimeters are calcium sulfate activated with manganese and lithium fluoride. Of the two, lithium fluoride is probably the best suited for reusable personnel monitoring devices. Lithium fluoride does not require an activator and is popular because it has almost negligible fading at room temperature and has a low average atomic number, bringing it close to air and tissue. Because of its close approximation to tissue's atomic number, the energy deposited is very closely correlated with the gamma/X-ray exposure, or dose equivalent for humans over a wide range of energies.

Thermoluminescent dosimeters can be read at will if the heating/recording instrument called a *reader* is available. The thermoluminescent dosimeter reader is a precision instrument with closely controlled heating and timing circuits to properly liberate the light from the thermoluminescent dosimeter. The heating chamber is coupled to a photomultiplier tube in a light tight enclosure. The photomultiplier tube detects the light photons emitted, amplifies the signal and produces current pulses of sufficient size to be counted and integrated electronically.

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The major disadvantage of thermoluminescent dosimeters as radiation detectors is lack of information about the incident radiation energy.

Natural lithium contains 7.4% Li-6 and therefore is somewhat sensitive to slow neutrons, via the (n,α) reaction, because of the thermal neutron cross section of Li-6. This response can be increased by using lithium enriched with Li-6, or decreased by using lithium consisting entirely of Li-7. Because of this capability, lithium fluoride thermoluminescent dosimeters can also be used as neutron dosimeters.

Film Badges

Photographic film has been in wide use for monitoring personnel exposure to gamma, X-ray, beta and neutron radiation since the early 1940s. This method of monitoring consists of placing a small packet or packets of film in a holder designed to protect the film and providing filters to account for the variation of absorption versus energy of the particular radiation to be measured. Filters are usually placed on the front and rear of the film holder. This placement produces images that allow the evaluator to determine from which direction the radiation emanated.

The response of photographic film varies with photon energy and becomes significantly greater at energies below 150 keV. Proper selection of filters allows the filter absorption versus energy response to match the film density energy characteristic, leaving an essentially energy independent radiation response on the film. Filters of lead, cadmium, tin, aluminum and brass are commonly used.

Filters are arranged in specific patterns and permanently mounted to the film badge holder. The filters cover only portions of the film, allowing windows or openings through which the various qualities of radiation may pass. Most badge designs provide an open window to admit low energy photons or beta radiation.

Thermal neutron exposure may also be measured using film techniques. Cadmium and brass filters are used and usually a special sensitivity neutron film. The cadmium and brass filters are designed so that they both attenuate photon radiation by the same amount. But because cadmium exposed to thermal neutrons will undergo an (n,γ) reaction, the film density produced behind the cadmium will be greater than that behind the brass. The differential in density between the two measurements can be calibrated to show the thermal neutron exposure.

The sensitivity of available emulsions is sufficient to detect as little as 0.1 mSv (10 mrem)

of gamma radiation at 1.33 MeV (Co-60) and as little as 0.02 to 0.03 mSv (2 mrem to 3 mrem) at 100 keV. Because of film fog, statistical variations, etc., most suppliers of film badge dosimetry do not attempt to report exposures below 0.1 mSv (10 mrem).

Use of film for personnel monitoring has several disadvantages. Fogging may result from mechanical pressure, evaluated temperature, and exposure to light and moisture as well as other environmental contaminants.

Selection of Survey Instrumentation

The selection of radiation survey instruments for use in monitoring radiographic operations should take many things into consideration. The ruggedness of the instrument and its suitability to perform in a dependable and reliable manner are probably more important than any other considerations. Ionization chamber instruments typically have many desirable features from the standpoint of health physics and accuracy of exposure/dose readings. This must be balanced against the ruggedness of most geiger-mueller instruments designed for radiography and whether the instrument will be used in a laboratory environment with reasonable environmental controls or in a temporary field job site location.

In general, geiger-mueller instruments for radiography are not as susceptible to moisture, exposure and physical damage as are ionization chamber instruments. The thin windows of many ionization chambers make them impractical for use in radiographic operations. Similarly, geiger-mueller instruments with external tubes and thin windows should also be avoided in radiographic operations.

Current federal and most state regulations require the use of a survey instrument when performing X-radiography or gamma radiography. At minimum, instruments in industrial radiography must be able to adequately measure radiation in the range of 0.02 mSv per hour (2 mrem per hour) through at least 10 mSv per hour (1000 mrem per hour). Many instruments are available that meet or exceed these requirements. In addition, the instrument should be capable of detecting the energy of radiation being used.

Geiger-mueller instruments of inexpensive design may exhibit a phenomenon known as saturation. If such an instrument is placed in a high radiation field, the geiger-mueller tube will go into continuous discharge and the meter movement will typically go to zero. This could

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cause an individual to inadvertently enter a high radiation area and receive an unnecessary exposure. Most modern geiger-mueller tube instrument circuits are designed to prevent meter movement zeroing when saturation of the tube occurs.

Geiger-mueller tube survey instruments are the most widely used in radiographic monitoring, although there are ionization chamber instruments available that are rugged and durable. Those instruments are usually much more expensive than the geiger-mueller tube instrument. Note that geiger-mueller instruments, unlike current ionization chambers, indicate pulses regardless of energy and register in pulses per minute. They are typically calibrated in coulombs per kilogram (milliroentgen per hour) at one specific energy, such as from Cs-137 (0.666 keV) or Co-60 (1.173 and 1.332 MeV). Use at other energies requires an energy response curve to make the instrument readings usable. Most well designed geiger-mueller tube instruments in radiography are relatively linear in energy response from 100 keV through 1.2 MeV.

Survey instruments using sodium iodide detectors and other inorganic scintillators are available, but are very seldom used in industrial radiography. They are generally fragile instruments and their extreme sensitivity is not required for normal monitoring purposes. They can be useful in the performance of surveys for lost sources by health physics personnel.

Area Monitors and Alarm Systems

Radiographic operations are generally classed into two major categories: mobile (or temporary) and permanent (or fixed). Radiographic operations carried out in permanent installations require the use of electrical interlocks, area monitors and alarm systems to prevent accidental entry into a high radiation area. Federal and state regulatory requirements are equally stringent, but should be consulted to ensure that you are aware of any recent revisions. These requirements can be found in 10CFR20 and 10CFR34 and the equivalent sections of state regulations.

Area monitors may use radiation detectors using geiger-mueller tubes, ionization chambers or proportional counters. The monitor is usually an instrument mounted in a permanent location and interlocked with entry doors to the radiography exposure cell. The monitor normally uses a meter face that indicates the radiation level within the room and is connected to audible and visible indicators. The radiation detector can be

located within the exposure cell and the monitor and alarms located outside the cell. The visible signal must be activated by radiation whenever a radiography source is in the *on* position, whereas the audible alarm must be activated whenever any attempt is made to enter the cell when the source is exposed.

Some area monitors have preset alarm levels, so that when the radiation level within the cell exceeds the preset level the alarm indicators will activate (audible and/or visible). Area monitors for exposure cells must be designed to alarm whenever the exposure level in the cell reaches 1 mSv per hour (100 mrem per hour) and the door is opened. Lower alarm levels may be desired by the individual user.

During a radiography exposure, the exposure cell door(s) are closed and the electrical interlock switches are opened, causing the audible and visible alarms to activate and thereby warning of the existence of a high radiation area.

Alarm systems should be checked on a daily basis to ensure they are functioning. Entry into radiography exposure cells should always be done with a portable radiation survey instrument in hand. Monitor/alarm systems are not intended to be a substitute for survey instruments.

Calibration and Maintenance

Survey instruments used in radiography require routine maintenance to ensure proper operation and are required to be calibrated periodically. The required calibration interval for survey instrumentation is 3 months and, for pocket dosimeters, annually.

Calibration should be performed using a source of radiation with intensity traceable to the National Institute of Standards and Technology. Calibration typically involves placing the instrument at a distance from the calibration source computed to give a desired field intensity, then reading the instrument. If the instrument reading is outside the allowable calibration limits at that point, an adjustment of the instrument potentiometer for that scale may be required. Typical calibration limits are +20% of the calibration source intensity. Good practice requires intensity checks at two positions on each instrument range. One measurement should be near the high end and one near the low end of the range.

Maintenance that should be performed daily includes a check of battery intensity and cleanliness of the instrument. Accumulations of dirt and moisture will eventually cause instrument malfunction or damage. Depleted

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batteries can cause severe damage to portable radiation survey instrumentation.

Records of calibration should include identification of the source used, specific points that were checked on the instrument, the calculated intensity and the actual instrument reading for each point, the individual performing the calibration and the date of calibration.

Exposure Control Techniques

The concepts of time, distance and shielding can be used to control the amount of exposure received by personnel working with sources of radiation.

The time concept relates to the amount of time spent near the exposed source. Obviously, shorter time spent near a source will reduce the radiation exposure. Every effort should be made to minimize the amount of time in areas adjacent to the sources of radiation. Working time in hours per week can be calculated. For example, for an exposure rate of 100 μSv per hour (10 μR per

$$\begin{aligned}\text{Working time} &= \frac{\text{Permissible occupational dose per week}}{\text{Exposure dose rate}} \\ &= \frac{1000 \mu\text{Sv} \times \text{wk}^{-1}}{100 \mu\text{Sv} \times \text{h}^{-1}} \\ &\left(= \frac{100 \text{ mR} \times \text{wk}^{-1}}{10 \text{ mR} \times \text{h}^{-1}} \right) \\ &= 10 \text{ h} \times \text{wk}^{-1}\end{aligned}$$

Equation 14

hour) to the whole body:

Radiation exposure can also be controlled via the distance between the individual and the source. This situation is governed by the inverse square law. As applied to radiation this states that the dose rate from a point source is inversely proportional to the square of the distance from the origin of the radiation source. This holds provided that the dimensions of the radiation source are small compared to the distance, and no appreciable scattering or absorption of the radiation occurs. In practice, the first condition is satisfied whenever the distance involved is at least 10 times greater than the largest source dimension. In situations where there is insignificant scattering or absorption, the primary beam is the total radiation field. This relationship

$$I_1 d_1^2 = I_2 d_2^2 \quad \text{is expressed as:}$$

Equation 15

where:

$$\begin{aligned}I_1 &= \text{radiation intensity at distance } d_1, \\ I_2 &= \text{radiation intensity at distance } d_2, \\ d_1 &= \text{distance from the source at which the} \\ &\quad \text{intensity is } I_1, \text{ and} \\ d_2 &= \text{distance from the source at which the} \\ &\quad \text{intensity is } I_2\end{aligned}$$

Common materials such as concrete and lead can be used as absorbers or shields to reduce personnel exposures. The thickness of any material that will reduce the amount of radiation passing through the material to one half is referred to as the half-value layer. Similarly, the thickness that will reduce the radiation to one tenth is referred to as the tenth-value layer.

Contamination Sources and Control

It is important to understand the difference between radiation and contamination and how they are related.

Radiation, whether it be X-rays or gamma rays, is energy. Energy may be dissipated or change its form but it in itself is not radioactive.

On the other hand, *contamination* is the actual deposition of radioactive matter in an unwanted location. This radioactive matter, although it has physical characteristics such as mass, usually occurs in such a minute quantity that it cannot be viewed with the naked eye. Contamination consists of particles of matter from a source of radioactive material and, as such, will emit radiation energy and have all the characteristics of the parent source.

One may be exposed to radiation without being contaminated; but one cannot be contaminated without being exposed to radiation.

The danger of contamination is that most radioisotopes emit alpha and/or beta particles and, if the particles are ingested, radiation will be very intense at their final position in the body. Contamination may occur in industrial radiography from a sealed source whose encapsulation has failed, from shipping containers and source changers that were not properly cleaned by the source manufacturer, and from uranium shielded exposure devices whose shield liner tubes have worn through to the uranium.

Sealed sources of radioactive material used in radiography are required by state and federal

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regulations to be leak tested for contamination at six month intervals. These tests must be capable of detecting 0.185 kBq (5 nCi) of removable radioactive material contamination.

Leak test samples of Ir-192 and Co-60 sources will not show visible contamination, although gross uranium contamination can be visually noted. Uranium contamination is normally in the form of uranium oxide, which is black. In both uranium and radioisotope sources, if contamination is present, the only positive method of detection is by measuring with a thin window (1 mg/cm²) or windowless radiation instrument.

Once a positive leak test sample has been discovered, every effort should be made to isolate the sealed source and its shielded container to prevent contamination. A common technique is to seal the container in a nonporous plastic bag or container. Individuals who have come into physical contact with the container should be monitored and have their hands and other exposed areas thoroughly washed. Smoking, eating or drinking in an area of known contamination should be prohibited.

Contamination from sealed radiography sources occurs very infrequently, but when it does occur the Level III should be thoroughly aware of its significance and of basic techniques to prevent the spread of contamination.

Radiography Operating and Emergency Instructions

The Level III is frequently called on to write the operating and emergency procedures to be used by radiography personnel using sources of ionizing radiation. Such procedures are required to be written and should convey the direction of management with regard to safe practice and emergency action in a clear and concise manner. Topics that should be a part of the radiography operating and emergency instructions include personnel monitoring, survey instruments, leak testing, use, care and maintenance of radiography exposure devices, safe work practices, survey records, state and federal regulations, and emergency action in the event of an overexposure situation. Operating and emergency instructions are required by state and federal regulatory agencies and apply to all sources of ionizing radiation.

Radiation Regulatory Standards

The federal government regulates industrial isotope radiography in areas under its

jurisdiction through the Nuclear Regulatory Commission. Many state governments have established agreements with the Nuclear Regulatory Commission which allow them to regulate the uses of radioactive material within their state in lieu of the federal agency. Such states are called Agreement States.

Most states have a radiation regulatory program with established rules for the regulation of all sources of ionizing radiation including X-ray machines. These regulations are administered through state nuclear energy or health departments and follow the federal requirements very closely.

Radioactive material use and possession are typically authorized by the appropriate regulatory agency via issuance of a Radioactive Materials License. The licensee applies for a license by submitting detailed instructions and procedures that describe how the licensee will implement regulations and how they will be used by their personnel in the administration of the licensee's radiation safety program. Regulatory agencies make frequent onsite inspections of licensee operations to ensure that public health and safety are being maintained during the use of ionizing radiation sources.

The licensee in industrial isotope radiography must comply with the Code of Federal Regulations (CFR) when operating under a Nuclear Regulatory Commission license. In particular, the following CFR Title 10 areas are of specific interest: 10CFR20 *Standards for Protection Against Radiation* and 10CFR34 *Licenses for Industrial Radiography and Radiation Safety Requirements for Industrial Radiographic Operations*.

In addition to licenses for use and possession of radioactive material, the Department of Transportation issues rules and regulates the transportation of radioactive materials. These regulations cover packaging, labeling and mode of transport requirements. The Department of Transportation requirements are specified in *Hazardous Materials Regulations*, 49CFR, Parts 171 to 179.

Different shipping packages are required for various types, forms, quantities and levels of radioactivity. Three common packaging types are Industrial Packaging, Type A Packaging and Type B Packaging.

Industrial Packaging is a fairly new category or package type. Industrial Packaging is used in certain shipments of low specific activity material and surface contaminated objects, which are usually categorized as radioactive waste. Most low level waste is shipped for disposal in secured

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packages like these. Department of Transportation regulations require that these packages allow no identifiable release of the material to the environment during normal transportation and handling. Requirements for industrial packaging are addressed in 49CFR 173.411.

Type A Packaging is used to transport small quantities of radioactive material with higher concentrations of radioactivity than those shipped in Industrial Packaging. They are typically constructed of steel, wood or fiberboard and have an inner containment vessel made of glass, plastic or metal surrounded with packing material made of polyethylene, rubber or vermiculite. Examples of material typically shipped in Type A packages include nuclear medicine (radiopharmaceuticals), radioactive waste and radioactive sources used in industrial applications. Type A Packaging and its radioactive contents must meet standard testing requirements designed to ensure that the package retains its containment integrity and shielding under normal transport conditions. Type A Packaging requirements are addressed in 49CFR 173.412. Type A Packaging must withstand moderate degrees of heat, cold, reduced air pressure, vibration, impact, water spray, drop, penetration and compression tests. Type A Packaging is not, however, designed to withstand the forces of an accident. The consequences of a release of the material in one of these packages would not be major because the quantity of material in this package is so limited. Type A Packaging is only used to transport nonlife endangering amounts of radioactive material.

Type B Packaging is used to transport material with the highest levels of radioactivity. Type B

Packaging ranges from small handheld radiography cameras to heavily shielded steel casks that weigh up to 125 tons. Examples of material transported in Type B Packaging include spent nuclear fuel, high level radioactive waste and high concentrations of some other radioactive material like cesium and cobalt. These package designs must withstand all Type A tests, but they must also withstand a series of tests that simulate severe or *worst case* accident conditions. Accident conditions are simulated by performance testing and engineering analysis. Type B Packages may contain potentially life endangering amounts of radioactive material. Packaging requirements for Type B Packaging are addressed in 49CFR 173.413 and 10CFR 71. To demonstrate that Type B Packages can withstand a severe accident, a tractor trailer carrying a Type B Package prototype was crashed into a massive concrete wall at 81 mph. While the truck was destroyed, damage to the package was external and superficial. Many handheld radiography cameras are Type B Packages. They are heavily shielded and contain a small high level radiation source.

Three different labels may be used on packages containing radioactive material:

- **Radioactive White-I:** minimal radiation levels detectable outside the package.
- **Radioactive Yellow-II:** medium level radiation levels detectable outside the package.
- **Radioactive Yellow-III:** highest radiation levels detectable outside the package.

Table 4.5 briefly summarizes the three labels and the conditions that apply to their use.

Table 4.5: Label requirements for radioactive materials.

Radioactive Label Type	Maximum allowed dose rate at package surface	Maximum dose rate at 1 m (3 ft) from package surface
White-I Label	$\leq 0.005 \text{ mSv/h } (\leq 0.5 \text{ mR/h})$	
Yellow-II Label	$0.5 \text{ mSv/h } (50 \text{ mR/h})$	$0.01 \text{ mSv/h } (1.0 \text{ mR/h})$
Yellow-III Label	$2.0 \text{ mSv/h } (200 \text{ mR/h})$	$0.10 \text{ mSv/h } (10 \text{ mR/h})$

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Chapter 4 Review Questions

- 4.1 If an individual is 32 years old on 1 June 2004, what is the maximum permissible lifetime dose allowed under the NCRP radiation banking concept through 1 July 2004?
- 0.7 Sv (70 rem)
 - 0.685 Sv (68.5 rem)
 - 2.6 Sv (260 rem)
 - 0.9 Sv (90 rem)
 - 0.65 Sv (65 rem)
- 4.2 Which one of the following radioisotopes is not naturally occurring?
- Cs-137
 - Ra-226
 - K-40
 - C-14
 - H-3
- 4.3 Which of the following human cell categories is the most sensitive to radiation exposure?
- granulocytes
 - basal cells
 - bile duct cells
 - muscle cells
 - lymphocytes
- 4.4 If a X-radiation exposure of 1.4 mC/kg (5.8 R) is received by an individual during an incident, what is the individual's dose equivalent?
- 0.058 Sv (5.8 rem)
 - 0.029 Gy (2.9 rad)
 - 0.232 Sv (23.2 rem)
 - 0.116 Sv (11.6 rem)
 - 0.116 Gy (11.6 rad)
- 4.5 The old English unit of radiation, the curie, is 3.7×10^{10} disintegrations per second. The new unit is how many disintegrations per second?
- 1000
 - 100
 - 10
 - 1
- 4.6 When using film as the method for neutron personnel monitoring, what filter material is used to produce an (n,γ) reaction, which will increase the film density after neutron exposure?
- tin
 - polyethylene terephthalate
 - cadmium
 - brass
 - lead
- 4.7 Specific areas of the Code of Federal Regulations used frequently by radiography licensees are:
- 10CFR20.
 - 10CFR34.
 - 10CFR50.
 - 10CFR70.
 - both a and b.
- 4.8 In accordance with Department of Transportation regulations, radioactive materials are classified into which two categories?
- hazardous and nonhazardous
 - normal and special
 - penetrating and nonpenetrating
 - Type I and Type II
 - flammable and nonflammable
- 4.9 If an exposure of approximately 3 Sv (300 rem) of gamma radiation was received to the whole body of an individual, which one of the following would not be likely?
- white cell count increase
 - vomiting
 - diarrhea
 - death

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- 4.10 The critical difference between the operation of detectors in the ionization, geiger-mueller and proportional region is the:
- pulse duration.
 - voltage applied to the center electrode.
 - specific ionization of the chamber gas.
 - amperage of the chamber circuit.
 - amperage of the electrode.
- 4.11 All other design parameters being equal, which of the following operates at the highest applied voltage?
- geiger-mueller detector
 - ionization chamber detector
 - proportional counter detector
 - photomultiplier tube
 - All operate at the same voltage.
- 4.12 The minimum amount of energy required to produce an ion pair in air is approximately:
- 100 eV.
 - 68 keV.
 - 0.510 MeV.
 - 1.02 MeV.
 - 34 eV.
- 4.13 Survey instruments used to monitor radiography operations should have a range of at least:
- 0.258 to 516 $\mu\text{C/kg per h}$ (1 to 2000 mR/h)
 - 0.516 to 2580 $\mu\text{C/kg per h}$ (2 to 10 000 mR/h)
 - 0.516 to 516 $\mu\text{C/kg per h}$ (2 to 2000 mR/h)
 - 0.516 to 258 $\mu\text{C/kg per h}$ (2 to 1000 mR/h)
 - 0.258 to 77.4 $\mu\text{C/kg per h}$ (1 to 300 mR/h)
- The following situation is to be used in answering questions 4.14 through 4.16. A survey instrument is to be calibrated using a 25.9 GBq (3.4 Ci) Co-60 source. It is desired to calibrate the 0.0258 to 258 $\mu\text{C/kg per h}$ (100 to 1000 mR/h) range of the instrument at $\pm 20\%$ at two locations on the range. The two locations are at the lower limit plus 15% and the upper limit minus 15% of the range at that point.
- 4.14 At what locations on the instrument range would you be checking in the above situation?
- 64.5 and 296.7 $\mu\text{C/h}$ (250 and 1150 mR/h)
 - 64.5 and 219.3 $\mu\text{C/h}$ (250 and 850 mR/h)
 - 21.93 and 296.7 $\mu\text{C/h}$ (85 and 1150 mR/h)
 - 29.67 and 219.3 $\mu\text{C/h}$ (115 and 850 mR/h)
 - 38.7 and 219.3 $\mu\text{C/h}$ (150 and 850 mR/h)
- 4.15 What is the distance from the calibration source to the instrument detector to obtain the calculated intensity required at the lower limit check in the above situation?
- 18.9 m (61.9 ft)
 - 6.3 m (20.6 ft)
 - 4.0 m (13.2 ft)
 - 12.1 m (39.6 ft)
 - None of the above
- 4.16 In the above situation, if the instrument indication was +30% of the required lower level reading, it would read approximately:
- 83.85 $\mu\text{C/kg per h}$ (325 mR/h).
 - 33.70 $\mu\text{C/kg per h}$ (150 mR/h).
 - 28.63 $\mu\text{C/kg per h}$ (111 mR/h).
 - 50.31 $\mu\text{C/kg per h}$ (195 mR/h).
 - 33.54 $\mu\text{C/kg per h}$ (130 mR/h).
- 4.17 The detection efficiencies of scintillation detectors over gas ionization chambers for photons is approximately:
- 10^6 times greater.
 - 10^3 times greater.
 - 10^4 times greater.
 - 10^9 times greater.
 - 10^{12} times greater.
- 4.18 Which of the following survey instrument types is usually considered least susceptible to moisture and physical shock?
- proportional counter instruments
 - ionization chamber instruments
 - geiger-mueller tube instruments
 - bonner sphere instruments
 - germanium detector instruments

Chapter 5

The Film Radiographic Process

Radiography technology has seen dramatic changes, especially in the areas of digital detectors and imaging, and computer aided methods such as tomography. Because those areas have seen such explosive development, they will be treated independently in their own chapters. This chapter deals exclusively with film methods.

Radiographic Image Quality

The amount of information contained in any photographic image, and in a radiographic image in particular, is strongly dependent on the quality of the image. *Radiographic sensitivity* is a qualitative term used to refer to the smallest detail that can be seen in a radiograph and hence is a measure of overall image quality. *Image quality* is a combination of the factors of contrast and definition of the radiograph.

Radiographic contrast is defined as the difference between the film densities of two areas of a radiograph. It, in turn, is broken down into the contrast provided by the subject being radiographed (subject contrast) and that provided by the film itself (film contrast).

Definition refers to the sharpness of the image outline. It depends on geometric factors such as focal spot size, source-to-film distance and shape of specimen, and on the inherent film/screen limitations of image sharpness. In practice, one refers to unsharpness rather than sharpness.

Density

The quantitative measure of blackening of a photographic emulsion is called *density*. Density is usually measured directly with a densitometer. Film density is defined by the equation:

$$D = \log \left(\frac{I_0}{I_t} \right)$$

Equation 16

where:

D = density

I_0 = intensity of incident light, and

I_t = intensity of the transmitted light.

The ratio of incident to transmitted intensities is called *opacity*. The inverse of this ratio is called *transmittance* and indicates the fraction of incident light transmitted through the film. The relationship of density to opacity and transmittance is tabulated in Table 5.1.

Subject Contrast

Subject contrast is the ratio of radiation intensities transmitted by two selected portions of a specimen. As the energy level of the radiation is increased, the radiation becomes more penetrating. This has the effect of flattening out the image of a typical test specimen at higher kilovoltages. For instance, consider a steel specimen having thicknesses of 12.5 and 25 mm (0.5 and 1 in.). If an optimum energy level is chosen for the 12.5 mm portion of the radiograph, the image of the 25 mm section will have density and contrast too low to be of any use. On the other hand, if an energy level is chosen to give a

Table 5.1: Transmittance, percent transmittance, opacity and density relationships.

Transmittance	Percent Transmittance	Opacity	Density
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	1000	3.0
0.0001	0.01	10 000	4.0

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high contrast image of the 25 mm portion, the 12.5 mm area will probably appear to be black.

These conditions represent high subject contrast. One can lower the subject contrast and thereby obtain usable images of both sections on one radiograph by increasing the energy level substantially so that radiation penetrating the thinner section will also penetrate the thicker section. In other words, as the radiation energy is increased, the ratio of photon transmission through the thicker portion to that of the thinner section is decreased to give a lower subject contrast. Subject contrast, therefore, depends primarily on the shape of the specimen, but is a parameter that can be altered by choice of energy level.

Another factor affecting radiographic contrast is that of scattered radiation reaching the film and raising the overall background level. The fog resulting from such scatter is not a subject contrast factor but usually is lumped in with subject contrast when considering those factors affecting overall radiographic contrast. Scattered radiation can lower image contrast and detail and is considered to be *noise*. Every practical method of reducing scatter should be used to enhance the signal-to-noise ratio of a radiograph.

Film Contrast

The relationship between the exposure applied to a given type of radiographic film and the resulting density is expressed in a curve known as the *characteristic curve*. The curve is generated by plotting density against the logarithm of relative exposure.

Relative exposure is used because there are no convenient units in which to express exposure suitable for all energy levels and other exposure conditions, and partly because it is easy to determine the logarithm of relative exposure. The logarithm is taken to compress an otherwise long scale. Furthermore, ratios of exposures are more significant in radiography than the exposures themselves. Pairs of exposures having the same ratio will be separated by the same interval on the log relative exposure scale no matter what the actual value may be.

The slope, or gradient, of the characteristic curve changes along the length of the curve. This has the effect of increasing or decreasing the contrast change on the film because of a given exposure ratio, the greater contrast change occurring when the slope is greater. That is, a small change in exposure results in a small change in contrast at a low slope, a correspondingly larger contrast change occurs if

the overall exposure conditions are moved to a point on the curve where the slope is greater.

Although the shape of the characteristic curve for a given film type is insensitive to changes in X-ray or gamma ray quality, it is affected by changes in degree of development; that is, type and temperature of developer and time of development. Within limits, an increase in the degree of development results in an increase in the speed and contrast of a radiographic film.

As the processing time is increased from 2 minutes to 10 minutes, the characteristic curve becomes steeper and moves to the left, corresponding to higher contrast (slope) and speed (less exposure for a given density). If characteristic curves for several film types are included on a single graph, the exposure technique for one film can be translated to another.

Film Speed

Film speed is inversely related to the time required for a given intensity of radiation to produce a particular density on the film – the faster the film, the shorter the exposure required. For most practical applications, it is convenient and effective to deal with relative speeds. To avoid making absolute measurements of film speed, it is convenient to refer to a group of film curves such as those shown in Figure 5.1. Curves positioned to the left of the chart require less exposure for a given density, those to the right more exposure.

Unsharpness of a Radiograph

The two major contributors to unsharpness are geometric unsharpness and film unsharpness. *Geometric unsharpness* is caused by radiation emanating from a source of finite dimension. This means that the shadow cast by any point in the object is not sharp because it is formed by rays coming from all over the target in the X-ray tube or the source of radioactive material.

It is easily seen that similar triangles are formed by the lines drawn in connecting the edges of the focal spot, the point in the object and the image as shown in Figure 5.2. Simple geometry shows the ratio of the target size F to the unsharpness U_g is equal to the ratio of the target to specimen distance d to that of the object-to-film distance D . Solving for U_g determines that $U_g = Fd/D$.

Geometric unsharpness, therefore, varies directly with the focal spot dimensions and with the distance from the focal spot (or source) to the object and inversely with the object-to-film

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distance. To minimize unsharpness, one uses a source with as small a focal spot size as practical, positions the source as far from the object as conditions will allow and positions the film as close to the object as physically possible.

If the unsharpness is of the order of magnitude of the smallest details to be imaged, interpretation becomes difficult if not impossible. This leads to the use of finely detailed objects to provide an index of the overall image quality. Such objects are called *image quality indicators* (IQI) or *penetrameters*.

Film unsharpness, also sometimes called *inherent unsharpness*, arises from the generation of secondary electrons in the film emulsion. When a quantum of ionizing radiation is absorbed in a silver halide crystal in the film emulsion there is sometimes sufficient energy both to make the crystal developable and to release secondary electrons with sufficient energy to travel through the emulsion to other silver halide grains, and also make them developable. Thus, instead of a single exposed grain from each X-ray quantum, there is a small volume or string of grains, and

from the imaging point of view this is equivalent to a reduction in image sharpness.

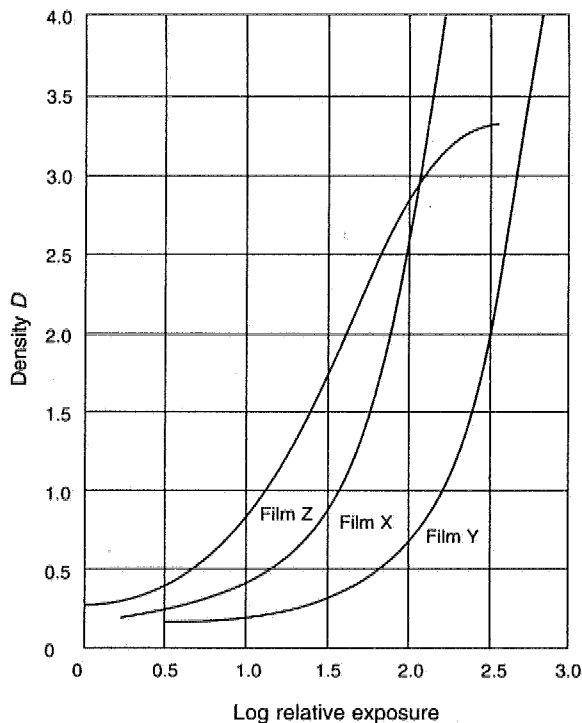
At higher energy levels, lead screens are generally used to intensify the image as well as to reduce scatter. This is because lead, being a heavy metal, provides a much higher probability of photon absorption than bare film. A shower of photoelectrons is emitted by the lead from the point of photon absorption. Because film is ultimately exposed by electrons, photoelectrons emitted from the lead screen result in film exposure at the point of contact. When lead screens are used, extreme care must be exercised to ensure intimate contact between screen surface and film surface: otherwise, divergence of the photoelectron shower will cause a local enlargement of the image formed by the incoming photon. This will result in more unsharpness.

Total unsharpness is given as:

$$U_{\text{total}} = (U_g^2 + U_f^2)^{1/2}$$

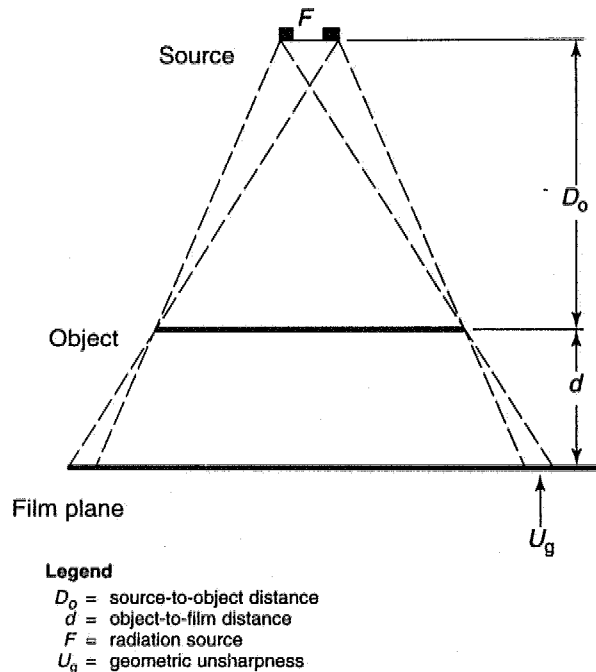
Equation 17

Figure 5.1: Characteristic curves of three typical X-ray films, exposed between lead foil screens.



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Figure 5.2: Geometric construction for determining geometric unsharpness U_g where source is smaller than object.



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Specific examples of unsharpness are illustrated in Table 5.2.

Film Processing

Exposure of the film to radiation results in the formation of what is called the *latent image*. A photographic emulsion consists of a suspension of silver halide grains, usually chloride or bromide, suspended in a thin layer of gelatin. When radiation such as light or X-rays falls on the emulsion, extremely small particles in the silver halide crystals are converted into metallic silver. The number of particles formed is proportional to the quantity of light or radiation incident on the area, so that there is a latent image in the emulsion.

When the film is placed in a developer, the silver grains that have received a high exposure are reduced quickly while those which received slight exposure are reduced or developed slowly. The latent image becomes overt through the reduction of silver halide and the formation of a stable, visible, black silver deposit. Once initiated, the development continues until all the silver halide is reduced to metallic silver. The process is stopped after a specified period of time by placing the film into a stop bath that neutralizes the developer and stops the development. This is followed by a fixing solution that continues neutralization, dissolves unexposed silver halides allowing them to fall off the film and hardens the film. Lastly the film is washed with clean running water to remove all the remaining chemicals.

The specifics of the film development process are beyond the scope of this guide, but excellent discussions of it can be found in many sources and from film manufacturers.

Viewing of Film Radiographs

Illuminator Requirements

To properly view a radiograph that meets the film density requirements of current codes and standards, a high intensity film viewer is required. Many styles of viewers are available, but in general they fit into four groups:

1. spot viewers,
2. area viewers,
3. strip viewers, and
4. combination spot/area viewers.

Viewers must have power ventilators to cool the intense light source required for viewing high density radiographs. Most viewers will use one or more photoflood incandescent lamps as the light source. In addition, a diffuser is required to eliminate variation in light intensity. A good illuminator will use a rheostat to vary the light intensity, allowing lower density radiographs or areas to be viewed with optimum light conditions.

A film density of 2.0 is allowing only 1% of the incident light to be transmitted through the film, whereas a 4.0 density allows only 0.01% transmission. This illustrates the necessity for high intensity film illuminators.

A good high intensity viewer should have an initial intensity of at least 3.426 cd/m² (1.000 fL) and be able to produce an intensity of 3.426 cd/m² to 6.853 cd/m² (1 fL to 2 fL) when viewing radiographs in excess of 3.0 density.

Table 5.2: Radiographic unsharpness resolution of film radiography is limited by the combination of film and geometric unsharpness.

Energy	Sources (in.)	Specimen Thickness (in.)	U_g (in.)	U_f (in.)	U_{Total} (in.)
50 kV	0.20	0.16	0.0006	0.0012	0.002
100 kV	0.20	0.24	0.0024	0.0020	0.003
200 kV	0.20	1.00	0.0052	0.0036	0.006
400 kV	0.28	3.00	0.0228	0.0060	0.024
Ir-192	0.16	2.00	0.0176	0.0052	0.018
Co-60	0.08	1.00	0.0044	0.0140	0.015

Where: $U_g = (s)(t)/(sfd)$
 $U_{Total} = (U_g^2 + U_f^2)^{1/2}$

Chapter 5: The Film Radiographic Process

Background Lighting

The film illuminator should be located in an area that allows for background light control. Although the viewing room need not be completely dark, no direct light should impinge on the radiograph being viewed except from the high intensity light source. All precautions should be taken to ensure that other light is not reflecting off the surface of the radiograph and, potentially, distracting the film interpreter.

It is desirable that the interpreter adapt to the lighting conditions of the viewing room for at least 10 minutes before interpreting radiographs.

Viewing Aids

Numerous aids may be used to enhance the ability of the interpreter in discerning small indications. These include masks to cover large portions of the film and allow concentration on small areas, and magnifiers such as those with comparators that employ an etched glass reticle.

Interpretation Aids

Reference radiographs with known discontinuity images are useful in evaluating and interpreting radiographs. References that show these indications in typical product forms, such as castings, welded pipe or tubing and pressure vessels, are also useful. Reference radiographs are commercially available from several sources.

Overlays of clear plastic with printed and sized indications can provide a convenient means for determining acceptance, particularly of scattered porosity and slag indications.

When interpreting radiographs, the specific code or standard, at the very minimum, should be available for the interpreter to use in making acceptance decisions. Reference 1 provides excellent coverage of radiographic viewing. Additional information can be found in references 3 and 8.

Judging Radiographic Quality

Film Density

The optical density of the film is an accepted measure of the amount of information that has been recorded. The density is in proportion to the number of silver halide grains that have been exposed and developed into metallic silver.

The greater the density, the more detail available for evaluation. In accordance with the most commonly used codes and standards, the following film density guidelines are used to

judge the quality of the radiograph in the area of interest.

1. Film density 1.8 minimum, 4.0 maximum for X-ray.
2. Film density 2.0 minimum, 4.0 maximum for gamma ray.

When viewing two superimposed radiographs, known as *composite viewing*, each film is usually required to be a minimum density of 1.3. The area of interest on each film being evaluated should be measured for acceptable density using densitometers that have been calibrated to a national standard.

Film Definition

The blurring of the object image on the radiograph is caused by poor definition. The sharper the image outline and features, the better the definition.

Definition is affected by two major components: inherent unsharpness and geometric unsharpness. *Inherent unsharpness* is affected primarily by the film and screens chosen, the film screen contact and the energy of radiation used. *Geometric unsharpness* is affected by the source-to-object distance, the focal size of the source and the object-to-film distance.

If radiographic images being evaluated have poor definition, selecting a finer grain film, decreasing the radiation energy, or suitably varying the source-to-film distance or source size will result in better geometric unsharpness.

Artifacts

Artifacts on film radiographs can reduce the quality of the radiographs significantly and can cause misinterpretation if not thoroughly understood. Most film artifacts are caused by improper film processing and careless handling of films, screens and cassettes. In addition, the film can be partially fogged or mottled because of improper storage. Commonly occurring film artifacts include:

1. pressure marks, caused by improper handling of film and cassettes;
2. scratch marks, caused by fingernails or abrasives;
3. static marks, caused by static electricity generated when film is removed rapidly from a tight container;
4. screen marks, caused by screen damage or contamination with chemicals;

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5. streaks, because of ineffective agitation of solutions during development or rinsing.

References 2, 6, 7 and 11 give extensive information with regard to identifying and taking preventive and corrective measures for artifacts.

Image Quality Indicators

The image quality indicator, or penetrameter, is the primary indicator of radiographic quality. It is a means to judge the quality relative to requirements.

The plaque type penetrameter of the ASTM design specified in ASTM E-142 is the primary type used in North America, although the DIN wire penetrameter is used in Europe.

The MIL-STD penetrameters are similar to the ASTM penetrameters, but require material type and thickness to be designated by lead markings on the penetrameter. In both types, ASTM and MIL-STD, the penetrameter is a rectangular metal plaque with three holes that are related to the penetrameter thickness. The holes are 1T, 2T and 4T in diameter, where T is the thickness of the penetrameter. A quality level may be specified for sensitivity by indicating percent of specimen thickness the penetrameter should be, as well as the minimum hole size that must be visible. Typical quality level designations would be 2-1T, 2-2T and 2-4T.

When evaluating the adequacy of the radiograph, carefully examine the penetrameter image to ensure that the complete penetrameter outline as well as the required hole can be seen. It is important that the density of the radiograph in the area of interest be within -15 to +30% of the density through the body of the penetrameter and that this density meets the minimum required by the particular code or standard. It is important also that the correct penetrameter is used for the material thickness and type being radiographed.

Equivalent Penetrameter Sensitivity

If the required thickness penetrameter is not available, or the thickness or hole size is more restrictive than required by the referenced code or standard, then an equivalent sensitivity may be determined for the available penetrameter. Alternately, the specific penetrameter sensitivity for any specimen thickness may be calculated. Equivalent penetrameter sensitivity in terms of penetrameter thickness, penetrameter hole diameter and specimen thickness is expressed in the following mathematical relationship:

$$\alpha = 100 / X(TH / 2)^{1/2}$$

Equation 18

where:

α = the equivalent penetrameter sensitivity (in percent),
 X = material thickness,
 T = image quality indicator's thickness,
 H = hole diameter expressed as a multiple of image quality indicator's thickness.

This relationship will yield the equivalent sensitivity of a specific penetrameter and a specific specimen thickness as shown in Table 5.3. A detailed explanation of how to use the above equation in practical applications can be found in reference 9, ASTM E-142-77 or ASTM E-1025-84.

Exposure Calculations

Selection of Energy

The importance of choosing the correct kilovoltage varies considerably with the kilovoltage range being considered. For X-rays below 150 kV the choice of correct kilovoltage is important because the attenuation coefficient varies rapidly. From 200 to 400 kV, only a considerable difference on the order of 30 to 40 kV, will make a significant difference in sensitivity. In the high energy region, kilovoltage is relatively unimportant in terms of attainable sensitivity.

A good rule of thumb when using X-ray energies below 400 kV is to keep the exposure within the range of 10 mA·min to 30 mA·min. Usually the only effect of using too low a kilovoltage on a uniform thickness specimen is that the exposure time will become impractical. If a long exposure time is tolerable, the discontinuity sensitivity will be somewhat better. The effect of using too high an energy is to shorten the exposure time, lose image contrast and so lose discontinuity sensitivity.

Table 5.3: Equivalent penetrameter sensitivity (see Equation 18).

1-1T = 0.7%	2-1T = 1.4%	3-1T = 2.1%	4-1T = 2.8%
1-2T = 1.0%	2-2T = 2.0%	3-2T = 3.0%	4-2T = 4.0%
1-4T = 1.4%	2-4T = 2.8%	3-4T = 4.2%	4-4T = 5.6%

Chapter 5: The Film Radiographic Process

X-ray Exposure Charts

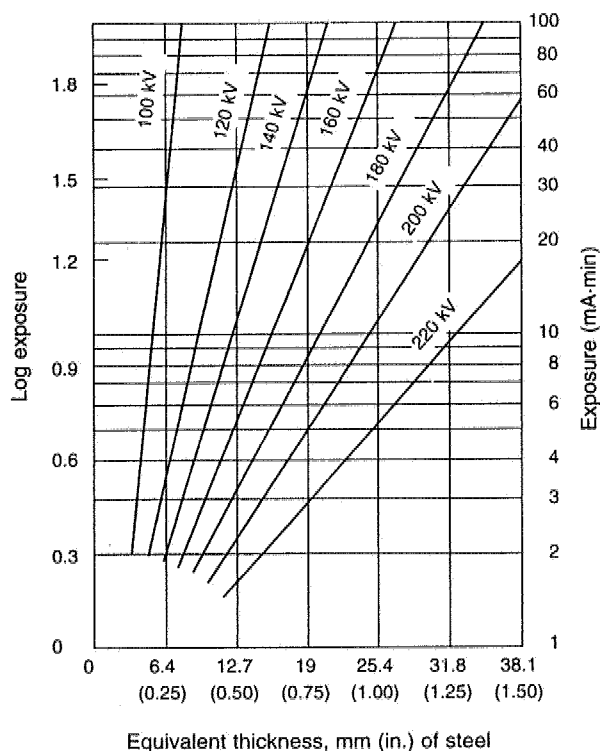
An exposure chart is a graph depicting the relationship between material thickness, kilovoltage, and exposure for a specific film density and specific processing conditions, specific source-to-film distance, and screens, if used.

Figure 5.3 illustrates a typical X-ray exposure chart. From this chart, prepared for a specific X-ray machine/tube combination, the appropriate exposure for a specific material thickness may be selected.

From Figure 5.3, if a 19 mm (0.75 in.) thick steel specimen were to be radiographed at 180 kV peak, then the exposure would be 8 mA-min. If, from the same data, one wishes to use the same technique but wants to increase the focal film distance from 100 to 150 cm (40 to 60 in.), the resulting exposure, using the source distance equation, would be 18 mA-min.

The X-ray exposure chart allows one to select exposures that will produce a specific density. In the case of Figure 5.3, that density is 1.5. If a

Figure 5.3: Typical X-ray exposure chart for steel may be applied to film X, (Figure 5.1) with lead foil screens, at 1.5 film density and 1.0 m (40 in.) source-to-film distance.



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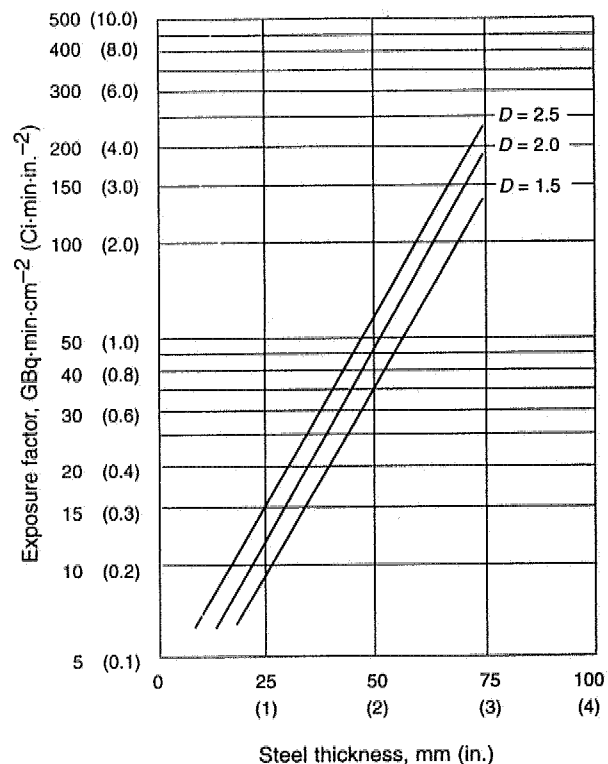
different density is desired, say 2.5, then a correction factor must be calculated from the characteristic curve for the specific film being used.

The characteristic curve for a film plots the density versus the log of the relative exposure needed to produce that density. The characteristic curve can be used to calculate the ratio of any pair of exposures by finding the antilog of the difference in the relative exposures. For example, if we wish to increase the density from 1.5 to 2.5 in the previous problem, we would determine the difference in the relative exposure for each density, as follows:

$$\begin{aligned}\log E \text{ at } D = 2.5 &= 2.0 \\ \log E \text{ at } D = 1.5 &= 1.80 \\ \text{difference in } \log E &= 0.20\end{aligned}$$

The antilog of this difference is 1.58; therefore the original exposure of 8 mA-min should be multiplied by 1.58 to give the correct exposure of 12.6 mA-min for a 2.5 density.

Figure 5.4: Typical gamma ray exposure chart for Ir-192, based on the use of film X (Figure 5.1).



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Radioisotope Exposure Charts

Gamma ray exposure charts are similar to X-ray exposure charts, but there is no variable corresponding to the kilovoltage. An exposure chart for a specific radioisotope such as Ir-192 would contain one line for each film type and density. Figure 5.4 illustrates this type of gamma ray exposure chart.

In addition to charts, gamma ray exposure data can be conveniently displayed on a special slide rule. Slide rules allow quick calculation of gamma ray exposure times for any becquerel (curie) activity of iridium or cobalt, any steel thickness and any desired source-to-film distance. The only external item required is the exposure in coulombs per kilogram (roentgen) specified by the film manufacturer for the particular film speed and desired density.

Exposure charts are readily available from all major film manufacturers and references 2, 4, 6 and 7 present methods for calculating exposure time and related factors.

Chapter 5 Review Questions

- 5.1 Release of hydrogen ions during film development:
- decreases the pH of the solution.
 - increases the pH of the solution.
 - fixes the latent image.
 - catalyzes the reduction of silver halide.
 - is accompanied by release of carbon dioxide gas.
- 5.2 From a chemical viewpoint, the effect of the latent image on film development is:
- latent.
 - catalysis.
 - fixation.
 - neurosis.
 - None of the above.
- 5.3 Fixation of an unexposed film will result in:
- film having a milky appearance.
 - milky fixer solution.
 - formation of a negative image.
 - a clear film.
 - None of the above.
- 5.4 Addition of replenisher to a developing solution:
- is not recommended.
 - causes streaking on the film.
 - must be done at an elevated temperature to assure dissolution of the reducing agent.
 - should not be done more often than once a week.
 - is subject to none of the above.
- 5.5 _____ is (are) widely used as a film developing agent.
- Trinitrotoluene
 - Acetylsalicylic acid
 - Parahydroxybenzene
 - Carboxymethylcellulose
 - Both a and c
- 5.6 As compared with film typically exposed to a density of 2.5, film exposed to an average overall density of 4:
- requires a special stop bath for proper fixation.
 - will exhaust the developer solution more quickly.
 - is especially difficult to dry.
 - requires both a and c.
 - requires none of the above.
- 5.7 Use of a stop bath:
- prevents frilling of the image.
 - inhibits fixation.
 - allows a shorter developing time.
 - neutralizes the acid fixer.
 - results in none of the above.
- 5.8 It is recommended that, as film is being removed from the developing tank, the excess developer not be drained back into the developer solution because:
- the developer clinging to the film is too exhausted to contribute to the developer solution.
 - tiny particles of emulsion released during the developing process will only contaminate the solution.
 - the developer residing on the film is needed to maintain a balanced stop bath concentration.
 - of both a and b.
 - of both b and c.
- 5.9 If the incident light intensity on a film is 30 units, and the measured transmitted light intensity is 1.20 units, what would the film density be?
- 3.2
 - 18.5
 - 1.39
 - 2.3
 - 1.0

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- 5.10 Using the characteristic curve in Figure 5.1, what is the exposure correction factor for film Z when increasing film density from 0.5 to 1.75 density?
- 3.4
 - 5.1
 - 6.3
 - 2.22
 - 17.8
- 5.11 Which one of the following is not a component of a typical developer solution?
- phenidone
 - sodium carbonate
 - acetic acid
 - hydroquinone
 - sodium sulfide
- 5.12 Development temperature in most automatic processors is in the range of:
- 81 to 85 °F.
 - 68 to 70 °F.
 - 74 to 78 °F.
 - 77 to 91 °F.
 - 95 to 98 °F.
- 5.13 Contamination of developer with as little as _____ fixer can result in serious developer malfunction.
- 10.0%
 - 1.0%
 - 0.025%
 - 0.05%
 - 5.0%
- 5.14 In general, when using the composite film viewing technique, each film should have a minimum density of:
- 1.5.
 - 1.8.
 - 2.0.
 - 1.3.
 - None of the above.
- 5.15 If an acceptable 2.5 density is obtained using a 30 mA-min technique at an SFD of 61 cm (24 in.), what would the exposure time be at 91.4 cm (36 in.) SFD using 5 mA-min to obtain the same film density?
- 45 minutes
 - 13.5 minutes
 - 9 minutes
 - 30 minutes
 - 22.5 minutes
- 5.16 The graphic presentation that depicts the relationship between exposure and the resulting photographic density for a particular film type is commonly referred to as a:
- linear curve.
 - characteristic curve.
 - spectral curve.
 - logarithmic curve.
 - All of the above.

Chapter 6

Radioscopy

Principles

While traditional radiography uses film as the imaging medium, radioscopy uses a fluorescent screen for direct viewing or electronic imaging. Fluorescent screens may be viewed directly by the human eye, amplified in an image intensifier tube with video output, or imaged directly by a low light level video camera. With electronic imaging systems, the image signal is amplified and presented as an analog signal for viewing on a television monitor, video recording, analog processing, or for converting to digital for computer display, storage and analysis.

Light Conversion

Fluorescent Screens

Fluorescent screens consist of phosphor particles dispersed in a binder and coated on a reflecting, supporting base. The basic function of the fluorescent screen is to convert X-rays to light. This happens in three steps as shown in Figure 6.1.

1. Absorbed X-ray energy is converted to high energy free electrons.
2. Part of the kinetic energy of the high energy electrons is used to excite other electrons to excited states within the phosphor material.
3. Light emission occurs when the excited electrons return to their normal state.

Light emitted simultaneously with the excitation energy (X-ray absorption) is called *fluorescence*. By contrast, light that persists after the excitation source is removed is called *phosphorescence*.

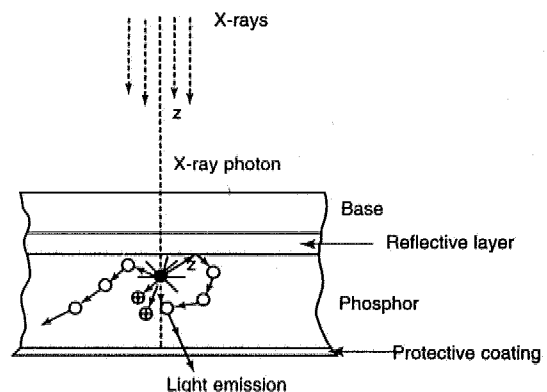
Fluorescent screens are characterized by their efficiency, spectral emission, persistence, unsharpness and gamma. The overall efficiency of the screen in converting X-rays to light is composed of three terms:

1. the fraction of incident X-rays absorbed by the screen,
2. the X-ray to light conversion efficiency, and
3. the light transmission efficiency.

Although the spectral emission of phosphors is broadband, it is distinguished by a maximum intensity at a characteristic wavelength. The spectral emission should be matched to the application, whether the human eye in a direct viewing system, a low light level camera or a photocathode for an image intensifier tube.

Persistence of a fluorescent screen is the amount of time it continues to emit light following excitation. Some persistence curves have an exponential decay, whereas others have long decay tails. The persistence, particularly with rapid decay phosphors, can vary significantly depending on the purity and the manufacturing process.

Figure 6.1: Structure of typical X-ray intensifying screen and typical paths followed by light photons.



Legend

- = Excited grain
- ⊕ = Absorption of light photon

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Unsharpness in images formed by fluorescent screens is primarily a function of the grain size of the phosphor and the screen thickness, increasing as the parameters increase. Light transmission characteristics of the screen can also affect the unsharpness. Figure 6.2 illustrates how unsharpness can affect the detection of a sharp edge discontinuity by spreading the edge shape. Here, C represents the contrast in percentage of brightness change, d represents width of discontinuity and U represents screen unsharpness. For a fixed value of U , a change in contrast C produces a change in the slope of the unsharp edge. It can be seen from Figure 6.2b that when d is smaller than $2U$, the discontinuity will vanish unless C_1 is above the minimum observable contrast level. The following relationship may be obtained from Figure 6.2:

$$d = 2C_1U / C \text{ for } C_1 < C$$

Equation 19

Typical values of screen unsharpness for commercially available screens vary from 0.50 to 1.0 mm (0.020 to 0.040 in.).

The fluorescent screen gamma is a measure of the contrast ratios between the output screen image brightness and the input radiation intensity. As in film radiography, the output image must have a minimum brightness ratio between adjacent areas for detection. For most screens at industrial energies, the screen gamma is very close to 1.0. Therefore the screen itself is very seldom the limiting factor as far as the total system gamma is concerned.

Special Screens

Neutron Sensitive Screens

Real time radiography may be performed using neutron beams when the fluorescent screen is a good neutron absorber. Screen composition and construction are more important in neutron imaging than in X-ray imaging because the neutron intensity is generally lower and the screen must absorb enough neutrons to obtain an acceptable light yield for adequate contrast.

High Energy Screens

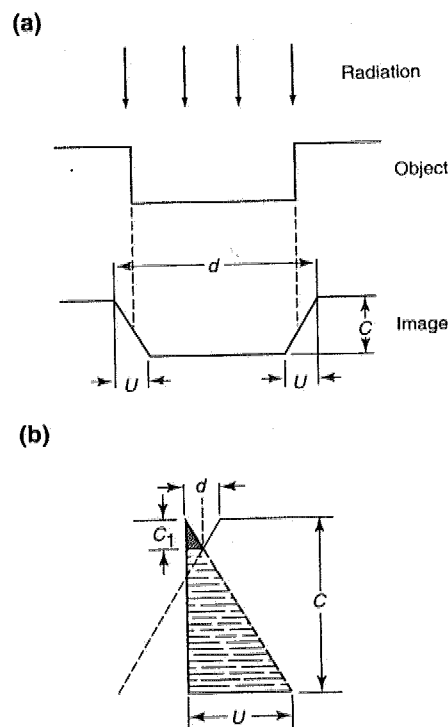
Because some materials emit large amounts of secondary electrons when they absorb X-rays, and fluorescent screens are generally more sensitive to electrons than X-rays, heavy metals are often used in high voltage radiography,

serving as filters in front of the screen. Besides producing secondary electrons to increase the absorbed energy in the adjacent screen, the heavy metal will shield the screen from low energy scattered X-rays. Both of these processes improve contrast sensitivity.

Scintillator Plates

Scintillators are materials that produce light from interactions with X-rays and are transparent to their own light emission, unlike phosphor materials that are more absorptive of their own emission. Conversion of X-rays to light follows the same process in scintillators as in phosphor materials. Light emission from scintillators is very fast and the amount of light emitted is proportional to the energy deposited in the interaction. Because scintillators are transparent

Figure 6.2: Effect of unsharpness on discontinuity detection: (a) spread of edge shape; (b) discontinuity above minimum contrast level.



Legend

C = contrast
 C_1 = minimum observable brightness difference
 d = dimension
 U = screen unsharpness

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Chapter 6: Radioscopy

to their own emissions, they can be used in thicknesses not possible with phosphors.

Image Quality

Contrast

Subject contrast for fluorescent screens is defined as the fractional change in brightness resulting from a change in absorber thickness. Observed contrast in radioscopic imaging is affected by several factors beyond the screen response. One must include the effect of all system components. For example if using a vidicon television, the system gamma would include the electron amplifier chain gamma, vidicon tube gamma, television tube picture gamma and fluorescent input screen gamma. Scattered radiation affects contrast in fluorescent screens by effectively increasing the background brightness level. The scattered radiation affects only the primary imaging component, the fluorescent screen.

Control of Scatter

The control of scatter for radioscopic imaging is the same as for film radiography. There is scatter from the room, object, fixtures and air path in the primary beam, and scatter from objects in the path of the beam. Some specific techniques to reduce scatter include the following.

1. Collimate the primary beam to the minimum viewing area.
2. Shield the setup to reduce room scatter from walls, ceiling and floor.
3. Filter the primary beam to remove the low energy portion of the spectrum.
4. Filter the beam between the object and screen.
5. Use antiscatter grids between the object and the screen.
6. Use projection magnification to increase the distance of the screen from the object scatter.

Definition

The same rules that apply for unsharpness and optimal magnification in film radiography apply to radioscopic imaging. In addition, in radioscopic imaging, unsharpness because of object movement can also limit definition. Determining factors for this are the X-ray excitation rate, the decay time of the screen's phosphor and the delay time or scan time of the imaging components. *Quantum mottle*

is the statistical fluctuation of brightness on fluorescent screens and is the result of the randomness of X-ray production and absorption. The numerous sources of this fluctuation include:

1. X-ray photon production,
2. X-ray photon absorption in the object and the screen,
3. conversion of X-ray photons to light photons,
4. fraction of the light photons reaching the eye after traversing the imaging system, and
5. light photon absorption in the retina.

The statistical fluctuations of screen brightness, which are caused by the randomness of the process, are important at low brightness levels such as occur with low intensity neutron sources. Most industrial X-ray machines produce sufficient intensity to render the fluctuations unimportant for most applications. Where quantum fluctuations do occur, they can be removed in near real time by video frame averaging or summing.

Radiation Sources and Energy

The radiation source plays an important role in radioscopic imaging just as it does in film radiography. Consideration must be given to the types of materials to be examined, densities, thicknesses, smallest feature size to be resolved, smallest thickness change to be detected, response of the radioscopic imaging system and rate of image acquisition. High output, high stability, constant potential X-ray systems are commercially available for these applications. Neutron radioscopic imaging is performed with portable accelerators and reactors with beam ports suitable for radioscopic imaging. The effective focal spot of neutron sources is typically large. For most neutron sources the focal spot is defined by the collimator opening at the neutron source. To transport a reasonable number of neutrons down the beam tube, these collimator openings are necessarily larger than the focal spots possible with an X-ray machine or linear accelerator. The size of the object to be imaged and the material type will determine the radiation type and energy to be used. As a general rule, the radiation type and energy should be selected so that the object thickness is 3 to 5 half-value layers. Satisfactory results can be obtained even in the range of 2 to 10 half-value layers.

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Imaging Systems

The fluorescent screen converts radiation to light and either an image intensifier is used to boost light intensity to a level suitable for pickup by a solidstate or television camera, or a low light camera is used to image the screen directly. The signal from the camera is sent to a television monitor or computer video card for viewing.

At X-ray energies above 1 MeV, shielding mirrors are used to protect electronic components from radiation damage. Below 300 kV, the intensifier and camera can be placed directly in the beam without damage. Given time outside the radiation field, most materials will recover from any radiation damage. Glass may fluoresce under strong irradiation resulting in undesired light signals. Noise may also be generated in the electronics, increasing with radiation intensity.

Image Intensifier Tubes

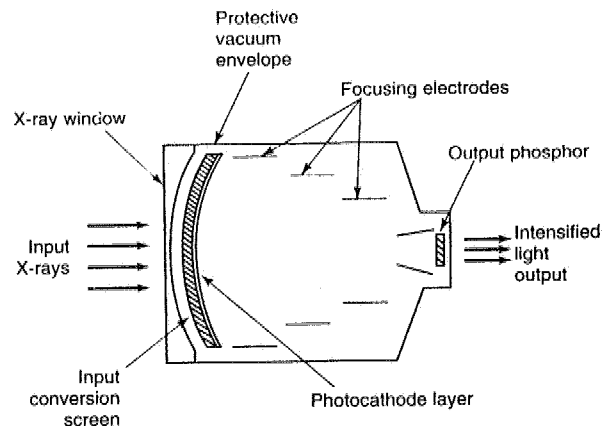
The image intensifier tube (Figure 6.3) converts photons to electrons, accelerates the electrons and then converts them to light. Intensifiers typically operate in the range of 30 to 10 000 light amplification factors. The intensification is not necessarily solely electronic but may also focus electrons from a large input screen onto a smaller output screen thereby reducing the image area.

Modern tubes are available with 100 to 400 mm (4 to 16 in.) input diameters, multiple modes that electronically select variable field size of the input and fiberoptic output for direct camera coupling. A typical 200 mm (8 in.) tube performs with resolution on the order of 4 line pairs per millimeter and gains on the order of 10 000. Resolution is at a maximum at the center of these intensifiers and decreases somewhat at the edges.

Channel Electron Multiplier

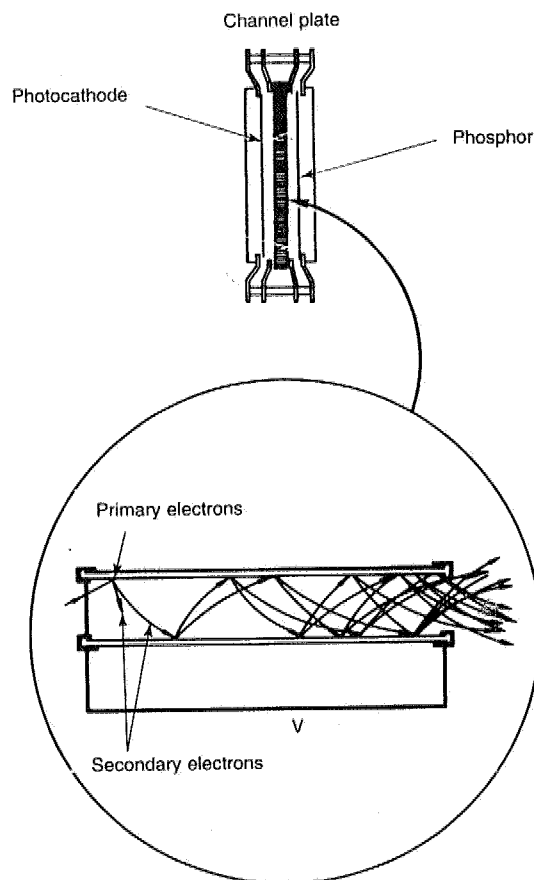
The channel electron multiplier or microchannel plate (MCP) is an assembly of small tubes for amplifying an electron signal using secondary emission as shown in Figure 6.4. The channels are glass or ceramic coated, with a high resistance material on the inside. A potential difference of 500 to 1000 V is applied across the channel plate. An electron entering the channel will strike a wall causing one or more secondary electrons to be released. These will continue to strike the channel wall yielding more electrons as they are accelerated by the field along the channel. The gain of the channel multiplier depends on the applied voltage and the ratio of length to diameter.

Figure 6.3: X-ray image intensifier tube design.



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Figure 6.4: Microchannel plate.



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Chapter 6: Radioscopy

Cameras

Until recently, real time X-ray imaging systems typically used a television camera in combination with a device (such as an image intensifier tube or fluorescent screen) to convert incident X-rays to visible light. Newer systems however, use charge coupled device cameras almost exclusively.

Charge Coupled Devices

Charge coupled devices and related solidstate cameras use an array of photodiodes as the sensitive layer. The photodiode arrays in solidstate cameras are simple photon detectors that absorb incident photons and liberate current carriers. This gives rise to a current referred to as the *photocurrent signal*, which is proportional to the arrival rate of the incident photons. Charge coupled devices work like photodiodes. A photon, incident on the charge coupled device will create an electron hole pair if absorbed. This creates a current flow that is stored in the potential well of the device. The amount of charge collected at the potential well is in direct proportion to the amount of local light intensity.

Image Tubes

A wide variety of television cameras and image tubes are used on real time imaging

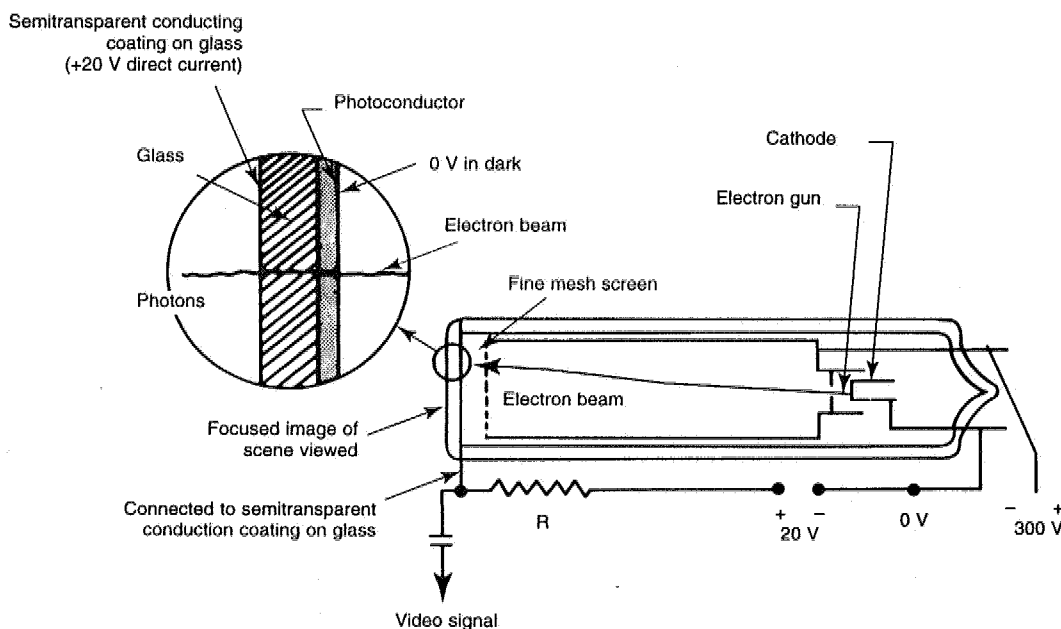
systems. The most common types for radioscopy applications are:

1. vidicons,
2. silicon intensifier targets,
3. image isocons, and
4. X-ray sensitive tubes.

A *vidicon* is a small, rugged, simple tube in which an electron beam scans a light sensitive photoconductive target as shown in Figure 6.5. Another type of tube called the *silicon intensifier target* uses a photocathode as an image sensor and focuses the photoelectrons onto a silicon mosaic diode target. The silicon intensifier target and the intensified silicon intensifier tube are used extensively for low light level applications. With the *image isocon* tube, the image on its photocathode forms a photoelectron pattern focused by an axial magnetic field onto a thin, moderately insulating target as shown in Figure 6.6. The scattered and reflected components in the return beam are separated, and only the scattered component enters the electron multiplier surrounding the electron gun. This signal is amplified to become the video output.

Although the usual input to a television camera is light, for radioscopy purposes it is possible to make a television camera sensitive

Figure 6.5: Vidicon television camera.

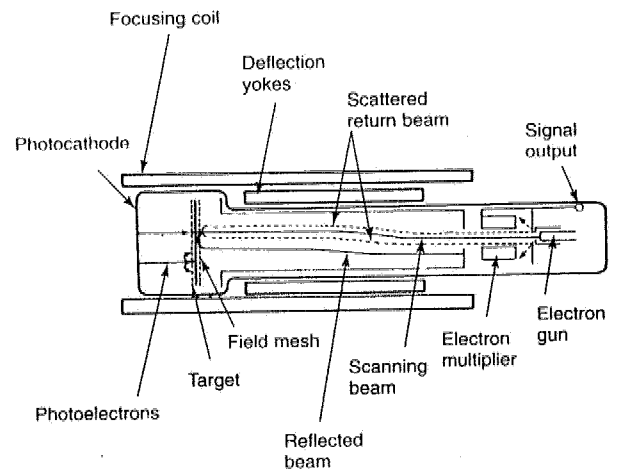


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directly to radiation. The *X-ray sensitive vidicon* system is an imaging system for small objects and low kilovoltages (150 kV or less). The X-ray sensitive vidicon cameras have a gamma on the order of 0.7 to 1.0 and penetrameter sensitivities of 2% have been obtained. However, these cameras may have problems with deterioration, possibly because of local overheating in the target layer, poor bonding to the heat sink layer, substrate irregularities or incompatibility between beryllium and target materials.

Figure 6.6: Image isocon television camera.



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Chapter 6 Review Questions

- 6.1 The basic function of a fluorescent screen is to convert X-rays to light. How well it does this depends on:
- the use of projection magnification.
 - the use of antiscatter grids.
 - the fraction of incident X-rays absorbed by the screens.
 - the screen's level of quantum mottle.
- 6.2 Fluorescent screens are generally:
- more sensitive to electrons than X-rays.
 - more sensitive to neutrons than X-rays.
 - not the limiting factor in the total system gamma.
 - producing the highest gamma when used with heavy metal filters.
- 6.3 Unsharpness in images formed by fluorescent screens is primarily a function of:
- incident energy.
 - phosphor grain size.
 - screen thickness.
 - contrast in percentage of brightness change in the slope of an unsharp edge.
 - a and d
 - b and c
- 6.4 Quantum mottle is an effect that:
- is not evident when using a charge coupled device for imaging.
 - is evident at low brightness levels.
 - requires very special image processing to eliminate.
 - is only evident with solidstate imaging devices.
- 6.5 Fluorescent screen gamma is:
- a measure of the contrast ratios between the output screen image brightness and the input radiation intensity.
 - equally dependent on the electron chain gamma and quantum fluctuations.
 - not a practical parameter in the actual use of fluorescent screens.
 - the least important element in describing screen efficiency.
- 6.6 Scintillators can be used in thicknesses not possible with phosphors because:
- scintillators are transparent to their own emissions.
 - they are solidstate devices that do not rely on an electrochemical reaction.
 - scintillators are not limited in spatial resolution by material grain size.
 - quantum mottle is not a factor.
- 6.7 In considering the use of a fluoroscopic technique to evaluate electrical components, the _____ is still considered a disadvantage.
- source of radiation
 - low brightness level of the screen
 - manipulating device
- 6.8 Real time systems employ fluorescent screens that affect the image quality. Some factors that affect the system contrast are listed below. Select the factor that does not affect system contrast.
- quantum fluctuation
 - gamma of screens
 - intensifiers
 - television monitors

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- 6.9 In images formed by fluorescent screens:
- the control of scatter is less important than with film images.
 - unsharpness is primarily a function of the phosphor grain size and screen thickness.
 - contrast and unsharpness are not as good as with real time radiography.
 - few of the principles of film radiography apply.
- 6.10 Fluorescent screens convert radiation to light and _____ can be used to boost the light to a level suitable for pickup by a television camera.
- an image intensifier tube
 - an electron multiplier screen
 - a charge coupled device
 - a and c
- 6.11 While vidicon television tubes are at a disadvantage compared to charge coupled devices because they use a scanning electron beam, an advantage of the vidicon is:
- its low cost.
 - simple construction.
 - high dynamic range.
 - All of the above.
- 6.12 The importance of the modulation transfer function in evaluating systems is that the total system modulation transfer function is the product of the individual MTFs of the components. Because the modulation transfer function can be difficult to calculate, _____ may be used as a more practical approximation.
- line spread function
 - square wave response
 - edge spread function
 - None of the above.

Chapter 7

Fundamentals of Digital Images

A digital image is simply a set of binary data acquired and stored in a computer. Numerous advantages accompany the use of digital imaging. They include greatly reduced exposure times, the ability to use image processing for analysis and interpretation, greatly reduced storage volume and improved storage life. In digital radiography, the information that comprises the image is captured either directly via a sensor, indirectly via a photostimulable phosphor, or by scanning a conventional film image. Problem areas and limitations of image analysis schemes can result from detector choices as well as processing schemes. Three fundamental properties of digital images are spatial resolution, contrast resolution and signal-to-noise ratio. Each identifiable feature corresponds to some change in measured intensity in the image. To decide whether this change in intensity derives from the state of the object or is some artifact of the image acquisition process requires an assessment of these three properties. The image performance achieved on any acquisition is the combined result of the radiographic technique, the detection scheme and all the processing steps that are used in the image used for the test.

Resolution

Digital images are made up of data points called *pixels* (an acronym for *picture element*), each of which can handle a certain amount of data for example 8, 12 or 16 bits. The pixel size defines the spatial resolution of the system. The more pixels per object's unit area, the greater the resolution. For example, if examining the same specimen with the same exposure geometry, an image of 512×512 pixels will have half the resolution of an image consisting of 1024×1024 pixels. If more resolution is required than is available with a given system, a smaller area can be imaged with the same number of pixels thereby effectively reducing the pixel size.

Resolution is often expressed in micrometers or line pairs per millimeter. Some useful conversions are shown in Table 7.1. Line pairs per millimeter is an expression of resolution in terms of spatial frequency. A line pair is defined as an X-ray opaque line and an adjoining transparent space of equal width. The opaque line is often made of lead foil on a glass or plastic substrate to provide a high subject contrast. Below are some useful conversions of these units.

Table 7.1: Resolution conversions.

1 mm	= 0.04 in.
1 μm	= 0.00004 in.
100 μm	= 0.004 in.

Resolution in line pair per millimeter (lp/mm)

2 lp/mm	= 0.04 in./4	= 0.010 in.	= 250 μm
5 lp/mm	= 0.04 in./10	= 0.004 in.	= 100 μm
6 lp/mm	= 0.04 in./12	= 0.0033 in.	= 83.25 μm
7 lp/mm	= 0.04 in./14	= 0.0028 in.	= 71.3 μm
12 lp/mm	= 0.04 in./24	= 0.0016 in.	= 41.6 μm

The bit depth, the range of discrete signal counts possible in each pixel, defines the limit of contrast resolution of the system. For example, an image with 16 bit data will have greater potential contrast resolution than an image with 12 bit data and will be able to discern more subtle contrast changes in the object or image. The effective dynamic range of the system defines the practical limit of contrast performance. The effective dynamic range is limited by the readout noise and the number of background scattered counts shown in Equation 20.

$$EDR = BD - N_R - N_{Sbk}$$

Equation 20

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Figure 7.1: Spatial and contrast resolution (bit depth).

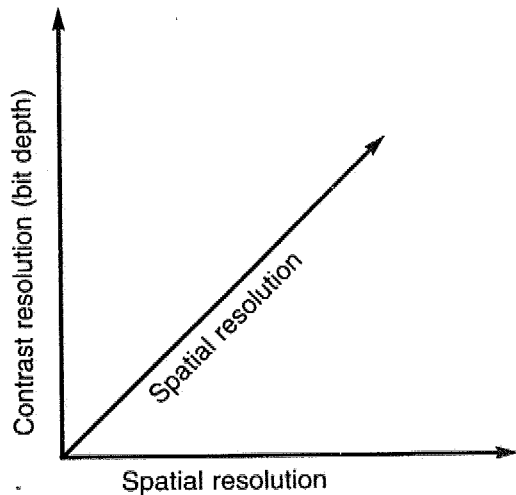
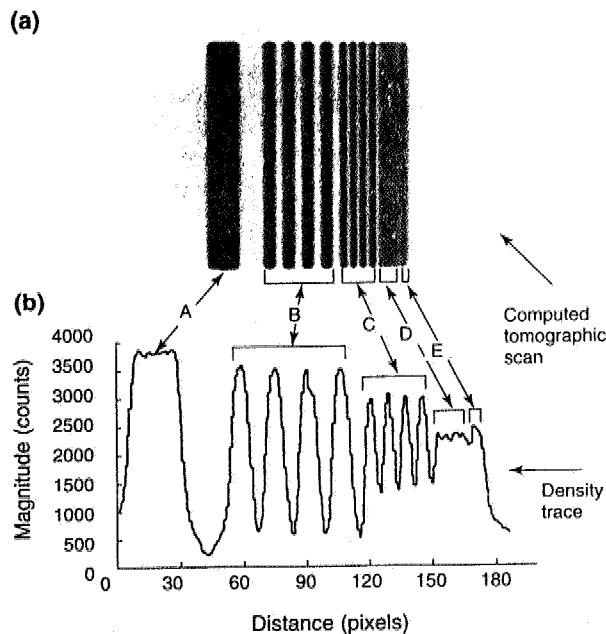


Figure 7.2: Computed tomography of line pair phantom: (a) tomographic image; (b) density trace evaluation.



Legend

- A. reference bar
- B. 0.5 line pairs per 1 mm (13 line pairs per 1 in.)
- C. 1 line pairs per 1 mm (25 line pairs per 1 in.)
- D. 2 line pairs per 1 mm (50 line pairs per 1 in.)
- E. 4 line pairs per 1 mm (100 line pairs per 1 in.)

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where:

EDR = effective dynamic range

BD = bit depth

N_R = readout noise and

N_{Sbk} = background scatter.

Effective dynamic range is the best contrast performance an inspector can achieve with a particular system for a particular technique.

Both spatial and contrast resolutions must be considered when specifying a system. These are illustrated in Figure 7.1. For example, systems with a pixel size larger than $3048 \mu\text{m}$ (0.012 in.) will not be able to detect features smaller than that, even though its contrast sensitivity can be less than 2%. Though the system could detect small changes in object contrast or density, it cannot detect features smaller than its pixel size. Conversely, while a system may have small enough pixels to detect a feature, it must also have sufficient contrast resolution to detect the required changes in density. Although both variables must be considered, they are not independent.

While *spatial resolution* is ideally defined as the smallest detectable feature, it also is a function of contrast performance. Image contrast must be at some minimal level in order for spatial resolution to be assessed at all. Alternatively, poor spatial resolution because of some sources of uncontrolled blur, for example background scatter or object scatter, can compromise the best contrast performance. The modulation transfer function for a system provides a measure of the contrast performance as a function of spatial frequency.

Modulation transfer function is the ratio of the image amplitude to the object amplitude, as a function of the sinusoidal frequency variation of subject contrast in the object. This can be visualized by considering a bar pattern as shown in Figure 7.2. As the pattern becomes finer, the image begins to lose contrast. A plot of this response is called the *square wave response* (when a bar pattern is used) and is very similar to the modulation transfer function. Square wave response factors can be used to evaluate imaging systems and under certain conditions may be corrected to the sine wave response or modulation transfer function equivalence.

In practice, various factors can result in information being scattered over several pixels, thereby reducing the resolution. Modulation transfer function is a useful measure of true or

Chapter 7: Fundamentals of Digital Images

effective resolution, because it takes into account the amount of blur (or contrast) through the system over a range of spatial frequencies.

Signal-to-Noise Ratio

Noise is the primary limiting factor in any image enhancement procedure. When noise is present, the ability to detect features of interest depends on the ratio of the signal intensity to the random intensity variations caused by the noise in the system. Most enhancement techniques also enhance the noise, sometimes more than the signal. Care must be taken to use imaging and analysis techniques that minimize noise and give the maximum signal-to-noise ratio.

Display

Pixel Mapping

A critical aspect of the electronic display is the monitor resolution. For example, monitors may have display resolutions of 1200×1600 or 2000×2500 , however, scan resolutions of 5000×6000 can be generated from the readout process. Therefore, it is important to remember that depending on the magnification of the image on the monitor, there may actually be more raw data available than is displayed. To display an image that either has more or less data displayed than is in the raw image, pixel mapping techniques are used. Pixel replication or pixel interpolation are used when magnifying beyond the image resolution. When reducing the image size, pixel averaging is used.

Gray Scale Mapping

A monitor may only be able to display a portion of the data available in each pixel. For example, digital images may contain 12 or 16 bit digital data that must be displayed on a monitor that may display only 8 bits. The system must properly map the 12 (or 16) bit gray scale data to a cathode ray tube. First, because only 8 bits can be displayed on the monitor, a dynamic look up table function can be used to select which 256 gray scale range of the original data are displayed; this is referred to as *window* and *leveling* in the case of 16 bits. If all 16 bits are mapped, the look up table equally divides the 4096 gray levels over the available 256 display levels. Typically, the useful radiographic information is contained over a narrow range of gray levels so that a window brackets the desired values within the 12 (or 16) bit range to map to

the display and the level of the window modulates the display brightness. In this way, it is possible to maximize the display contrast associated with small change in object contrast.

Archiving and Data Compression

Archiving requirements, such as file sizes and storage devices, must be carefully considered when developing techniques. For example, a radiograph for moisture may use a 35×43 cm (14×17 in.) image area and, because of the low resolution required, use a $200 \mu\text{m}$ (0.008 in.) pixel. This would produce an image of 1780 pixels horizontally and 2160 pixels vertically for a total of 3.8 million pixels, or a 7.6 megabyte file size. If, on the other hand, one is looking for fatigue cracks and still wants to use a 35×43 cm (14×17 in.) image area, then a $50 \mu\text{m}$ (0.002 in.) pixel size would be more desirable. This would result in an image that is 7000×8500 pixels, or about 60 megapixels and a corresponding file size of 120 megabytes. This is equivalent to more than eighty floppy disks for a single image!

Data compression techniques reduce the size of files by removing unneeded information so they take up less storage space. There are a variety of compression techniques available and care must be taken to ensure that the one chosen does not remove necessary discontinuity related information. Lossless compression techniques provide a reduction in file size while maintaining data integrity.

As can be readily seen, as image resolution increases, storage requirements and therefore cost of storage will increase as well. There are key capacity and performance tradeoffs which must be evaluated to minimize production delays such as having to wait for an acquired image to be written to, or recovered from, a storage device.

Chapter 7 Review Questions

- 7.1 The limit of contrast resolution of a digital imaging system is:
- limited by the spatial size of the pixel.
 - limited by the spatial frequency.
 - the bit depth.
 - the bit clock.
- 7.2 Three fundamental properties of digital images are:
- signal-to-noise ratio.
 - contrast resolution.
 - spatial resolution.
 - None of the above.
 - All of the above.
- 7.3 Effective dynamic range of a system defines the practical limit of contrast performance. The effective dynamic range is limited by:
- the readout noise.
 - the limits of data compression.
 - the number of background scattered counts.
 - the image acquisition speed.
 - both a and c.
 - both b and d.
- 7.4 Pixel mapping is a technique used to:
- display an image that has either more or less data displayed than is in the raw image.
 - map pixel data from one location to another for image processing.
 - maximize the display contrast associated with a small change in object contrast.
 - None of the above.
- 7.5 Data compression:
- reduces the size of files by removing unneeded information.
 - is not possible without losing important data.
 - is only possible with pixel mapping.
 - both a and c.
- 7.6 Line pairs per millimeter is an expression of resolution in terms of:
- bit depth.
 - spatial resolution.
 - pixel size.
 - All of the above.
- 7.7 Lossless data compression:
- is a technique that reduces file size, but permits the recovery of compressed data.
 - is a technique that provides a reduction in file size without any loss of data.
 - is a technique that provides a reduction in file size while maintaining data integrity.
 - results in a ZIP file that can be reexpanded, thereby retaining the original data.
- 7.8 The range of discrete signal counts (bits) possible in each pixel:
- defines the number of entries possible in the look up table.
 - defines the spatial resolution.
 - defines the data compression limit.
 - defines the limit of contrast resolution.
- 7.9 As image resolution increases:
- data compression is required.
 - file size, and accordingly storage costs, increase.
 - larger monitors are required.
 - None of the above.
- 7.10 Which of the following makes it possible to maximize the display contrast associated with a small change in object contrast?
- data compression
 - pixel mapping
 - gray scale mapping
 - None of the above.

Chapter 7: Fundamentals of Digital Images

- 7.11. A 35×43 cm (14×17 in.) image area is made up of 0.02 cm (0.008 in.) pixels. How many pixels are in the image?
- a. 3.8 megapixels
 - b. 7.6 megapixels
 - c. 60 megapixels
 - d. 120 megapixels
- 7.12 A 35×43 cm (14×17 in.) image area is made up of 0.005 cm (0.002 in.) pixels. How many pixels are in the image?
- a. 3.8 megapixels
 - b. 7.6 megapixels
 - c. 60 megapixels
 - d. 120 megapixels

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Chapter 8

Film Digitization

Film digitization provides the ability to digitize a conventional film image, thereby permitting better analysis and storage, and allows disposal of the film that would degrade over time.

Charge Coupled Device Film Digitization Systems

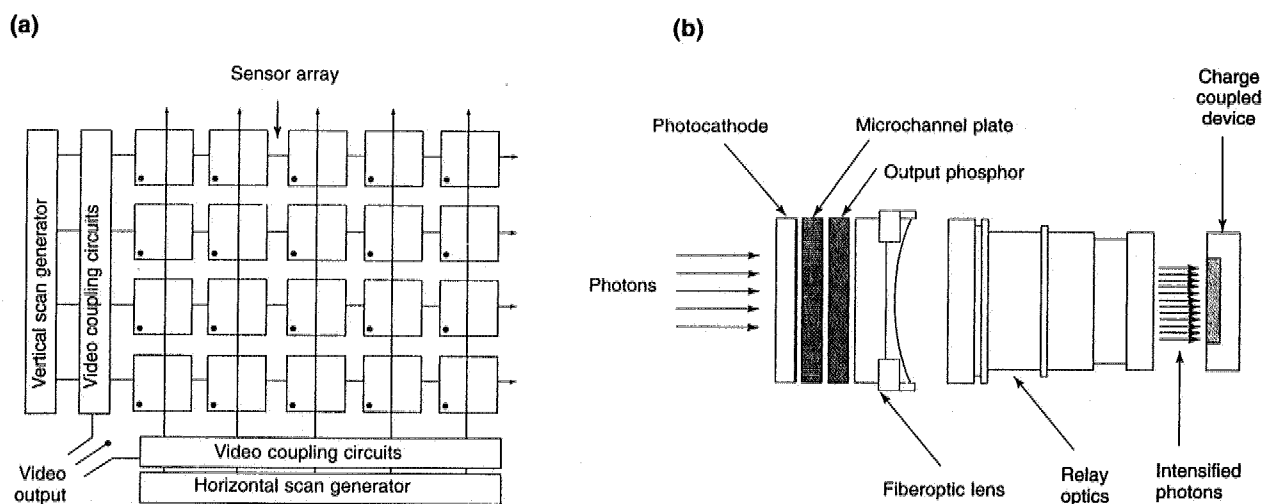
A charge coupled device is a silicon semiconductor device consisting of a large number of grid like elements which are sensitive to light. When light energy impinges on the charge coupled device elements, the photons generate a charge within each element. Periodically, the element is discharged and the amplitude of the charge measured. In this way, light amplitude can be converted to a proportionate electrical signal and digitized.

Charge coupled devices have a limited light intensity dynamic range. This occurs when there

is a rapid and drastic change in light level and the charge coupled device momentarily saturates. The image is corrected by changing the sampling time or integration period. At high light levels, the integration period is reduced to avoid saturation of the charge coupled device, whereas at low light levels, the integration period is increased to achieve an adequate signal-to-noise ratio. To obtain optical density dynamic ranges up to 5, multiple scans are performed at varying charge coupled device integration periods and scan speeds.

Another aspect of charge coupled devices is their spatial resolution. The elements can be arrayed along one dimension or in two dimensions. The array's resolution is generally given as the element size. Thus, the 1 cm² chip in a video camera that has 512 by 512 elements is said to have a resolution of about 20 μ m. Once the various focusing lens aberrations are coupled together, the true resolving capability of a charge

Figure 8.1: Charge coupled device: (a) array schematic; (b) intensified camera.



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coupled device chip is quite low. A home video camera is surely not capable of discerning objects that are $20\text{ }\mu\text{m}$ apart. Thus, it is important to differentiate between the chip specifications versus those of the imaging system. The resolution of the imaging system depends in part on the quality of the focusing optics, and in part on the cross talk between charge coupled device elements (i.e., one photon activates more than one element), so that actual system resolutions are limited. The only way to actually determine the resolution of a charge coupled device digitizer is to scan a modulation transfer function pattern to validate performance.

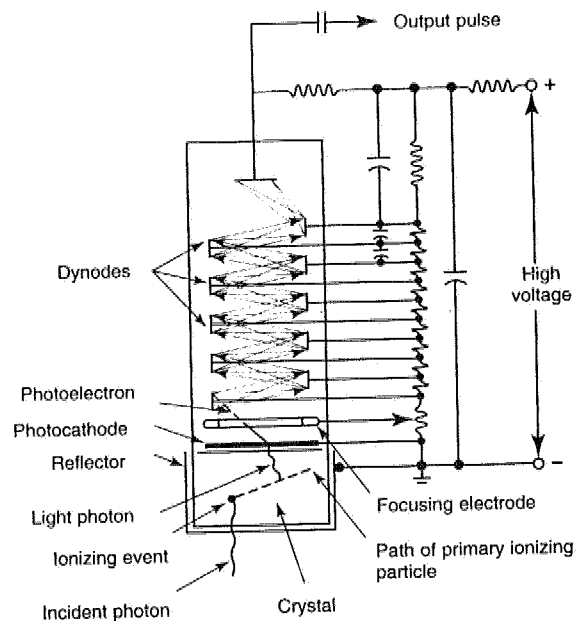
In the case of film digitization systems, a linear array is used with appropriate optics to focus the film image onto the much smaller charge coupled device element as shown in Figure 8.1. A narrow line of diffused light is passed through the film and the transmitted light is focused onto the charge coupled device array, one line at a time. Once one line of data is collected, a second line is then scanned.

Laser Film Digitization Systems

Laser scanners utilize a nonimaging photomultiplier tube, as shown in Figure 8.2, to detect light transmitted through the film. The tube has a wide dynamic range, good signal-to-noise ratio and uses a log amplification process such that a uniform density resolution is maintained over the entire range.

The spatial resolution of a laser scanner is determined by the size of the point of laser light that impinges on the film. Because there is only a single beam, there is no cross talk between pixels and a true limiting resolution equal to the laser spot size can be achieved. However, the actual modulation transfer function will depend on overall laser beam quality, detector noise and electronic noise.

Figure 8.2: Cutaway drawing of photomultiplier tube showing crystal, photocathode, collecting dynodes and voltage divider network.



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Chapter 8 Review Questions

- 8.1 Laser digitization systems that use a photomultiplier tube:
- a. always result in images with the same resolution as the original film image.
 - b. have no issues with resulting dynamic range.
 - c. require multiple scan because the laser is diffused through the film.
 - d. None of the above.
- 8.2 In order to reach an optical density range from 0 to 5, charge coupled devices must be scanned several times. This is because:
- a. photomultiplier tubes have a limited dynamic range.
 - b. the integrating cylinder is so much larger than the desired pixel size.
 - c. charge coupled devices have a limited intensity dynamic range.
 - d. None of the above.
- 8.3 When using charge coupled devices, the resolution of the imaging system depends on:
- a. the quality of the imaging optics.
 - b. the intensity of the laser used.
 - c. the frequency of the laser used
 - d. All of the above.
- 8.4 One disadvantage of using charge coupled devices is that:
- a. they have a fixed pixel size that cannot be adjusted.
 - b. they must be scanned several times in order to reach a wide range of densities.
 - c. the logarithmic density scale is converted to a linear voltage scale.
 - d. quantum fluctuations degrade efficiency.
- 8.5 Crosstalk between charge coupled device elements occurs when:
- a. the elements are not sufficiently electrically isolated.
 - b. the elements become too small.
 - c. very high energies are used.
 - d. one photon activates more than one element.
- 8.6 The spatial resolution of a laser scanner is determined by:
- a. the size of the laser spot and the laser frequency.
 - b. the size of the laser spot and overall beam quality.
 - c. the system modulation transfer function.
 - d. All of the above.

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Chapter 9

Digital Radiographic Imaging

There are various methods of acquiring digital radiographs by electronic means. These include:

1. conversion of X-rays to light and then to electronic images,
2. photoconductive conversion of X-rays to electronic images,
3. photostimulable storage phosphors,
4. array detectors,
5. line scan imaging, and
6. scanning electron beams.

This subject differs from radioscopic imaging in that these systems are not video based. Rather, they employ discrete sensors with the data from each detection element being read out into a file structure to form the pixels of the digital image. In radioscopic imaging the major emphasis is on the conversion of X-rays to analog electronic data that are viewed as video signals in real time.

An exception to the discrete sensor based systems is the photostimulable phosphor system that forms a latent image, similar to film, on a phosphor screen. The screen is then read out electronically using a special laser scanner.

Detection devices that support imaging systems include:

1. phosphors deposited on amorphous silicon thin film transistor diodes,
2. photoconductors such as amorphous selenium deposited on thin film transistors,
3. phosphors deposited on, or coupled through, fiber optic lenses onto charge coupled device based detectors and complementary metal oxide silicon based detectors,
4. photostimulable storage phosphors,
5. phosphors deposited on linear array systems, and
6. X-ray scanning source and geometry detectors.

Thin Film Transistors (Amorphous Silicon Detectors)

Most designs are based on a flat glass panel that has a coating on one side that contains several million amorphous silicon transistors (TFTs) that are arranged in rows and columns. Each individual transistor has bias and control lines that are brought to the edge of the panel. A large pixel space is required to accommodate the transistor, data lines and scan lines, thus limiting how small a pixel this device can permit. The length and makeup of these control lines also play a role in how fast image data can be scanned out of the array.

On top of the thin film transistor is an X-ray conversion layer. This layer may consist of phosphors, as shown in Figure 9.1, that convert the X-rays to visible light photons. In this case each detector element is made up of a transistor and a photodiode. The light from the phosphor is captured by the photodiode, converted to electrons and then read out through the transistor.

Other X-ray conversion layers may consist of photoconductors, such as amorphous selenium. These are referred to as *direct* because the incident X-ray photons are directly converted into electrons with no intermediate step as shown in Figure 9.2. The high voltage bias field applied to an amorphous selenium layer creates vertical field lines. Because these field lines are parallel to the incident X-ray beam, the field prevents the charge from scattering and thus there is virtually no blur. Consequently the amorphous selenium conversion layer (excluding the pixel electrodes) exhibits extremely high resolution.

Charge Coupled Devices

Charge coupled devices are essentially photon detectors. An incident photon creates an electron hole pair. This creates a current flow which, in a charge coupled device, is stored in the

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potential well of the device. The amount of charge collected at the potential well is in direct proportion to the amount of local light intensity.

Charge coupled devices, although made with high pixel densities, are typically small in size because they are based on crystalline silicon, cut from silicon wafers, which are traditionally available in sizes only as large as 100 to 150 mm (4.0 to 6.0 in.) in diameter or less. Larger fields of view can be achieved through the use of tiling of charge coupled devices, through a lens or a fiber optic transfer device to view an X-ray conversion screen. The lens approach has very poor light collection efficiency while fiber optics and tiling do not provide large fields of view but will result in more efficient light collection.

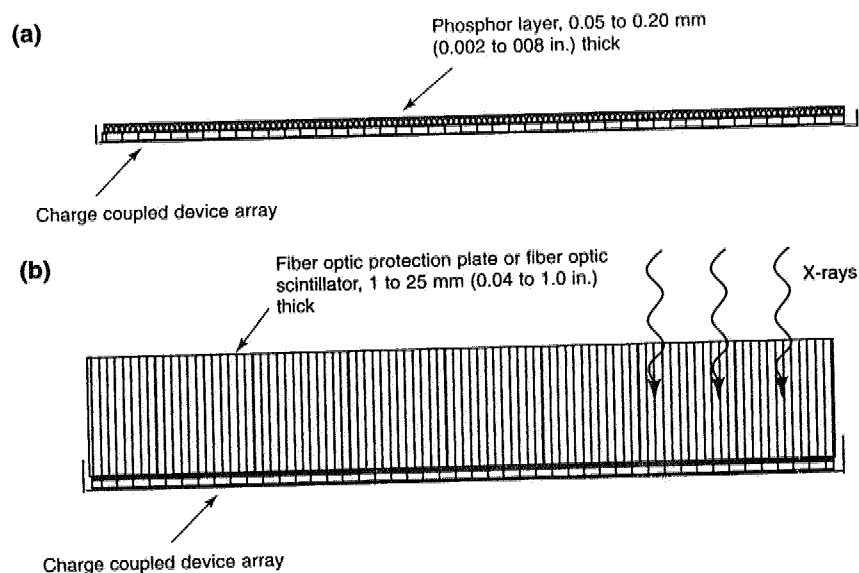
Charge coupled devices are typically used in combination with phosphor materials as shown in Figure 9.3. On a per pixel basis, the charge coupled device is more efficient in collecting the light produced from the phosphor material than is the thin film transistor. For small field of view applications, the directly coupled charge coupled device will provide high spatial resolution and high light collection efficiency.

Storage Phosphors

Storage phosphor imaging utilizes a screen that is exposed with geometries that are the same as with conventional film and uses the same X-ray sources as conventional film. The screen itself is made up of a plastic substrate on which is deposited a phosphor material that is then covered with a clear protective overcoat and is fully reusable after erasure. Additionally, these screens are somewhat flexible which gives them an advantage over other digital approaches that use rigid plates.

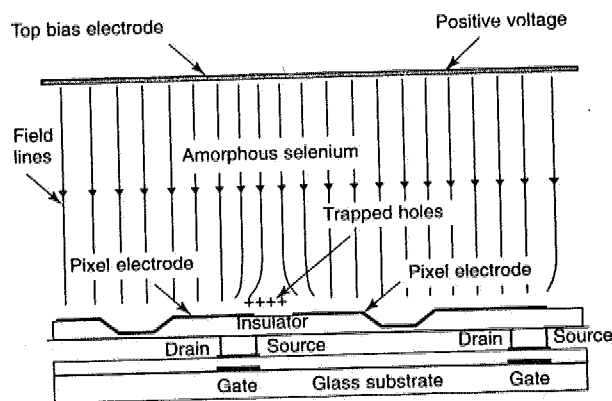
Storage phosphors operate by trapping electrons that are excited by incident X-rays, at higher energy levels. For example, in the case of SrS:Ce Sm , the Ce^{3+} ion's 4f ground state electron is excited to its 5d state and subsequently to the Sm^{3+} where it becomes trapped. This trapping

Figure 9.1: Charge coupled device based X-ray detector: (a) X-rays directly excite charge coupled device; (b) fiber optic scintillator coupled directly to charge coupled device provides shielding to sensor.



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Figure 9.2: Schematic cross section of amorphous selenium X-ray detector.



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process constitutes the latent image formation within the phosphor layer. However, this does not produce a permanent chemical change, but one that can be reversed by stimulating trapped electrons with external energy. This process reversal produces photostimulated luminescence. The intensity of the photostimulated luminescence is directly proportional to the number of trapped electrons, which is in turn

Chapter 9: Digital Radiographic Imaging

proportional to the amount of radiation energy absorbed by the storage phosphor screen. As a result, the characteristic curve, or exposure curve, is linear as opposed to logarithmic as with film.

The photostimulated luminescence from a small area (determined by the laser spot size) is then collected at a photomultiplier tube that converts the incident luminescence photons to photoelectrons (current) and amplifies it. This current is then converted to a voltage, digitized and stored as a function of x - y position. This process is repeated until every point on the phosphor screen has been scanned, the image computed and digitally displayed.

After scanning, a residual image may remain on the screen. The image is eliminated (erased) by using an intense source of energy at the same wavelength used for scanning. This feature

makes the phosphor screens fully reusable and provides a major advantage over film.

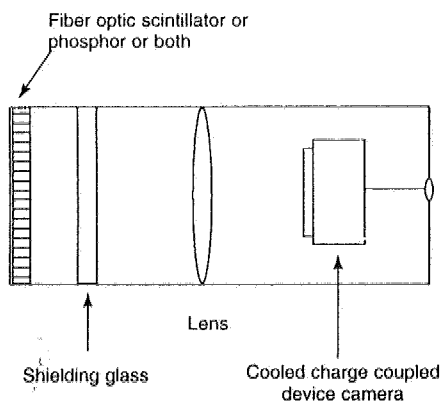
Various systems are available that utilize different phosphor materials and different wavelength lasers to extract the latent image. This scanning process is where this technology departs from the other digital approaches. The screen is then erased and can be reused. This technology produces an image that is identical in perspective to that produced with film and eliminates the need for darkrooms and film processing chemicals.

Inherent unsharpness in phosphor images is a factor of grain size, screen thickness and pixel size. Unsharpness is reduced and resolution improved as these three parameters are reduced.

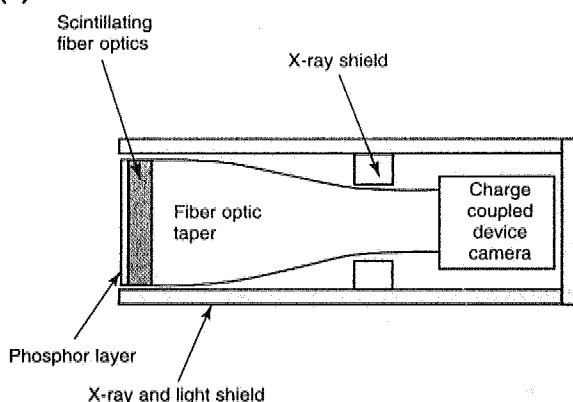
The main advantage of storage phosphor imaging over film is the reduction of film use, the ability to digitally acquire a film quality image and the corresponding benefits of that digital image file, such as easy archival and retrieval.

Figure 9.3: Coupling of light from phosphor to charge coupled device in X-ray detector system: (a) lens coupling; (b) fiber optic coupling.

(a)



(b)



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Linear Arrays

Linear array detectors are much like charge coupled devices, except that they typically have pixels in only one dimension or they may be composed of a small rectangular array such as 30 pixels $\times$ 1024 pixels. The advantage of linear arrays is their scatter rejection capability. The key is that the radiation beam is collimated to match the size of the detector. This dramatically reduces the object's scatter field. The scatter detected at each of those lines is substantially less than that of individual lines in an array area.

Scanned Beam

With scanned beam radiography the test object is placed near the X-ray source, unlike conventional radiography where the object is placed near the detector. As shown in Figure 9.4, the X-ray source is large and operates in a manner similar to a video monitor. An electron beam is electronically scanned over the inner surface of the front of the X-ray source. Where the electrons collide with the inner surface of the tube, X-rays are generated. By electronically scanning the beam, the position of the X-ray emission is determined and correlated with the detected energy and an image can be formed.

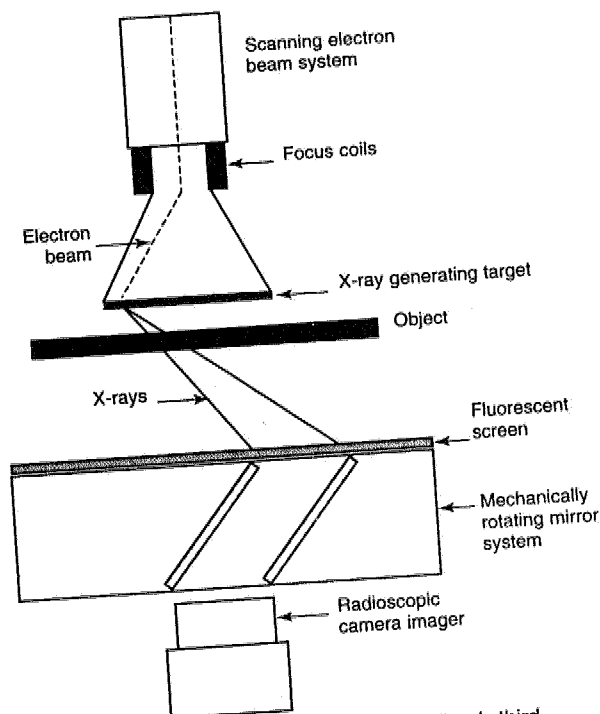
Because a single small area detector is used and the object is placed at the source, not at the detector, the X-ray scatter from the object is essentially zero. The disadvantage of this approach is that, because it is reverse geometry,

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the effective focal spot size is that of the detector size. The detector is typically much larger than a typical industrial X-ray focal spot. As a result, any specimen that has some thickness will show significant unsharpness as the features of interest move away from the X-ray source.

detector, and thus the image contrast, are therefore dependent on the transfer of information along the entire imaging chain.

Figure 9.4: Scanned beam laminography system.



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Detection Efficiency

The selection of the phosphor or photoconductive material, its thickness and effective atomic number, will affect the total number of X-rays absorbed. Once energy is absorbed, each material has its own efficiencies for conversion of this energy into either light or charge carriers. Following this, there are other coupling steps to transfer the signal onto pixelized readout circuitry.

The performance of the X-ray detector to convey the information in the radiation beam is then dependent on the efficiency of each step in the X-ray conversion process leading to an electronic signal. The signal-to-noise ratio of the

Chapter 9 Review Questions

- 9.1. Digital imaging systems differ from radioscopic systems in that:
- radioscopic images have significantly better image quality.
 - radioscopic systems are video based.
 - digital systems are faster.
 - There is no fundamental difference. They just use different sensors.
- 9.2 All of the following are methods of acquiring digital radiographs except:
- thin film transistors.
 - photoconductive conversion of X-rays to electronic images .
 - photophosphoric detection screens.
 - phosphors coupled through fiberoptic lenses onto charge coupled devices.
- 9.3 All of the following detection methods of acquiring digital images utilize discrete sensors except:
- charge coupled devices.
 - thin film transistors.
 - photostimulable storage phosphors.
 - All of the above use discrete sensors.
- 9.4 Thin film transistors are coated with either phosphors or photoconductors. The purpose of these coatings is:
- intensification.
 - X-ray filtration.
 - scatter control.
 - X-ray conversion.
- 9.5 One benefit of using amorphous selenium rather than phosphors is that:
- incident photons are directly converted into electrons.
 - they are more efficient per photon of energy.
 - a thinner layer can be used because of their efficiency.
 - None of the above.
- 9.6 One disadvantage of TFTs is:
- the relatively large pixel size required for the readout circuitry.
 - the need to use a scintillator with them.
 - the need to couple them with fiber optic relays.
 - the lighter weight of the electronics associated with them.
- 9.7 An advantage of storage phosphors over other digital imaging schemes is:
- they are less expensive to replace.
 - they do not have a large array of individual elements that can fail.
 - they can be rescanned or reused.
 - the phosphor screens are somewhat flexible.
- 9.8 The major difference between imaging with storage phosphors and imaging with other digital methods is:
- the images created with storage phosphors are easier to manipulate.
 - storage phosphor imaging is faster.
 - storage phosphor imaging produces a latent image.
 - None of the above.
- 9.9 The storage phosphor imaging process consists of all of the following except:
- incident X-rays trapping electrons at higher energy levels.
 - the charge on a metal oxide semiconductor is depleted.
 - a PMT converts incident luminescence into electric current.
 - energy is released when stimulated by a scanning laser.

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9.10 The emission of light by a storage phosphor when exposed to the appropriate wavelength laser is called:

- a. photophosphorescence.
- b. fluorescence.
- c. photostimulated luminescence.
- d. electroluminescence.

9.11 An advantage of storage phosphors over film is that:

- a. storage phosphors can be erased and reused.
- b. they are less expensive.
- c. they produce much higher quality images.
- d. their images can easily be transported by fiber optic transfer.

9.12 Amorphous selenium conversion layers exhibit extremely high resolution because:

- a. the modulation transfer function is not dependent on the spatial frequency.
- b. lateral scattering is prevented by the presence of vertical field lines that are parallel to the incident X-rays.
- c. no gain or offset correction is required.
- d. there are no electronics associated with them.

Chapter 10

Radiographic Techniques

Reduction of Scatter

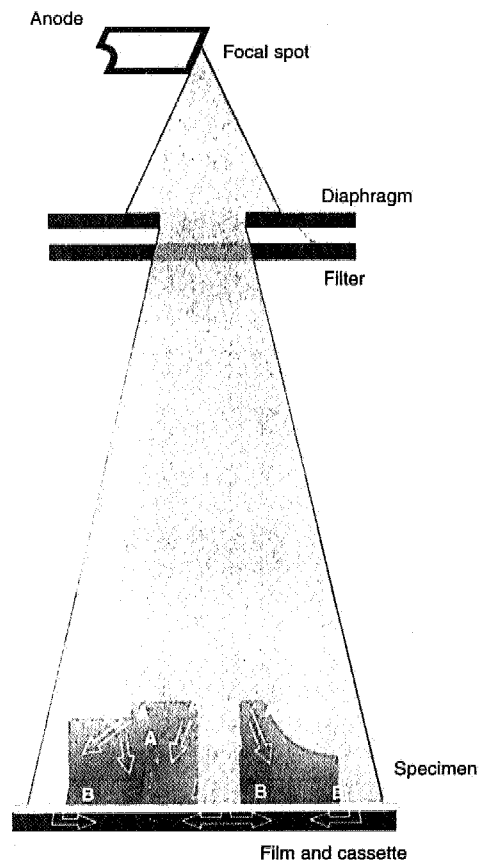
When a beam of radiation strikes any object, some of the radiation is absorbed, some is scattered and some passes straight through. The wavelengths of much of the primary radiation are increased by the scattering processes with the resulting scatter being softer and less penetrating than the primary radiation. Any material that is subjected to direct radiation becomes a source of scattered radiation and steps must be taken to reduce this scatter because it reduces the contrast of the images recorded on the film. Preventing scatter from reaching the film (or any detector) markedly improves the quality of the radiographic image. Scatter occurs, and is a problem, with all types of energies and detectors. The discussion which follows is in terms of X-rays and film, but the same basic principles apply in general.

As a rule, the greater portion of the scattered radiation affecting the film is from the test object (A in Figure 10.1). However any portion of the film holder or cassette that extends beyond the specimen and receives direct radiation also becomes a source of scatter which can affect the film. The influence of this scatter is most noticeable just inside the borders of the image of the specimen (B in Figure 10.1). In a similar manner, primary radiation striking the film holder or cassette through thin portions of the specimen will cause scattering into the shadows of the adjacent thicker portions. Such scatter is called *undercut*. Another source of scatter that may undercut a specimen is *diffraction*, shown as C in Figure 10.1.

Any other material, such as walls or floor, on the film side of the specimen may also scatter an appreciable quantity of radiation back to the film, especially if the material receives direct radiation from the source as shown in Figure 10.2. This is referred to as *backscattered radiation*. This can also be significant and can even produce an image of cinder block walls overlaying the entire film.

Although scattered radiation can never be completely eliminated, a number of means are available to reduce its effect. Techniques to control scatter include masks, diaphragms, screens and filters.

Figure 10.1: Sources of scattered radiation.



Legend

- A = transmitted scatter
- B = scatter from cassette
- C = diffraction scatter

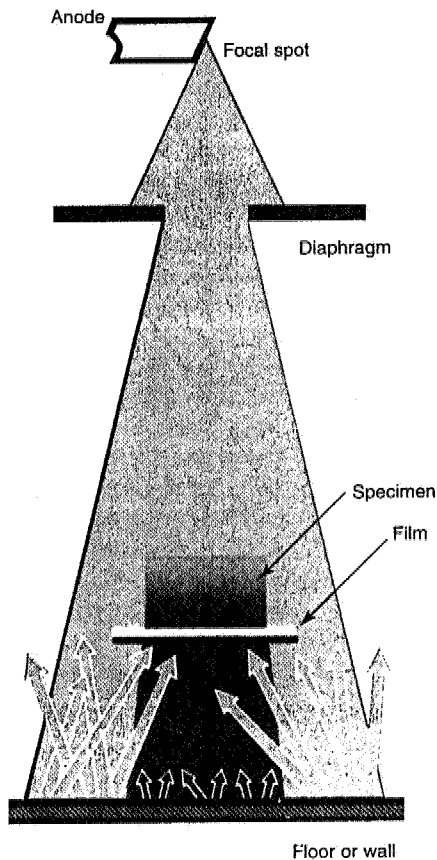
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Masks

Scatter radiation originating in matter outside the specimen is most serious for specimens which have a high absorption for X-rays because the scattering from external sources may be large compared to the primary image forming radiation that reaches the film through the specimen. Depending on the energy range of the radiation emitting source being used and the thickness of the specimen being radiographed, masking the specimen with sheets of lead may reduce scatter radiation to an acceptable level as shown in Figure 10.3. To be successful, the lead must be cut to fit tightly around the edges of the specimen. Any major gaps or crevices will provide a path to the film resulting in very erratic scatter patterns on the film. Masking is used primarily on those specimens that do not cover

Figure 10.2: Intense backscattered radiation may originate in the floor or wall. Collimating, masking or diaphragming should be used. Backing the cassette with lead may give adequate protection.



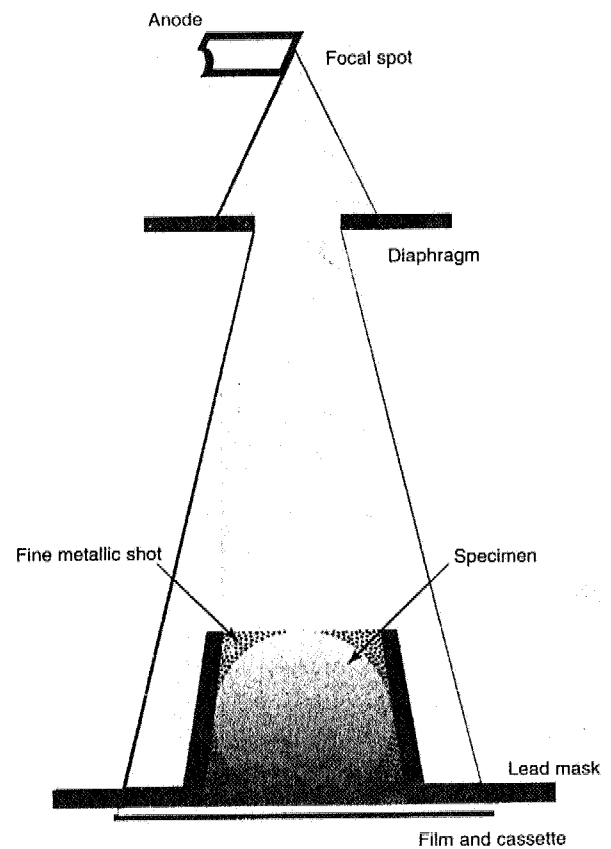
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the film completely, such as small castings, bars and qualification samples. Additional masking techniques involve the use of barium clay, a saturated solution of lead acetate and lead nitrate, or copper and/or steel shot.

Diaphragms

Often the most satisfactory method of lessening scatter is by the use of diaphragms. The purpose of diaphragms is to limit the radiation reaching the film to only that passing through the specimen or area of interest. Frequently the diaphragm is located at the tube head to allow a cone of radiation to cover only the film as shown in Figures 10.1, 10.2, 10.3 and 10.4, or to limit the beam cross section to only the area of the

Figure 10.3: Combined use of metallic shot and lead mask for lessening scattered radiation is conducive to good radiographic quality. If several round bars are to be radiographed, they may be separated along their lengths with lead strips held on edge by wooden frame and voids filled with fine shot.



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specimen that is of interest in the examination. This minimizes scatter off cabinet walls and other objects.

Another method of lessening scatter is by the use of cutout diaphragms or some other form of mask mounted over or around the object radiographed. If many specimens of the same article are to be radiographed, it may be worthwhile to cut an opening of the same shape, but slightly smaller, in a sheet of lead and place it on the object. The lead serves to reduce the exposure in surrounding areas to a negligible amount and to eliminate the scatter from this source.

Screens

Lead screens in contact with a film reduce the effects on the film of scattered radiation from all sources. Front lead screens between 0.025 and 0.25 mm (0.001 and 0.01 in.) thick, in intimate contact with the film, are typically used for all radiographs taken with X-rays or gamma rays that exceed 150 kV. Lead screens lessen the scatter reaching the film regardless of whether the screens permit a decrease or necessitate an increase in the radiographic exposure.

X-ray exposure cassettes often incorporate a sheet of lead foil, usually 1.6 to 3.2 mm (1/16 to 1/8 in.) thick, in the back for the specific purpose of protecting the film from backscatter. This lead will not serve as an intensifying screen; first, because it usually has a paper facing and second, because it often is not of *radiographic quality*. If using such a cassette for gamma rays or million volt X-rays, the film should always be enclosed between double lead screens. Otherwise, the secondary radiation from the lead backing is sufficient to penetrate the intervening felt or paper and cast a shadow of this material on the film, giving a granular or mottled appearance.

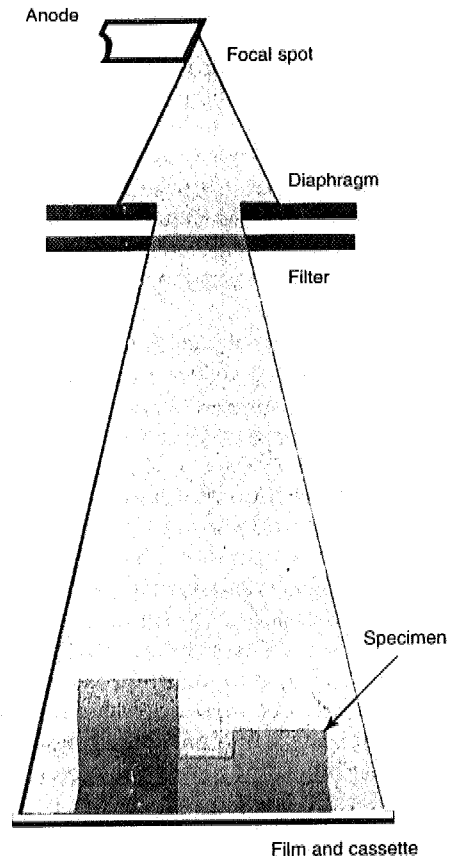
In high energy applications, lead screens up to 3.0 mm (0.12 in.) thick or more may be used.

Filters

Filters may be placed either between the object being radiographed and the X-ray source, as in Figure 10.4, or between the object and the film. When the filter is placed between the object and the film, the filter is intended to reduce scatter. In general, the use of filters is limited to radiography with X-rays.

A metallic filter placed between the source and object reduces subject contrast by hardening the radiation. The longer (soft) wavelengths do not penetrate the filter to the same extent as the

Figure 10.4: Filter placed near X-ray tube reduces subject contrast and eliminates much of secondary radiation, which tends to obscure detail in periphery of specimen.



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short (hard) wavelengths. The beam emerging from the filter therefore contains a higher proportion of the shorter wavelengths. The low energy radiation, if not filtered out, would increase the undercutting or burning out of the edges in thinner sections.

Rules for filter thicknesses are difficult to formulate exactly because the amount of filtration required depends not only on the material and thickness range of the specimen, but also on the distribution of material in the specimen and on the amount of scatter to be eliminated.

Typical filters for aluminum and steel are shown in Table 10.1. The values in this table are maximum values, and depending on circumstances, useful radiographs can often be made with far less filtration.

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In X-radiography, up to about 250 kV, front lead screens 0.013 cm (0.005 in.) thick are customarily used. Additional filtration between the specimen and film only tends to contribute additional scatter from the filter itself. The scatter undercut can be decreased by adding an appropriate filter at the tube. Although this filter gives rise to scattered radiation, it is emitted in all directions, and because the film is far from the filter, scatter reaching the film is very low in intensity. Further advantages of placing the filter near the tube are that specimen film distance is kept to a minimum and that scratches and dents in the filter are so blurred that their images are not apparent on the radiograph.

Control of Diffraction Scatter Effects

A special form of scatter caused by X-ray diffraction is encountered occasionally. It is most often observed in the radiography of metallic specimens whose grain size is large enough to be an appreciable fraction of the part thickness, or multiple of the X-ray wavelength. This effect is sometimes seen in castings. The radiographic appearance of this type of scattering is mottled and may be confused with the mottled appearance sometimes associated with porosity or segregation. It can be distinguished from these conditions by taking two successive radiographs, with a slight shift of the radiation angle (1 degree to 5 degrees) by moving the specimen or the source. A pattern caused by porosity or segregation will remain essentially unchanged, while one caused by diffraction will change significantly or be eliminated. The mottling caused by diffraction can also be reduced, and in some cases eliminated, by increasing the kilovoltage or by using filters.

Multifilm Techniques

Extreme part thickness variations and component configuration can result in the transmission of too wide a range of intensities to be successfully recorded on a single film. In such situations, rather than simply taking multiple exposures, a multifilm technique may be used in which two or more films of different speeds are combined in a single cassette and exposed simultaneously.

The exposure parameters are selected so that the thick sections are recorded on the faster film and the thinner on the slower film. This method is not limited to only two films being exposed together. In special cases, three to five films may be used, expanding the range of thickness over

Table 10.1: Typical filters for aluminum and steel.

Material	Filter	Thickness
aluminum	copper	4% of maximum specimen thickness
steel	copper	20% of maximum specimen thickness
	lead	3% of maximum specimen thickness

which high contrast can be achieved with a single exposure. Films may also be viewed separately or superimposed. However, the number of films simultaneously exposed or viewed may be limited by certain specifications because of unsharpness considerations.

A commonly used variation of this method is to use two films of the same speed. With the correct exposure parameters, the details in the thick section can be evaluated by superimposing the images of both films. The thinner portion is recorded on both films and either film can be used for the evaluation. Again, this technique is specifically prohibited by some specifications.

Enlargement and Projection

In conventional radiography, it is desirable to have the film as close as possible to the object being radiographed to reduce geometric unsharpness U_g . An exception to this rule occurs when the source of radiation is very small, a fraction of a millimeter in a microfocus tube or in a betatron for example. In such a case, the film is placed at a distance from the object, rather than in contact with it. A setup of this type will produce enlarged radiographic images without introducing objectionable geometric unsharpness. Useful enlargements of up to three diameters have revealed structures otherwise invisible radiographically. Enlargements on the order of 10 times or more have been found feasible in microradiography with very small focal spots (near 1 μm , or 4×10^{-5} in.).

Geometric enlargements also reduce scattered radiation because an increase in test object to film distance reduces the proportion of scattered to direct beam radiation reaching the film.

Stereo Radiography

Stereo radiography is a radiographic method using two separate radiographs made with a source shift exactly parallel to the film plane, as

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in Figure 10.5. The stereoscopic method is infrequently used in industrial radiography, but on occasion it can be used to localize and characterize indications or to visualize the spatial arrangement of hidden structure.

Because a single radiographic image does not possess depth perspective, it cannot give the impression of depth or indicate clearly the relative positions of the various parts of the object along the direction of vision. Stereoradiographic techniques can be used to create depth perception similar to that of natural vision. Objects viewed with a normal pair of eyes appear in their true perspective and in their correct spatial relation to each other, largely because of the natural stereoscopic vision of the human eyes (depth perception). Each eye receives a slightly different view and the two images are combined by the brain to give the impression of three dimensions.

To duplicate this stereoscopic vision in radiography requires two radiographs made from two positions of the X-ray tube separated by the normal human interpupillary distance. After processing, the two radiographs are viewed in a stereoscope, a device that by an arrangement of prisms or mirrors permits each eye to see only one of the stereoradiographs. As in normal vision, the brain integrates the two images into one in which the various features stand out in relief in true perspective and in correct spatial relation.

It is important to remember that the radiograph exposed in the right shift position of the tube is viewed by the right eye and the one exposed by the left shift position is viewed by the left eye. In fact, the conditions of viewing the radiographs should be analogous to the conditions under which they were exposed. The two eyes take the place of the two positions of the focal spot of the X-ray tube, and the radiograph as viewed in mirrors or prisms occupies the same position with respect to the eyes as did the films with respect to the tube during the exposures. The eyes see the X-ray representation of the part just as the X-ray tube exposed the actual part.

Parallax Methods

Triangulation, or parallax, methods are based on the principle that from two exposures made with different positions of the source, the depth of the discontinuity is computed from the shift of the shadow of the discontinuity. An object close to the film does not appear to change position much, while an object farther from the film appears to shift more. The amount of left or right movement of the projected shadows is directly

Figure 10.5: Diagram of stereoscopic radiographic setup (top) and stereoscopic viewer (bottom).

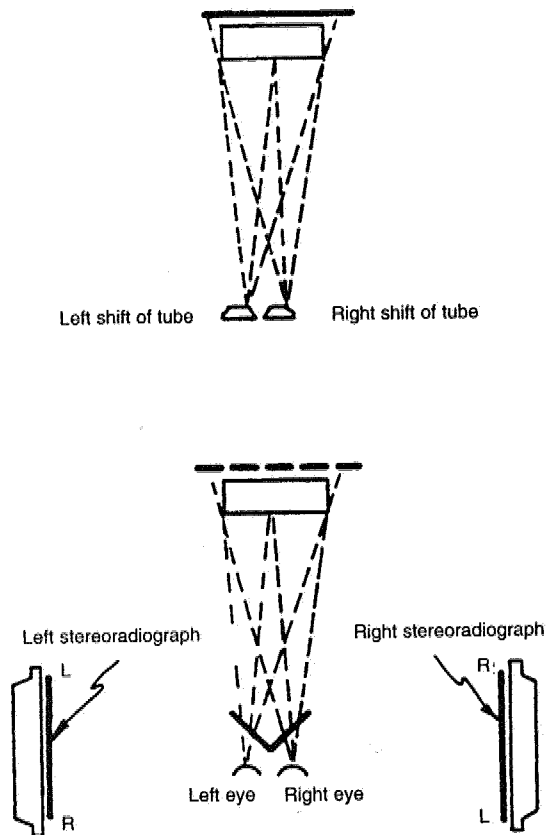
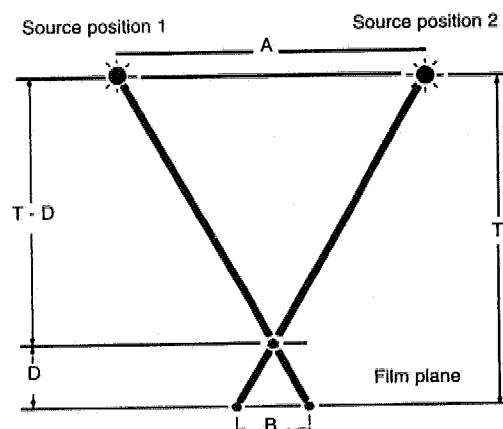


Figure 10.6: Similar triangle relationship.



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proportional to the closeness of the object to the source.

A similar triangle relationship is the basis for most of the calculations used in the radiographic parallax methods. Figure 10.6 shows this relationship graphically.

Radiographic parallax methods use three variations of the similar triangle relationship. These three methods are:

1. rigid formula,
2. single marker approximate formula, and
3. double marker approximate formula.

The data for a similar triangle relationship are derived from the displacement of the image on the film plane. The film plane is used, rather than the depth below the surface, because it is not always possible to have the film in intimate contact with the surface of the part.

In addition to problems encountered in calculating the object's height above the film, certain orientation or discontinuity geometries can cause measurement errors. These are not because of a failure of the method, but rather a failure of the radiographer to recognize and compensate for variations in object displacement.

Rigid Formula

A schematic diagram of the rigid formula method is shown in Figure 10.7a. The method is also defined in the following equation:

$$\frac{D}{T-D} = \frac{B}{A}$$

Equation 21

$$D = \frac{BT}{A+B}$$

Equation 22

$$H_s = D - K + \frac{BT}{A+B} - K$$

Equation 23

where:

A = the source shift between exposures,
 B = the image shift of the discontinuity,
 D = the distance of the discontinuity above the film,

H = the height of the discontinuity above the back surface of the part,
 K = the distance of the part to the film, and
 T = the source-to-film distance.

By measuring or knowing the first three parameters, the fourth parameter can be calculated on the basis of the similar triangle relationship. With the rigid formula method, no markers are necessary. However, the part thickness, the source-to-film distance and the source shift must be accurately recorded. In addition, the image of the discontinuity must be shown on a double exposed radiograph.

The following exposure techniques should be used when applying the rigid formula method.

1. Calculate necessary exposure time.
2. Make first exposure at one half of this exposure time.
3. Move source parallel to (and a specified distance along) the film plane.
4. Make second half of the exposure.

The rigid formula method can be used when the film is placed in intimate contact with the bottom of the part and when there are no limitations on the height of the source above the film plane. It is important to have significantly large source-to-film versus top of object-to-film ratios when using the rigid parallax method.

It is important to remember that the fundamental relationship between discontinuity height and image shift is nonlinear. As the discontinuity height approaches the source-to-film distance, the image shift increases without limit. When the discontinuity height is small compared to the source-to-film distance, the curve of accuracy approaches linearity.

Single Marker Formula

When the part thickness and discontinuity height are small relative to the source-to-film distance, the relationship between D and B approaches linearity and the height of the discontinuity above the film plane becomes approximately proportional to its parallax. A proportional relationship offers certain advantages in that an artificial discontinuity or marker can be placed on the source side of the object, as shown in Figure 10.7b. The height of the discontinuity can be estimated or calculated by comparing the shift of its radiographic image with that of the marker. For example, if the single marker shift is twice the shift of the

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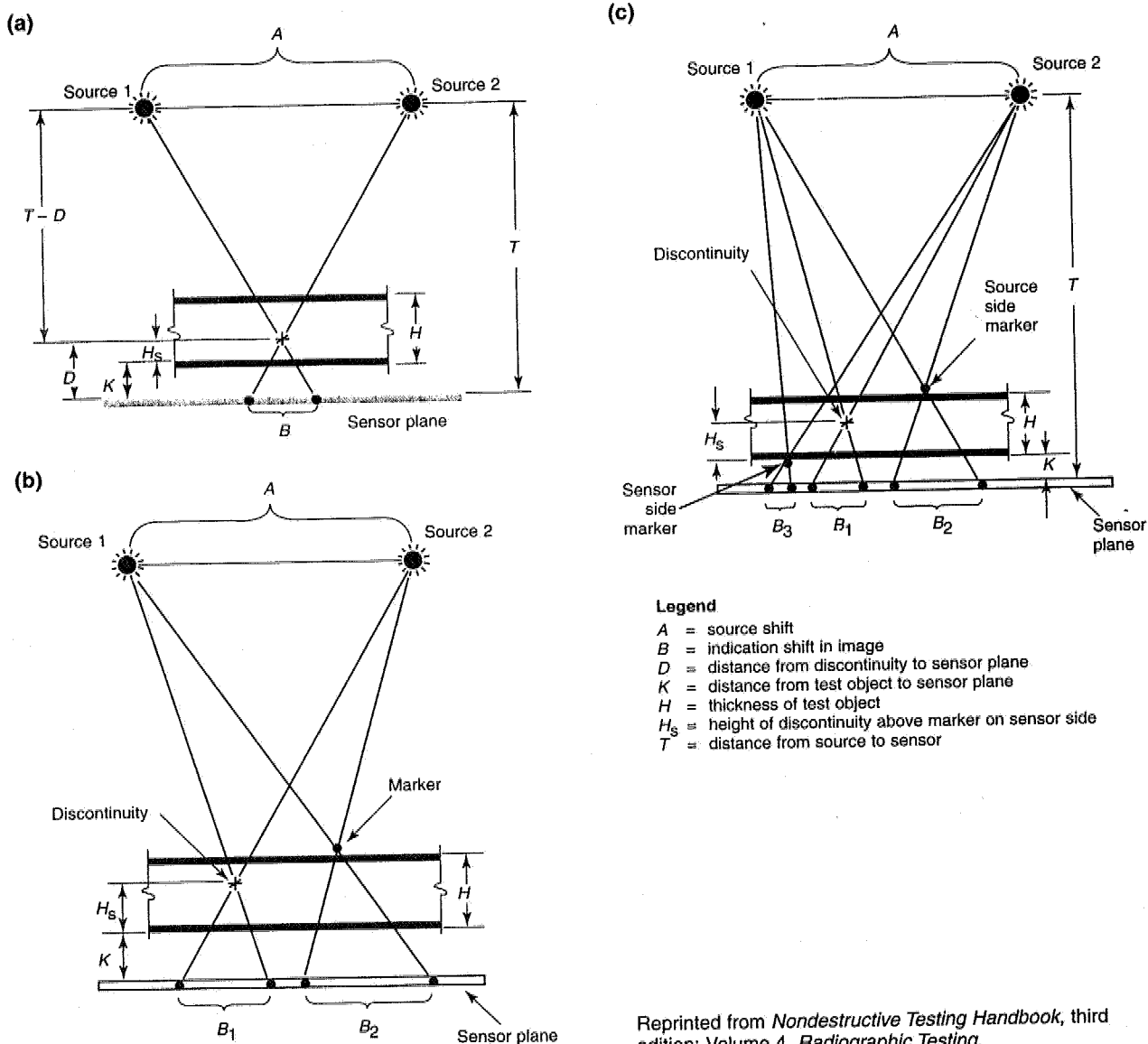
discontinuity, it would indicate that the discontinuity is about midwall.

The single marker method eliminates the need for detailed measurement of part thickness, source-to-film distance and the source shift, as required by the rigid formula method. Provided the film is in intimate contact with the part and a source-to-film distance at least ten times the thickness of the part is used, the maximum error that can be expected is on the order of 3% of the part thickness.

Double Marker Formula

If the film cannot be placed in direct contact with the object or if the image of the discontinuity is not present on a double exposed radiograph, the double marker method would be applicable as shown in Figure 10.7c. If both markers are thin, neglect the thickness and assume that they represent the top and bottom of the part. By measuring the parallax (image shift) of each marker as well as that of the discontinuity, the relative position of the

Figure 10.7: Stereo technique diagrams: (a) rigid formula parallax technique; (b) single marker approximate technique; (c) double marker approximate technique.



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discontinuity between the two test surfaces of the part can be obtained by linear interpolation using the following equations:

$$B_1 - B_3 \cong \Delta B_f$$

and

Equation 24

$$B_2 - B_3 \cong \Delta B_m$$

and

Equation 25

$$\frac{H_f}{H_m} \cong \frac{B_1 - B_3}{B_2 - B_3}$$

or

Equation 26

$$\frac{H_f}{H_m} \cong \frac{\Delta B_f}{\Delta B_m}$$

or

Equation 27

$$H_f \cong H_m \left(\frac{\Delta B_f}{\Delta B_m} \right)$$

Equation 28

where:

H_f = the height of discontinuity above the film side marker, and

H_m = the distance between the source side marker and the film side marker.

Flash Radiography

Flash radiography is a special type of radiography that is used to produce a single stop motion image or a series of sequential images of high speed phenomena. Exposure times of one millionth of a second or less can be achieved through the use of specially designed high voltage generating equipment and X-ray tubes. Such exposure times are significantly short to provide stop motion radiographs of projectiles, high speed machinery and other objects.

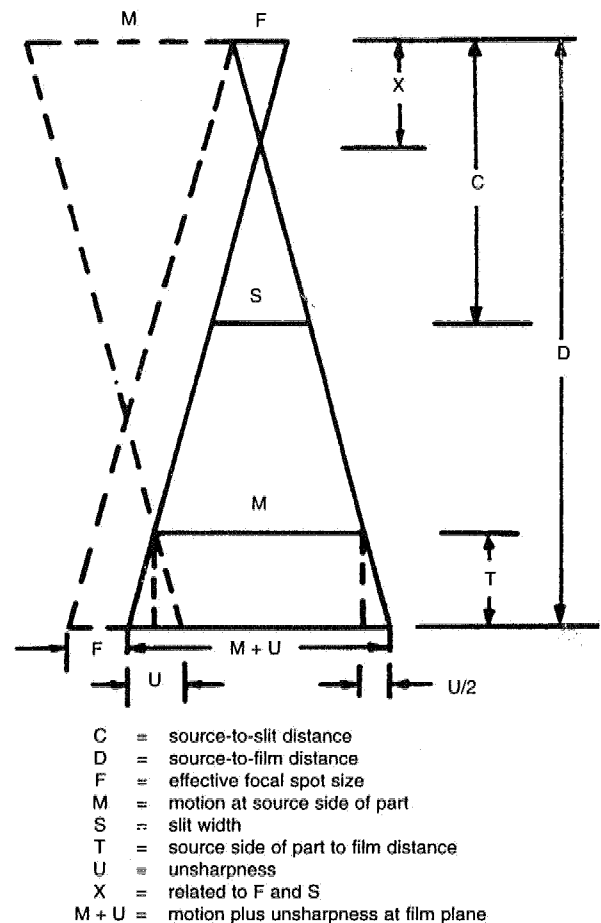
The general principles that govern the production and the imaging characteristics of X-rays are identical for conventional static radiography and flash radiography. In conventional X-ray tubes, a thermionic cathode is used to produce an electron beam that is accelerated and focused to strike a small spot on a metal plane target. This basic mechanism is also used in flash radiography. However, because thermionic cathodes are not capable of producing the very high peak current densities and total

currents required for flash radiography, different electron sources must be used. These sources do not allow effective focusing of the electron beam, so special X-ray tube and target geometries must be designed to achieve the necessary confined focal spot.

Film Recording

Fast film/screen combinations are used to obtain adequate film exposures. A dual emulsion light sensitive film is placed in close contact with and between two fluorescent screens that absorb and convert a portion of the incident X-rays to light, exposing the emulsion facing each screen. The film density range is more limited than that of film used in conventional radiography and the slope of the characteristic curve (gamma factor) is small at both short and long exposures, resulting

Figure 10.8: Unsharpness due to motion.



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in very low image contrast. Careful adjustment of the exposure is required to achieve image quality and contrast.

The choice of screens is a trade off between speed and resolution. Thicker screens have more output but reduced resolution. High speed film is generally selected but, on occasion, a slower film speed is used to avoid excessive quantum noise in the image.

In Motion Radiography

The techniques used for in motion radiography are the same as for conventional static radiographic techniques except for the exposure time. The exposure time is converted to speed of travel and is recorded as some distance per minute. Two methods are available for density control: decrease density by increasing speed or increase density by decreasing speed. These are affected by:

1. type of material being radiographed,
2. thickness of material,
3. film speed,
4. use of intensifying screens, and
5. source-to-film distance.

Advantages of in motion radiography are that it:

1. permits testing of almost unlimited part sizes with slightly modified conventional equipment,
2. can be used in production shops without radiation hazard because of equipment used, and
3. permits images to be recorded on a continuous sheet of film.

An exposure is made with one of the following techniques.

1. A part is moved through a collimated beam of radiation emitted by a stationary source.
2. A collimated source is moved relative to a stationary part.

Image blurring has been determined to be greatest in the direction of motion. Variables must be established to determine the influence of blurring. These variables are determined through the use of equations derived from equations used in static radiography to determine unsharpness U_g .

$$U_g = \frac{Fd}{D-d}$$

Equation 29

where:

D = source-to-film distance,
 d = defect-to-film distance, and
 F = effective focal spot size.

Unsharpness because of motion is derived from Equation 30 using the relationships in Equations 31, 32 or 33 (see Figure 10.8 for definitions):

$$\frac{F}{X} = \frac{S}{C-X}$$

Equation 30

$$\frac{F}{X} = \frac{M}{D-(X+T)} = \frac{M+U}{D-X}$$

Equation 31

$$U = \frac{T(F+S)}{C}$$

Equation 32

$$\frac{F+M}{F+S} = \frac{D-T}{C}$$

Equation 33

The conditions for unsharpness because of motion are shown graphically in Figure 10.8. In motion radiography techniques currently used in industry are linear motion, rotary motion and synchronous radiography.

Linear motion – The part under testing is moved past the collimated X-ray beam or the collimated X-ray beam is scanned over the surface of the part, as in Figure 10.9.

Rotary motion – The X-ray source and slit are stationary and the cylindrical part rotates 360 degrees or more through the collimated X-ray beam, as in Figure 10.10.

Synchronous radiography – Applicable to cyclical motion: requires a short pulse X-ray generator capable of adjustments of the pulse to match the speed of the cyclical motion.

Since its conception in 1956, applications of in motion radiography have been to examine weldments, brazed honeycomb structures, adhesive bonded honeycomb structures, nuclear fuel elements and rocket motors.

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As with any nondestructive testing technique, the user must consider the advantages and disadvantages of in motion radiography.

Advantages

1. Radiographic setup time is reduced.
2. There are fewer individual films to interpret.
3. Distortion of specimen image is reduced.
4. Area of interest on thicker sections will appear sharper than with a conventional stationary radiograph.

Disadvantages

1. Because of the motion between the source and the recording medium, this method is limited to thin specimens.

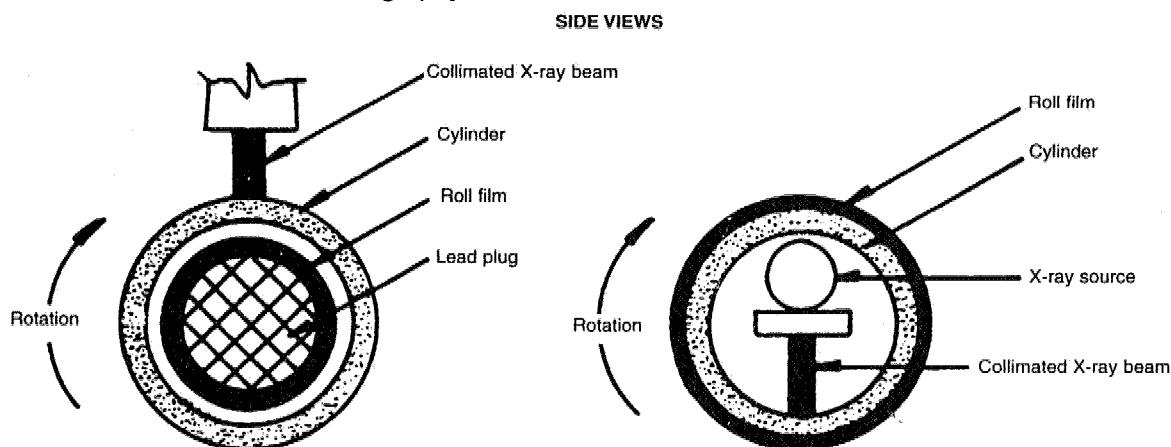
2. Large focal spot creates a need for tight collimation, which in turn results in a higher percentage loss of X-ray energy.

Electron Radiography

This technique uses high energy secondary photoelectrons instead of X-rays for recording a specimen image on film. There exist two distinct types of electron radiography, transmission and emission.

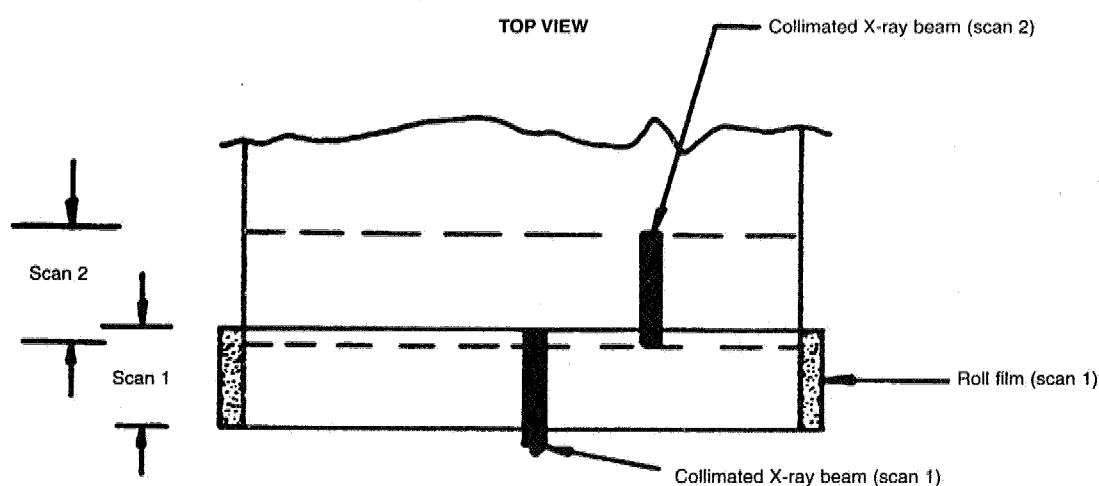
Electron transmission radiography has been used to evaluate paper thin, low atomic number specimens when X-ray photons of about 250 kV produce secondary photoelectrons. These electrons are normally from lead foil and are used to register a latent image on a film.

Figure 10.9: Linear in motion radiography.



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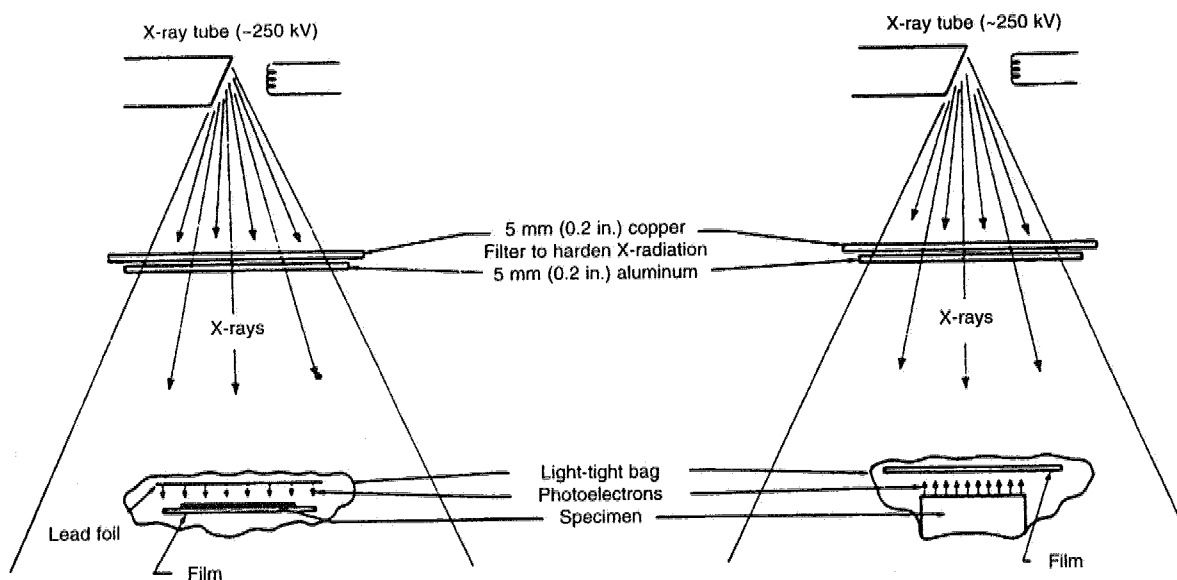
Figure 10.10: Rotary in motion radiography.



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Figure 10.11: Electron radiography: (a) transmission technique, (b) emission technique.



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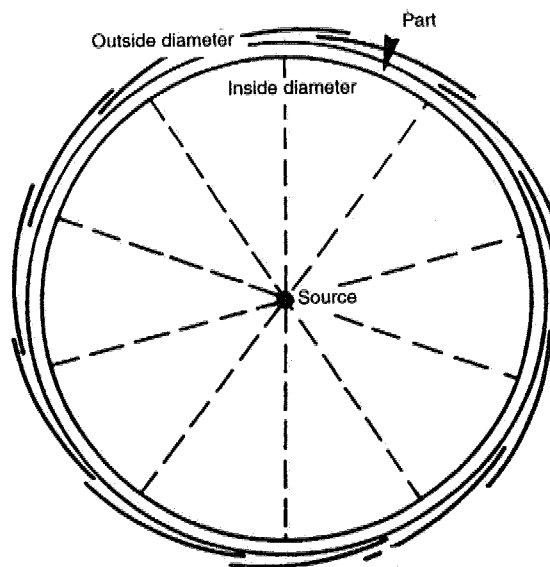
Electron emission radiography (specimen electron emission) uses X-ray photons to produce secondary photoelectrons at the surface of a suitable specimen, enabling a material related surface image to be formed on the film.

The radiographic setup for both of the electron radiographic techniques is shown in Figure 10.11. Note that in the transmission technique, the photoelectrons are produced from the lead foil above and adjacent to the specimen. However, in the emission technique, the specimen itself is the source of the photoelectrons.

Panoramic Exposures

In those instances where both the inside and outside surfaces of a pipe or cylindrical vessel, hemispherical head, or small parts with the same geometries are accessible, the panoramic technique can be used. Figures 10.12, 10.13 and 10.14 show the general arrangement of the source of radiation and the film. The basic radiographic exposure principles are the same for panoramic exposures as for the more conventional arrangements. Depending on the diameter of the exposure, source size should be considered to control geometric unsharpness U_g , and when examining numerous specimens, care should be taken to maintain identification of all parts.

Figure 10.12: Weld radiography of larger diameter pipes and pressure vessels.



This technique is by far the fastest and most economical method of performing radiographic examination of these types of configurations and is acceptable to most codes, standards and specifications, but requirements that must be controlled vary.

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Radiation Attenuation Gaging Techniques

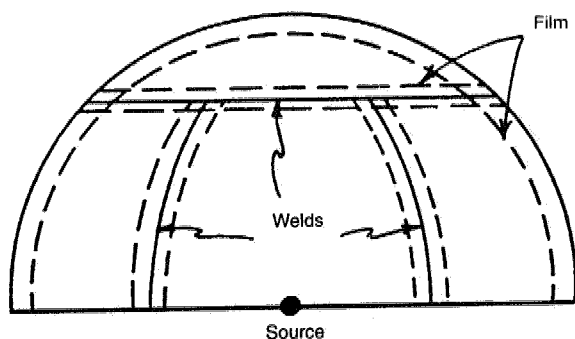
Radiation attenuation gaging is used when information on changes in specific parameters such as thickness, density or composition is desired. A nonimaging radiation detector is used to measure transmitted radiation intensity, which is related to the attenuation caused by the specimen, which in turn is related to some specific material parameter of interest. The basic attenuation gage, in its simplest form, consists of a source, source shielding and collimation, an air gap where samples can be introduced and a collimated detector as shown in Figure 10.15.

If the intensity of the radiation measured by the detector with no sample in place is I_0 , then when a sample of thickness T is introduced so as to intercept the radiation beam, the intensity I measured by the detector is given by:

$$I = I_0 e^{-\mu \rho T}$$

Equation 34

Figure 10.13: Hemispherical orange peel head exposure arrangement.



where:

μ = mass attenuation coefficient of the sample material for the energy used, and
 ρ = density of the sample.

Measurement of radiation intensity I can be used to determine characteristics of the sample which depend on the product $\mu \rho T$. The results are either numerical values or strip chart recordings that represent the amount of radiation passing through, or scattering from, the area of interest. These measurements can usually be made very rapidly, even automatically. The information can be related to a property of the

Figure 10.14: Panoramic exposure arrangement.

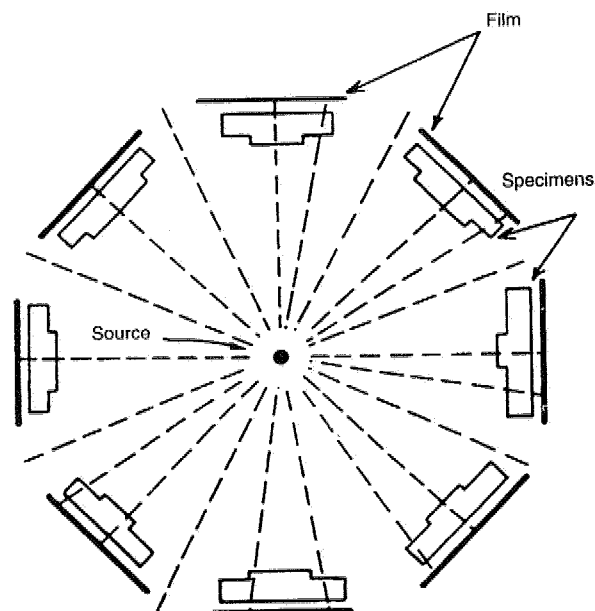
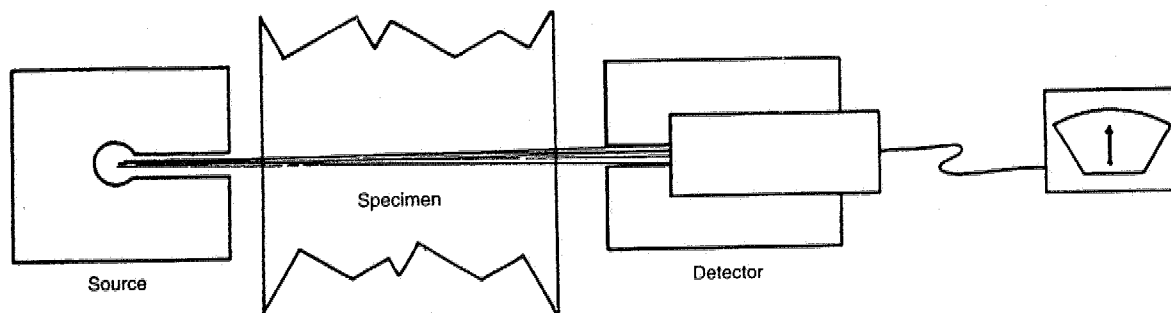


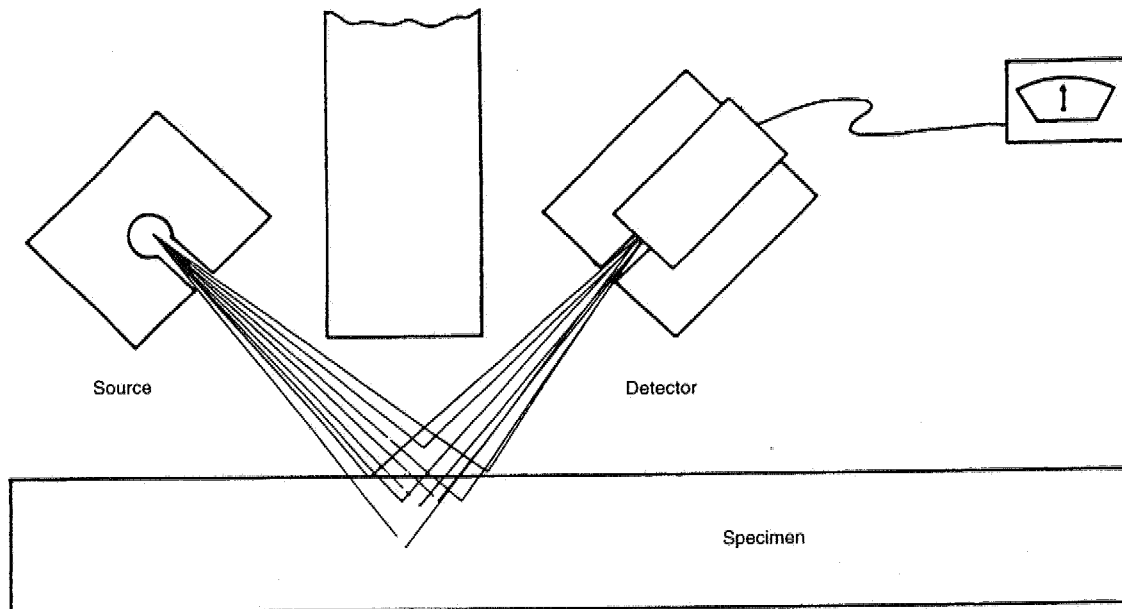
Figure 10.15: Diagram of a simple transmission gage.



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Figure 10.16: Diagram of a simple backscatter gage.



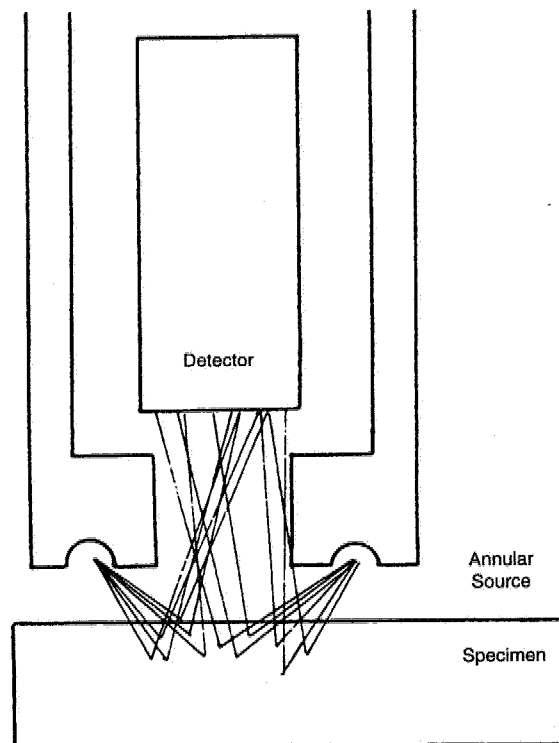
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specimen that changes with location along the specimen or that changes with time at a specific location on the specimen.

Thickness gages may use a beam of radiation passing through the specimen, as do the level gages, or they may use radiation scattered back from the specimen to measure its thickness. Figures 10.16 and 10.17 are diagrams of transmission and backscatter gages, respectively. The backscatter gages become useful when only one side of the specimen is available, when plating thicknesses are to be measured, or when the radiation interaction depends on a scattering in the specimen. Thickness gages have been applied to materials as thin as gold plating on electronic circuit boards (less than 1×10^{-4} in., or $2.5 \mu\text{m}$) or as thick as armor plate or shielding at a power plant. Testing rates can be as high as several hundred feet per minute for materials such as paper or plastic, with accuracies as good as 1% of the target thickness.

Density gages normally use a beam of radiation passing through a fixed or known thickness of the specimen, most often confined in a pipe or on a conveyor belt. Larger sources and longer measurement times may be involved for density measurements. Sensitivity and accuracy are often related to the radiation path length in the specimen. Careful consideration of counting statistics is necessary in gage design and operation.

Figure 10.17: Diagram of an X-ray fluorescence gage.



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Composition gages use either neutrons, which interact with hydrogen or some other component in the specimen, or use photons (X-rays or gamma rays), which interact with one element in the specimen more than the rest. An example is a moisture gage that determines the moisture content (or other hydrogenous materials) of soil, concrete or geological structures along an oil well wall by detecting thermal (0.01 to 0.05 eV) neutrons scattered by the specimen when it is bombarded by fast neutrons. Hydrogen is a more effective moderator of fast neutrons than any other element.

X-rays also may interact more with one element than others in a specimen. The interaction may be either absorption or fluorescence. The fluorescence interaction gives rise to a new X-ray, which has an energy characteristic of the element involved. X-ray fluorescence gages may provide qualitative and quantitative information on several elements simultaneously. Such gages permit identification of alloys or the measurement of the thickness of one metal on another.

Chapter 10 Review Questions

- 10.1 Various radiographic techniques will require special consideration to reduce scatter radiation reaching the film. Which of the following does not constitute a good masking material?
- lead acetate/lead nitrate in water
 - steel shot
 - aluminum
 - barium clay
- 10.2 When radiographing a steel specimen 1.9 cm (0.75 in.) thick with 275 kV peak X-ray, the use of a copper filter of the specimen thickness is recommended (if more latitude is necessary).
- 20%
 - 10%
 - 4%
 - 15%
- 10.3 A multifilm technique may be necessary when radiographic inspection is to be performed on a:
- butt weld between 5 cm (2 in.) thick plates.
 - consumable insert weld on small diameter pipe.
 - long seam weld on a storage tank.
 - large vessel nozzle weld.
- 10.4 One of the major benefits of the use of a radiographic enlargement technique is that it:
- increases the focal spot size.
 - reduces scatter radiation.
 - decreases geometric unsharpness.
 - decreases exposure time.
- 10.5 In stereoradiography, the shift of the X-ray tube for the required second exposure is based on the:
- thickness of the part.
 - type of indication being evaluated.
 - type of prisms used in the stereoscope.
 - normal interpupillary distance.
- 10.6 The triangulation method to determine the depth of a discontinuity is based on the relationship:
- source-to-film distance.
 - similar triangle.
 - markers-to-film.
 - shift-to-time.
- 10.7 When using the rigid formula for triangulation, it is important to remember that the discontinuity height and image shift are:
- linear.
 - proportional.
 - nonlinear.
 - critical.
- 10.8 The relative position of a discontinuity between the outside and inside surfaces can be obtained by linear interpolation when using the:
- double marker formula.
 - step down technique.
 - single marker formula.
 - rigid formula.
- 10.9 In flash radiography various sources of high energy electrons are available. Which of the following is not a source of these electrons?
- gas discharge tubes
 - vacuum discharge
 - field emissions
 - gamma ray sources
- 10.10 The technique for in motion radiography is essentially the same as conventional techniques except the exposure time is based on:
- source-to-film distance.
 - DIT ratio.
 - speed of travel.
 - geometric unsharpness considerations.

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- 10.11 There are currently three in motion radiographic techniques used in industry. Which of the following listed techniques is not an in motion radiographic technique?
- linear motion
 - rotary motion
 - stereographic motion
 - synchronous radiograph
- 10.12 A higher percentage loss of usable radiation is expected during in motion radiographic techniques as the result of:
- collimation.
 - filtration.
 - speed of travel.
 - absorption.
- 10.13 The electron radiographic technique utilizes _____ in lieu of X-rays when using either the electron transmission or electron emission procedure.
- photoelectrons
 - photomicrons
 - scattered secondary radiation
 - secondary photoelectrons
- 10.14 X-ray diffraction and the resultant patterns recorded on the inspection medium are of primary concern when radiographing:
- thick sections of steel specimens.
 - aluminum specimens.
 - bimetallic weld samples.
 - grainy metallic specimens.
- 10.15 If the panoramic technique of radiography is selected, one of the most important factors to be considered is the:
- material composition.
 - thickness uniformity.
 - film type.
 - penetrameter requirements.
- 10.16 In high energy radiographic applications, screens vary depending on the energy used. When using an 8 MeV linear accelerator, which of the following thicknesses would be the most appropriate front screen thickness?
- 0.76 mm (0.030 in.) Pb
 - 3.18 mm (0.125 in.) Pb
 - 0.25 mm (0.010 in.) Pb
 - 6.4 mm (0.250 in.) Al
- 10.17 The photoconductive material used in xeroradiography is:
- iridium - powdered.
 - cesium oxide - spheres.
 - zinc sulfide - crystalline.
 - selenium - vitreous.
 - sodium - powdered.

Chapter 11

Computed Tomography

Basic Principles

Computed tomography differs from conventional radiographic imaging in that it uses X-ray transmission information from numerous angles about an object to digitally reconstruct cross sectional images of the interior structure. To generate a computed tomography image, X-ray transmission is measured by an array of detectors, see Figure 11.1. Data are obtained by translating and/or rotating the object so that many viewing angles around the object are used. A computer mathematically reconstructs the cross sectional image from the multiple view data collected. This reconstructed image is a two dimensional presentation of a two dimensional cross sectional cut through the object. A primary benefit of computed tomography is that features are not superimposed in the image, thus making it easier to interpret than radiographic projection images. The image data points are small volumetric measurements directly related to the X-ray attenuation coefficient of the material present in the volume elements defined by the slice thickness and the image plane resolution of the computed tomography system. The computed tomography image values and locations provide quantitative data for dimensional and material density/constituent measurements.

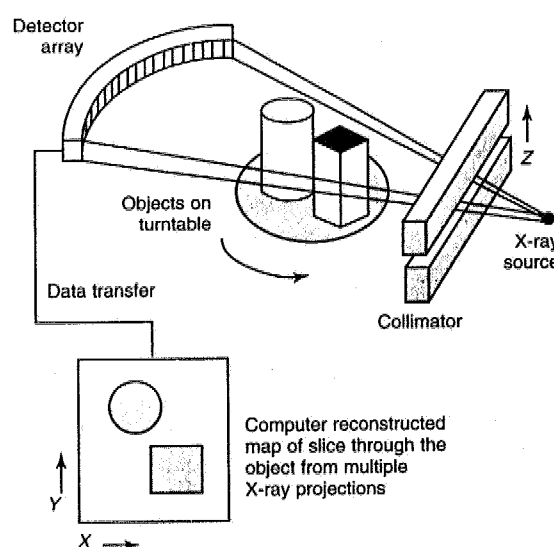
To determine the depth location of a feature found on a radiograph, a triangulation technique is used. This (as shown in Figure 11.2) consists of obtaining a second film of the area in question, but with the source in a different angular position relative to the test specimen than was obtained on the first exposure. The geometry is carefully laid out on paper; measured positions of source, test specimen and discontinuities on the films are noted; and the position of the discontinuities along the intersecting lines-of-sight is determined.

Triangulation is a rudimentary tomographic reconstruction that contains the essential elements of computed tomography. The first step

is to recognize the features of interest. The second step is to correlate the test specimen, the source position and the radiographic image together for both exposures. The final and third step is to note the position of the attenuation corresponding to the feature and to project it back to the source along the original attenuation line. This backprojection is performed for each exposure and the combined effects of these two backprojections is the constructive interference of the two attenuation patterns.

In computed tomography the basic methodology can be considered in a similar manner. The X-ray beam is collimated to a narrow slit and aligned with a solidstate X-ray detector array to define a computed tomography

Figure 11.1: Computed tomography using a collimated fan beam and linear detector array data acquisition to reconstruct cross section of object.



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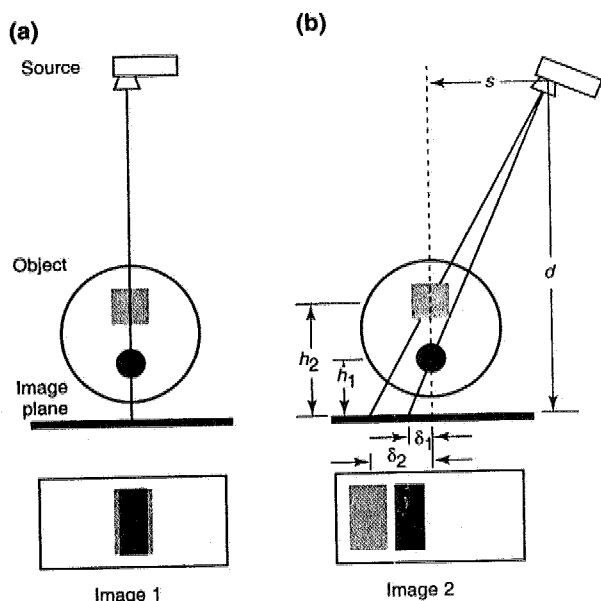
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slice plane in the object. The slit collimation reduces scatter, improving the signal-to-noise ratio in the image. Data are obtained by translating and rotating the object so that many viewing angles around the object are acquired. When a series of projections is taken from many angles, the projection data can be backprojected to create an image. As the number of projections increases, the ability to more exactly reconstruct the object increases. In a computed tomography system, the projections are actually subjected to an incredible amount of mathematical massaging, but the steps are effectively the same as those in the manual triangulation.

Resolution

Both horizontal and vertical resolution must be considered in the case of a computed tomography system. The *horizontal resolution* of a

Figure 11.2: Example of triangulation as basis for computed tomography: (a) first image, with line of interrogation normal to sensor plane; (b) second image, with line of interrogation oblique to sensor plane.



Legend

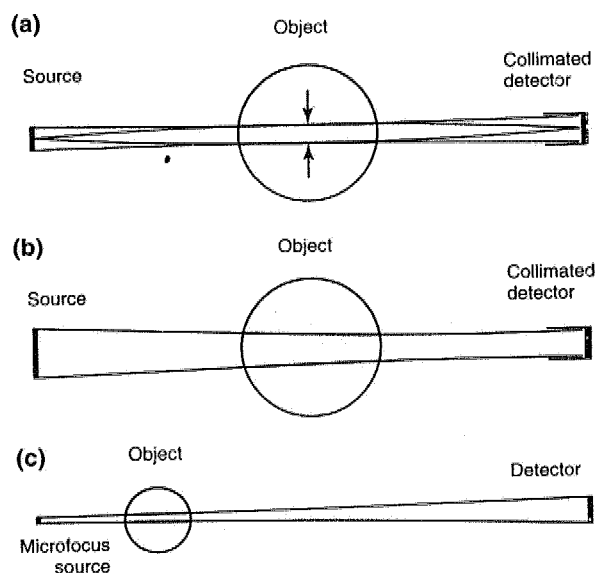
- d = distance from source to image plane
- h_1 = distance from round discontinuity to image plane
- h_2 = distance from square discontinuity to image plane
- s = source travel distance
- δ_1 = apparent travel distance of round discontinuity in image plane
- δ_2 = apparent travel distance of square discontinuity in image plane

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computed tomography system is determined by the effective beam width of the X-ray beam in the object. The *effective beam* is a function of the source and detector dimensions and the position of the object with respect to them. The *vertical resolution* of the slice volume will be determined by the effective slice thickness of the collimation apertures.

Figure 11.3 shows the configuration of a source and detector for the horizontal resolution of a computed tomography slice through an object. In Figure 11.3a, a source and detector of equivalent aperture size have an object positioned midway between them. With this configuration the effective beam width is minimized at the center. At the edges of the object the effective beam width will be slightly larger and the resolution is decreased. When the source and detector apertures differ in size, as shown in Figure 11.3b, then the best resolution will be off center. In this case the rotation of the computed tomography system, whether 180 degrees or 360 degrees, could make a difference on the resolution of details in either side of the object. Figure 11.3c shows the case of a very small source (microfocus) and larger detector. By using

Figure 11.3: Examples of source-object-detector configurations and effective beam widths: (a) source and detector of equivalent aperture size; (b) source larger than detector; (c) source smaller than detector.



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projection magnification, very fine resolution may be possible in the object. The resolution can be estimated by taking an average of the effective beam size in micrometers, multiplying by 2 and inverting to obtain line pair per micrometer resolution values.

The number of data points, number of projection views and slice thickness define the testing volume. The operator will normally select the slice thickness. Increasing the slice thickness will allow more photons for better imaging statistics or greater scanning speed. However, it will increase the smearing of sloping edges on objects or features and decrease sensitivity to details that may be thinner than the slice thickness. Narrowing the slice provides finer detail sensitivity to axial variations in the object but at the cost of scan time and increased statistical noise.

Contrast

The contrast sensitivity in computed tomography images is inherently high because each reconstructed volume element is composed of backprojected rays from many orientations about the object. The contrast ratio is given by:

$$\text{Contrast ratio} = 6 / (R_{SN} \times Z)^{1/2}$$

Equation 35

where:

- Z = number of pixels over which the contrast is observed, and
 R_{SN} = signal-to-noise ratio.

The equation below gives an estimate of the signal-to-noise ratio in a voxel element as a function of various computed tomography system characteristics for a reconstruction of a cylindrical object:

$$R_{SN} = 0.655 \mu w^{1.5} [(Vnt / \Delta p) e^{-2\pi}]^{1/2}$$

Equation 36

where:

- μ = linear attenuation coefficient,
 w = X-ray beam width,
 V = number of views,
 n = photon intensity rate at the detector,
 t = integration time of the detectors,
 Δp = ray spacing, and
 r = radius of the object.

The number of views n can be estimated by allowing a ray through each beam width on the outer radius of the field of view:

$$V = \pi D / w$$

Equation 37

Computed tomographic systems often provide contrast sensitivity measurements in the range of 0.1% to 1.0%. What the equations show is that the signal-to-noise ratio improves with increases in computed tomography system characteristics of X-ray beam width, number of views, X-ray beam intensity and integration time. The signal-to-noise ratio will also be improved by decreasing the ray spacing and object diameter. These characteristics reflect the tradeoffs in optimizing a computed tomography system. Fast scan times, fine resolution, high contrast sensitivity and large object size are mutually exclusive, requiring compromise in system design.

System Configurations

Computed tomography requires more sophisticated equipment for data acquisition and reconstruction than conventional radiography. The total time required to test an object volumetrically can also be relatively long, making computed tomography a significantly more expensive test. However, for many structures computed tomography provides unique information. Computed tomography has several variations. The most useful forms for industrial computed tomography are the *rotate and translate* scheme (second generation) and the *rotate only* scheme (third generation) as shown in Figure 11.4.

Rotate and Translate Tomography

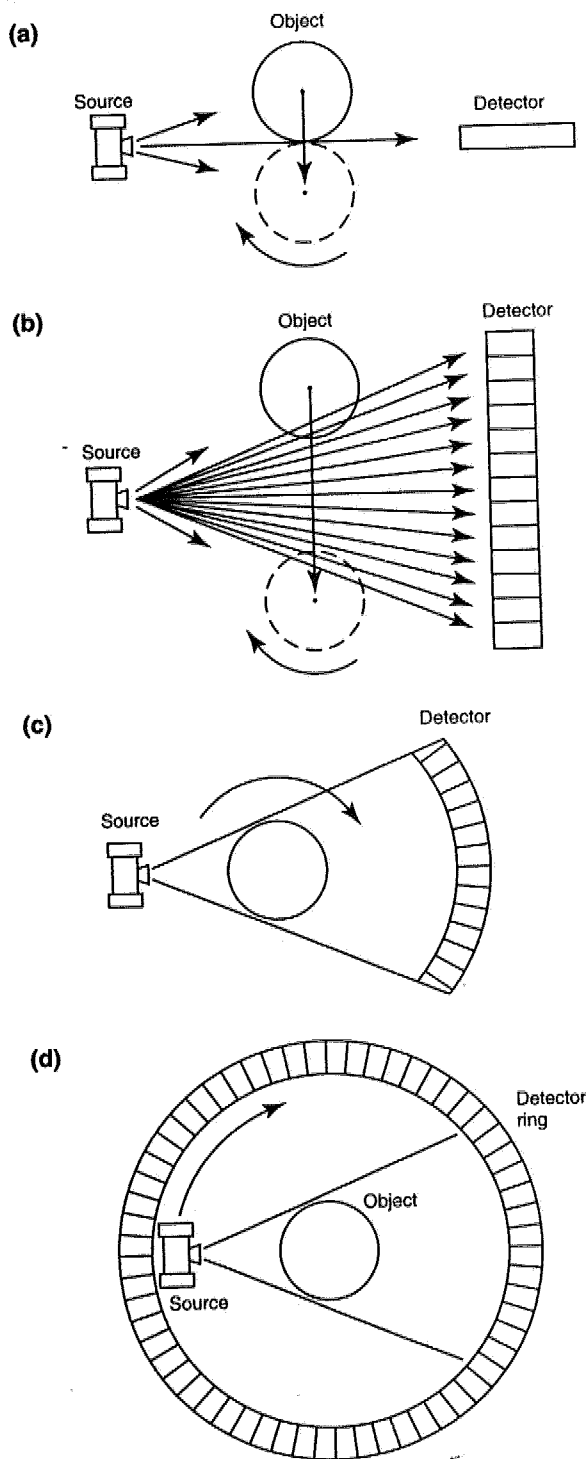
The rotate and translate scheme utilizes a single source and a bank of detectors arranged to subtend a fan beam of the source. (The fan beam is collimated so that the fan lies in the plane of interest.) This allows all views that are within the fan angle of the source to be obtained on the same traverse. After traversing the fan, the object rotates the number of degrees of the fan and traverses back across the fan beam. Rotations continue until 100 degrees or 360 degrees have been covered.

Rotate Only Tomography

Rotate only tomography also utilizes a single source and a bank of detectors that spans the test

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Figure 11.4: Computed tomographic system generations: (a) first generation; (b) second generation (rotate and translate); (c) third generation (rotate only); (d) fourth generation.



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specimen as seen from the source. The detectors provide a single view simultaneously, and the view consists of a series of fan shaped measurements, rather than parallel ray measurements. By continuously turning the test specimen and taking data, many fan views are acquired for reconstruction. In rotate only scanning, no detector will see the entire object as in rotate-and-translate. Thus detector imbalance causes ring artifacts in the image.

Both methods use a collimated fan beam of X-rays and one-dimensional array of detectors. The rotate and translate scheme is commonly used for industrial objects because objects larger than the X-ray beam fan angle can be accommodated. The rotate only scanning approach is used on small industrial objects because it is faster than rotate and translate. Both methods image only one slice through the part in a single scan. That slice inspection volume is the size of the fan beam height collimation.

Volume Computed Tomography

Volume computed tomography or cone beam computed tomography uses a two-dimensional area detector and an uncollimated cone of radiation such that the entire object may be tested in one scan. This technique sacrifices some detail in the image quality for a higher throughput when the entire object must be tested and has limitations on the applicable part size. It generally works well only for relatively small objects.

Limited Angle Tomography

Limited angle, tangential and annular reconstruction computed tomography are methods that can be beneficial to large composite structures. Limited angle computed tomography does not require that the computed tomography data be taken from all angles completely around the part. This can be particularly advantageous for large planar composite structures. Tangential and annular reconstruction offer advantages for large cylindrical structures where information is needed only along annular rings, particularly near the outside of the structure.

Mechanical Handling

Mechanical handling system tolerance budgets are almost always expressed in terms of the spatial resolution. For rotate-and-translate tomography, the total tolerance stack up is given as 0.25 to 0.33 times the spatial resolution. Thus, for a resolution corresponding to good spatial

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discrimination of adjacent pixels of size 1.0 mm (0.04 in.) the nominal tolerance stack up would be 0.33 mm (0.013 in.). This means that all the imprecisions in the individual mechanical components must, when added together, be less than this absolute tolerance.

System Design

Table 11.1 lists key attributes of a computed tomography system and the ramifications of choices of the attributes on system component selection. In the selection of a computed tomography system to perform nondestructive tests it is important to define the desired testing characteristics, particularly object (size, type,

weight), testing parameters (spatial resolution, contrast sensitivity, slice thickness, time for testing) and the operator interface (system control panel, image display, processing functions and data archiving).

The sensitivity to fine detail of computed tomography systems is a function of resolution and contrast sensitivity. Computed tomography resolution is fundamentally determined by the beam width of the X-ray optics design and is driven by the selection of source and detector aperture sizes and the source, object and detector distances. The beam width, size of the object and image reconstruction matrix must all be considered in a system design.

Table 11.1: Computed tomography system attributes and their major ramifications.

Attribute	Ramifications
Test specimen size, weight and shape	mechanical handling equipment, loading and unloading
Test specimen X-ray penetrability	X-ray source X-ray detector type dynamic range of detector and front end electronics
Spatial resolution	accuracy of mechanical handling equipment configuration of source, object and detector source and detector aperture size
Contrast sensitivity	strength of X-ray source integration time
Artifact level	reconstruction algorithm software accuracy of mechanical handling equipment
Speed of computed tomographic process	size of object X-ray source strength number and configuration of detectors bus structure speed and architecture of processors mechanical hardware — motors, brakes and others
Number of pixels in image	number and configuration of detectors amount of data acquired choice of computer and hardware
Slice thickness range	detector configuration system dynamic range
Operator interface	instrument control panel image processing system control software interface to remote workstation
Archival requirements	choice of computer and hardware

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A typical reconstruction matrix size for computed tomography is 1024×1024 . To a first approximation, this would make the resolution limit roughly 1 part in 1000 and the system would be designed to match the X-ray optics to 0.001 times the size of the part. For example, a system designed to handle a 0.5 m (20 in.) size part might allow for 0.5 mm (0.02 in.) size beam width, and a system designed for a 10 mm (0.4 in.) size part might have a 0.010 mm (0.0004 in.) beam width.

It is possible to reconstruct the 1024×1024 matrix over subregions of a

component so that a higher resolution beam width finer than 1 part in 1000 of the object can be used effectively. However, the scan must still cover the full size of the part. As the part size is increased, the source to detector distance increases, and X-ray intensity at the detector falls off quadratically. Thus, it is impractical to use a very small beam width on large parts because of the very long scan time that will result. As shown in Table 11.2, practical resolutions for computed tomography systems that handle large components greater than 300 mm (12 in.) in diameter are in the range of 1 to 2 line pair per 1 mm (25 to 50 line pairs per 1 inch). For components less than 300 mm (12 in.) in diameter 2 to 4 line pairs per 1 mm (50 to 100 line pairs per 1 inch) can be obtained. For higher resolution, greater than 4 line pairs per 1 mm (100 line pairs per 1 inch) and feature sensitivity on the order of 0.1275 mm (0.005 in.), the computed tomography systems are designed to only handle objects of 25 or 50 mm (about 1 or 2 in.) in size.

Table 11.2: Part size versus resolution.

Part size mm (in.)	Resolution lp/mm (lp/in.)
> 300 (12)	1 to 2 (25 to 50)
< 300 (12)	2 to 4 (50 to 100)
30 to 40 (1 to 2)	0.125 (0.005)

Table 11.3: Parameters of interest for computed tomography standards.

Parameter	Notes
Alignment dimensional accuracy	image artifacts caused by mechanical alignment
Slice thickness/geometry	vertical coverage alignment and uniformity of computed tomography plane in object
Spatial uniformity	variation of computed tomography measurement across scan plane
Noise	random variation in attenuation measurements (measured by statistical variation or noise power spectrum)
Low contrast sensitivity	ability to detect small contrast changes (this is mainly limited by noise)
Spatial resolution	ability to distinguish two objects as separate (measurement should be under noise free conditions)
Modulation transfer function	quantitative measurement of high contrast spatial resolution
Effective energy and linearity of computed tomography numbers	monochromatic photon energy that would give the equivalent result as the polychromatic spectrum used
Accuracy and precision	reliability and stability of the computed tomography measurements

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The important conclusion to draw from this discussion is that no one computed tomographic system can provide both large object testing and very fine resolution.

Reference Standards

Table 11.3 lists parameters that may be measured from data taken by a reference standard that contains features that represent the parameter. A single reference standard unit may contain a variety of subsections that will measure various parameters. The parameters themselves are not independent, but often are different manifestations of the fundamental performance characteristics of the system.

Table 11.4 lists some key categories for a reference standard and potential methods of obtaining the measurements.

Resolution

In this context *resolution* refers to the ability to sense that two features are distinct. Measurements of resolution by a reference standard can be performed in a wide variety of ways. Holes in a uniform material of either fixed diameter and changing separation or decreasing diameter with separations that also decrease accordingly, are very common. The resolution is defined as the minimum separation detectable.

Plates of alternating high and low density material can be used to make line pair gages. The resolution limit is determined by the ability to see the line pairs. Because of the definition of the modulation transfer function, it can be measured by mathematical calculation of the fourier transform of the one-dimensional line spread function or the two-dimensional point spread function. The line spread function and/or point spread function is obtained by measuring the spreading of the image from a pin or wire. Because of the difficulty finding an adequate line or point source reference standard, the line spread function is very often measured by differentiation of the edge spread function. The edge spread function is readily obtained from a data trace across a sharp edge in the image.

Contrast Sensitivity

In this context contrast *sensitivity* refers to the graininess in an image. The best way to measure contrast sensitivity is to obtain a histogram of pixel values in a region of uniform density. In practice it is of interest to measure the contrast sensitivity as a function of the feature size because small contrast changes are easier to

Table 11.4: Reference standard categories and measurement technique.

Type	Example construction/technique
Resolution	holes squares line pairs pins/wires modulation transfer function calculation
Contrast	signal-to-noise in a uniform material sample small density variation
Material/density	various solids liquids of different mixture percentages porous material compaction
Dimensional accuracy/distortion	pin sets hole sets
Slice thickness	pyramids cones slanted edges spiral slit

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detect over larger areas than in small areas where they may be easily masked by noise.

The inverse of this contrast sensitivity value is commonly referred to as a signal-to-noise measurement of the system. The signal-to-noise ratio is an important measure of system performance. The values improve with higher signal strengths. Large slice thickness and longer scan times will also improve signal-to-noise. Signal-to-noise will also improve with smoothing algorithms in the reconstruction; however, this will decrease the resolution. Thus, the signal-to-noise ratio and resolution must be considered together in assessing level of performance quality.

Material Density

An important reference standard function is to establish the correlation between computed tomography value and material density. Such a reference standard can be quite difficult to manufacture because it is difficult to change density significantly without changing atomic number. The X-ray attenuation coefficient is dependent on both density and atomic number.

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A reference standard that consists of differing materials of significant density variation for a wide range of industrial material applications may be fabricated. However, the evaluation of the results from such a reference standard must consider the X-ray energy and the atomic elements involved when extrapolating to other materials not included in the reference standard. An example might consist of an acrylic disk with inserts of ten various materials.

measurement reference standard is needed to establish the precision of this equivalence.

Other Functions of Reference Standards

Numerous reference standards of all sizes and shapes have been made to evaluate various characteristics of a system. Most commonly, pyramids or slanting edges of some type or other have been used to assess the slice plane thickness and field uniformity of computed tomographic systems. Reference standards that represent actual parts that have discontinuities of known dimensions are excellent for monitoring testing sensitivity day-to-day and should be implemented if possible.

Artifacts are features present in the image that are not present in the object. All imaging systems, even the human eye, will have artifacts at some level. Artifacts in computed tomographic systems range from those associated with the particular configuration, such as circular rings in rotate only computed tomography systems, to those that are process dependent, such as partial volume streaks. Beam hardening is a primary source of artifacts from polychromatic sources. Mechanical inaccuracies, material densities and partial voluming effects can also produce artifacts. It is important to recognize an artifact as such and to understand the limitation the artifact places on the recognition of discontinuities or measurement of some critical characteristic. For unambiguous interpretation, artifacts must not mask the presence of discontinuities. This is accomplished if the artifact noise level can be kept below the required signal level for discontinuity detection.

Extraction of positional and dimensional information from complex assemblies is an important application of computed tomography. An important assumption in the extraction of this information is the absolute equivalence of the computed tomography image frame of reference and the scanned object frame of reference. This equivalence depends on a variety of factors including mechanical, motion, physical element, analysis methods, software implementation and calibration methods. Therefore, a dimensional

Chapter 11 Review Questions

- 11.1 Computed tomography is:
- best used with X-radiography.
 - closely related to holography, but uses different energies.
 - an imaging technique that is independent of the type of energy detected.
 - a process that produces images similar to conventional radiography, but at much higher resolutions.
- 11.2 Laminography differs from computerized axial tomography in that:
- the source, object and detector are manipulated so that registration is maintained for focusing on a plane of interest.
 - it can only image a single plane per scan.
 - it must be moved in a linear fashion.
 - None of the above.
- 11.3 A commonly used technique in conventional radiography that is used to determine the depth of a discontinuity, and contains all the essential elements of computed tomography is:
- the panoramic exposure.
 - stereoradiography.
 - fluoroscopy.
 - triangulation.
- 11.4 Signal-to-noise ratio will improve with:
- increased noise.
 - decreased noise.
 - smaller voxels.
 - a and c.
- 11.5 A primary benefit of tomography is that:
- features are not superimposed in the image.
 - it generally uses lower energies than shadow radiography.
 - since it builds on medical technology, it is less expensive than conventional imaging.
 - since it is a self-contained system, safety is not an issue.
- 11.6 Tomographic image data points are small volume elements defined by:
- the size of the object being examined.
 - resolution of the computer screen.
 - the slice thickness and the image plane resolution of the system.
 - the relative sizes of the source and detector.
- 11.7 The slice thickness is a very important operator defined parameter. Decreasing the slice thickness will:
- provide better imaging statistics.
 - provide better detail sensitivity, but slower scan time.
 - decrease statistical noise.
 - increase the smearing of sloping edges on objects.
- 11.8 The following equation shows an estimate of the signal-to-noise ratio (R_{SN}) in a voxel element as a function of various tomographic system characteristics for reconstruction of a cylindrical object.
- $$R_{SN} = 0.655\mu w^{1.5}[(Vnt / \Delta p)e^{-2\pi}]^{1/2}$$
- where:
- μ = linear attenuation coefficient
 - w = X-ray beam width
 - V = number of views
 - n = photon intensity rate at the detector
 - t = integration time
 - Δp = ray spacing
 - r = radius of the object
- Based on this equation, what can be said about signal-to-noise ratio?
- It will be improved by increasing the object diameter.
 - Signal-to-noise ratio will be increased by increasing the ray spacing.
 - It will be improved by increasing the beam width.
 - It will get worse with longer integration time.

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11.9 Signal-to-noise ratio will improve when:

- a. ray spacing and object diameter increase.
- b. beam width and integration time increase and ray spacing decreases.
- c. beam width, ray spacing and integration time increase.
- d. linear attenuation coefficient and photon intensity rate at the detector decrease.

11.10 Increasing the slice thickness will:

- a. provide fewer photons per unit area for greater scan speed and imaging statistics.
- b. provide finer sensitivity to axial variations.
- c. decrease scan time.
- d. decrease sensitivity to details that are thinner than the slice thickness.

11.11 Signal-to-noise ratio will be worse when:

- a. beam width and the number of views are increased.
- b. beam width is decreased and object diameter is increased.
- c. integration time is reduced and photon intensity is increased.
- d. ray spacing and the number of views are increased.

11.12 The contrast ratio will increase with:

- a. a decrease in signal-to-noise ratio and the number of pixels over which the contrast is observed.
- b. an increase in the signal-to-noise ratio and the number of pixels over which the contrast is observed.
- c. an increase in the signal-to-noise ratio and a decrease in the number of pixels over which the contrast is observed.
- d. a decrease in the signal-to-noise ratio and an increase in the number of pixels over which the contrast is observed.

11.13 The inverse of the contrast sensitivity value is commonly referred to as:

- a. contrast resolution of the system.
- b. spatial resolution of the system.
- c. the signal-to-noise measurement of the system.
- d. None of the above.

11.14 Obtaining a histogram of pixels across a region of uniform density provides a measure of:

- a. contrast sensitivity.
- b. material density.
- c. modulation transfer function.
- d. None of the above.

11.15 Although the modulation transfer function provides a quantitative measurement of spatial resolution, it is difficult to calculate and is often not practical. Another measurement that is more practical, and from which the modulation transfer function can be calculated, is:

- a. edge spread function obtained from a data trace across a sharp edge in an image.
- b. line spread function obtained from a data trace across the image of two holes.
- c. noise measurement taken across a uniform density.
- d. measurement of the noise power spectrum taken from a data trace across a uniform density.

Chapter 12

Neutron Radiography

Basic Principles

Neutron radiography is a nondestructive testing technique similar but complementary to conventional radiography. Like other forms of energy, the penetrating radiation can be studied to reveal clues about the internal structure of the object. Whereas the attenuation of X-rays in materials increases with increasing atomic number of the absorbing material, the mass attenuation coefficients of the elements for thermal neutrons, if arranged in order of increasing atomic number of the absorber, appear almost completely random.

This apparently random distribution of attenuation coefficients with atomic number occurs because neutron absorption does not depend on the electron structure of the atom as does the absorption of X-rays, but on interaction with the atomic nucleus. As a result, certain light elements such as hydrogen, lithium and boron, and some rare earth elements such as gadolinium, dysprosium and indium have high or very high thermal neutron absorption.¹

The ability to image low atomic number materials in the presence of a high atomic number matrix can be of considerable interest in a variety of industries. Rubber, plastic or wood can be observed in specimens made of steel, aluminum or lead. The hydrogenous explosive charge can be seen inside a brass shell casing. Fluid levels can be seen inside high atomic number containers such as steel or lead. Corrosion and water entrapment can easily be seen inside metal structures such as honeycomb aircraft assemblies.

Because neutron interactions involve nuclei rather than the orbiting electrons, certain elemental compositions can be differentiated by neutrons that would not be possible with photon radiography. For example, U-235 can be imaged in the presence of U-238.

1. *Industrial Radiology, Theory and Practice*, Halmshaw, pg. 284.

Disadvantages

Disadvantages of neutron radiography include the high cost and relatively large size of the source assemblies, which combined become a major limitation – no really portable or inexpensive system is available. In addition, certain materials become radioactive when exposed to neutrons and there are personnel protection concerns associated with neutrons. Nevertheless, equipment is available and in certain circumstances, the unique information provided by neutron radiography outweighs the disadvantages. Even though neutron radiography service centers have been available for many years, there has been no inhouse neutron radiography available at any general service, commercial nondestructive testing center. The interested user is therefore advised to seek a current supplier of neutron radiography services.

Neutron Energies and Sources

It is usual to group neutrons into four categories:

1. fast neutrons with energies exceeding 0.1 MeV,
2. epithermal neutrons with energies in the range of 0.3 to 102 eV,
3. thermal neutrons with energies in the range of 0.01 to 0.3 eV,
4. cold neutrons with energies in the range of 0.0 to 0.01 eV.

Neutrons can be produced from various sources, including reactors, accelerators and radioactive isotopes. Most practical neutron radiography has been performed using a nuclear reactor. Reactors are prolific sources of neutrons and the beams generated are rich in thermal neutrons. Accelerators generate neutrons by positive ion bombardment of selected materials. These produce a moderate intensity with medium resolution and have the advantage of on-off

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operation. Isotopic sources have been used for many years for a variety of applications, however, the thermal neutron intensities that can be achieved from such sources tend to be low, especially when compared to that from a reactor. On the basis of technical performance, spontaneous fission from Cf-252 is the most attractive isotopic source for neutron radiography.

Because slower neutrons are usually desired for radiography, this energy must be dissipated through numerous collisions with nuclei in the host material. The transformation from fast neutrons to slow neutrons is achieved by a moderating material. Its presence produces a slowing down of the fast neutrons by elastic scattering collisions (between the moderator nuclei and the neutrons) until the average kinetic energy of the neutrons is the same as that of the moderator nuclei. *Thermal neutrons* are so called because they are in thermal equilibrium with their surroundings at, or near, room temperature. These thermal neutrons have a higher probability of interaction with the specimen's material than higher energy neutrons, and are therefore most often used for radiography.

Because the source of neutrons is a dispersed volume, rather than a point source, it is necessary to use a collimator between the source and the object. Many types of collimators have been designed and used including point source, parallel wall and divergent collimator schemes. The most frequently used design uses divergent beam geometry.

Although divergent collimators are similar to point source geometry, they are generally used to extract a beam from a relatively large moderator assembly. Therefore, walls are required to limit the background radiation from reaching the image plane. Limiting the background radiation is generally as important as geometric collimation for obtaining good quality radiographs.

Besides static radiography with thermal neutrons, there are also specialized neutron radiography techniques for which different energies may be selected. These include neutron computed tomography, dynamic neutron imaging, high frame rate neutron imaging, neutron induced autoradiography and neutron gaging.

Neutron Imaging

Images from neutron radiography are obtained in two principal ways: direct and indirect. In the *direct method*, the film is actually

present in the neutron beam during exposure and involves converting the transmitted portion of the neutron beam into a type of radiation that will expose a photographic emulsion. In the *indirect*, or *transfer method*, the film exposure is made by autoradiography of a radioactive, image carrying metal screen. The two techniques are illustrated in Figure 12.1.

Direct sensitivity of film to neutrons is relatively low. Therefore, conversion or intensifying screens are used with both techniques. For the direct exposure method these screens increase the detector response by the emission of radiation that the adjacent film is sensitive to. The most widely used detection method for industrial neutron radiography is the direct exposure technique with a gadolinium conversion screen.

For the indirect method, the screens are chosen from materials that tend to become radioactive upon thermal neutron exposure. Indium or gadolinium screens used for indirect neutron radiography give clearer neutron images and are less susceptible to interference by other radiation. However, the indirect technique is much slower than the direct. A thin film or foil of an element with a high neutron absorption cross section is exposed to the transmitted neutron beam. The foil is then removed from behind the specimen and placed on radiographic film in a remote location. The film is exposed by decay of the radioactive nuclei produced by neutron capture. Elements such as indium, gadolinium, silver, rhodium, gold and dysprosium are useful for the indirect technique. The indirect technique does provide excellent discrimination against gamma photons from neutron sources or from the object.

A comparison of the two general classes of film detection methods shows that indirect techniques yield high contrast images with no gamma interference. Direct exposure methods, on the other hand, provide much faster results and have yielded much better spatial resolution.

Dynamic Neutron Radiography

The development of dynamic (real time) neutron radiography capitalized on the availability of very high intensity steady state neutron beams and very high frame rate video cameras used with rapid response neutron sensitive scintillator screens. Various services are available that provide frame rates that range from 30 frames per second (real time motion display similar to television) to 1000 or even 10 000 frames per second.

Chapter 12: Neutron Radiography

Subthermal Neutron Radiography

The neutron attenuation coefficient of a material can change significantly as the neutron energy is changed. The pattern of this variation also changes abruptly from one element to another. Therefore, selection of different energies provides possibilities for quite different neutron radiography penetration and contrast. The effect of using subthermal energy is typically to increase the transparency of certain materials while simultaneously increasing the detectability of hydrogenous materials.

Epithermal and Fast Neutron Radiography

A reactor beam, though consisting primarily of thermal neutrons, will contain a portion of both subthermal and epithermal neutrons. With a filter such as cadmium, the thermal and subthermal neutrons can be removed and only the epithermal part of the neutron energy spectrum will be transmitted. The term *fast neutron radiography* refers normally to those neutron energies yielded by an unmoderated accelerator source or a radioactive source. Fast neutron radiography provides high penetration but little contrast between elements.

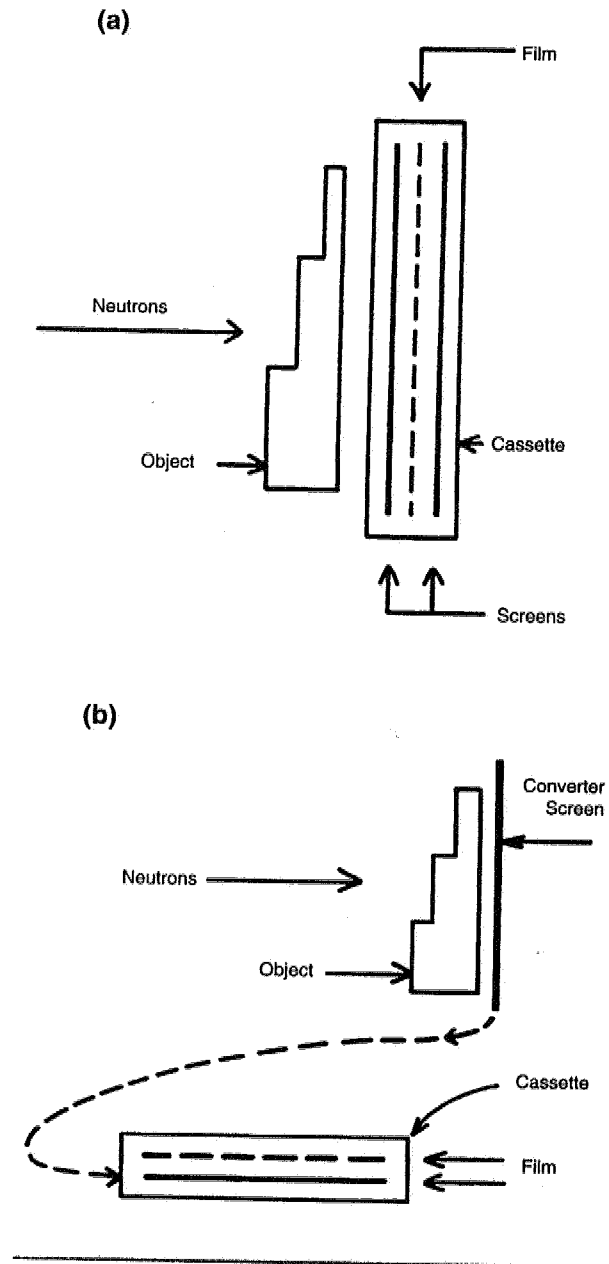
Neutron Computed Tomography

Computed axial tomography has been developed for neutron radiography and can provide detailed cross sectional slices of the object to be analyzed. While the information provided is unique to the neutron interaction with the specimen's material, the principles are similar to those of X-ray computed tomography.

Neutron Gaging

Neutron gaging is the measurement of attenuation of a collimated, small diameter beam of radiation as it is transmitted through a specimen. It has been used for static gaging of discrete assemblies and for continuous scanning of long objects for acceptable uniformity. The gaging technique can test items of greater thickness than can be tested with neutron radiography.

Figure 12.1: Direct and indirect methods of neutron radiography: (a) direct and (b) indirect.



Chapter 12 Review Questions

- 12.1 Ionization is not a major absorption processes for neutrons because:
- neutrons are very large.
 - neutrons have no charge.
 - neutrons are relatively low energy.
 - None of the above.
- 12.2 The neutron is one of the primary particles that make up the atomic nucleus. Its mass is:
- less than that of the proton.
 - essentially the same as the proton.
 - more than the proton.
 - the same as the atomic mass for an atom.
- 12.3 What makes neutron radiography uniquely useful?
- The interaction of neutrons and X-rays with matter is fundamentally different.
 - Neutrons are easily shielded.
 - Personnel safety is easier than with X-rays.
 - Imaging neutrons requires less sophisticated equipment.
- 12.4 Neutron imaging is uniquely suited to detection of corrosion in aircraft because:
- neutrons are easier to image with light elements and metals.
 - neutrons are strongly attenuated by aluminum.
 - neutrons are strongly attenuated by cadmium and gadolinium.
 - neutrons are strongly attenuated by hydrogen and water.
- 12.5 Neutron sources include:
- reactors.
 - accelerators.
 - radioisotopes.
 - All of the above.
 - None of the above.
- 12.6 The selection of different neutron energies provides possibilities for quite different penetration and contrast because:
- the conversion screens react differently to different energies.
 - the attenuation coefficients of light elements and metals reverse with high energies.
 - the pattern of neutron attenuation coefficients of the elements changes dramatically with energy.
 - None of the above.
- 12.7 The neutron energy most commonly used in nondestructive testing is:
- cold.
 - thermal.
 - fast.
 - slow.
- 12.8 All of the following are neutron imaging processes except:
- conventional X-ray film.
 - gadolinium converter with X-ray film.
 - neutron sensitive storage phosphor.
 - dysprosium or indium foils activation transfer to film.
- 12.9 The radioisotope most commonly used as a source of neutrons for nondestructive testing imaging is:
- Ar-39.
 - Ir-191.
 - Co-59.
 - Cf-252.

Chapter 13

Backscatter Imaging

Physical Principles

Backscatter imaging involves the collection of scattered radiation, rather than the transmitted radiation, to form an image. Although a typical X-ray test scatters as many photons as are transmitted, imaging the scattered photons is much more difficult. Consequently, backscatter imaging is usually a digital technique.

The unique nature of backscatter imaging has made it particularly useful in several areas. The backscatter technique images from one side, making it useful in applications such as aircraft pressure bulkheads and other structures where access to both sides of the object is impractical or not possible. Another property of backscatter imaging is its ability to be configured for direct measurement of the electron density of the object being measured. This property can be exploited to detect the difference between filled and unfilled voids within steel casings, such as the explosive within artillery shells. In fact, testing of baggage for explosives or contraband has been a major driving force in the development of backscatter radiography. Another motivation for using backscatter radiography is that it can perform a certain amount of chemical analysis on the object being examined. This faculty is most acute at very low (1 keV) and very high (> 2 MeV) energies. At energies around 60 keV, a dual energy technique permits the estimation of the atomic number of the material being examined through comparison of scattering and absorption coefficients.

Scattering takes place through the interaction of an X-ray or gamma ray photon with either an electron or the nucleus. For imaging purposes, interactions with electrons is most important. In most interactions, there is a transfer of energy between the photon and the electron. There are four scattering processes used for backscatter imaging: *elastic*, *compton*, *fluorescence* and *resonance fluorescence*.

Elastic scattering, also called *rayleigh scattering* or *coherent scattering*, involves no energy loss. In elastic scattering the photons of the radiation are reflected, they bounce off the atoms and molecules without any change of energy. In this type of scattering there is a change of phase, but no frequency change. The entire field of X-ray diffraction is based on elastic scattering. Because the energies involved are on the order of just a few kilovolts, penetration is limited. Elastic scattering is used primarily for one dimensional measurements at a point, such as the measurement of very thin coatings.

Compton scattering also involves the electrons that surround the nucleus of an atom. In this case there is energy loss from the incident photon to the electron that recoils in a collision. There are definite relations between the amount of energy lost and the angle of scatter. Compton scattering occurs in the range of tens to hundreds of thousands of electronvolts. It is the basis for most of the attenuation of high energy photons and is also the basis for most backscatter imaging techniques.

Fluorescence occurs when K or L shell electrons are liberated in the photoelectric process. These electrons may also interact with other atoms to eject further K or L shell electrons. The cascade that results to refill the missing electrons results in the emission of photons in a process called *fluorescence*. As with elastic scattering, X-ray fluorescence has very limited penetration and is the basis for several chemical analysis tools. X-ray and gamma ray fluorescence are used to sort alloys and to detect and measure the lead in paint coatings.

Another type of fluorescence occurs at very high energies and is called *resonance fluorescence*. At energies around 10 MeV, incident photons can cause changes in the energy of the nucleus of atoms. After absorption of a photon the nucleus relaxes, emitting other photons at lower energies, but still in the megaelectronvolt range. This

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technique has advantages for the examination of thick or dense structures and is also capable of chemical analysis. The chief drawbacks to the resonance fluorescence technique are that bulky, expensive particle accelerators are required to generate the incident X-rays, and that above

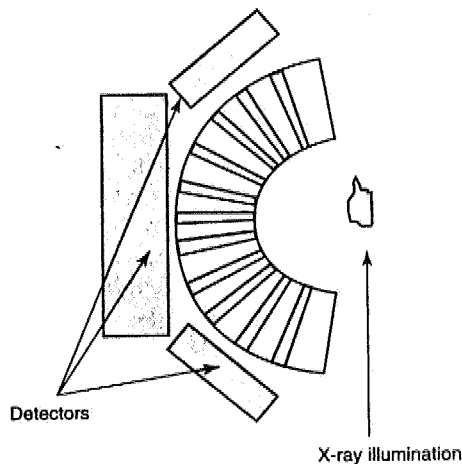
500 keV it is possible to generate residual radioactivity.

Backscatter Imaging Techniques

Pinhole

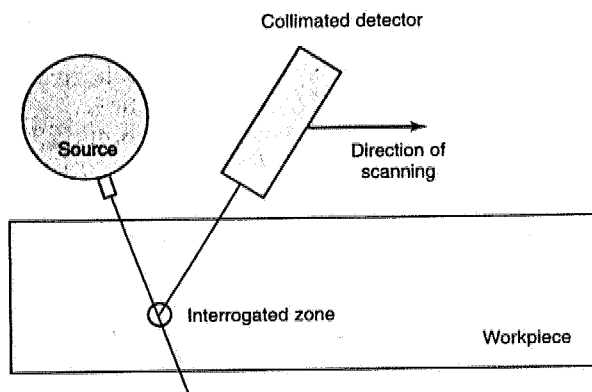
One of the earliest examples of industrial scatter imaging was performed using a pinhole camera. The pinhole camera technique gives a two-dimensional image. Its simplicity is offset by the very small throughput obtainable because of the small solid angle subtended by the pinhole.

Closely related to the pinhole camera is the multiple aperture collimator. This is essentially a number of pinholes and masks designed to image a selected volume element repeatedly onto a detector. Figure 13.1 illustrates one form of multiaperture detector. Conical holes are drilled radially in a shielding material such as lead. The specimen is illuminated from the side and only those photons scattered at the geometric center of the collimator are detected.



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Figure 13.2: Moving detector depth scanning. In slit imaging configuration, source and one slit are stationary while detector and imaging slit are moved across surface to collect scatter from progressively deeper layers.



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Moving Slits

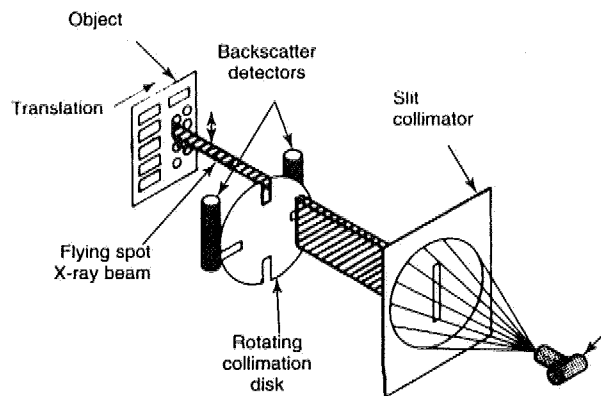
By elongating a pinhole into a slit, its solid angle may be significantly increased without sacrificing resolution in one direction. When applied to Compton scattering, slit imaging has been used in several depth profiling schemes. In these, the slits are configured to give high resolution in the depth direction at the sacrifice of resolution in other directions. In one case the source slit detector assembly is rigid and is physically moved relative to the surface under study. In a second configuration, the source and one slit are stationary while the detector and an imaging slit are moved across the surface to collect scatter from progressively deeper layers as shown in Figure 13.2.

Flying Spot

Flying spot scanning is by far the most popular backscatter technique because of the high throughput obtainable. The detector solid angle can reach nearly 2π steradian. The most common technique involves placing a chopper wheel in front of a long, often semicircular, slot as shown in Figure 13.3. The combination of the slot in the chopper wheel and the fixed slot together form a moving mask that limits the incident beam to whatever will pass through the mask. The backscattered photons are usually detected with broad area uncollimated detectors. This technique is used extensively in luggage scanners to test for

Chapter 13: Backscatter Imaging

Figure 13.3: Flying spot X-ray backscatter system.



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bombs. Flying spot scanners have also been scaled up to sizes that allow the testing of entire trucks and freight cars.

Applications of Backscatter Imaging

The principles and techniques of backscatter imaging have evolved in different ways to meet the needs of numerous applications. What follows are just a few examples of applications that may assist in understanding the principles.

Ordnance

X-ray backscatter has proven itself useful in two areas related to ordnance. The most direct is the checking of fuses and explosives in artillery shells and similar devices. The fuses and explosives are made of organic materials that show little contrast with transmission radiography. Their composition, however, scatters radiation well and absorbs little, making backscatter imaging an ideal solution. The second area of backscatter application to ordnance is in mine detection. Although mines no longer rely on the metallic housings which were the basis of many previous detection schemes, the high density and low atomic number materials needed to make the explosives are ideally suited to detection by backscatter techniques. Therefore, mine detectors using Compton backscatter have evolved along the same lines as baggage scanners.

Aircraft Corrosion

The need for corrosion detection and evaluation of aircraft often permits access to only one side, making this an ideal application for backscatter imaging. Backscatter can use depth scans to examine the thickness of subsurface layers and determine how much metal has been removed by corrosion. In forming, corrosion products separate metal structural members. Corrosion products between lap joints causes swelling between rivets leading to a phenomenon called *pillowing*. In some cases the corrosion product may be leached out or dried leaving a gap. Exfoliation corrosion causes the metal itself to swell and in extreme cases to burst in pocklike eruptions. Because X-ray backscatter imaging is also very good at detecting gaps or voids it is often applied to these situations.

Chapter 13 Review Questions

- 13.1 Which of the following is not one of the scattering processes used for backscatter imaging?
- elastic
 - incoherent
 - fluorescence
 - resonance fluorescence
- 13.2 Resonance fluorescence is used for the examination of thick or dense structures, but has the distinct disadvantage of possibly generating residual radioactivity. Why is this?
- Because the sources needed for this method have very long half lives.
 - Because this type of fluorescence occurs at very high energies.
 - Because the materials best suited to this inspection are naturally radioactive.
 - None of the above.
- 13.3 In which type of scattering is there a change of phase, but not energy?
- elastic
 - compton
 - fluorescence
 - resonance
- 13.4 Which type of scattering is used primarily for thickness measurement of very thin coatings?
- resonance
 - compton
 - rayleigh
 - fluorescence
- 13.5 As with elastic scattering, which other type has limited penetration and as a result is often used for material identification and sorting of alloys?
- resonance
 - compton
 - rayleigh
 - fluorescence
- 13.6 Which backscatter imaging method uses a chopper wheel in front of a slit collimator?
- pinhole
 - moving slits
 - flying spot
 - moving detector scanning
- 13.7 What is the advantage of a moving slit over a pinhole?
- It increases throughput without sacrificing resolution in one direction.
 - It provides better depth resolution.
 - It views a larger area at equal resolution.
 - None of the above.
- 13.8 X-ray fluorescence measurements utilize which type of scattering?
- rayleigh
 - fluorescence
 - resonance fluorescence
 - None of the above.
- 13.9 Why is backscatter imaging ideally suited to the examination of explosives?
- Explosive materials are made of organic materials that absorb little, but scatter well.
 - Because there is little danger of an explosion.
 - Because of the high energies involved.
 - None of the above.
- 13.10 Why is backscatter imaging well suited to some aircraft inspections?
- Because its backscatter is based on nuclear rather than electron interactions.
 - Because its energies are best suited to aluminum densities.
 - Because it only requires access to one side.
 - a and c

Chapter 14

Radiographic Interpretation

Image Object Relationships

Interpretation of a radiograph is much more than looking at film. To interpret and analyze the results of any radiographic examination, the interpreter must first verify that the radiograph corresponds to the specimen or portion of the specimen being examined. Secondly, he or she must verify that the technique was appropriate and adequate to the testing (technique sheets, codes, density, penetrameter selection and sensitivity, etc.). Thirdly, the interpreter must be able to identify any artifacts that may mask a rejectable discontinuity. Lastly, discontinuities in the specimen must be identified and reported.

Knowledge of the component or part configuration and its manufacturing process is required for the interpreter to make sound judgments. These data will enable the interpreter to anticipate possible discontinuities and their locations within the component or part.

Awareness of the following information permits the inspector to intelligently interpret images on the radiograph:

1. thickness,
2. surface finishes,
3. welding process,
4. weld joint design,
5. material form,
6. heat treatment,
7. accessibility,
8. composite material forms,
9. internal structure.

The use of drawings, weld data sheets, manufacturing processing data, etc., is essential for the interpreter. Knowledge of the product may eliminate erroneous conclusions.

Material Considerations

Radiographic examination in industry today is applied to many items and is frequently required for heavy wall weldments and castings.

This section addresses the processes of welding, casting and composites manufacturing as well as the expected or inherent discontinuities.

Welding

Over forty welding processes are available to manufacturers. They include, but are not limited to, arc welding, brazing, gas welding, resistance welding and solidstate welding. Regardless of the process, there are three common variables:

1. source of heat,
2. source of shielding, and
3. source of chemical elements.

Control of these variables is essential. When any of these, for whatever reason, becomes unstable, the individual interpreting a radiograph of the weld would expect to detect:

1. porosity,
2. slag inclusions,
3. lack of fusion,
4. incomplete penetration,
5. cracks,
6. tungsten inclusions, and
7. other indications.

Casting

The ability of molten metal to fill a mold is based on the fluidity of the molten metal. It varies with material type and temperature. The process of solidification occurs when the liquid metal contracts to solid and solid contracts to room temperature.

Some of the factors affecting the solidification of cast material are:

1. thermal properties of the mold,
2. liquid/solid temperatures of the metal,
3. thermal properties of the solidifying metal, and
4. pour temperature.

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Typical of the types of discontinuities formed during the casting process, which may or may not be detrimental to the casting integrity are:

1. porosity,
2. gas voids,
3. sand inclusions,
4. slag inclusions,
5. shrinkage,
6. tears,
7. cracks,
8. unfused chaplets, and
9. cold shuts.

The radiographer must interpret the acceptability of these discontinuities to the applicable code, standard, engineering document, etc.

Composites

Composites are basically two or more materials that are combined such as skins and a honeycomb core. They are also often described as a *matrix* and a *reinforcement*, such as graphite fibers in an epoxy matrix.

Composites are numerous and the number is growing rapidly. They can be grouped into reinforcing materials and matrix materials. Reinforcements include fiberglass and carbon (graphite), and may come in a wide variety of forms, including whiskers, filaments (single fibers), strands (untwisted bundle of fibers), yarn (a twisted bundle), roving (a number of yarns or strands collected into a parallel bundle without twisting) and mat (randomly oriented chopped or swirled fibers in a sheet or woven fabrics).

Matrix materials come in just as wide a variety and may include polyester resins, epoxy resins, thermoplastics, polyimides, phenolics, carbon and ceramics.

There are also a great many different ways to combine all these materials to produce structures of various desired properties.

Expected Discontinuities

The text below discusses discontinuities and their effects by category.

Welding Discontinuities

Cracks result from fractures or ruptures of weld metal. They occur when stresses in localized areas exceed the material's ultimate tensile strength. Cracks in all forms are considered the most detrimental discontinuities because their sharp extremities act as severe stress concentrators.

Incomplete penetration or lack of penetration results when weld metal did not penetrate and fuse at the root. Normally this occurs when there is a problem with heat input, improper joint design, poor fit up, or incorrect electrode angle. Incomplete penetration is normally cause for rejection because of its potential as a stress riser.

Lack of fusion or incomplete fusion is a result of nonadhesion between successive weld passes or between a weld pass and the weld edge preparation on a side wall. Lack of fusion is considered to be detrimental to fatigue strength.

Porosity is the result of gas being trapped as weld metal solidifies. In general, porosity is not considered critical unless it is present in large quantities, contains sharp tails or is aligned in a short distance.

Slag inclusion is caused when nonmetallic materials become trapped in the weld metal between weld passes or between a weld pass and the base material.

Tungsten inclusion is the result of pieces of the tungsten electrode breaking off and being trapped in the weld.

Casting Discontinuities

Cold shuts are the result of splashing, surging, interrupted pouring, or the meeting (without fusion) of two streams of molten metal.

Cracks result from stresses in cast material which occur at relatively low temperatures.

Gas voids, such as gas holes, worm holes or blowholes, are also formed during solidification and are considered more critical when in a tail like linear pattern, which indicates a potential through wall leak path or stress riser.

Hot tears are cracks or ruptures occurring while metal is very hot.

Porosity occurs when gas is trapped in the metal during solidification. The pores vary in size and distribution.

Sand inclusion results from sand breaking loose from the casting mold and becoming trapped.

Shrinkage results from localized contraction of the cast metal as it solidifies and cools. It may or may not be acceptable, depending on population, design function and several other factors.

Slag inclusions result when impurities or oxides are introduced into the casting along with the molten metal.

Unfused chaplets result from the failure of the liquid metal to consume the metal device used to support the core inside the mold.

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Composite Discontinuities

The field of composite structures is extremely broad. With all the different types of materials and accompanying combinations, the possibilities for defects are many and varied. Every place that two different materials meet can be a source of disbands (adhesive to skin, adhesive to core, adhesive to substructures, etc.) All materials that start as liquid, such as adhesive or foam, have the potential for casting like defects (porosity, shrink cracks, etc.) Most bonding processes involve heat and many structures are composed of materials of very different coefficients of thermal expansion. This often results in internal stresses that in turn result in defects. An example would be microcracking between a matrix and the reinforcing fibers. A further complication is that these issues can occur, or be oriented, in all three dimensions, which is a major concern when considering radiographic imaging and interpretation.

Radiographic Appearance of Discontinuities

The previously identified and discussed discontinuities are normally identifiable by their radiographic images.

Welding Discontinuities

Cracks normally show as dark, irregular, wavy or zigzag lines and may have fine, hairline indications branching off the main crack indication.

Incomplete penetration typically appears as a sharp, dark, continuous or intermittent line. Depending on weld joint fit-up geometry, this dark line may occur in the center of the weld or along the edge of a weld bevel.

Lack of fusion normally shows as a thin, straight dark line parallel to the weld. Lack of fusion occurring between the weld and the side wall generally appears straight on one side and irregular on the other side. It will typically appear some distance from the weld centerline.

Porosity shows as rounded well defined high density spots with sharp contours.

Slag inclusions usually appear as dark irregular shapes of varying lengths and widths. They are dark when the oxide that makes up the inclusions is of a lower atomic weight than the weld metal.

Tungsten inclusions appear as very light, almost white, indications because of tungsten's higher radiation absorption.

Casting Discontinuities

Cold shuts appear as dark lines or linear areas of varying length.

Cracks normally appear as dark, irregular, intermittent or continuous lines, usually quite well defined.

Gas voids appear as large, rounded, dark indications, normally with smooth edges.

Hot tears appear as dark, ragged, irregular lines and may have a number of branches of varying densities that are less clearly defined than cracks.

Porosity appears radiographically as rounded dark spots of various sizes.

Sand inclusions appear as light or dark indications of irregular shapes depending on the relative densities of the inclusion and the base metal.

Shrinkage appears as irregularly shaped spots of varying densities, which often appear to be interconnected.

Unfused chaplets are easily identified as circular dark lines about the same diameter as the core support device.

Composite Discontinuities

Foam adhesive separation in radiographs of bonded assemblies is significantly lighter than adjacent areas and is located at core splices, closures, shear ties and at certain fasteners that have no accessible heads. Foam adhesive is usually associated with honeycomb core. The foam may contain cracks and may be separated from core, closure webs or shear ties.

Skin to structure disbands can only be detected if the disbond is the result of a lack of adhesive. This is because the plane of the bond is perpendicular to the radiation beam. To be detected by radiography a disbond must be oriented parallel to the X-ray beam just as with a crack.

Honeycomb defects such as crushed or misaligned core and defective shear ties are easily imaged and produce distinctive indications.

Image Analysis Techniques

One advantage of working with digital images is the opportunity for enhancement. While it is important to preserve the original image, variations can be generated that yield greater understanding of object properties. It is often possible to effectively increase dynamic range, improve contrast in regions of interest, emphasize subtle features, reduce background

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noise and provide more robust detection of discontinuities.

Signal enhancement offers sharper contrast and improved visibility of edges, lines, details and other features. While no information is added in the process, enhancement makes the information more easily viewed and understandable. Furthermore, enhancement can be specified and controlled and thus offers an objective means for improving an image. Because of this, processing techniques become an integral part of the documentation, similar to source-to-film distance, energy and exposure time. It must be emphasized that while processing is advantageous, raw data must be preserved.

Numerous digital image processing schemes have been developed and are in common use. Those evaluating digital images should learn the more common tools and techniques of image analysis, especially those that are installed with a particular system. Not all enhancement techniques developed for reflected light images, such as photography, apply well to radiographic transmission images. Some commonly used tools include contrast enhancement, histogram equalization, unsharp masking, edge enhancement and spatial filtering.

Codes, Standards, Specifications and Procedures

In all nondestructive test disciplines, the use of applicable codes, standards and specifications in the preparation of the procedures for performing the test is essential. This applies to radiographic testing as well. Contractual requirements usually dictate the specific requirements that are applicable to a particular component.

The radiographic interpreter must be capable of interpreting and applying specified acceptance criteria. In addition, he or she must also be knowledgeable in the technique used to make the exposure and its effects on the image. For the interpreter to properly determine technique acceptability, the following guidelines should be used.

1. Component

What is it? Circumferential piping weld, pressure vessel long seam, valve body, nozzle, pump housing? Obtain a drawing, sketch or weld data sheet. Study the configuration, the material type, the joint design and the thickness involved.

2. Fabrication data

How was it fabricated? Are there heat treatment requirements? What is the surface finish? What manufacturing process was used?

As you review this information, some of the basic parameters needed to determine technique acceptability can be evaluated.

1. Part thickness determines the penetrameter requirements and the required or permitted radiation energy.
2. Reinforcement determines the need for shims.
3. Fabrication process provides an indication of the types of discontinuities that are expected.
4. Configuration has a direct bearing on exposure and viewing technique.
5. Heat treatment may have a bearing on whether graininess is a problem to be expected or whether stress related discontinuities may be present.
6. Accessibility affects technique, such as placement of penetrameters.
7. Surface finish may aid or hinder interpretation of nonrelevant indications.

The radiographic interpreter should also be knowledgeable of the effects of the following variables on the radiographic image:

1. source size,
2. source-to-film distance,
3. source placement,
4. film placement,
5. radiographic coverage required,
6. film selection,
7. screens,
8. film processing technique, and
9. processing variables.

Radiographic film interpretation is more than knowing or understanding codes, standards, specifications, procedures and the proper application of acceptance standards. A knowledge of manufacturing processes, as well as radiographic testing in general, is imperative.

Chapter 14 Review Questions

- 14.1 Proper interpretation of a radiograph requires that the film interpreter have an understanding of:
- film speed.
 - configuration and manufacturing variables.
 - exposure time.
 - All the above.
- 14.2 Which of the discontinuities listed below would not be classified as a welding discontinuity?
- lack of fusion
 - incomplete penetration
 - slag inclusion
 - cold shut
- 14.3 Generally speaking, rounded or spherical voids resulting from trapped gas during the welding process would be identified as:
- slag inclusion.
 - wagon tracks.
 - porosity.
 - tungsten inclusion.
- 14.4 A lack of adhesion between successive passes or along the edge of a weld preparation is called:
- lack of fusion.
 - incomplete penetration.
 - cracks.
 - root concavity.
- 14.5 Localized contraction of cast metal as it solidifies and cools may result in:
- gas voids.
 - cold shuts.
 - shrinkage.
 - cracks.
- 14.6 Dark irregular images of varying length, density and width on a radiograph of a submerged arc-welded joint would probably be the result of:
- lack of fusion.
 - trapped slag.
 - incomplete penetration.
 - hot tears.
- 14.7 An area of incomplete fusion at the root area of a weld, which normally occurs when there is a problem with heat input, improper joint design, poor fit up or improper electrode selection, is generally referred to as:
- lack of fusion.
 - wagon tracks.
 - slag lines.
 - incomplete penetration.
- 14.8 A very light (almost white) indication detected in a piping joint that was welded using the tungsten inert gas process would probably be:
- crater pits.
 - porosity.
 - weld spatter.
 - tungsten inclusion.
- 14.9 Porosity in a weld may not be critical. Which of the following porosity conditions is not normally considered detrimental to welds?
- It is present in large quantities.
 - It is randomly dispersed and less than 0.4 mm (1/64 in.) diameter.
 - It contains sharp tails.
 - It is aligned in short distances.

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- 14.10 All welding processes have three common variables. Which of the following is not one of those variables?
- a. source of heat
 - b. source of shielding
 - c. size of electrodes
 - d. source of chemical elements
- 14.11 _____ and reinforcement requirements are important in determining if the proper penetrameter(s) were used.
- a. Surface finish
 - b. Welding
 - c. Thickness
 - d. Heat treatment
- 14.12 One of the factors that affects the solidification of cast material is the:
- a. pour temperature.
 - b. heat treat condition.
 - c. elasticity.
 - d. root opening.
- 14.13 _____ in all forms are considered the most detrimental because their sharp extremities act as stress concentrators.
- a. Slag inclusions
 - b. Tungsten inclusions
 - c. Oxides
 - d. Cracks
- 14.14 Image analysis techniques convert analog television images into a digitized image that is further quantized in:
- a. time and space.
 - b. space and intensity.
 - c. distance and time.
 - d. brightness and clarity.
- 14.15 Image enhancement techniques currently used include three of the four applications listed below. Identify the nonimage enhancement technique.
- a. edge enhancement
 - b. spatial filtering
 - c. pseudocolor enhancement
 - d. static radiography

Review Question Answers

Review questions in this *Level III Study Guide* use a modular numbering system, so that question 3.1 is the first review question in Chapter 3. Comments about this table should be directed to the Educational Materials Supervisor at ASNT. See the copyright page or www.asnt.org for ASNT staff contact information.

1.1	c	2.1	c	3.1	a	4.1	a	5.1	a	6.1	c	7.1	c
1.2	b	2.2	b	3.2	d	4.2	a	5.2	c	6.2	a	7.2	e
1.3	a	2.3	b	3.3	c	4.3	e	5.3	d	6.3	f	7.3	e
1.4	b	2.4	b	3.4	e	4.4	a	5.4	e	6.4	b	7.4	a
1.5	c	2.5	b	3.5	b	4.5	d	5.5	c	6.5	a	7.5	a
1.6	a	2.6	c	3.6	a	4.6	c	5.6	b	6.6	a	7.6	b
1.7	b	2.7	c	3.7	d	4.7	e	5.7	e	6.7	b	7.7	c
1.8	c			3.8	e	4.8	b	5.8	a	6.8	a	7.8	d
1.9	b			3.9	b	4.9	d	5.9	c	6.9	b	7.9	b
1.10	a			3.10	c	4.10	b	5.10	c	6.10	d	7.10	c
1.11	d			3.11	a	4.11	a	5.11	c	6.11	d	7.11	a
1.12	a			3.12	d	4.12	e	5.12	a	6.12	b	7.12	c
1.13	b			3.13	b	4.13	d	5.13	b				
1.14	d					4.14	d	5.14	d				
1.15	c					4.15	b	5.15	b				
1.16	a					4.16	b	5.16	b				
1.17	a					4.17	d						
1.18	d					4.18	c						
1.19	b												
1.20	a												
1.21	a												
1.22	a												

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8.1	d	9.1	a	10.1	c	11.1	c	12.1	b	13.1	b	14.1	b
8.2	c	9.2	c	10.2	a	11.2	a	12.2	b	13.2	b	14.2	d
8.3	a	9.3	c	10.3	d	11.3	d	12.3	a	13.3	a	14.3	c
8.4	b	9.4	d	10.4	b	11.4	b	12.4	d	13.4	c	14.4	a
8.5	d	9.5	a	10.5	d	11.5	a	12.5	d	13.5	d	14.5	c
8.6	b	9.6	a	10.6	b	11.6	c	12.6	c	13.6	c	14.6	b
		9.7	d	10.7	c	11.7	b	12.7	b	13.7	a	14.7	d
		9.8	c	10.8	a	11.8	c	12.8	a	13.8	b	14.8	d
		9.9	b	10.9	d	11.9	b	12.9	d	13.9	a	14.9	b
		9.10	c	10.10	c	11.10	d			13.10	c	14.10	c
		9.11	a	10.11	c	11.11	b					14.11	c
		9.12	b	10.12	a	11.12	b					14.12	a
				10.13	d	11.13	c					14.13	d
				10.14	d	11.14	a					14.14	b
				10.15	b	11.15	a					14.15	d
				10.16	a								
				10.17	d								