CHAPTER 6

RADIOGRAPHIC TESTING

I. HISTORY AND DEVELOPMENT

The history of radiographic testing (RT) actually involves two beginnings. The first commenced with the discovery of x-rays by Wilhelm Conrad Roentgen in 1895 and the second with the announcement by Marie and Pierre Curie, in December of 1898, that they had demonstrated the existence of a new radioactive material called "radium."

The Discovery of x-Rays

One of the true giants in radiography is the man who discovered x-rays—Wilhelm Conrad Roentgen (Figure 6-1). Roentgen was born on March 27, 1845 in Lennep, Germany. His birth house is still in existence and is presently a magnificent museum containing many of the artifacts that he used in his early days of experimenting. It also includes many radiographic devices and interesting radiographs that had been taken over the years as a result of his discovery.

Roentgen was educated in Utrecht and Zurich and ultimately became a Professor of physics at Strasbourg in 1876, Giessen in 1879, and Wurzburg in 1888, where his famous discovery took place. He later became a Professor of physics in Munich in 1899.

There are various accounts as to how x-rays were actually discovered during those days in his experimental laboratory at the University of Wurzburg (Figure 6-2). Most accounts agree that the discovery took place on November 8, 1895, while he was working in his laboratory. He apparently had been working in a semidarkened laboratory room and was experimenting with a vacuum tube, referred to as a Crooke's tube, which he had covered with black photographic paper in order to better visualize the effects that the cathode ray tube produced. As he was experimenting that day, he observed that as the tube was energized, a cardboard coated with barium platinocyanide happened to be lying on a bench not too far from the tube. Even though no visible light escaped from the Crooke's tube because of the dark paper that encompassed it, Roentgen noted that the barium platinocyanide screen fluoresced. He also observed that as he moved the cardboard with the barium platinocyanide coating closer to the tube, it fluoresced with an even higher intensity, which proved that some unknown ray was emanating from the tube. Another account indicates that the cardboard contained a letter "S," which a student had painted on it with barium platinocyanide salts, and the glowing image was actually in the form of that letter "S." Regardless of which of these accounts is factual, it remains that this discovery that occurred on that November day in 1895 had a major impact, not only on industrial nondestructive testing, but also the world of medicine. As a result of this discovery, Roentgen began conducting further experimentations that involved taking radiographs of different objects in his laboratory, including a wooden box containing metal weights, a

FIGURE 6-1   Wilhelm Conrad Roentgen. (Courtesy Charles J. Hellier.)

lock on the laboratory door, and a double-barreled shotgun with different size pellets inside (Figure 6-3). He also x-rayed other materials, such as playing cards, a book, wood, and even some thin sheets of metal. He also observed while he was experimenting that as he placed his hand between the tube and the cardboard containing the fluorescent salts, a faint shadow outline of the parts of his fingers appeared. The actual structure of his bones within his living flesh was observed. Following this came the most historic demonstration of his new discovery, when his wife, who was apparently concerned about all the time he was spending away from home while at the laboratory, came for a visit. It was during this visit that Wilhelm Conrad Roentgen took an x-ray radiograph of his wife's hand (Figure 6-4).

Notice in that early radiograph, that the bones produce a lighter image, since they were higher in density than the surrounding flesh. History does not give any further details as to why Roentgen x-rayed his wife's hand rather than his own. Some suggest that even in those early days, Roentgen was aware of the biological effect that radiation may have had, but that is pure conjecture. In the first days of his discovery, he referred to this unknown ray as "X light," but many of his fellow scientists referred to them as "Roentgen rays." In fact, the expression "Roentgen rays" was quite popular into the early 1900s. In 1902, the term that Roentgen designated for this discovery, "x-rays," began to take hold.

Obviously, Roentgen was very involved with this remarkable finding and on December 28, 1895 (less than two months after first observing x-rays and making the x-ray of

(a)

IN DIESEM HAUSE
ENTDECKTE
W.C.RÖNTGEN
IM JAHRE 1895
DIE NACH IHM
BENANNTEN
STRAHLEN
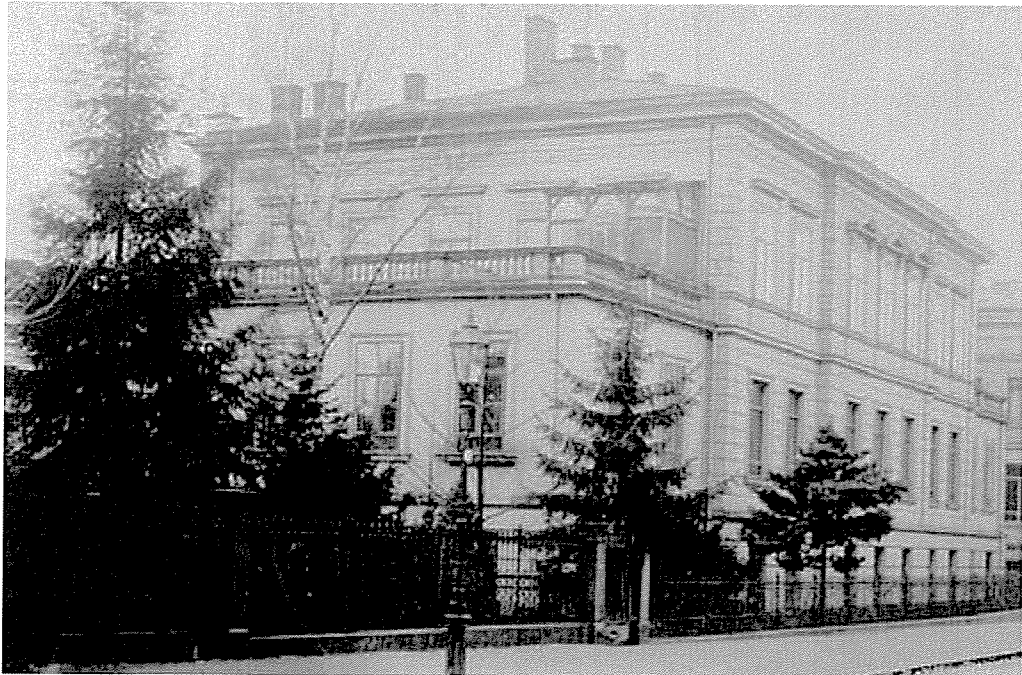
(b)

FIGURE 6-2 University of Wurzburg. (a) Then and (b) now. Author is standing (and pointing) outside Roentgens' laboratory with Dr. Dietmar Henning. (Courtesy Charles J. Hellier.)
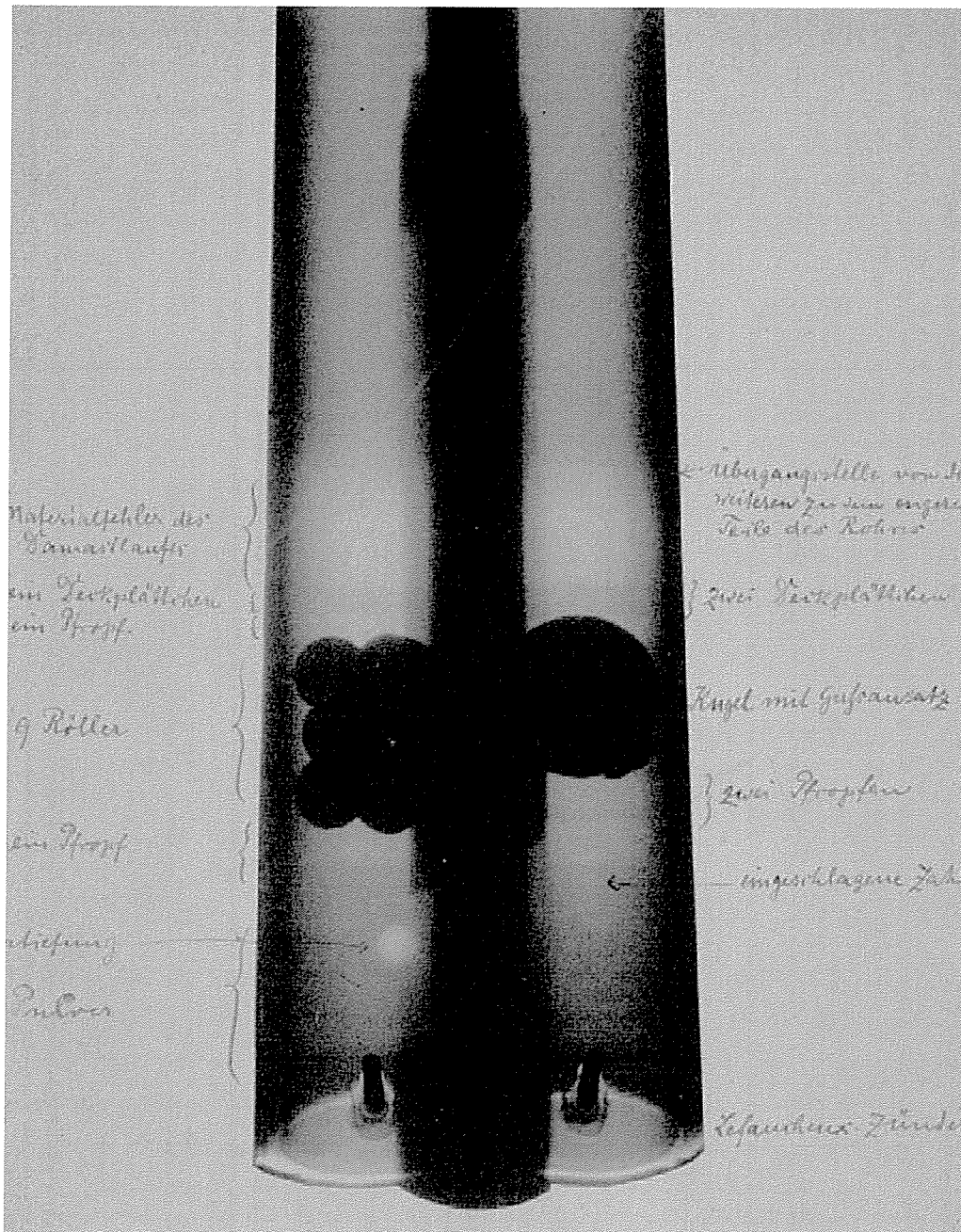
6.3

FIGURE 6-3   Early Roentgen radiograph of a shotgun.

his wife's hand) he presented his first official paper entitled, "On A New Kind of Rays" to the Wurzburg Physical Medical Society. He obviously did not celebrate New Year's Day because, on January 1, 1896, he mailed reprints of this paper together with copies of the x-ray of his wife's hand and other radiographs he had at taken to many of his colleagues. As a result of this, the very first news of this discovery appeared in the Sunday edition of the *Vienna Presse* on January 5, 1896. From there, it was wired to London and

FIGURE 6-4   x-Ray of Mrs. Roentgen's hand.

then on to newspapers around the world. The earliest recorded newspaper article in the United States was in the *Milwaukee Journal* on January 7, 1896. Even in those days, before e-mail and satellite transmission of information, the good news traveled fast. In fact, the *Milwaukee Journal* account was published before it was announced in Roentgen's own hometown newspaper, *The Wurzburg General Anzeiger,* which finally reported the event on January 9, 1896. Roentgen made his first public presentation before the Wurzburg Physical Medical Society on January 23, 1896 and after the lecture, Roentgen took an x-ray of the hand of a famous anatomist named Kolliker who proposed that the new discovery be called Roentgen's Rays.

The first recorded use of x-rays in the United States was on February 8, 1896 when a young man by the name of Eddie McCoughey from Hanover, New Hampshire, was x-rayed for a broken wrist. That first American x-ray was taken by a Dr. Frost and his wife, who was the first head nurse at the Dartmouth College Medical Center.

One might wonder what this all has to do with nondestructive testing, since medical x-ray examinations cannot, theoretically, be considered nondestructive. But if it weren't for this early discovery, many of the early industrial x-ray experiments would have never occurred. In 1901, Roentgen was awarded the first Nobel Prize in science for his work with x-rays (Figure 6-5).

There is so much more to Roentgen's life and how science recognized him, but his desire was not to be in the limelight. He rejected all of the different commercial offers relating to his discovery. There were false reports that it was really his laboratory assistant who was responsible for first observing x-rays, and he had taken all the credit for the discovery. In his later years, Roentgen withdrew from public life. He died on February 10, 1923 of carcinoma of the rectum and was buried beside his wife in the family grave in Giessen. Another remarkable fact regarding Roentgen is that he refused to patent this dis-
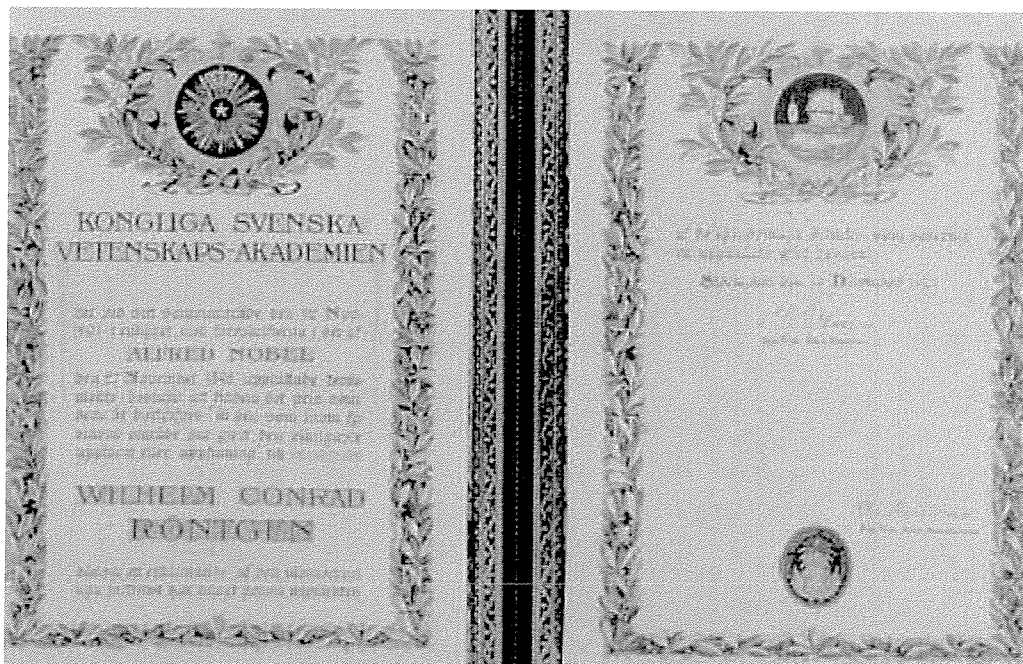

FIGURE 6-5   Nobel Prize for Physics awarded to Roentgen in 1901. (Courtesy Charles J. Hellier.)

covery, so that the world could freely benefit from his work. At the time of his death, he was nearly bankrupt as a result of the inflation that followed World War I.

In the first 20 years that followed Roentgen's famous discovery, x-rays were primarily used in the medical arena by doctors who were developing medical x-ray techniques, looking inside the human body while the patient was still alive. In 1912, Laue, Knipping, and Frederick made the first successful experiment using the diffraction of x-rays. Almost immediately after this experiment, W. D. Coolidge of General Electric Co. invented the Coolidge tube, which allowed a much greater intensity of x-rays to be produced and permitted uniform control of the radiation. On the nondestructive testing scene, Dr. H. H. Lester began experimenting with different materials in the early 1920s at the Watertown Arsenal in Watertown, Massachusetts. This laboratory is illustrated in Chapter 1, Figure 1-7.

While some work continued, the importance of x-rays in NDT did not really become fully known, nor the technology widely utilized, until World War II. The importance of industrial radiography was reflected in the first name of the technical society now known as the American Society for Nondestructive Testing. It was founded in 1941 under the name of The American Industrial Radium and X-ray Society. The developments, triggered by World War II, resulted in significant innovation and invention with radiographic equipment that produced more intense beams and higher energies. Figure 6-6 depicts a "mobile" x-ray unit that was capable of producing energies of up to 250 kV. Certainly,
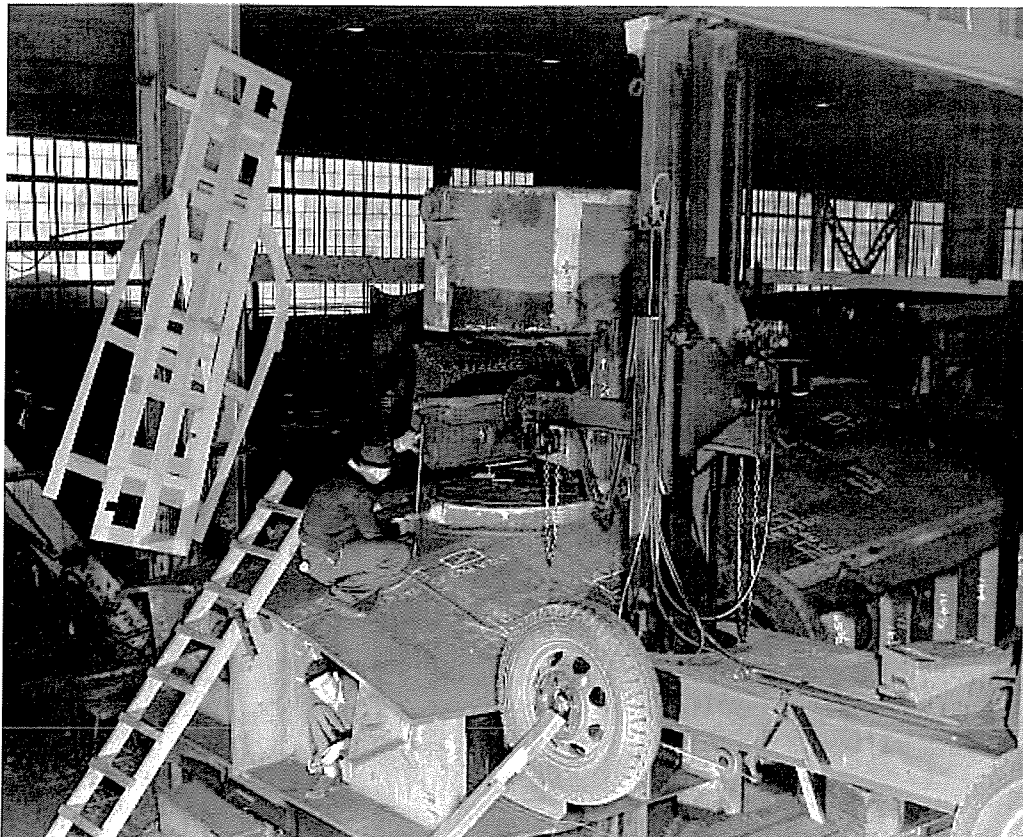

FIGURE 6-6 Early "mobile" 250 kV x-ray unit. (Courtesy Charles J. Hellier.)

the works of Horace Lester and William Coolidge were significant; however, other contributions were made by early scientists and engineers, such as Gerald Tenney, James Bly, Donald O'Connor, Edward Criscuolo, Daniel Polansky, Samuel Wenk, and many others too numerous to name.

The Discovery of Gamma Rays

There are many accounts about Marie and Pierre Curie (Figure 6-7) and there is no doubt that these two physicists led very interesting, unique lives. Marie Sklodowska, as she was known before she was married, was born in Warsaw on November 7, 1867. When she was twenty-four, she traveled to Paris to study mathematics and physics. While there, she met Pierre Curie, who was thirty-five years old, eight years older than Marie. He was an internationally known physicist and a very serious scientist who was dedicated to spending his life doing scientific work. They married in July of 1895 and began to work together on various scientific experiments.

One of their early observations was that thorium gave off the same rays as uranium. They also discovered that there were some reactions coming from materials containing bismuth and barium. When Marie took away a small amount of bismuth, a residue with a much greater activity remained. At the end of June 1898, the Curies had obtained a sufficient amount this substance and proved it was about three hundred times more active than uranium.

They also extracted a substance from pitchblende, similar to bismuth, which they claimed contained a metal never known before. It was suggested that this new, highly active material be called polonium after the country of Marie's origin. In those early days of experimenting, the term "radioactivity" was introduced. Finally, on December 26, 1898,
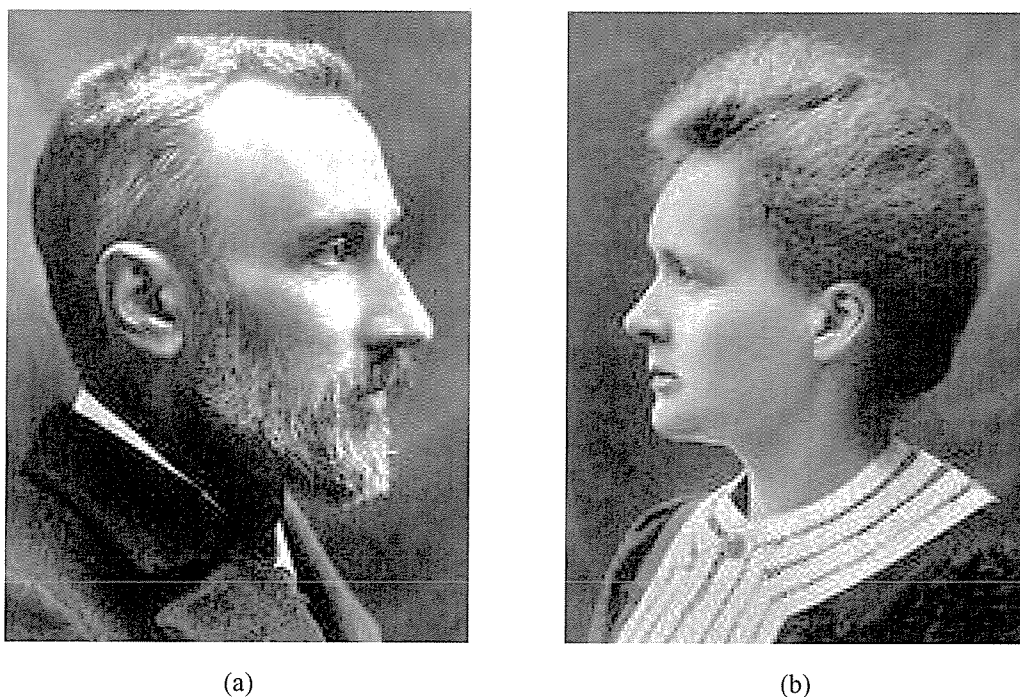

(a)   (b)

FIGURE 6-7   Pierre (a) and Marie Curie (b).

they produced evidence that there was a very active new material that reacted and behaved chemically, almost like pure barium. At that point, they suggested the name radium be used for this new element.

In order to provide proof that this element did exist, they would have to produce it in a sufficient amount and to determine such characteristics as its atomic weight. In order to do this, they would need a great amount of the pitchblende from which the radium could be extracted. They were able to obtain several tons of pitchblende and the intensive, laborious work of separating the radium from the pitchblende began. Obviously, it was very hard work and Marie Curie was quoted as saying, "Sometimes I had to spend a whole day stirring a boiling mass with a heavy iron rod nearly as big as myself. I would be broken with fatigue at day's end." She worked in a shed with an earth floor (see Figure 6-8), which had a glass roof and did not provide adequate protection against rain. In the summer, it was like a hothouse. And yet, history records that this is where they spent the best and happiest years of their lives. While they were conducting all these experiments, both Pierre and Marie were still teaching, so their days must have been very tiresome and long. Ultimately, from the several tons of pitchblende, they were able to isolate one decigram of almost pure radium fluoride and, at that time, determined the atomic weight of the radium to be 225. Marie presented this work in her doctoral thesis on June 25, 1903. As a result of the discovery of this new element, Marie Curie was awarded the Nobel Prize. She was the first woman to receive this award.

Working closely with radium, which is highly radioactive, and the gas radon, a by-product, took its toll. Pierre Curie had scarred and inflamed fingers from holding small glass tubes containing radium salts and solutions. He actually conducted medical tests on himself by wrapping a sample of the radium salts on his arm for up to ten hours and then evaluated the results of the exposure, which was in the form of a burn, day by day. After
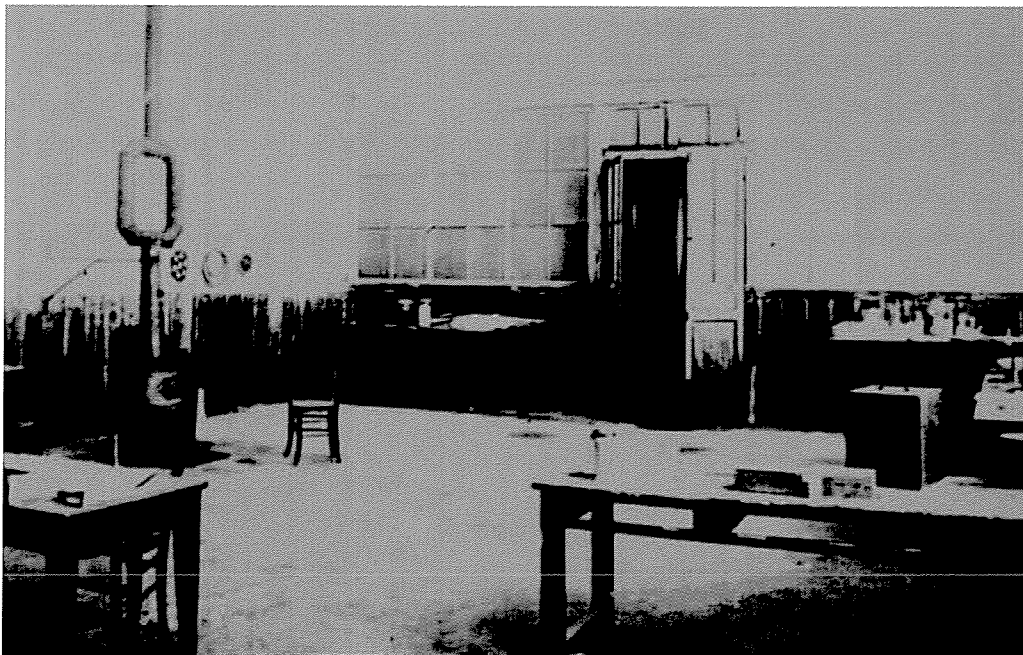

FIGURE 6-8   Laboratory where the Curies extracted radium from pitchblende. (Courtesy Charles J. Hellier.)

many days, a scar still remained and Pierre suggested that the radium might one day be used for the treatment of cancer. Fifty years after those days of experimentation, the presence of radioactivity was still observed in the laboratory where the Curies had worked so hard, requiring extensive clean-up.

Marie also had started to notice the effects of radiation exposure. Her fingers were cracked and scarred. Both Pierre and Marie were beginning to experience signs of fatigue. They obviously had no idea as to the effect of radiation on the human body at that time. Contrary to the expected, Pierre Curie did not die as a result of his exposure to radiation. He was killed when he was run over by a horse-drawn wagon in Paris on April 1906. This left Marie, who was only thirty-eight years old, alone with two daughters, aged nine and two at the time. Ultimately, Marie Curie would die of leukemia on July 4, 1934.

The work of the Curies marked the beginning of many other developments that would ultimately lead to the radioactive sources that are primarily used in industrial radiography today, namely Iridium 192 and Cobalt 60. The scientific community owes much to the Curies for their early sacrificial work, especially considering the damage that they personally suffered as a result of early exposure to radium.

Before the Curies began their work in isolating and identifying radium, the scientist Becquerel discovered that certain radiations were given off by uranium ore. He was responsible, in some respects, for directing and motivating the Curies to begin their work with radium. Another key scientist from England, Rutherford, was one of the scientists who identified the radiation emitted by certain radioactive elements. He also developed the theory that elements had isotopes and was responsible for identifying the existence of the neutron.

With the advent of nuclear reactors capable of generating high neutron intensities, the possibility of producing artificial isotopes became a reality. Iridium 191 and cobalt 59, both elements existing in nature, are quite stable. When exposed to thermal neutrons, the stable isotopes capture a thermal or slow neutron, becoming one unit heavier in mass. With the addition of this neutron, the iridium 191 becomes iridium 192 and cobalt 59 becomes cobalt 60. Both isotopes are unstable and therefore radioactive. More details about these two artificially produced radioactive isotopes will be presented in Section II. Other key developments in the area of radioactive isotopes involve the equipment used to encapsulate the radioactive isotopes and the projectors or "cameras" that store the isotopes, and from which they are operated.

II. THEORY AND PRINCIPLES

There are many excellent references that contain in-depth information regarding the principles of radiation and radiography. It is not the intent of this chapter to cover principles and theory in great depth but to provide the reader with an understanding of the basics, so that the entire process of producing radiographs with a radiation source will be comprehended. Whether the radiation is emitted from an x-ray tube or a gamma ray source, there are some essential components that apply to the process of radiographic testing.

The first component is the source of radiation. x-Rays emanate from an x-ray tube and gamma rays are emitted by a radioactive isotope. The second component is the test specimen that is to be examined. The third includes the development of the technique. The fourth involves the taking of the radiograph and the processing of the film. The final component, which is extremely critical, is the interpretation of the radiographic image.

Characteristics of Radiation

There are certain unique characteristics relative to radiation that must be understood in order to realize the physics and variables involved with producing a radiograph with the use of a radiation source. These characteristics apply to both x-radiation and gamma radiation. Recall that the only difference between x- and gamma radiation is their origin. x-Rays are produced by an x-ray tube and gamma rays come from a radioactive source that is disintegrating. The following characteristics apply to the radiation that will be used in the nondestructive examination of materials.

1. Radiation is Absorbed and Scattered by Material

There are four common absorption processes that influence the amount of radiation that passes through a part. The four absorption processes are:

1. Photoelectric effect

2. Rayleigh scattering

3. Compton scattering

4. Pair production

The *photoelectric effect* is that process in which a photon of low radiation energy (less than 500 kV) transfers all of its energy to an electron in some shell of the material atom. The energy may simply move an electron from one shell to another, or if there is energy above that required to interact with the orbital electron in the material, it will impart kinetic energy and the electron will be ejected from the atom.

Another name for *Rayleigh scattering* is "coherent scattering" and it is a direct interaction between the photon and the orbital electrons in the atom of the material. However, in this case the photon is deflected without any change or reduction of the kinetic energy of the photon or of the energy of the material atoms. In this process, there are no electrons released from the atom. It is estimated that Rayleigh scattering accounts for no more than about 20% of the total attenuation.

Compton scattering is a direct interaction between photons in the 0.1–3.0 MeV energy range and an orbital electron. In this case, when the electron is ejected from the material atom, only a portion of the kinetic energy of the photon is used. The photon then scatters in a different direction than the direction from which it came and actually emerges with a reduced energy and, therefore, a lower wavelength. Compton scattering varies with the atomic number of the material and varies, roughly, inversely with the energy of the photon.
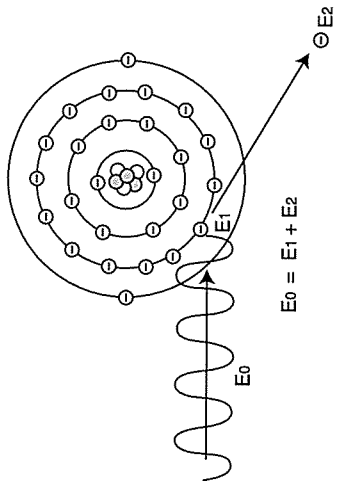
Pair production is an attenuation process that results in the creation of two 0.51 MeV photons (as a result of annihilation of the electron-positive pair) of scattered radiation for each high-energy incident photon that is at or above an energy of 1.02 MeV. The two 0.51 MeV photons travel in different directions, causing the production of electromagnetic radiation through interaction with other material particles. Energies exceeding 1.02 MeV result in additional kinetic energy being applied to the pair of particles.

These four forms of attenuation or absorption are depicted in Figure 6-9.

Total absorption, therefore, is the combined sums of the four different types of absorption.

2. Radiation Penetrates

The variables relating to the penetration of the radiation can be expressed with the term "half-value layer." The half-value layer is defined as the thickness of a specific material that will reduce the radiation intensity to one-half of that entering the part. If the initial ra-

6.12

E_2

E_1

$E_0 = E_1 + E_2$

E_0

a) Photoelectric Effect

E_2

E_1

$E_0 = E_1 + E_2$

E_0

E_3

c) Compton Scattering

E_0

E_0
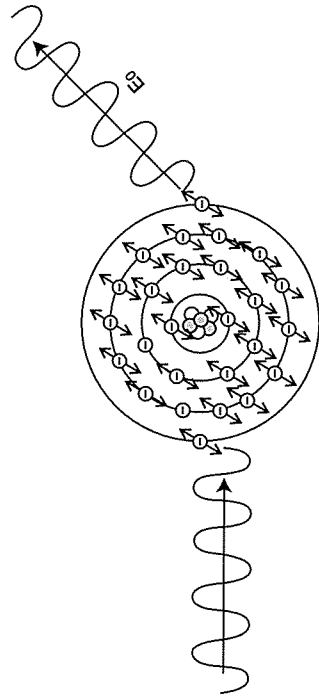
b) Rayleigh or Coherent Scattering

Annihilation Radiation

0.51 MeV

0.51 MeV

Positron

Electron

E_1
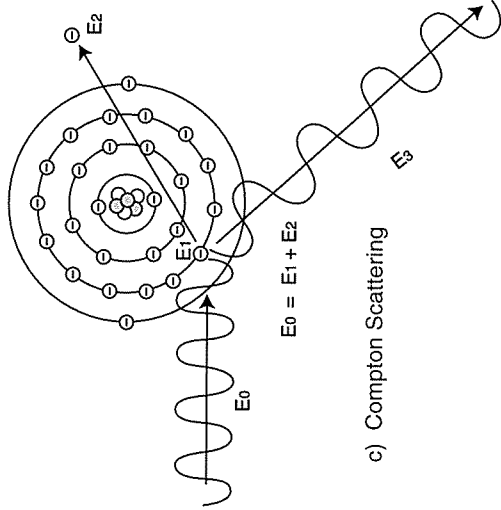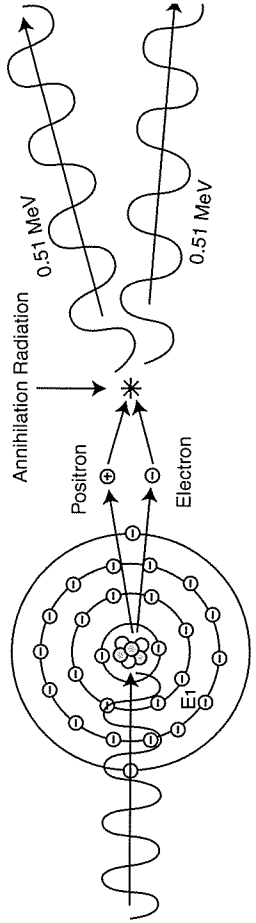
d) Pair Production

FIGURE 6-9 Forms of scatter.

6.13

diation intensity is 100 roentgens (100 R), a material that is exactly one half-value layer will reduce that 100 R to 50 R. Another half-value layer thickness will reduce that 50 R to 25 R, and so on. If this is carried forward, the radiation never reaches zero. Another term used is the "tenth-value layer." The same principle as the half-value layer applies, except that the thickness is somewhat greater and reduces the initial radiation to one-tenth on the opposite side. The factors involved with these half- and tenth-value layers are:

*   *Energy.* The higher the energy, the thicker the half- or tenth-value layers. This is supported by the fact that the higher energy radiation produces shorter wavelength radiation, resulting in better penetration. The half- and tenth-value layers are especially useful for calculating the thickness of shielding when designing an enclosure or room for radiography. (See Table 6-1 for examples of half and tenth-value layers).

*   *Material type.* The greater the material density, the thinner the half-value layer. Material that is low in density, such as aluminum or titanium, will allow more radiation to pass through, and there will be less absorption and scattering. Materials with higher density, such as steel and lead, provide a much greater chance of interaction because of their higher atomic number. With higher-density materials there will be more absorption and the half-value layer thickness will be considerably less than with the lower-density materials.

*   *Thickness.* As mentioned, the half-value layer thickness is specific for a given material and energy. As the thickness of the material increases, the amount of absorption and scatter increases and the amount of radiation that passes through that thickness.

Figure 6-10 illustrates the half-value layer principle, using two different energies with the same test specimen. When there are discontinuities present in the material, the density through the cross section in that area of the test material will also vary, thereby affecting the amount of radiation that passes through the part. It is for this reason that radiography is so effective for the detection of discontinuities, especially those that result in the reduc-

TABLE 6-1   Half- and Tenth-Value Layers

x-ray (kV)	Half-value Lead (inches)	Half-value Concrete (inches)	Tenth-value Lead (inches)	Tenth-value Concrete (inches)	Half-value x-ray	Half-value Steel (inches)
50	0.002	0.2	0.007	0.66	120 kV	0.10
70	0.007	0.5	0.023	1.65	150 kV	0.14
100	0.009	0.7	0.028	2.31	200 kV	0.20
125	0.011	0.8	0.035	2.64	250 kV	0.25
150	0.012	0.9	0.039	2.79	400 kV	0.35
200	0.020	1.0	0.065	3.30	1 MeV	0.60
250	0.032	1.1	0.104	3.63	2 MeV	0.80
300	0.059	1.2	0.195	3.96	4 MeV	1.00
400	0.087	1.3	0.286	4.29	6 MeV	1.15
1000	0.315	1.8	1.04	5.94	10 MeV	1.25
2000	0.393	2.45	1.299	8.60	16 MeV+	1.30
Isotopes						
Iridium 192	0.190	1.9	0.640	6.20		0.60
Cesium 137	0.250	2.1	0.840	7.10		0.68
Cobalt 60	0.490	2.6	1.620	8.60		0.87

Low Energy (eV)
100 R

1 HVL - 50 R
2 HVL - 25 R
3 HVL - 12.5 R
4 HVL - 6.25 R

6.25 R   25 R

1 HVL - 50 R
2 HVL - 25 R

High Energy (eV)
100 R

1 HVL - 50 R
2 HVL - 25 R
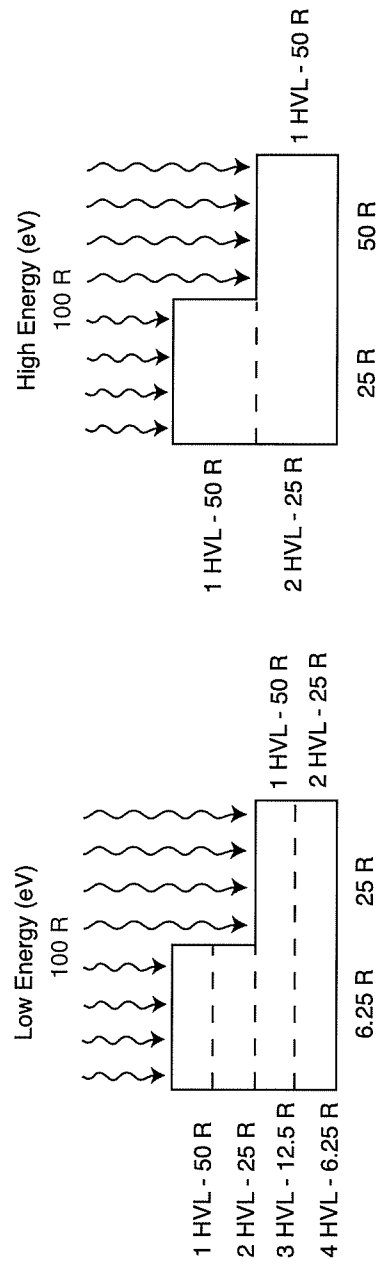
25 R   50 R

1 HVL - 50 R

FIGURE 6-10   Half-value layers.

tion of material cross section. The densities of the different discontinuities vary greatly from the base material. If, for example, a weld or casting contains gas pores or other void-type discontinuities, the radiation will pass through these areas with relative ease, creating a higher exposure effect on the radiographic film, resulting in a darker region on the finished radiograph.

3. Radiation Travels in Straight Lines and at the Speed of Light
The speed of light is 186,300 miles per second or 299,800 km per second.

4. Radiation Exhibits Energy
On the electromagnetic spectrum, the wavelengths of x- and gamma rays are much shorter than that of visible light. Recall that as the radiation energy increases, shorter wavelengths are produced that provide greater penetration through the material being examined.

5. Radiation Ionizes Matter
Ionization is a change in the electrical nature or characteristics of matter. Electrons are displaced or knocked out of orbit, thereby changing the electrical balance. This, coincidentally, is what causes the greatest concern to humans. When radiation passes through living tissue, the cells are affected—electrically changed—and damage will result.

6. Radiation is Not Particulate
Radiation has no mass, and even though x- and gamma rays behave like particles, they are actually weightless. To describe the effect of radiation as it interacts with matter, the radiation is sometimes referred to as photons, which is another way of saying high-speed energy traveling at the speed of light that behaves like particles; but in fact, there are no particles in x- or gamma radiation.

7. Radiation Has No Electrical Charge
X- and gamma radiation are not affected by either strong electrical or magnetic fields.

8. x- and Gamma Radiation Cannot be Focused
If x- or gamma radiation is directed toward a glass lens, the radiation would not focus like light does. In fact, the radiation passing through that lens would be absorbed to a greater extent in the thicker portion of the lens and more radiation would pass through the thinner regions of the lens.

9. Humans Cannot Sense x- or Gamma Radiation
Radiation cannot be seen, tasted, or felt. It has no odor and if humans are subjected to radiation exposure, the effects are not realized for a period of time. In other words, the body goes through a latent period before the harmful effects of the radiation exposure are evident.

10. Radiation Causes Fluorescence in Some Materials
Some minerals and salts will fluoresce when subjected to radiation. Fluoroscopy utilizes a fluorescent screen that converts some of the radiation to light. When used in radiography, the light that is emitted from the fluorescent screen creates a much higher exposure effect on the film that is adjacent to it, thereby significantly reducing exposure.

11. Intensity of Radiation
Radiation is expressed in roentgens per hour (R/hr), roentgens per minute (R/min), or milliroentgens per hour (mR/hr). The intensity decreases with distance. This is a function of

the inverse square law, which states that the intensity of the radiation varies inversely with the square of the distance. As the distance from the radiation source is doubled, the intensity is decreased to one-fourth. This will be discussed in more detail in Section IV, Variables.

12. Radiation Produces Chemical Changes in Exposed Film
The film's emulsion is chemically changed through ionization as radiation interacts with it. If it weren't for this characteristic, it would not be possible to produce a radiographic image on film.

Principles of x-Radiography

X-rays are produced in a vacuum tube when high-speed electrons, which are negatively charged, are attracted by a positive potential in the anode and collide with a target material. The electrons are produced when a filament, usually tungsten, is heated to incandescence. The resulting electrons "boil" off and collide with the target material in the anode.

A higher current applied to the filament will result in a greater number of electrons and, therefore, higher radiation intensity. The energy of the radiation is a function of the applied voltage, or kilovoltage to the anode. This causes an increase in velocity of the electrons and, as higher voltage is applied, higher-energy radiation results. The energy of the radiation is its single most important characteristic. It is directly related to the wavelength and to the ability of that radiation to penetrate. The higher the energy, the shorter the wavelength, and the greater the penetration. The target in the anode in most x-ray tubes is typically made of tungsten. Tungsten has a high atomic number, which makes it an ideal material to interact with the high-speed electrons. It also has a high melting point, 5880 °F (3249 °C), which is essential since the target is subject to high temperatures as a result of electron impingement. Since almost all of the kinetic energy from the electrons is transformed or converted into heat, the anode must have the capability of dissipating that heat. In fact, 97–99% of the energy conversion results in the generation of heat and approximately 1–3% is converted to x-rays.

In summary, as the energy is increased, radiation with shorter wavelengths results in greater penetration. On the cathode side of the tube, which contains the filament and a focusing cup, the number of electrons increases with an increase of applied milliamperes, which results in an increase in intensity of the radiation. Figure 6-11a illustrates several typical x-ray tubes and a cross-sectional sketch of a tube can be found in Figure 6-11b.

The target size in the anode is very important, since this affects the image sharpness of the object being radiographed. This is directly related to the definition of the final image. The smaller the target or radiation source, the sharper the resultant radiographic image.

As mentioned above, the energy of the radiation is expressed in voltage or kilovoltage, with one electron volt being the amount of voltage that is necessary to energize and displace one electron. The common expression for x-ray energy is in units of kiloelectron volts (keV), but this is shorted to the kV. A kilovolt is equal to one thousand volts. The majority of industrial radiographic techniques use an energy range from about 100 kV to 400 kV. The intensity of the radiation is expressed in milliamperes (mA) (one milliampere = one one-thousandth of an ampere). In a general way, the energy of the radiation can also be described as the "quality" of the radiation and the intensity (in milliamperes) as the "quantity." Energies above the 400 kV range are considered to be high-energy x-radiation. Equipment producing high-energy x-rays include:

- X-ray tubes with a resonance-type transformer
- Betatrons
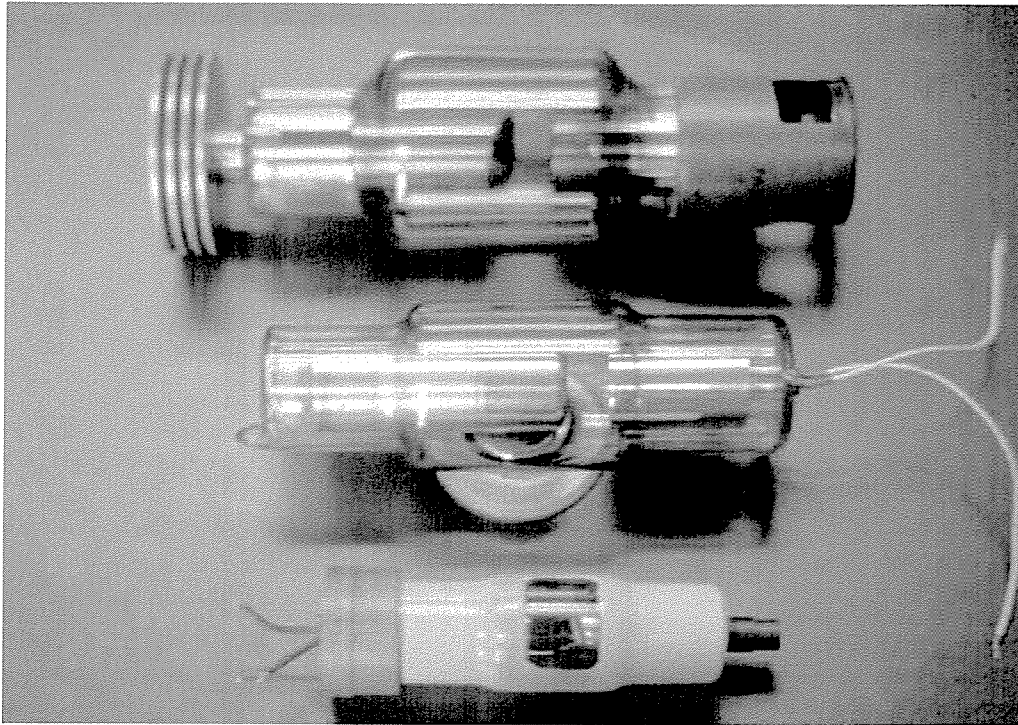
(a)
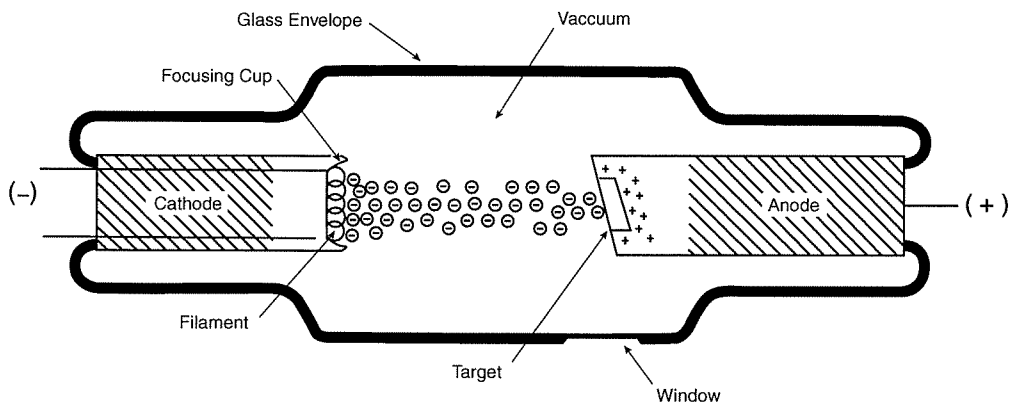
(b)

FIGURE 6-11 x-Ray tubes (a) and sketch of cross section sketch (b). (Courtesy Charles J. Hellier.)

- Linear accelerators
- Van de Graaff generators

The older of these high-energy x-ray units are the *resonant transformer* x-ray units, which were developed in the 1940s. Their energy range is from 250kV to 4 MeV. The x-ray tube is symmetrically located within the transformer. The electrons are accelerated to very

high velocities by electrodes and focused by a coil as they enter an extension chamber. It is possible to penetrate up to 8″ of steel with this equipment.

Betatrons accelerate the electrons in a circular path by using an alternating magnetic field, and typically produce energies in the range of 10–30 MeV. The tube is doughnut-shaped and the electrons increase their velocity with each orbit until they reach a very high energy. They are eventually guided from their circular path to a target and x-rays are generated.

Linear accelerators produce high-velocity electrons by the use of radio frequency energy coupled to a waveguide and have energies from 5 up to about 25 MeV. These systems contains an electron gun, an accelerator, and a waveguide. The electrons are accelerated along the waveguide by an electrical field.

The *Van de Graaff generators,* also known as electrostatic generators, produce x-ray energies from about 500 kV to as high as 6 MeV. The systems consist of high-speed belts that travel about 4000 feet/minute and build up electrical charges that are carried to a high-voltage terminal. This results in a high electrostatic charge that is used to accelerate the electrons through the tube to the target.

Table 6-2 contains a list of the different energy levels produced by x-ray sources and approximate thickness penetration ranges that would be typical for steel.

Principles of Gamma Radiography

As mentioned earlier, the two most commonly used gamma ray sources in industrial radiography are iridium 192 and cobalt 60. Other sources that have been used to a limited extent in the industrial area are thulium 170 and cesium 137, and of course, radium 226. Table 6-3 contains a summary of these sources with characteristics and data regarding their half-life, energy, and penetration capabilities in steel.

TABLE 6-2 Radiation Energies and Practical
Thickness Ranges

x-Ray energy	Thickness range in steel
100 kV	up to 0.100″
150 kV	up to 0.250″
200 kV	0.250″ to 0.500″
250 kV	0.330″ to 0.850″
300 kV	0.350″ to 2.00″
400 kV	0.500″ to 3.00″
1.0 meV	0.800″ to 4.0″
2.0 meV	1.00″ to 5.0″
6.0–10.0 meV	3.00″ to 16.0″
10.0–20.0 meV	10.0″ to 24.0″
15.0–30.0 meV	12.0″ to 30.0″
Sources	
Indium 192	0.500″ to 1.50″
Cesium 137	0.650″ to 2.0
Cobalt 60	1.0″ to 5.0″

TABLE 6-3 Gamma Ray Source Data

Source	Symbol	Atomic number	Atomic weight	Isotope	Half-life	Energy	Emissivity
Cesium	Cs	55	132.91	137	30 years	0.66 meV	4.2 R/C hr @ 1 ft
Cobalt	Co	27	58.9	60	5.3 years	1.17 meV 1.33 meV	14.5 R/C hr @ 1 ft
Iridium	Ir	77	192.2	192	75 days	0.61 meV 0.21 meV	5.9 R/C hr @ 1 ft
Radium	Ra	88	226	226	1,602 yrs.	2.2 meV 0.24 meV	9.0 R/C hr @ 1 ft

There are certain characteristics regarding radioactive isotopes that should be understood. The first is energy. Energy of a radioactive isotope is unique to that particular, specific radioactive material. Some of these radioactive isotopes actually give off a spectrum, or a number of unique energy bundles. For sources, energy never changes for a given radioactive isotope. Radioactive isotopes decay with time. With the decay comes reduction in activity or quantity. The radioactive half-life is the amount of time that it takes for a specific radioactive isotope to decay or be reduced to one half of its original activity. Refer to Table 6-3 for examples of isotope half-lives. Recall that with an x-ray source, the intensity or quantity of radiation is a function of the applied milliamperes. With a radioactive isotope, the activity, or the amount of radiation that is given off by a source, is expressed in curies or becquerels. One curie is equal to 3.7×10^{10} disintegrations per second and one becquerel is equal to one disintegration per second.

One way to understand disintegration is to visualize the atom of a radioactive isotope as having one neutron too many in the nucleus. In time, the nucleus literally breaks apart or disintegrates. In that act of disintegration, a bundle of radiation with a unique energy is given off. In addition, other by-product materials are created. When there are 37 billion of these disintegrations occurring in a unit time of one second, there is one curie of that radioactive isotope. Again, the half-life is the time it takes for the source activity to be reduced to one half of what it was originally. So, if an iridium 192 source is used when new and the activity is 100 curies, at the end of a half-life, which for iridium is approximately 75 days, the activity would be reduced to one-half, or 50 curies. If the source goes through another half-life, it will reduce to 25 curies; another half-life to 12½ curies; and so on. In other words, it does not matter how many half-lives the source goes through; it never reaches absolute zero. For cobalt 60, the half-life is 5.3 years. Its energy is higher than iridium. For iridium 192, there are seven principal energy packets produced during the disintegration process ranging from just over 0.2 to about 0.6 MeV (approximately 200 to 600 kV). With cobalt 60, there are two discrete gamma energies (sometimes expressed as photon energies), 1.17 and 1.33 MeV. With this higher energy, it is possible to examine materials that are somewhat thicker or denser. Another factor to consider when using radioactive isotopes is their specific activity. The specific activity of a source is expressed in curies per gram. The greater the number of curies for a given physical size, the higher the specific activity. The major benefit of a high specific activity source is the improved definition that will result from the high activity (curies) and small physical size.

III. RADIOGRAPHIC EQUIPMENT
AND ACCESSORIES

x-Ray Equipment

In general, industrial x-ray equipment can be categorized by energy groups. Those x-ray units that produce energies up to about 125 kV are considered low energy; from 125 up to 400 kV, medium energy; and those systems that produce radiation energies above 400 kV are considered high energy. As mentioned above, the majority of examinations performed today are done in the medium energy range, from 125 kV up to about 400 kV. It is the most widely used for a broad range of applications and this chapter will focus primarily on that energy range.

When energy such as 300 kV is mentioned, it usually denotes the maximum energy output for that particular unit. For any given x-ray unit, the energy can usually be varied from a low energy up to the maximum energy for which the tube is rated. As discussed, x-rays are produced in a vacuum tube, by heating a filament that boils off negatively charged electrons. They are attracted to a positively charged anode, where there are very complex collisions and interactions that produce mainly heat, with only a small amount of the energy converted into x-rays.

Industrial x-ray systems come in different sizes, shapes, and duty cycles. There are x-ray units in cabinets that are ideal for radiographing smaller parts made of low-density material or with limited thickness. These cabinet units typically produce lower energies, usually up to about 150 kV, such as the one in Figure 6-12.

There are x-ray units that are portable, with gas filled tube heads. These are light-weight and are relatively easy to transport for field radiography. Many of the stationary units are self-rectified and continuous duty, such as the *constant potential units,* which can operate continuously for long periods of time. The gas filled tubes operate with partial duty cycles, such as 50%. This means that the x-ray tube can operate for a specific time with an equal amount of time permitted for cool-down before the next exposure. Figure 6-13 illustrates a 300 kV constant potential x-ray system.

Gamma Ray Equipment

As mentioned above, the first gamma ray source used in industrial radiography was radium. Figure 6-14 illustrates the "fish pole" technique in which the radium was transported inside a capsule on the end of a line that was attached to a fishing pole. The radiographer would place the "hook" on the end of the line through an eyelet on the capsule, then remove it from the lead storage pig and carry it to the area where the object to be radiographed was located, as illustrated.

The major component in a gamma ray system is the exposure device, such as the one depicted in Figure 6-15. These exposure devices have shields that contain an S-tube in which the iridium source is maintained inside a stainless steel capsule and is securely locked into place when not in use. The shield material is usually made from depleted uranium, unlike earlier gamma cameras that used shielding made of cast lead. Depleted uranium is slightly heavier than lead and has unusually good radiation shielding capabilities. A gamma ray set-up is illustrated in Figure 6-16, showing the camera with the source drive control, the source tube that is positioned in a source stand just above the pipe weld that will be radiographed. The radiographer "cranks" out the source to the extended position. The predetermined exposure time is allowed to elapse and then the source is cranked back into the camera.
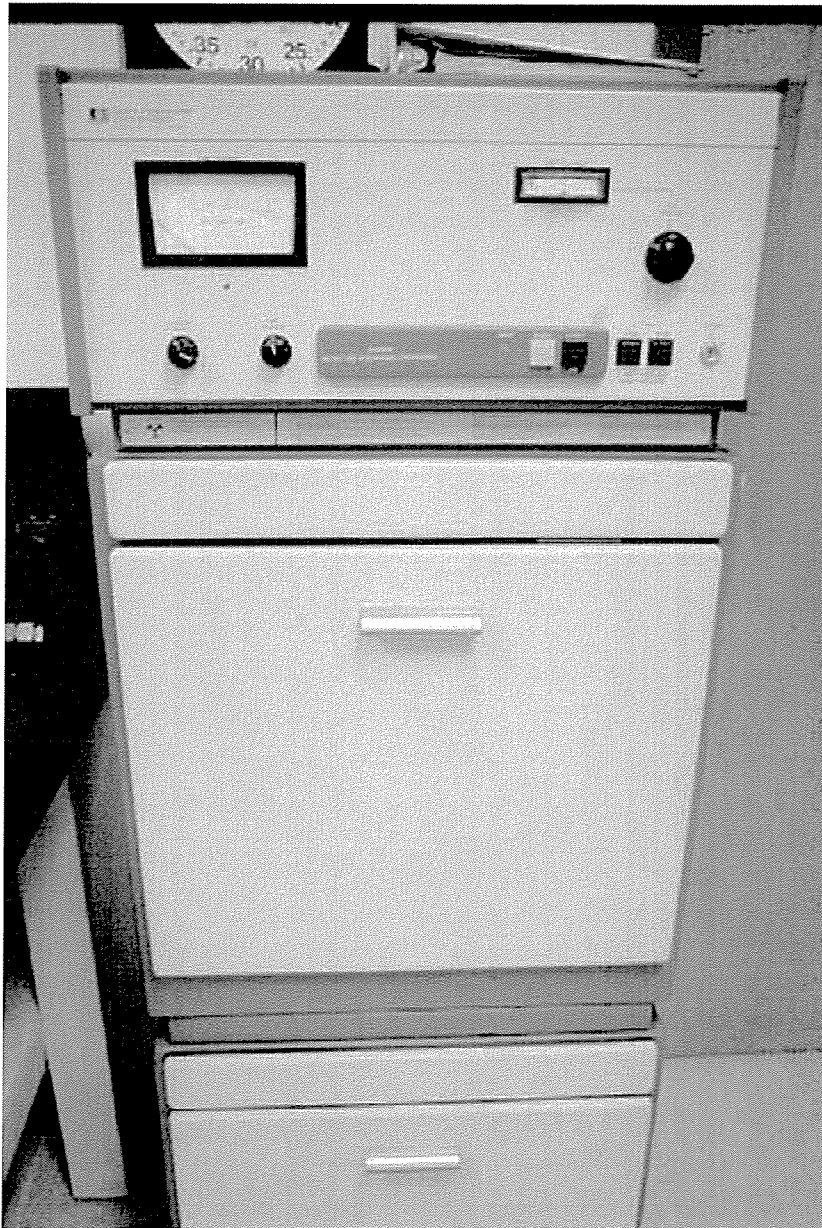
FIGURE 6-12 x-Ray cabinet. (Courtesy Charles J. Hellier.)

Accessories
There are many different accessories that are used in conjunction with taking radiographs. These accessories include, but are not limited to:

* Film and cassettes
* Lead screens
* Lead numbers and letters
* Penetrameters (image quality indicators)
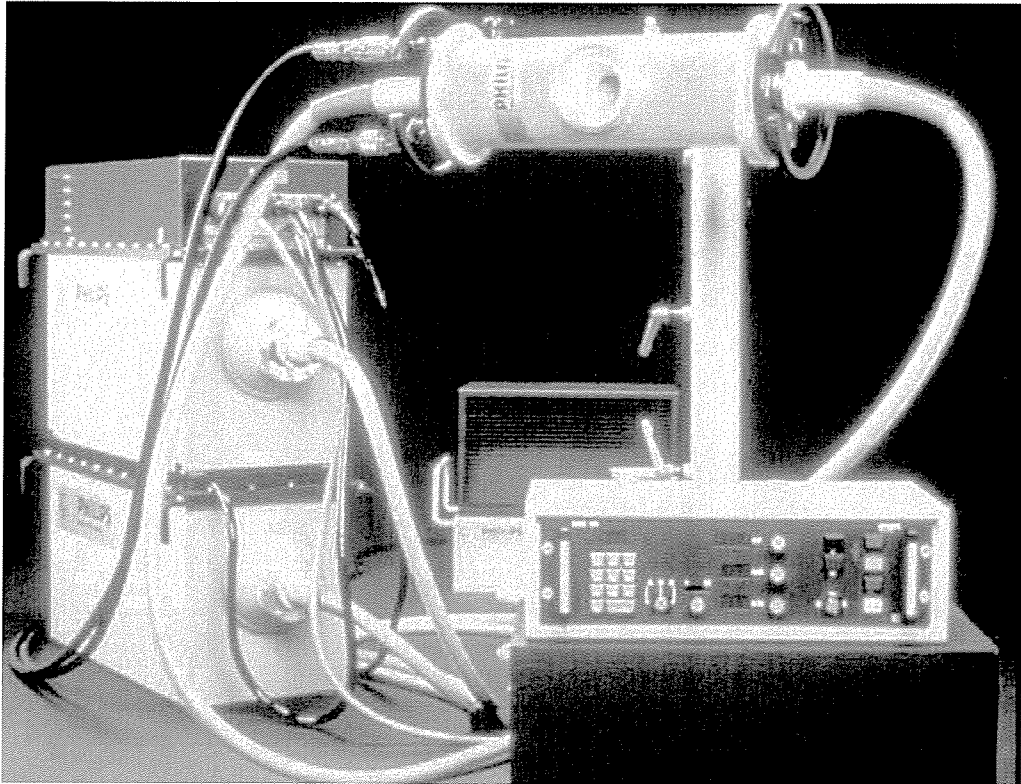
FIGURE 6-13   300 kV x-ray system. (Courtesy Charles J. Hellier.)

FIGURE 6-14   The "fishpole" technique. (Courtesy Charles J. Hellier.)
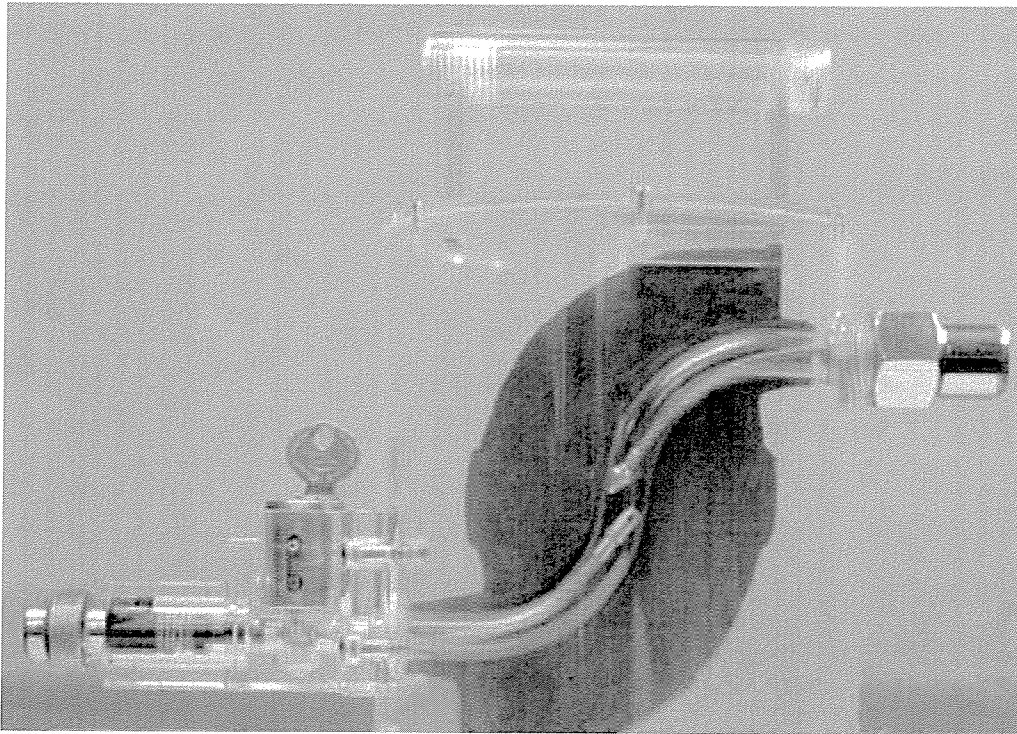
(a)
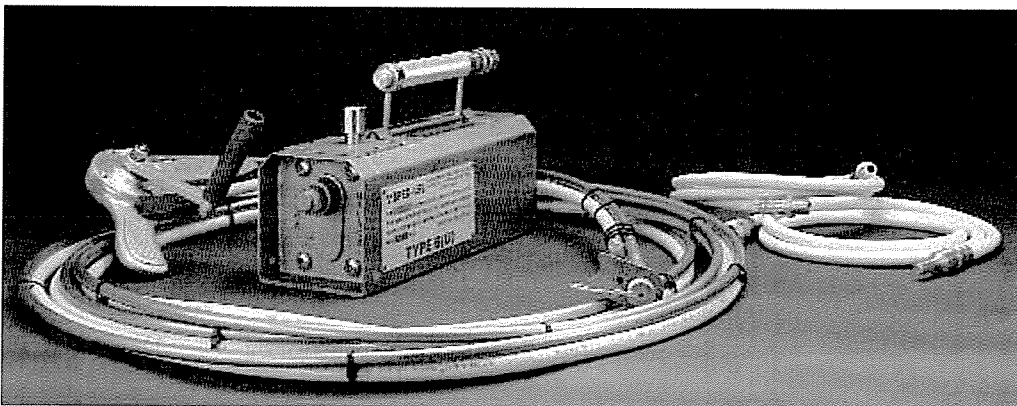
(b)

FIGURE 6-15 Gamma ray camera cutaway (a) and actual camera system (b). [(a) Courtesy Charles J. Hellier; (b) used with permission of Source Production and Equipment Company.]

- Densitometers
- High-intensity film illuminators
- Processing equipment (manual or automatic)
- Film hangers (for manual processing)
- Collimators (especially for use with radioactive sources)

FIGURE 6-16 Gamma ray exposure setup. (Courtesy Charles J. Hellier.)

IV. VARIABLES

Of all the nondestructive testing methods described in this book, radiography certainly has the most variables. These variables include:

1. Energy*
2. Exposure time
3. mA (x-ray) or curies (gamma ray)
4. Material type and density
5. Material thickness
6. Type of film
7. Screens used
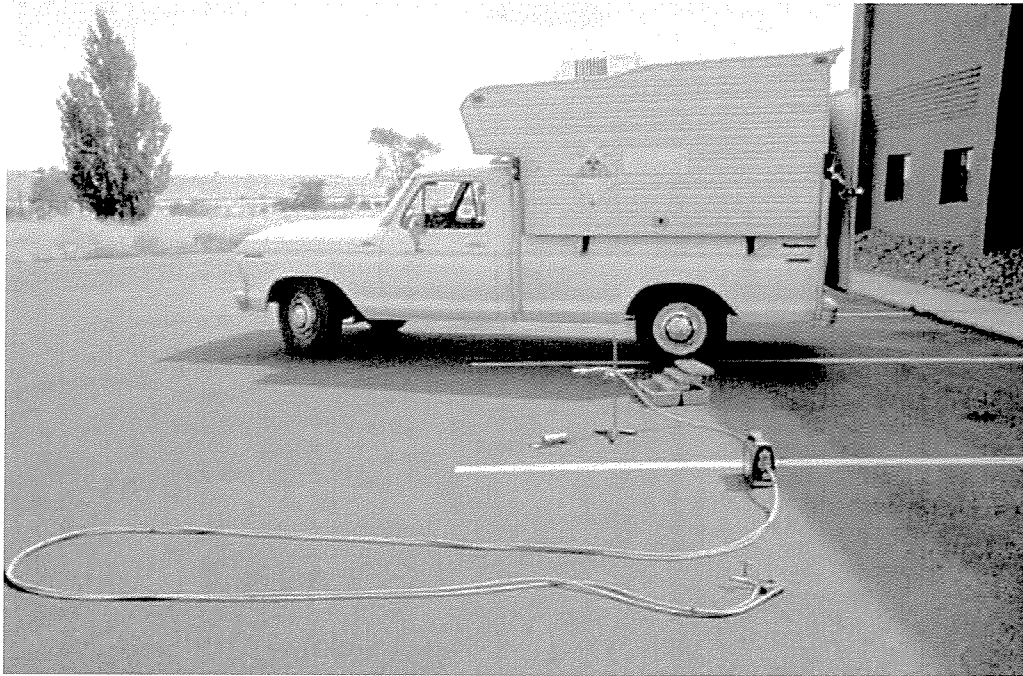8. Film processing (procedure development time and temperature, etc.)
9. Film density
10. Distance from the radiation source to the object
11. Distance from the object to the film
12. Physical size of the target (x-ray) or source (gamma ray)

---

*Recall that energy is a function of the applied kilovoltage for x-rays and can be varied up to the maximum for a specific x-ray tube. The energy is fixed with a specific gamma ray source. Also recall that energy is the most important variable, since it affects the contrast (to be discussed later), and determines the thickness of material that can be effectively examined. It also influences the amount of scatter, which affects the definition or sharpness of the image.

In order to control these variables so that the benefits can be maximized for each one, a technique chart should be used. Unfortunately, there are still many radiographs taken by the "trial and error" technique. Some radiographers will take three, four, or more exposures using different techniques, then, after processing the film, will decide which image looks best. The best way to produce a high-quality radiograph every time is through the use of exposure charts. An example of an exposure for a 270 kV x-ray machine is illustrated in Figure 6-17. Notice that all of the variables are addressed in this chart. The use of this chart is quite simple. It can be easily understood by following a few logical steps. (*Note:* This chart is for demonstraion purposes only and will not necessarily work for other x-ray machines of similar energy ratings.)

Step #1. Verify the material type (steel in this case) and find its thickness on the horizontal axis.

Step #2. Project a straight line vertically from that thickness up to the top of the technique chart and notice that there are a number of energies that can be used. If the material were one inch thick, for example, the energies that could be used would range from 160 kV to a maximum of 270 kV. It would not be advisable to use the lowest energy, since the exposure time would be unusually long. If, for example, 160 kV were to be used, the exposure time would be 50 minutes if a tube current of 10 mA were used (30 M or 30 thousand milliampere seconds divided by 10 mA = 3000 seconds divided by 60 = 50 minutes). This is done by projecting a line horizontally from the thickness/kV intersect point to the vertical. The other problem with this technique is that a greater amount of scatter will result due to the longer wavelengths that occur at the lower energies coupled with the long exposure time. Scatter reduces the clarity or sharpness of the image. If the highest energy were used (270 kV), the exposure time would be 22 seconds (220 milliampere seconds divided by 10 mA = 22 seconds). This would not be advisable, since high-energy techniques result in lower-contrast images. Contrast is the difference in density between two adjacent regions of the part, which are different in thickness or material density. So, it is not advisable to use the lowest or the highest kV based on the technique chart. The obvious choice would be to select energy somewhere in the middle. For this example, either 200 or 220 kV would be good choices.

Step #3. As explained in Step #2, once the energy is selected, a line is projected to the left vertical axis, where the exposure time and intensity are combined in units of milliampere seconds (mAs). Again, mA is the current applied to the filament that controls the quantity of radiation. Time, in this case in units of seconds, and mA are inversely proportional values. If, for example, a radiograph were taken with an exposure of 5 mA at 240 seconds (4 minutes), the exact same image would be produced if 10 mA were used for 120 seconds (2 minutes), a reduction in exposure time of 50%. In each case, there is an exposure time/intensity value of 1200 milliampere seconds (20 milliampere minutes). So, at the intersection of 1″ and the 200 kV curve, project over to the vertical axis, and the exposure time in milliampere seconds will be 1400 mAs (2 minutes 20 seconds), and at 220 kV, the exposure time would be about 650 mAs (1 minute 5 seconds). The exposure times were calculated using a tube current of 10 mA. Notice that with just an increase of 20 kV, there is virtually a 50% reduction in exposure time. The resultant image quality would be virtually the same using either of these kV settings.

A similar exposure chart for iridium 192 is illustrated in Figure 6-18. As with the x-ray technique chart, this is an example and may not provide exact results. Notice that there are no energy curves since energy is a fixed value for a given gamma ray source. In this technique chart, there are three different film types having different speeds. The way to establish the correct exposure time is similar to that of the x-ray technique chart. The first step (assuming the material is steel) is to project the material thickness vertically un-

The chart axes:
- Y-axis: Exposure (Milliampere Seconds), ranging from 100 to 100M
- X-axis: Steel Thickness-Inches, ranging from 0.5 to 3.0

Curves labeled: 80 kV, 100 kV, 120 kV, 140 kV, 160 kV, 180 kV, 200 kV, 220 kV, 240 kV, 260 kV, 270 kV

X-ray machine
Serial 1234
0.005 Lead screen front
0.010 Lead screen back

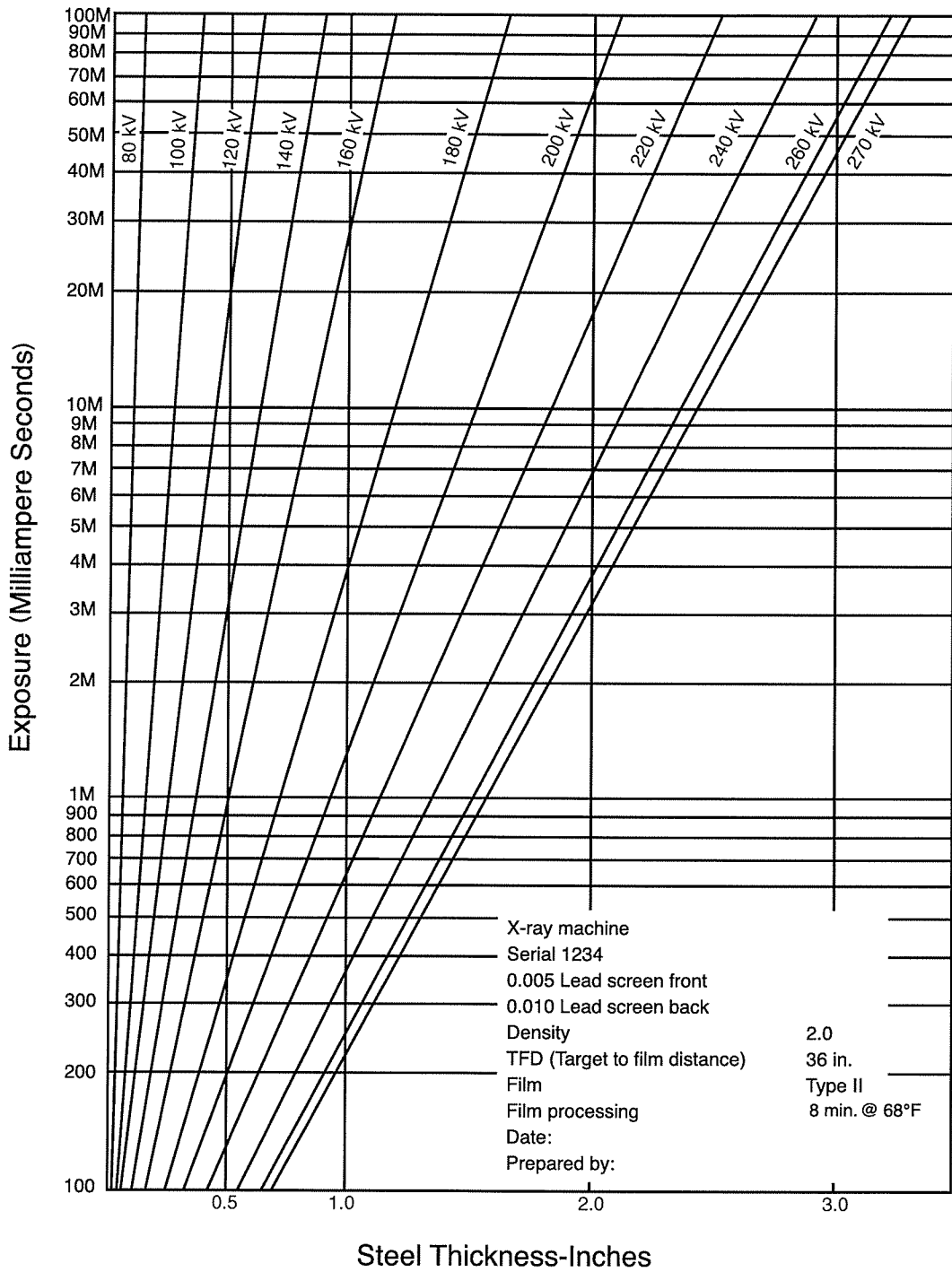|	
Density	2.0
TFD (Target to film distance)	36 in.
Film	Type II
Film processing	8 min. @ 68°F
Date:	
Prepared by:	

Steel Thickness-Inches
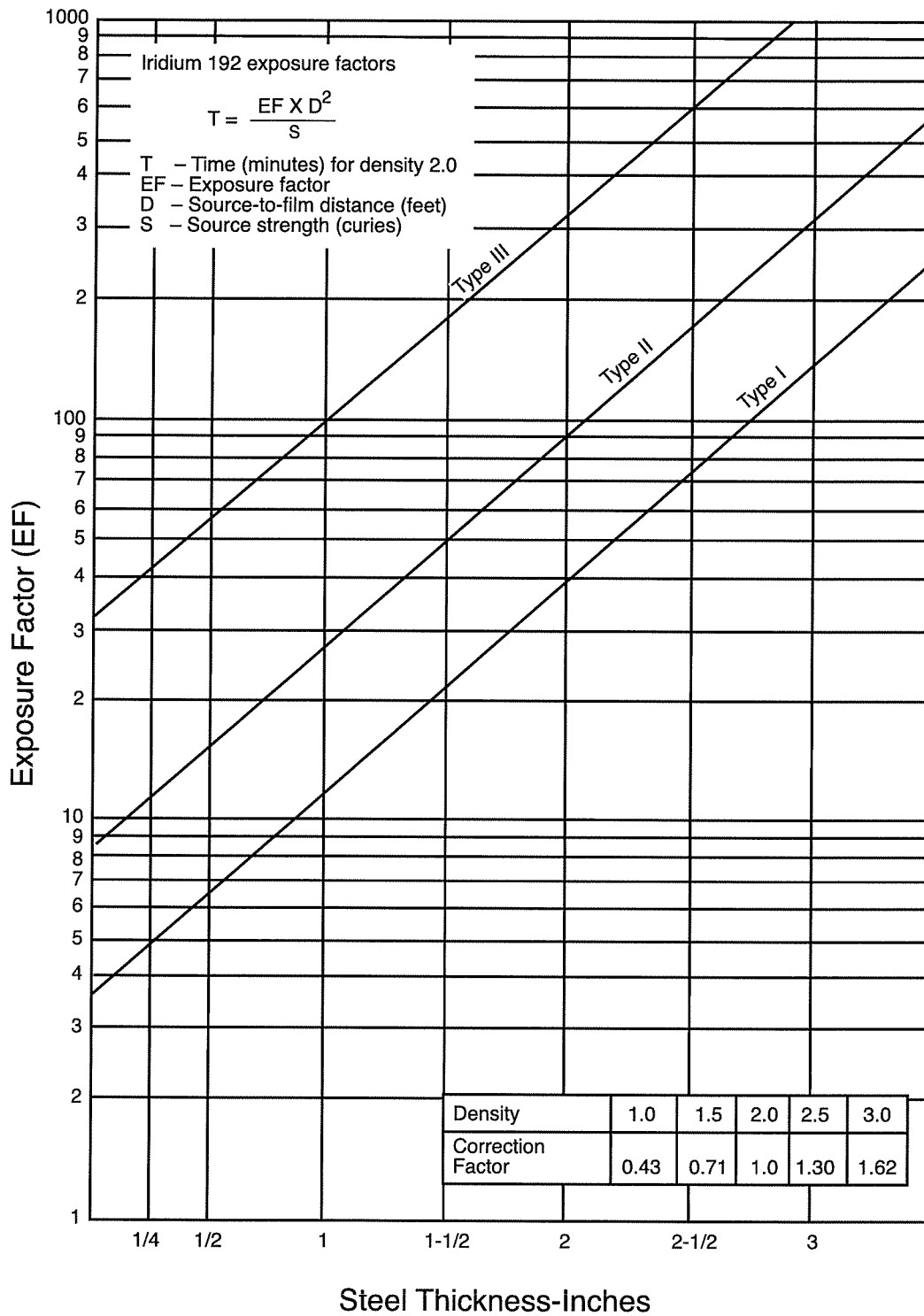
FIGURE 6-17   x-Ray technique chart.

FIGURE 6-18   Gamma ray technique chart.

til it intersects with the film type being used. Then draw a line horizontally to the vertical axis. From that axis, the exposure factor (EF) is determined. Using the equation at the top of the chart and knowing the number of curies of iridium 192, an exposure time in minutes can be easily calculated.

Example:
Thickness = 1.5″
Type II film will be used
D (source to film distance) = 36″ or 3′
S = 60 curies
T = exposure time in minutes (for a film density of 2.0)

Projecting vertically up the chart, the point of intersection with the Type II film is then projected horizontally. The EF (exposure factor) is 50.

$$T = \frac{50 \times (3')^2}{60}$$

$$T = \frac{450}{60}$$

$$T = 7.5 \text{ minutes}$$

If the material to be examined is other than steel, exposure times can be easily calculated by using the radiographic equivalent factors (REFs). Some REFs are illustrated in Table 6-4. (*Note:* It should be mentioned that these factors are approximate but will be sufficient to enable a useable technique to be established.) In order to obtain an equivalent thickness of a material other than steel, the REF should be multiplied by the material thickness. The relevant answer will be the equivalent thickness of steel. Once this thickness is known, the technique chart can be used as if the material were steel.

Example:
Material is aluminum
Thickness = 5.0″
Energy to used is 220 kV

TABLE 6-4 Radiographic Equivalence Factors

	x-rays (kV)							Gamma rays		
	50	100	150	220	400	1000	2000	fr 192	CE-137	CO-60
Magnesium	0.6	0.6	0.05	0.08				0.22	0.22	0.22
Aluminum	1.0	1.0	0.12	0.18				0.34	0.34	0.34
Titanium		8.0	0.63	0.71	0.71	0.9	0.9	0.9	0.9	0.9
Steel		12.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper		18.0	1.6	1.4	1.4	1.1	1.1	1.1	1.1	1.1
Zinc			1.4	1.3	1.3	1.1	1.0	1.1	1.0	1.0
Brass			1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.0
Lead			14.0	12.0		5.0	2.5	4.0	3.2	2.3

Note: Aluminum is taken as the standard metal at 50 KV and 100 KV, and steel at the higher voltages and with gamma rays.

The REF obtained from the chart for aluminum at 220 kV is 0.18″. So:

$$\text{REF}_{\text{AL}} \times \text{material thickness} = \text{equivalent thickness in steel}$$

$$0.18 \times 5.0'' = 0.9''$$

Therefore, a technique for 0.9″ of steel from the technique chart can be used for the 5.0″ of aluminum.

In the event there is reason to use a film other than Type II, film characteristic curves (Figure 6-19) can help to determine the new exposure time. (*Note:* These characteristic curves are examples only. Film manufacturers can provide accurate curves that can be used to calculate precise correction values.) Notice that for gamma rays, the technique chart (Figure 6-13) has provisions for three different films.

Example:
If it is desired to obtain a radiograph with better definition, a change from the Type II film to a Type I would be appropriate. The 2.0 density (vertical axis) intersects with the Type II film at 1.9 (horizontal axis), which is the log relative exposure. Continuing on the 2.0 film density line over to the Type I film will result in a log relative exposure of approximately 2.55 or a difference of 0.65 in the log relative exposure. The inverse log of 0.65 is 4.5 (rounded off). The new exposure time would be calculated by multiplying the correction factor of 4.5 by the original exposure time used to achieve the 2.0 film density. If the original exposure was 3 minutes, the new exposure time required to achieve a film density of 3.0 would be 13 minutes, 30 seconds.

This film characteristic curve approach can also allow a given density to be changed to any desired density. For example, on the technique chart for x-rays, the resultant film density will be 2.0. For many codes and specifications, a film density of 2.0 is the minimum permitted. It would be much more desirable to produce a radiograph with a higher density. Higher densities produce better radiographic contrast. So, in order to achieve a film density that is different than the one stipulated on the technique chart, the film characteristic curves can be used.

Example:
Using a Type II film, a density of 3.0 is desired instead of the 2.0 as indicated on the technique chart (Figure 6-19). As in the previous example, the log relative exposure for a Type II film with a density of 2.0 is 1.9. The 3.0 density intersects the Type II film at approximately 2.1. The difference between the 2.1 and 1.9 log relative exposures is 0.2. The inverse log of 0.2 equals 1.6 (rounded off). If the original exposure time were calculated from the technique chart to be 3 minutes (for the 2.0 density), that time would be multiplied by the correction factor of 1.6, for a new exposure time of 4.8 minutes. If all other variables are the same as with the original exposure, a film density of 3.0 will be achieved if the new exposure time of 4 minutes, 48 seconds is used. It should be noted that correction factors are included on the technique chart for iridium 192.

In addition, a specific type of film with one density can be changed directly to another film type with a different density using the same approach.

Example:
If the Type II film and the film density as indicated on the x-ray technique chart is to be changed to a different film (Type I for example, with a density of 2.5), it can be accomplished as in the previous examples. As seen, the Type II film with the 2.0 density has a log relative exposure of 1.9. The Type I film with a 2.5 density has a log relative exposure value of approximately 2.65. The difference in log relative exposures is 0.75 and the inverse log is about 5.6. Multiplying the original exposure time by the correc-
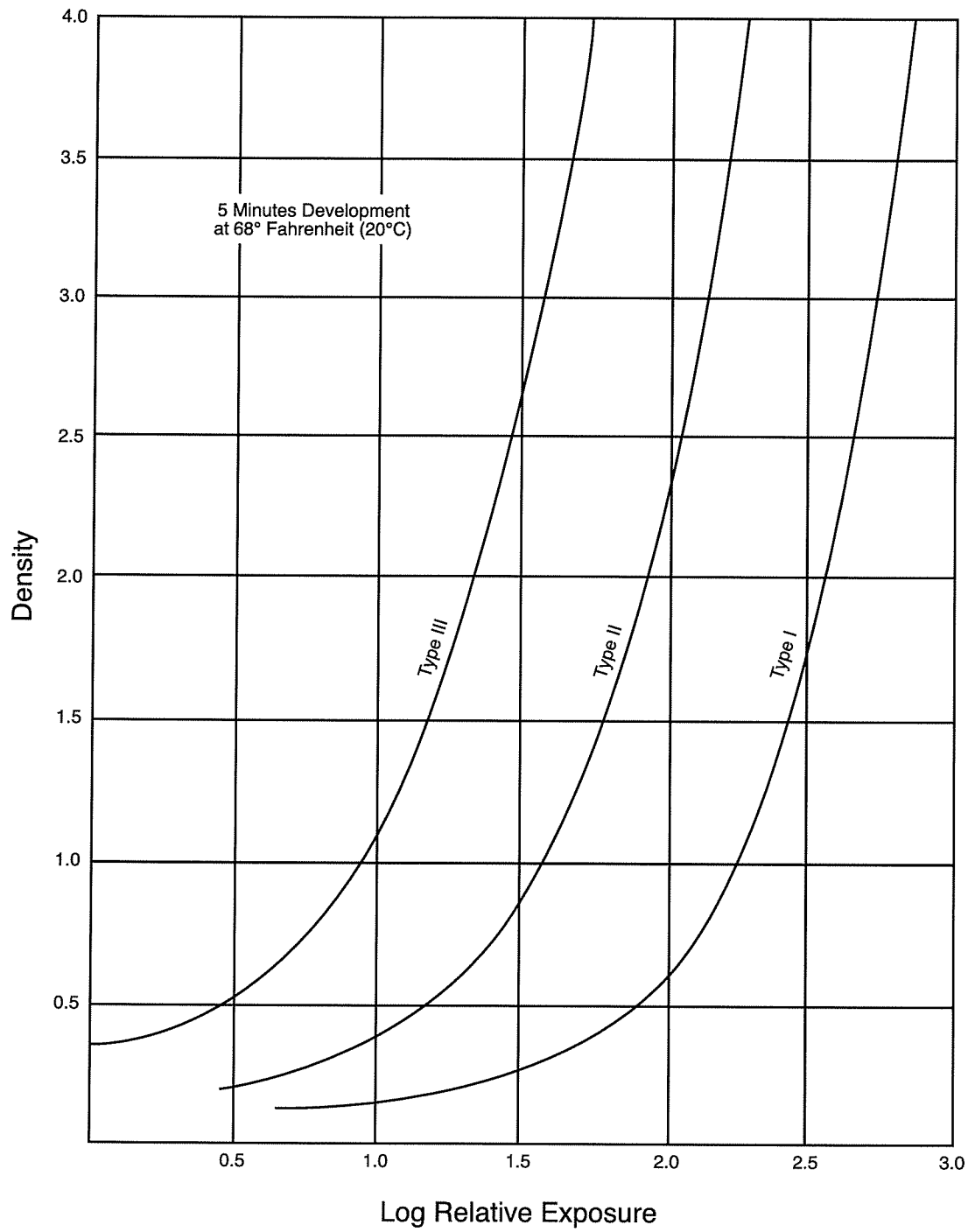
FIGURE 6-19   Film characteristic curves.

tion factor of 5.6 will give a suitable exposure time to achieve a film density of 2.5 with Type I film.

Another variable to be considered is the source to film distance (SFD). Occasionally, the source to film distance is also referred to as the target to film distance (TFD). The TFD generally applies when using an x-ray source and the SFD applies when radioactive isotopes are used. This distance is very critical and plays a major role in establishing the correct technique. Notice on the x-ray technique chart that the TFD is 36 inches. There may be occasions when the 36 inch TFD is not possible because of geometric limitations and a shorter distance may be necessary. On the other hand, the TFD may be increased, which would result in an image with better definition. There is a mathematical relationship between the exposure time and the distance. The technique chart, if used properly, will provide the correct exposure time at a distance of 36 inches. If a different distance is used, a simple equation that gives the relationship between time and distance should be used. The results are very precise and enable the radiographer to essentially use any TFD (x-ray) or SFD (gamma ray) that is appropriate for the object that is being radiographed. The equation for this calculation is:

$$\frac{T_1}{T_2} = \frac{D_1^2}{D_2^2}$$

where:

T_1 = original exposure time derived from the technique chart
T_2 = new exposure time
D_1 = original distance
D_2 = new distance

Example:

A new distance of 48″ is desired to achieve better definition. The original exposure time at 36″ was 3 minutes. The exposure time required at the new distance can be calculated as follows:

$$T_1 = 3 \text{ minutes}$$

$$D_1 = 36'' \ (3')$$

$$D_2 = 48'' \ (4')$$

$$T_2 = x$$

$$T_2 = 3 \text{ minutes} \times \frac{(4)^2}{(3)^2}$$

$$T_2 = 3 \text{ minutes} \times \frac{16}{9}$$

$$T_2 = 5.33 \text{ minutes or 5 minutes and 20 seconds}$$

The other variable that all radiographic personnel must be aware of is the inverse square law. This is important as it applies to technique development but also, more importantly, as it relates to safety. As mentioned, the intensity of radiation varies inversely proportional to the square of the distance and is expressed mathematically in the following equation:

$$\frac{I_1}{I_2} = \frac{D_2^2}{D_1^2}$$

where:

I_1 = intensity at distance D_1
I_2 = intensity at distance D_2
D_1 = initial distance
D_2 = new distance

Image Quality

By optimizing the variables that have been discussed, it is feasible to achieve a radiographic image with a high quality level. The goal of the radiographer should be to achieve the highest possible quality image of the object that is being radiographed. The quality of the radiographic technique is a established by comparison with the image of a "image quality indicator"(IQI), also referred to as a penetrameter, on the completed radiograph. There are two major types of penetrameters in use today: the shim and wire types. The "shim" or hole type contains a lead identification number at one end and three holes of different diameters. The thickness of the shim type penetrameter is based on a percentage of the material thickness that is being radiographed. The most common penetrameter thickness is 2% of that thickness. The three holes as seen in Figure 6-20a have different diameters, which are based on the penetrameter thickness.

The smallest hole located in the center is referred to as the 1T. The "T" in the penetrameter designation represents the penetrameter thickness. The 1T hole, therefore, will have a diameter equivalent to the thickness of the penetrameter, which again is usually 2% of the thickness of the material being radiographed. The hole diameter at the end opposite to the lead identification numbers is referred to as the 2T hole. Its diameter will be two times the penetrameter thickness. The largest hole is the 4T hole and that diameter will be four times the penetrameter thickness. The outline of the penetrameter and the image of the holes on the finished radiograph establish the quality level for that radiographic technique. It is unfortunate that the hole sizes are, at times, used as a comparison to estimate the size of discontinuities that are detected. This is not the intent of the penetrameter. For example, if the diameter of a 2T hole is a $0.020''$, a discontinuity of that size will not necessarily be detected. Penetrameter holes are very precisely manufactured into the penetrameter shim. They have sharp edges. Discontinuities are quite different from these holes. The penetrameter is used to establish the quality level of the radiographic technique and should not be compared to discontinuities. The typical designations for radiographic quality levels (RQL) using the shim type penetrameters will be a combination of two numbers and a letter. For example, the most common quality level is 2-2T. This designation means that a penetrameter whose shim is 2% of the material being radiographed, must display the 2T hole (which is two times the thickness of the penetrameter) clearly and distinctly on the radiograph. When the 2T hole is clearly discernible, the 4T hole, which is larger, should also be discernible. The 1T may, or may not, be clearly visible. If a 2-1T quality level is specified, the 1T hole must be clearly discernible in a 2% thick penetrameter shim. A 2-4T quality level will require the 4T-hole image to be discernable in the radiograph. Although the standard penetrameter shim thickness is typically about 2% of the material being radiographed, a 1% shim thickness may also be specified. This means that the penetrameter thickness is 1% of the material being radiographed. This designation is used when a higher level of quality is required in the radiographic technique. A listing of common shim type penetrameter designations is found in Table 6.5.

The second most commonly used image quality indicator is known as the "wire" penetrameter. The wire penetrameter has been in use for decades in Germany and other Euro-

(a)

(b)

FIGURE 6-20   Hole-type penetrameter on a shim (a) and wire penetrameters (b). (Courtesy Charles J. Hellier.)

6.34

pean countries. In fact, the first wire penetrameter was developed in Germany and was known as the DIN (Deutsche Industrie-Norm) type penetrameter. Typical ASTM wire penetrameters are illustrated in Figure 6-20b. Notice that they contain a series of six wires encased in a clear plastic holder with lead identification numbers. Each of the six wires is of a slightly different diameter. There are four general wire sets described in Table 6-5.

Both shim and wire type IQIs must be placed on the source side of the object being radiographed whenever possible. There may be occasions when it is impossible to put the penetrameter on the source side due to geometric considerations or accessibility and, in those cases, some codes permit them to be placed on the film side, between the object being radiographed and the film. When a film side penetrameter is used, the required penetrameter designation is less than stipulated for the source side, since the quality level is somewhat easier to achieve, due to the closeness of the penetrameter to the film.

There are a number of other different designs and types of penetrameters; however, the shim and wire types are the most widely used. There is also a step-hole type that is used, primarily in France. There are codes today that permit the use of either the shim-type penetrameter or the wire-type penetrameter and their equivalence has been proven. Table 6-6 makes a comparison between the shim-type penetrameter and the wire-type penetrameter for the purpose of comparable quality levels.

The importance of achieving the highest possible quality level cannot be stressed enough. Those variables affecting quality level are listed in Table 6-7.

Note that the two major factors that influence sensitivity are contrast and definition. Contrast is the difference in density on two adjacent regions of the radiograph. Definition is the sharpness, or clarity, of the image as has been mentioned. Contrast is affected primarily by energy. Other factors, such as film type, differences in thickness of the specimen, density of the test object, and the degree of scatter radiation will also influence contrast. Placing a filter at the source of radiation also affects contrast. On the other hand, the sharpness of the object's image is mostly controlled by geometric considerations such as the size of the source of radiation, the source to object distance and the object to film distance. The type of screens that are used and their contact with the film will also affect sharpness. In fact, many codes stipulate that the unsharpness, or lack of definition in a radiographic technique, be calculated by using the unsharpness equation:

$$Ug = \frac{F \times t}{d}$$

where:

Ug = geometric unsharpness

F = the physical size of the target or source of radiation (*Note:* For some codes the physical size is defined as the maximum projected dimension, i.e., the diagonal.)

t = the distance from the source side of the test object (area of interest) to the film

d = the distance from the source to the op of the test object (area of interest)

At times, this equation may be used improperly. The unsharpness equation should be used to verify or to assure that the image sharpness meets the various code and specification requirements. Often, radiographers will use this equation to calculate the absolute minimum source to film distance that can be used and still meet the code required unsharpness values. In fact, in far too many cases the goal is to just "barely meet" the quality level requirements. It seems that the variables that directly reduce the quality of the image are those that some radiographers will employ to take the radiographs in the shortest practical time. For example, it should be obvious that when the source to film distance is greater, the image will be sharper, but this requires a longer exposure time. Many radiographers will use the absolute minimum source to film distance to reduce the exposure time. The

TABLE 6-5 Shim and Wire Type Penetrameter Data

Wire Penetrameter			
Set A		Set B	
Wire diameter in. (mm)	Wire ID No.	Wire diameter in. (mm)	Wire ID No.
0.0032 (0.08)[a]	1	0.010 (0.25)	6
0.004 (0.1)	2	0.013 (0.33)	7
0.005 (0.13)	3	0.016 (0.4)	8
0.0063 (0.16)	4	0.020 (0.51)	9
0.008 (0.2)	5	0.025 (0.64)	10
0.010 (0.25)	6	0.032 (0.81)	11
Set C		Set D	
Wire diameter in. (mm)	Wire ID No.	Wire diameter in. (mm)	Wire ID No.
0.032 (0.81)	11	0.10 (2.5)	16
0.040 (1.02)	12	0.126 (3.2)	17
0.050 (1.27)	13	0.160 (4.06)	18
0.063 (1.6)	14	0.20 (5.1)	19
0.080 (2.03)	15	0.25 (6.4)	20
0.100 (2.5)	16	0.32 (8)	21

Shim (Hole) Penetrameters				
Penetrameter designation	Penetrameter thickness	1T Hole diameter	2T Hole diameter	2T Hole diameter
5	0.005	0.010	0.020	0.040
7	0.0075	0.010	0.020	0.040
10	0.010	0.010	0.020	0.040
12	0.0125	0.0125	0.025	0.050
15	0.015	0.015	0.030	0.060
17	0.0175	0.0175	0.035	0.070
20	0.020	0.020	0.040	0.080
25	0.025	0.025	0.050	0.100
30	0.030	0.030	0.060	0.120
35	0.035	0.035	0.070	0.140
40	0.040	0.040	0.080	0.160
45	0.045	0.045	0.090	0.180
50	0.050	0.050	0.100	0.200
60	0.060	0.060	0.120	0.240
80	0.080	0.080	0.160	0.320
100	0.100	0.100	0.200	0.400

[a]The 0.0032 wire may be used to establish a special quality level if agreed upon between the purchaser and the supplier.

TABLE 6-6   Penetrameter Comparison

Shim (hole) type penetrameter designation	Wire diameter equivalence to hole diameter		
	1T	2T	4T
5	—	—	0.0006
6	—	0.004	—
8	0.0032	0.005	0.008
10	0.004	0.006	0.010
12	0.005	0.008	0.013
15	0.006	0.010	0.016
17	0.008	0.013	0.020
20	0.010	0.016	0.025
25	0.013	0.020	0.032
30	0.016	0.025	0.040
35	0.020	0.032	0.050
40	0.025	0.040	0.063
50	0.032	0.050	0.080
60	0.040	0.063	0.100
70	0.050	0.080	0.126
80	0.063	0.100	0.160
100	0.080	0.126	0.200

TABLE 6-7   Radiographic Quality Variables