Chapter 6

X-Ray Circuit and Tube Heat Management

Learning Objectives

At the conclusion of this chapter, you will be able to:

- Explain the x-ray circuit, label the principal parts, and state the function of each
- Explain what is meant by rectification and compare the three basic types
- Draw the voltage waveform for each of the following types: unrectified, half-wave rectified, full-wave rectified, three-phase rectified, and high frequency
- List the primary features of all x-ray control panels and discuss the principal differences between conventional and computerized control consoles
- Describe the components of the automatic exposure control system and anatomically programmed exposure system
- List five possible causes of x-ray tube failure and describe methods to prevent each

Key Terms

anatomically programmed radiography (APR)
autotransformer
control console
diode
electronic timer
exposure switch
exposure timer
heat unit (HU)
high-frequency (*HF*)
mA selector
phototimer
rectification
rectifier
rotor switch
single-phase current
three-phase current
tube rating chart

This chapter centers on a greatly simplified diagram of an x-ray circuit and is intended to aid your understanding of the various components of the circuit and how they work together to produce and control x-rays. The various features of the x-ray circuit and the x-ray control panel are discussed. *It is not necessary to memorize or understand the circuits in detail.* The circuits help you to understand how three relatively complex electric circuits are integrated to produce x-rays. Because x-ray tubes may be damaged by improper use and are expensive to replace, this chapter provides guidelines for the safe operation of tubes and suggestions for prolonging tube life.

X-RAY CIRCUIT

As indicated in Fig. 6.1, the x-ray circuit is divided into three sections or subcircuits: the *low-voltage circuit*, the *filament circuit*, and the *high-voltage circuit*. Each circuit contains a specialty transformer. The various components of each section are numbered so that you can easily refer to them in the discussion that follows.

Low-Voltage Circuit

The low-voltage circuit is illustrated in the upper left portion of Fig. 6.1 and is expanded in Fig. 6.2A. It is the subcircuit between the alternating current (AC) power supply (1) and the primary (input) side of the high-voltage (step-up) transformer (7). If you trace this circuit beginning at the AC power supply, you will note that current flows through several devices before reaching the primary side of the step-up transformer. From the transformer, it returns to the power source, forming an enclosed loop. With the exception of the step-up transformer, all of the devices in this subcircuit are actually located within the **control console**. The control console is the unit where the operator sets all of the exposure techniques, such as kilovolts peak (kVp), milliamperes (mA), and exposure time. They include the main switch (2), **autotransformer** (3), kVp selectors (4), **exposure switch** (5), and **exposure timer** (6).

The AC power supply (1) is wired into the building, providing electric power from the local power company. Most outpatient facilities have a 220-V power supply going into the x-ray room. Hospitals with more powerful equipment may have a larger supply. The main switch (2) controls the power to the control console. Many of the components in this circuit operate at the standard 120 V.

Although the power supply may be rated at 220 V, the actual voltage can vary as much as ±5%, depending on the demand for power in the building or the neighborhood. Small variations in the incoming line voltage may cause large variations in the kVp to the x-ray tube. For this reason, the incoming voltage is monitored and stabilized by a voltage compensator.

The autotransformer (3) is a single-coil transformer that serves three functions: it provides the means for kVp selection, it provides compensation for fluctuations in the incoming line voltage, and it supplies power to other parts of the x-ray circuit.

The autotransformer's primary purpose is to vary the voltage to the primary side of the step-up transformer. This is

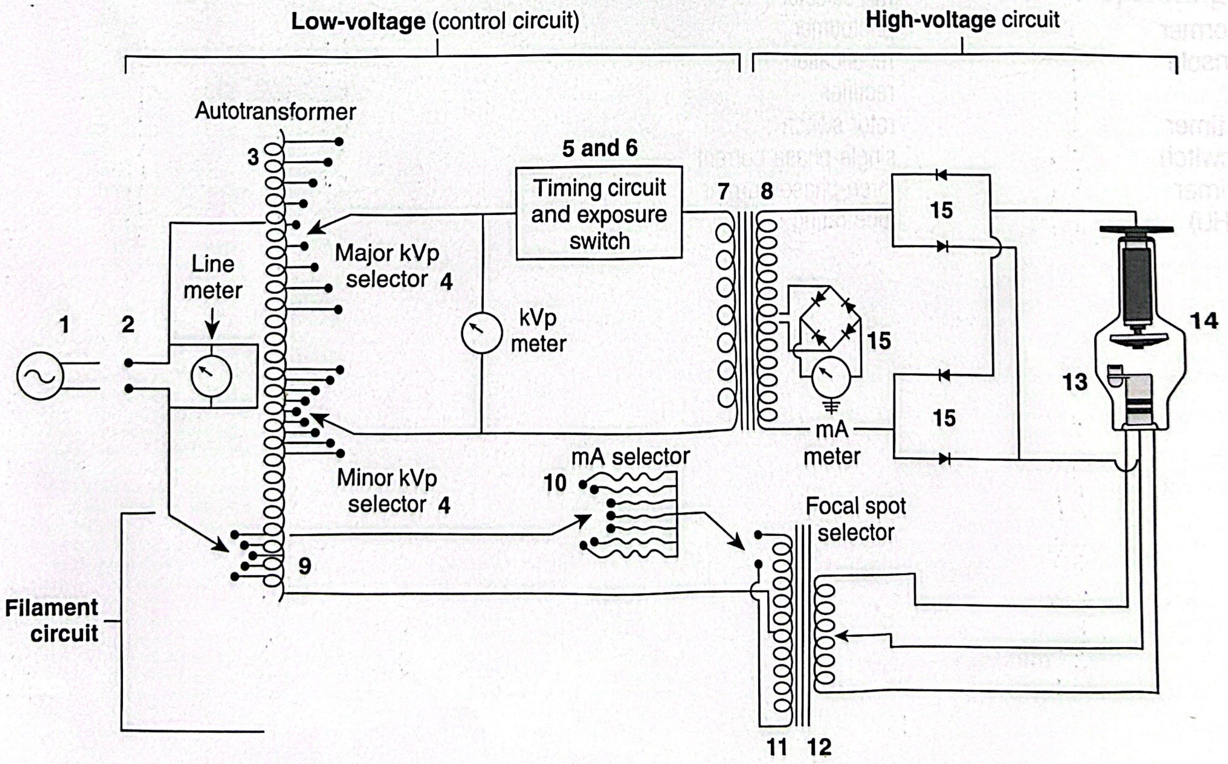

Fig. 6.1 Simplified diagram of an x-ray circuit. Electric circuit going into the x-ray room is at far left *(1)*, and circuit ends at x-ray tube at far right *(14)*.

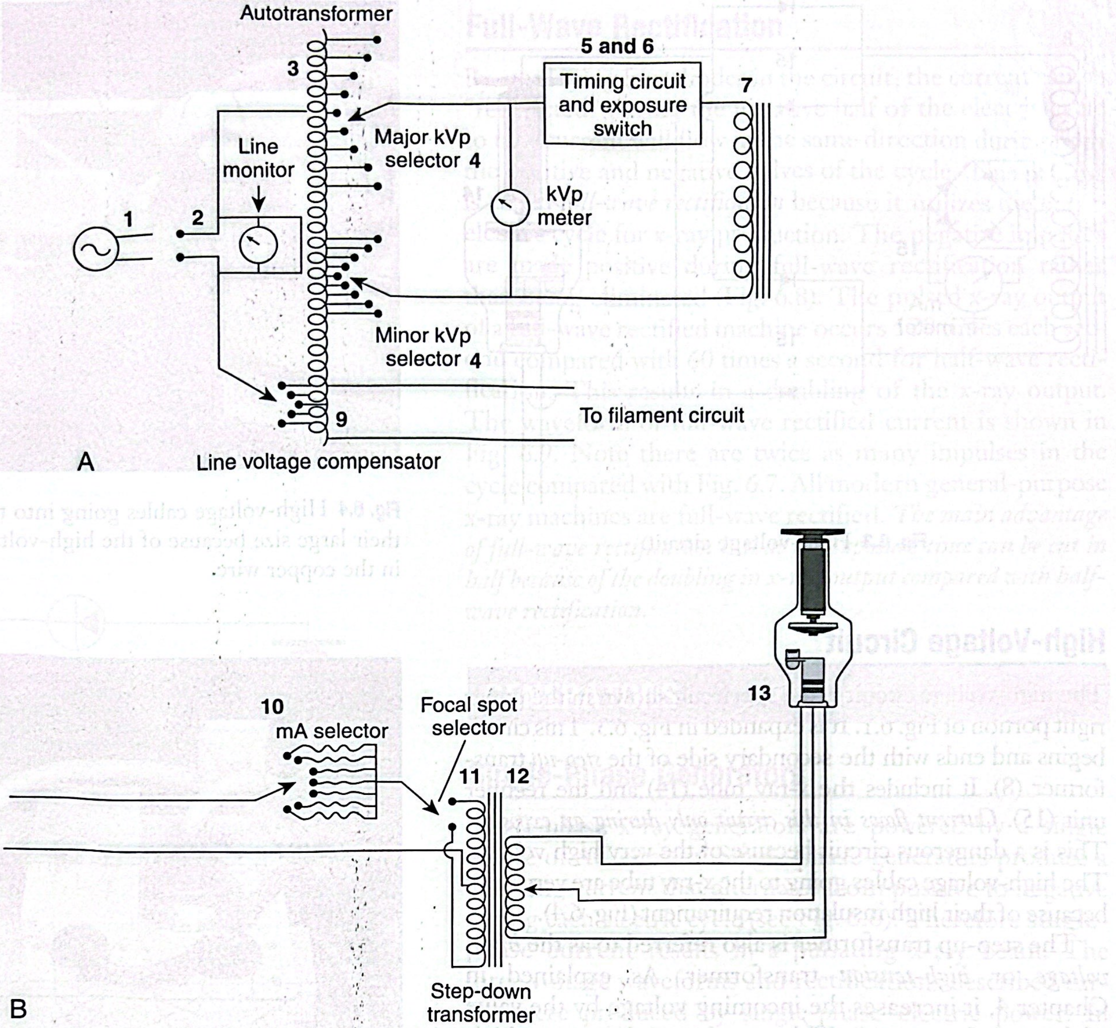

Fig. 6.2 (A) Low-voltage circuit. (B) Filament circuit.

accomplished by the kVp selector (4), which is on the secondary (output) side of the autotransformer. The autotransformer varies the kVp to the tube by controlling the input to the step-up transformer.

The exposure switch (5) closes the circuit, allowing electric current to flow through the primary side of the step-up transformer. When this occurs, current is *induced* to flow through the secondary side of the transformer, creating voltage across the x-ray tube. As discussed earlier, this voltage causes the electron stream to flow across the tube, producing x-rays. The exposure timer (6) is a device that terminates the exposure and is set by the operator on the control console.

Filament Circuit

The filament circuit is the subcircuit of the main x-ray circuit shown as the lower portion of Fig. 6.1. It is expanded in Fig. 6.2B. This circuit is divided into two parts by the *step-down* transformer (11 and 12). *The primary purpose of the filament circuit is to supply a low current to heat the x-ray tube filament for thermionic emission of electrons.* The filament circuit is activated any time the operator adjusts the mA on the generator.

The primary side of this circuit begins and ends with the contacts on the autotransformer (9). Current in this circuit flows from the autotransformer, through the mA selector (10) and the primary side of the *step-down* transformer (11), and back to the autotransformer. The secondary side begins and ends with the secondary side of the step-down transformer (12) conducting current through the x-ray tube filament (13). The step-down transformer reduces the voltage on the secondary side, providing an appropriate current to heat the filament.

The **mA selector** (10) controls amperage in the filament circuit. Because the current through this circuit controls filament heat, this setting determines the number of available electrons at the x-ray tube filament and thus determines the mA in the high-voltage circuit that includes the x-ray tube.

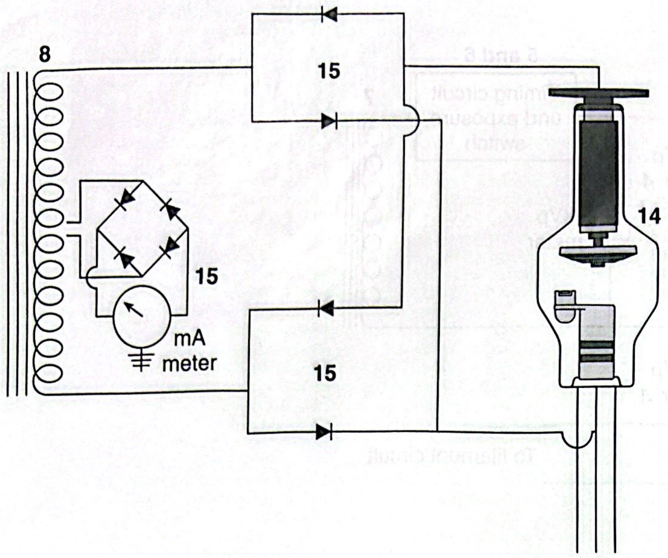

Fig. 6.3 High-voltage circuit.

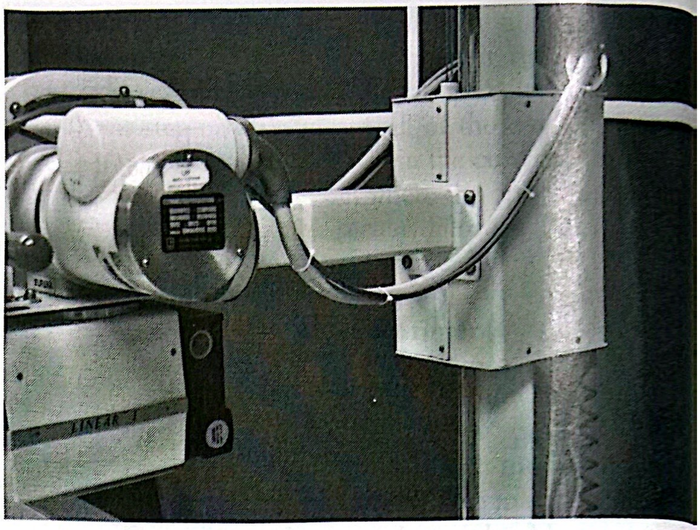

Fig. 6.4 High-voltage cables going into the x-ray tube. Note their large size because of the high-voltage electricity moving in the copper wire.

High-Voltage Circuit

The high-voltage circuit is the subcircuit shown in the upper right portion of Fig. 6.1. It is expanded in Fig. 6.3. This circuit begins and ends with the secondary side of the *step-up* transformer (8). It includes the x-ray tube (14) and the rectifier unit (15). *Current flows in this circuit only during an exposure.* This is a dangerous circuit because of the very high voltage. The high-voltage cables going to the x-ray tube are very thick because of their high insulation requirement (Fig. 6.4).

The step-up transformer is also referred to as the *high-voltage* or *high-tension* transformer. As explained in Chapter 4, it increases the incoming voltage by the value of the *transformer ratio.* This transformer has a very high ratio of at least 500:1. For example, if the primary side of the step-up transformer receives 180 V from the autotransformer, and the ratio is 500:1, the voltage induced on the secondary side will be 90,000 V, or 90 kVp.

The primary purpose of the high-voltage circuit is to supply the x-ray tube with voltage high enough to create x-rays.

The autotransformer, step-down transformer, and high-voltage transformer are all located in a tank near the x-ray machine (Fig. 6.5). Oil surrounds the transformers inside the tank for heat dissipation.

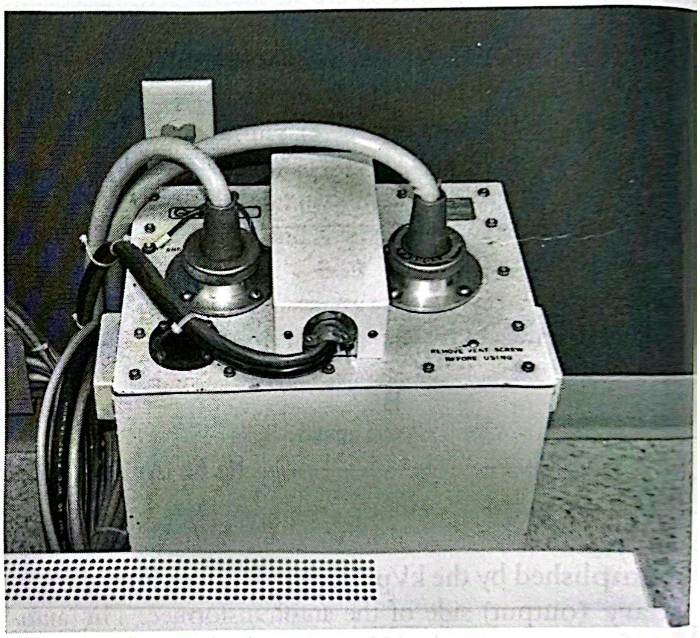

Fig. 6.5 X-ray transformer tank containing the autotransformer, filament transformer, high-voltage transformer, and rectifier. The transformers are immersed in oil.

Rectification

The process of changing alternating current into direct current so it flows in one direction only.

RECTIFICATION

The primary purpose of the **rectifier** *unit (15) is to change the AC into direct current (DC).* The process of **rectification** prepares the current for x-ray production by ensuring that it flows in the right direction, in this case from the filament to the target. There are three ways in which current is rectified: *self-rectification, half-wave rectification,* and *full-wave rectification.* Self-rectification was an inefficient form of rectification and is no longer used. Half-wave rectification and full-wave rectification are described next.

Half-Wave Rectification

AC electrical current travels in the copper wire as a sine wave. It moves in a pulsating manner from positive to

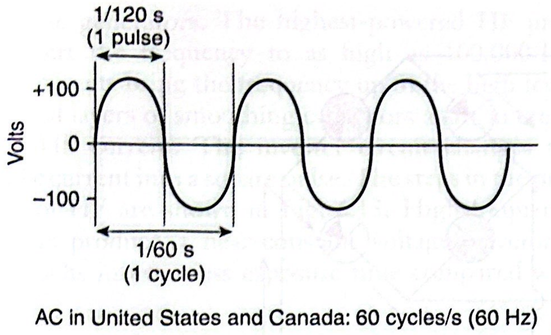

Fig. 6.6 Electric current moves in a copper wire as a series of alternating (alternating current *[AC]*) waves called a sine wave. One positive and negative pulse equals one cycle or 1 Hz. U.S. current contains 60 Hz/s.

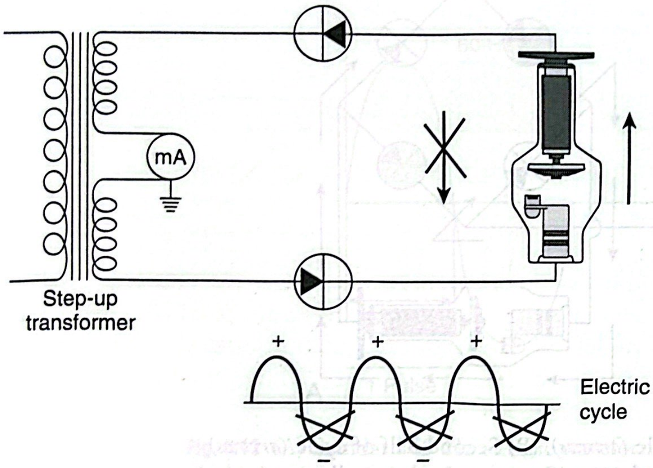

Fig. 6.7 Voltage waveform for half-wave rectification. Note: Negative phase (X) is eliminated.

negative at a rate of 60 pulses, or waves, per second and is stated as 60 Hz (Fig. 6.6). Rectifiers use diodes to convert the circuit from AC to DC. A **diode** is an electronic device that permits current to flow in one direction only. Two diodes are used in half-wave rectification (Fig. 6.7). Diodes prevent "backflow" of current during the negative half of the electric cycle. This causes the negative half of the cycle to be eliminated. Note that the arrow direction of the diode symbol indicates the direction of current flow permitted by the diode.

In half-wave rectification the negative phase of the electric cycle is totally eliminated and a gap remains. The x-rays are turned off during the eliminated (negative) phase. With only the positive phase remaining, the electric current is "direct" only, or DC. The x-rays are pulsating on, off, on, off, and so forth at a rate of 60 pulses per second.

Full-Wave Rectification

By employing four diodes in the circuit, the current can be "redirected" during the negative half of the electric cycle so that current will flow in the same direction during both the positive and negative halves of the cycle. This process is called *full-wave rectification* because it utilizes the entire electric cycle for x-ray production. The negative impulses are made positive during full-wave rectification rather than being eliminated (Fig. 6.8). The pulsed x-ray output of a full-wave rectified machine occurs 120 times each second compared with 60 times a second for half-wave rectification. This results in a doubling of the x-ray output. The waveform of full-wave rectified current is shown in Fig. 6.9. Note there are twice as many impulses in the cycle compared with Fig. 6.7. All modern general-purpose x-ray machines are full-wave rectified. *The main advantage of full-wave rectification is that the exposure time can be cut in half because of the doubling in x-ray output compared with half-wave rectification.*

GENERATORS

Single-Phase Generators

Single-phase x-ray generators are powered by a single source of AC current. Single-phase generators produce a pulsating current that alternates from positive to negative during each electric cycle (see Fig. 6.6). Therefore **single-phase current** results in a pulsating x-ray beam. The three voltage waveforms and rectifications described earlier were produced by single-phase electric power. In single-phase current with full-wave rectification, there are 120 pulses of electricity per second that create 120 pulses of x-rays per second. Single-phase generators are considered the lowest power and most basic x-ray machines. These are also the least expensive, which makes them a popular choice in small clinics and physician offices.

Three-Phase Generators

Three-phase x-ray generators are powered by three separate sources of AC current at the same time. A more constant and efficient voltage source is provided by a three-phase power supply. AC is generated in three overlapping cycles that produce the waveform illustrated in Fig. 6.10. When this current is rectified, its waveform has the appearance of a "ripple" with no real low points. In **three-phase current** with full-wave rectification there are 360 pulses of electricity per second that create 360 pulses of x-rays per second. The resulting waveform is shown in Fig. 6.11. *A major advantage of three-phase current is that it is more efficient and produces approximately 40% more x-rays than single-phase current.* This greater output enables exposure times to be decreased by 40%. The purchase and installation of three-phase x-ray equipment is

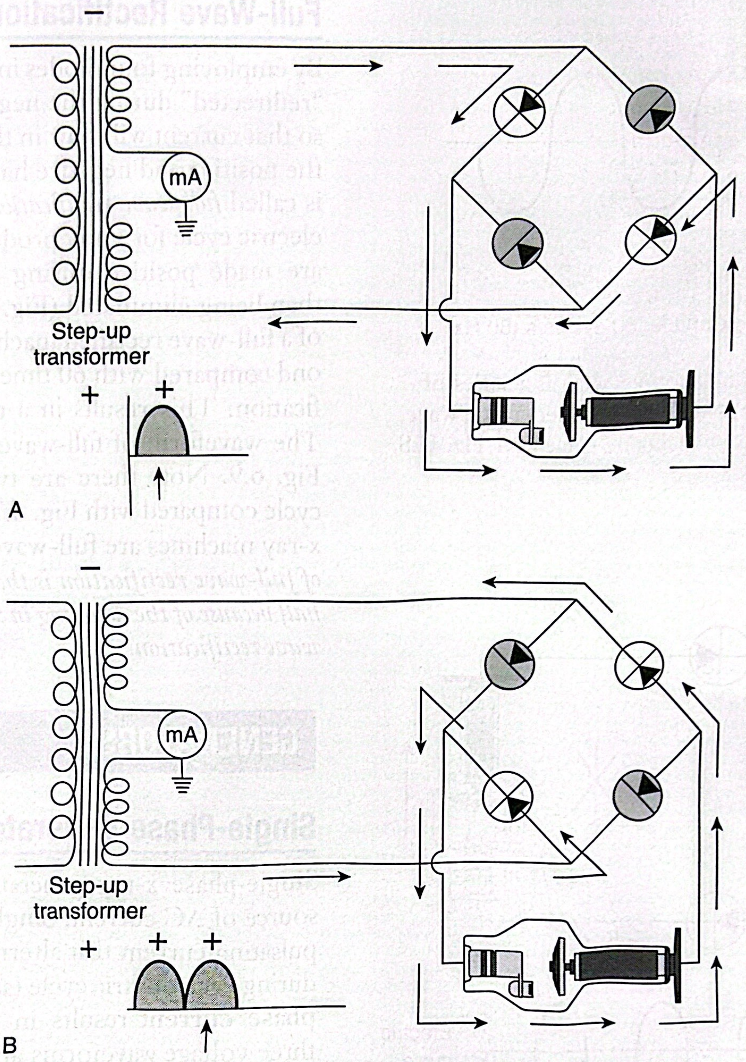

Fig. 6.8 Full-wave rectification. (A) First half of cycle *(arrows)*. (B) Second half of cycle *(arrows)* rectified from negative to positive. This more complex rectification unit electrically moves the negative pulse above the line, changing it to positive in the process.

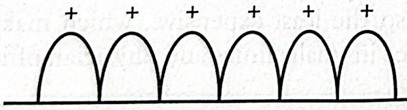

Fig. 6.9 Full-wave rectification voltage waveform produces 120 impulses (x-rays) per second compared with 60 impulses in half-wave rectification.

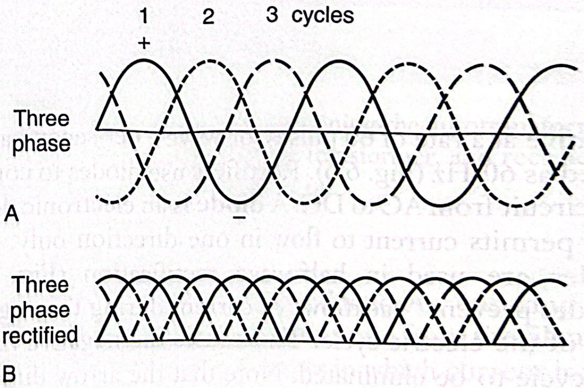

Fig. 6.10 Three-phase current voltage waveform. (A) Unrectified. (B) Rectified. Note how the negative pulses are moved above the line to positive.

very expensive compared with that of single-phase equipment. The three-phase generator was previously the predominant type of x-ray machine in hospitals and large clinics because of its increased power. The manufacture of three-phase generators is being phased out.

High-Frequency Generators

High-frequency (HF) x-ray generators are the most common generators used today. They produce x-rays much more efficiently than single-phase or three-phase generators. A single source of AC current, similar to single-phase, is used to power the generator. *The primary function that occurs in the complex HF circuitry is that the 60-Hz full-wave rectified circuit is converted to a significantly higher frequency of about* 6000 Hz (Fig. 6.12) for most general use generators. The highest-powered HF units can convert the frequency to as high as 100,000 Hz. Inverter circuits bring the frequency up to the high level, and several layers of smoothing capacitors assist in creating the HF current. The inverter circuit changes the wave-like current into a square pulse. The steps in the production of HF are shown in Fig. 6.13. High-frequency generators produce a near-constant voltage waveform, which results in even less exposure time compared with three-phase (Fig. 6.14). They produce the greatest amount of x-rays for the same exposure technique. The very high frequency produced in an HF generator can sometimes be heard as a singing sound.

High-frequency generators are not only used because of their efficient x-ray production, but also because their overall size is smaller. The high-voltage step-up transformer tank is about one-tenth the size of that in a three-phase generator because it produces x-rays more

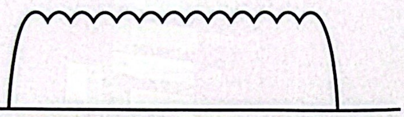

Fig. 6.11 Rectified three-phase voltage waveform.

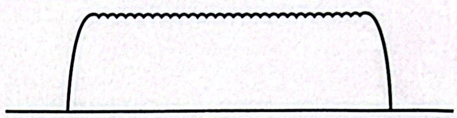

Fig. 6.14 High-frequency voltage waveform.

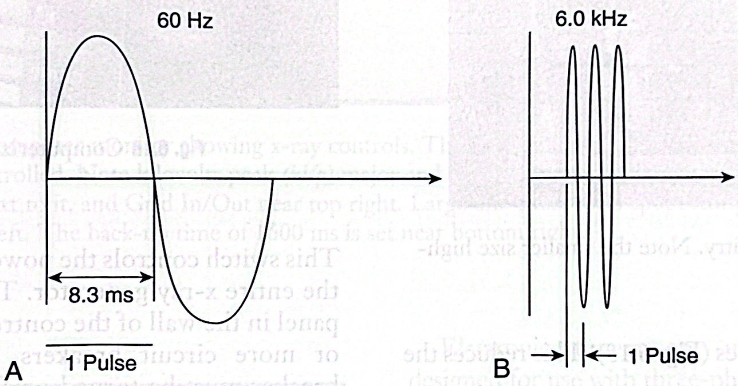

Fig. 6.12 (A) Standard 60 Hz electric waveform. (B) High-frequency waveform. An inverter circuit has increased the frequency to 6500 Hz (labeled 6.5 kHz).

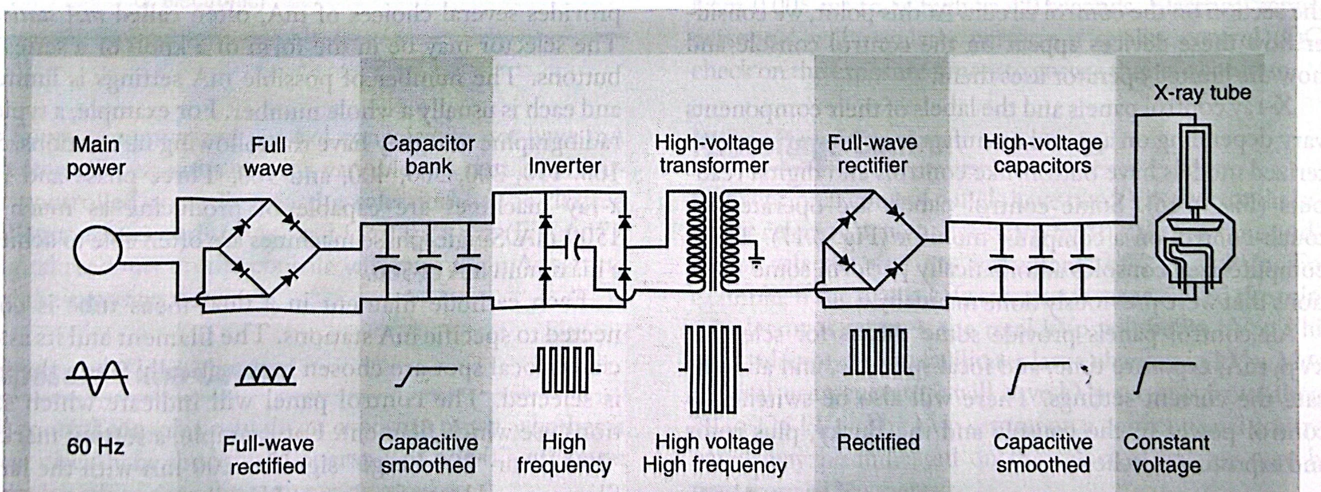

Fig. 6.13 Complex electric circuit for a high-frequency transformer. Note 60 Hz alternating current power entering the circuit at left, undergoing six conversions, and achieving a constant voltage before entering the x-ray tube.

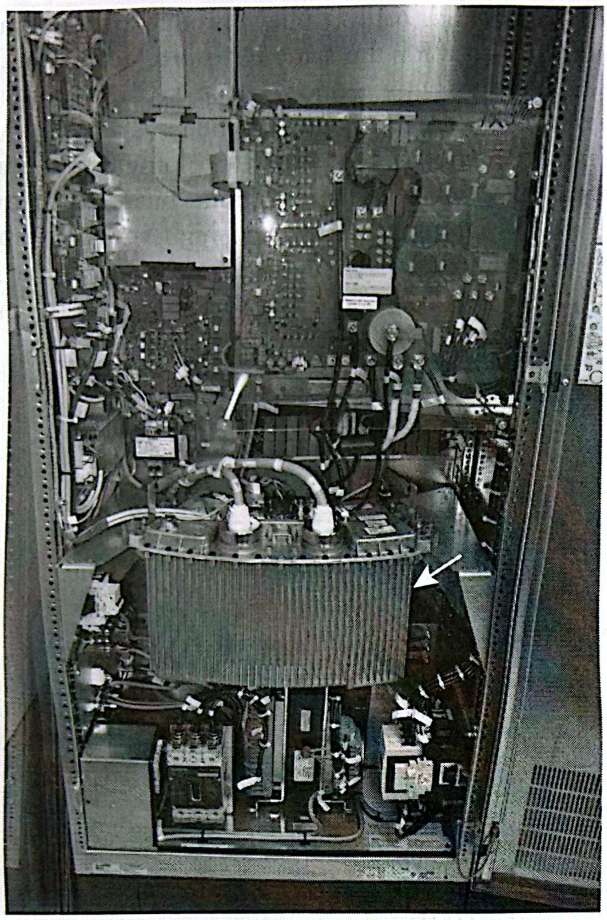

Fig. 6.15 High-frequency circuitry. Note the smaller size high-voltage transformer *(arrow)*.

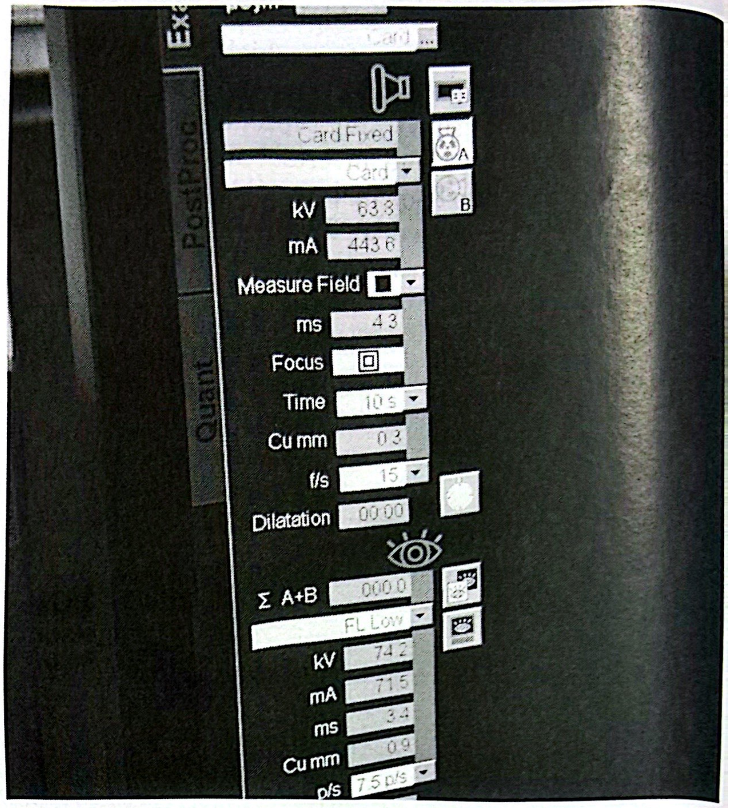

Fig. 6.16 Computerized control panel.

efficiently at high frequencies (Fig. 6.15). This reduces the overall cost of the system.

X-RAY CONTROL PANEL

The devices of the x-ray control panel were introduced in the section on the control circuit. At this point, we consider how these devices appear on the control console and how the limited operator uses them.

X-ray control panels and the labels of their components vary depending on age and manufacturer. Newer, computerized models have button-like controls and digital readouts (Fig. 6.16). Some control panels are operated by touch-control on a computer monitor (Fig. 6.17). These computerized consoles automatically perform some functions that were previously done manually.

All control panels provide some means for selecting kVp, mA, exposure time, and focal spot size, and all indicate the current settings. There will also be switches to control power to the console and the Bucky, plus rotor and exposure switches.

Power Control

The on/off switch on the console corresponds to the main power switch in the circuit diagram (see Figs. 6.1, 2). This switch controls the power to the control panel and the entire x-ray generator. There is usually an electric panel in the wall of the control booth that contains one or more circuit breakers. The appropriate circuit breaker must be turned on for the machine to receive power.

Milliamperage Control

Conventional control panels have an mA selector, which provides several choices of mA, often called *mA stations.* The selector may be in the form of a knob or a series of buttons. The number of possible mA settings is limited, and each is usually a whole number. For example, a typical radiographic unit may have the following mA stations: 50, 100, 150, 200, 300, 400, and 500. Three-phase and HF x-ray machines are capable of producing as much as 1500 mA. Single-phase machines are often able to achieve a maximum mA of 500.

Each cathode filament in a dual-focus tube is connected to specific mA stations. The filament and its associated focal spot are chosen automatically when the mA is selected. The control panel will indicate which stations use which filament. For example, a setting marked "200 L" or "200 Large" signifies 200 mA with the large filament and large focal spot. Usually mA settings of 200 to 250 or less employ the small filament; the large filament supplies mA requirements of 250 or more. The rationale for selection of mA stations is discussed in Chapter 12.

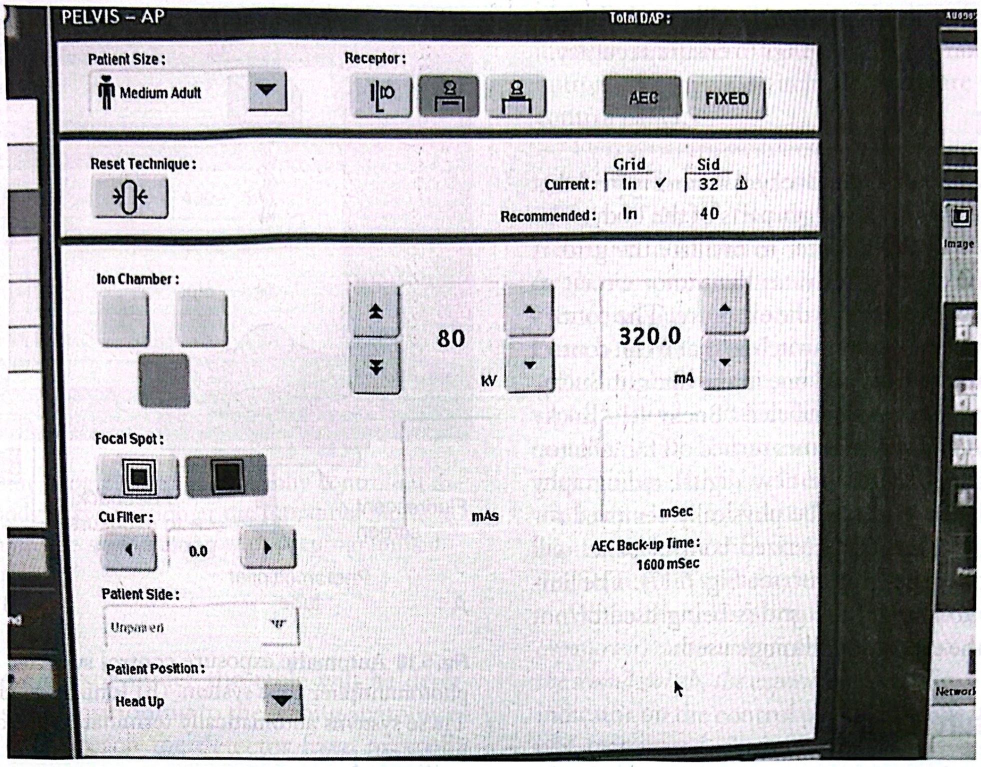

Fig. 6.17 Computer monitor showing x-ray controls. This is from a digital system and is finger-touch controlled. Note kilovolts peak *(kVp)* major and minor controls, milliamperes *(mA)* control next to it, and Grid In/Out near top right. Large and small focal spot setting is shown at center left. The back-up time of 1600 ms is set near bottom right.

TABLE 6.1
Types of Timers

Type	Minimum Exposure Time
Electronic	1 ms (0.001 s)
Automated	Depends on back-up timer (may be synchronous or electronic)

Some computerized control consoles do not have mA selectors. These units provide variable mA that is computer controlled according to the selection of the desired milliampere-seconds (mAs) and focal spot size (Fig. 6.17). Digital readouts on the console will state the mAs setting and the exposure time.

Exposure Time Control

All control consoles contain an exposure timer, whether it is set directly by the limited operator or not. The time set is the length of time the x-rays are turned on.

Computerized controls may select the exposure time using an **electronic timer** when the mAs is set. In addition, some units have automated exposure controls, which are discussed in the following section.

Electronic timers are more sophisticated devices designed for use with three-phase and high-frequency generators. Electronic timers are more capable of ultrashort exposure times (1 ms or less) than are synchronous timers, and exposure times are expressed in decimals (0.03, 0.05, and 0.07 second) (Table 6.1). These are the most accurate timers. The range of exposure times on a generator will be from 0.005 ms to as high as 4.0 seconds. Electrical service personnel will regularly perform a quality control (QC) check on the exposure timers to ensure they are accurate.

Kilovoltage Control

Conventional control panels have two kVp selector dials: a major selector that changes kVp by 10 kVp at a time and a minor selector that has increments of 1 or 2 kVp. For example, if the major kVp selector is set at 70 and the minor selector is set at 4, the total kVp will be 74 kVp. This dual-selector system facilitates large changes in kVp. Most general-use generators will have kVp settings from about 40 to 125 kVp. The kVp setting on a conventional control panel may be indicated on the selector dials or may be read from a kVp meter.

Computerized controls will have a digital read-out for the current kVp setting and arrow buttons that can be pressed to increase or decrease the kVp (see Fig. 6.17). The rationale for changes in kVp is discussed in

Chapter 5. Electric service personnel will regularly perform a QC check on the kVp settings to ensure accuracy.

Bucky Control

As mentioned in Chapter 2, the Bucky is a moving grid that is used for radiography of the larger parts of the body. The Bucky device incorporates a motor to oscillate the grid. A switch on the control panel activates the motor circuit so that the grid will oscillate during the exposure. The control panel may have a three-position switch so that it can control two Buckys, one in the table and one in the upright Bucky. The three positions are usually labeled "Bucky 1," "Bucky 2," and "Off." The grid is sometimes turned off for tabletop exposures of the limbs. On the new digital radiography (DR) x-ray tables, the grid can be physically removed for nongrid exposures. The computerized control panel will indicate if the grid is in place or not (see Fig. 6.17). The limited operator has to know if the grid is being used or not because it affects the exposure technique used.

Manual Exposure Control

Every x-ray exposure that is made will have had three prime factors set on the control panel: *mA*, *kVp*, and *exposure time*. In many basic x-ray systems, the limited operator "manually" sets these three factors on the control panel. For example, an anteroposterior (AP) knee might require 200 mA, 80 kVp, and 0.20 seconds, and these technical factors will come from the exposure technique chart. The technique is set by simply pushing the three buttons. Two automated exposure systems are described next; however, even with these sophisticated systems, many of the x-ray images will still have to be set with a manual technique.

Automatic Exposure Control

Many x-ray machines provide automatic exposure control (AEC), terminating the exposure time when a certain quantity of radiation has been detected at the image receptor (IR). The AEC system is a complex microprocessor circuit built into the generator and x-ray table and tied directly to the mA, kVp, and exposure time controls. When activating the AEC system on the generator, the mA and kVp values are set as usual; however, *the exposure time is automatically determined*. This eliminates the need to know in advance just how much exposure time a radiograph will require.

A sensing device is located under the x-ray table and detects when a given amount of x-ray photons has been reached. When this happens, the sensor will terminate the exposure time. There are two types of automated exposure control sensors: **phototimers** and *ionization chambers* (Fig. 6.18). It is not important to know details of these two sensing systems. The sensors under the table are referred to by several names: *phototimers*, *detectors*, and *sensors*. As the Bucky moves along the table, the AEC system moves with it.

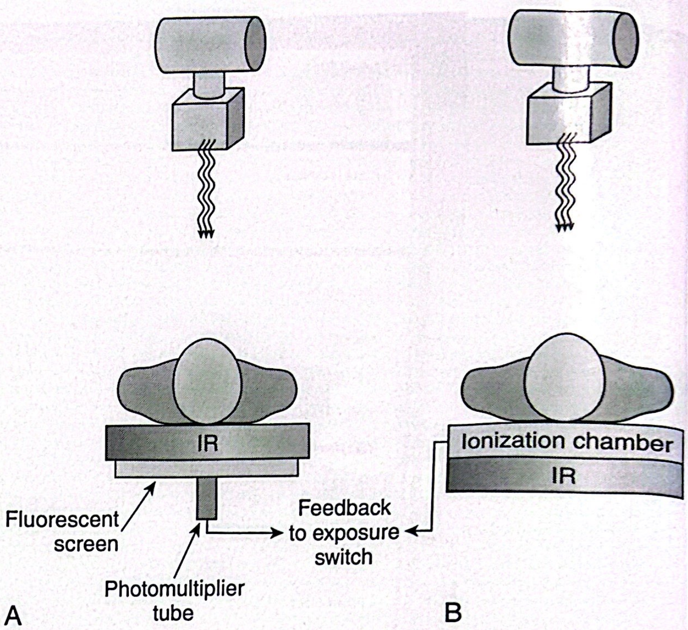

Fig. 6.18 Automatic exposure control systems. (A) The photomultiplier tube system. (B) Ionization chamber system. These systems automatically terminate the exposure time. *IR*, Image receptor.

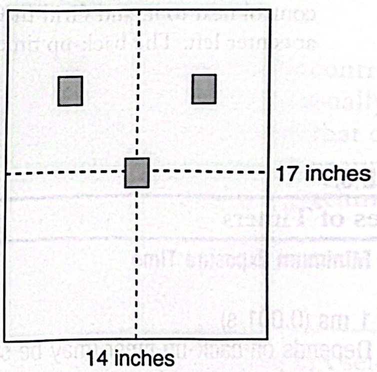

Fig. 6.19 Automated exposure control systems have three detectors below the tabletop. Detectors are positioned as shown relative to a 14 × 17-inch image receptor (IR). Note: Center detector is in the center of the IR.

The AEC system will usually have three detectors so that limited operators can select the specific location or locations within the radiation field where the radiation quantity will be measured (Fig. 6.19). The selection of active detectors is determined by the IR size and the specific radiographic examination. For example, a knee radiograph will use a central detector, whereas a chest film requires activation of the two upper detectors with positions that correspond to the lungs. The center detector is always in the center of the IR at the central ray. With three detectors, the operator can select from seven different combinations. The kVp and mA are set manually. When using an AEC system, patient positioning *must be absolutely*

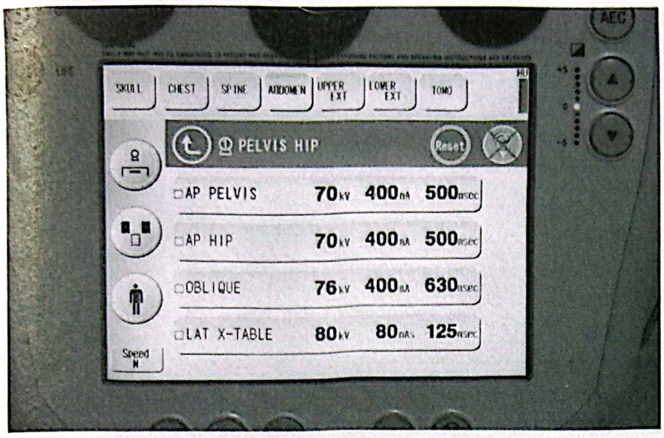

Fig. 6.20 Anatomically programmed radiography control on the generator. Note body part selection at the top, different projections shown on the screen along with preprogrammed exposure techniques.

accurate. Because a sensor under the table will be determining the exposure, positioning to the wrong anatomy or having primary beam reach the detector from overcollimation could cause overexposure or underexposure.

Anatomically Programmed Radiography Control

One of the most widely used electronic techniques for exposure control is called **anatomically programmed radiography (APR).** With this system, a microprocessor controls the exposure technical factors. These systems are essentially the exposure technique chart stored in the computer memory. By typically selecting only one or two controls, usually the body area and the projection, the kVp, mA, time, AEC detectors, body habitus, Bucky, and source–image receptor distance (SID) will be selected automatically (Fig. 6.20). For example, if the physician orders an x-ray of the pelvis, the operator selects "Pelvis" and then selects "AP-Projection" and the exposure is ready to be made. The limited operator does have the option to override the automated factor selection for specific patient situations. When an APR system is used, a technique chart may not need to be posted in the room, except for manual exposure techniques. The AEC system described above is utilized within the APR system. With proper and accurate positioning, APR systems can produce excellent radiographs and fewer repeat examinations.

Exposure Controls

Until about 25 years ago, exposure switches were incorporated into a hand switch that was attached to the control panel by a cable. Some of this equipment is still in use, but regulatory agencies now require that it be permanently fastened to the control console so that exposures cannot be made from a position outside the control booth. More modern equipment has exposure switches in the form of buttons or toggle switches, which are mounted on the control panel.

Two separate switches are necessary to make an exposure. The first is the **rotor switch**, which may be labeled "Rotor," "Prep," "Ready," or "Standby." This switch has two functions. When it is activated, the rotating anode begins to spin, and heat is applied to the filament to create electrons via thermionic emission. When this switch has been held in the "on" position for several seconds, a signal will indicate that the tube is ready for an exposure. The signal may be a particular sound or a light on the control panel or both. Making an exposure before the tube is ready may damage the tube. Nearly all x-ray machines in current use have a lockout feature that prevents the initiation of an exposure before the rotor has reached operating speed and the filament has reached operating temperature.

When the tube is ready, *the limited operator initiates the exposure by continuing to hold the rotor switch and also pressing the second switch, the exposure switch* (Fig. 6.21). An exposure indicator on the control panel will indicate when the timer has terminated the exposure. Only then are the two switches released. *Premature release of either the rotor switch or the exposure switch will abort the exposure before it is complete.*

On older equipment, the exposure indicator will be an mA meter on the control panel. It will indicate the mA during the exposure and return to zero as soon as the exposure is complete. Newer models will have an exposure light, usually red, that is on during the exposure. When the light goes off, the exposure is complete and an audible beep will be heard.

The process of setting a *modern* control panel may take place in any order. It is wise to form a habit of setting the controls in the same order each time so that nothing is overlooked. Box 6.1 lists, in order, the steps for setting the controls and making an exposure with a conventional control console.

PROLONGING X-RAY TUBE LIFE

The anode of the tube accumulates enormous heat during exposures, and this is a primary cause of problems that may shorten tube life. The design of modern tubes incorporates several features for the purpose of rapid heat dissipation. The rotating anode prevents excess heat in any one area of the target, spreading it around the focal track. The anode disk consists of several layers of material (tungsten, molybdenum, and graphite) chosen for their heat-management characteristics. The stem of the anode conducts heat to a copper mass surrounding the rotor mechanism. Also, the space between the tube and the tube housing is filled with oil. This feature provides electric insulation and also disperses heat from the glass envelope.

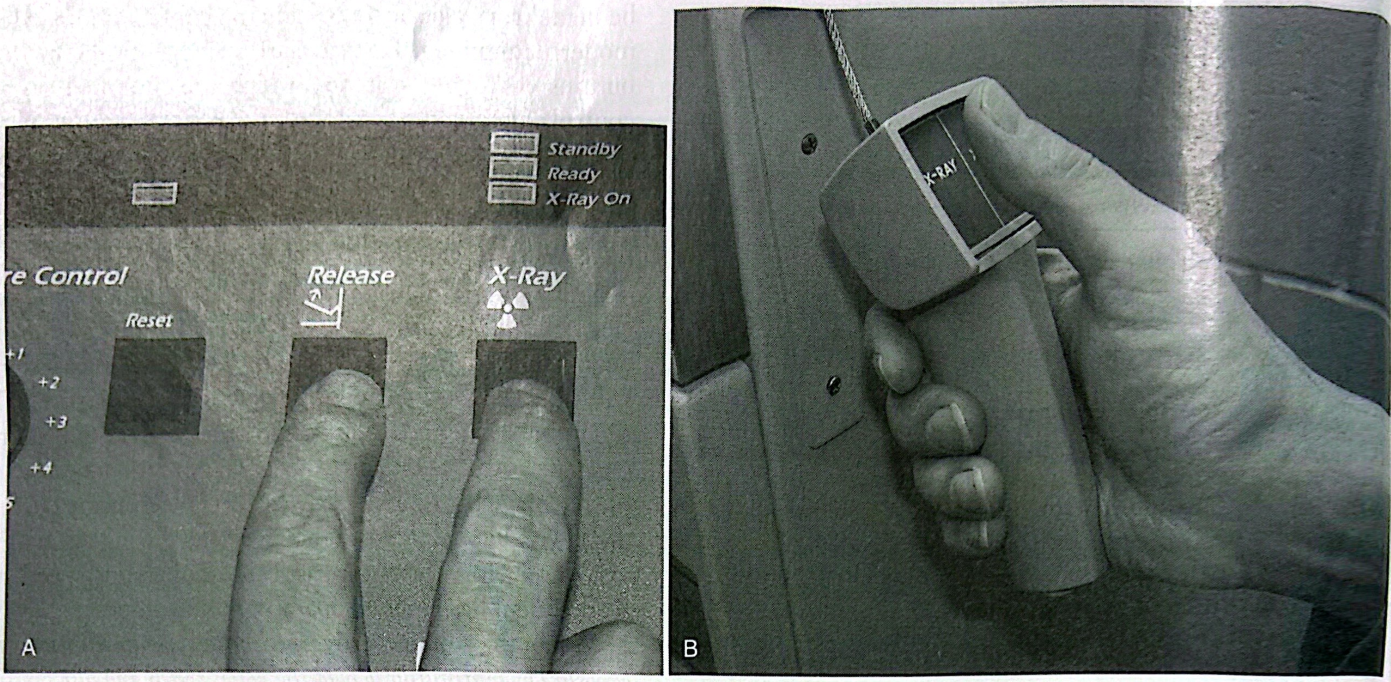

Fig. 6.21 Exposure devices. (A) Two-button finger exposure device. The left finger activates the rotor and, when ready, the right finger initiates the x-ray exposure. (B) Handheld device. The four fingers depress the rotor activator and, when ready, the thumb initiates the x-ray exposure.

Box 6.1
Setting Control Panel and Making an Exposure (Traditional X-Ray Control)

- Select milliamperes.
- Select exposure time.
- Select kilovolts peak major first, then minor.
- Set Bucky switch.
- Activate and hold rotor switch.
- On signal, activate and hold exposure switch.
- Observe exposure indicator to validate exposure and to determine when it is complete.
- Release rotor and exposure switches.

X-ray tubes that receive good care provide many years of service. Careless use, however, can significantly shorten the life of a tube and may result in sudden tube failure. Tube replacement is expensive and may cause the x-ray equipment to be out of service for some time. *The factors that affect tube life are controlled by the limited operator.* Responsible operators take care to ensure that x-ray tubes are not abused.

An excessive exposure on a cold tube will cause the anode to expand too rapidly and may cause it to crack and to fail. For this reason, a cool tube should be warmed up before any large exposure. The manufacturer may specify the warm-up procedure. Warm-up settings are preprogrammed into some computerized controls. In the absence of an established warm-up procedure, three exposures—30 seconds apart, at a setting of 200 mA, 0.5 second, and 80 kVp—will safely distribute heat throughout the anode. The warm-up procedure must be repeated if the tube has been idle for more than an hour. Exposures smaller than prescribed warm-up settings may be made without warming the tube. Warm-up exposures must be done before the patient enters the x-ray room. *Do not forget to do a preexposure safety check before doing warm-up exposures.*

A rapid series of large exposures or a single excessive exposure may damage the tube by melting the tungsten surface of the focal track. This melted tungsten boils and then cools to an irregular, pitted surface (Fig. 6.22). A tube that has been damaged in this way provides inconsistent radiation output and does not produce sharp images because of changes in the focal spot.

Nearly all x-ray generators in use today have lockout circuits that prevent single exposures beyond the tube's maximum heat capacity, but this feature should not be relied on as the only measure for tube heat protection. Tubes that are frequently used at or near their capacity will not last as long as tubes that are operated consistently at 80% of capacity or less. Generators today will have a red indicator light that will turn on if the exposure technical factors are too high for the tube rating.

Maximum tube capacity for a single exposure is determined by consulting the **tube rating chart** (Fig. 6.23). The chart is supplied by the tube manufacturer and is specific for each tube model. Today, rating charts do not have to be reviewed before each exposure because of the automated circuits that do not allow the wrong factors to be

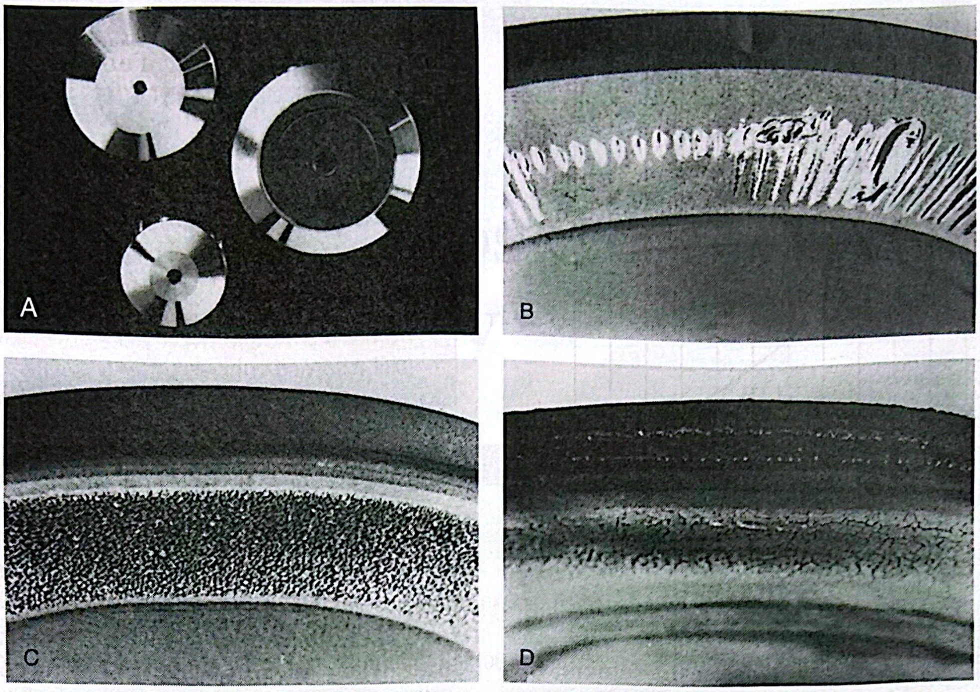

Fig. 6.22 Comparison of smooth, shiny appearance of rotating anodes when new (A) and their appearance after failure (B through D). Examples of anode separation and surface melting shown were caused by slow rotation due to bearing damage (B), repeated overload (C), and exceeding of maximum heat storage capacity (D).

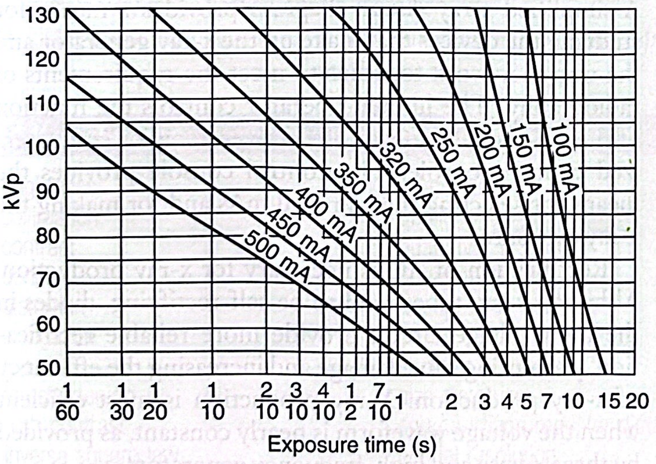

Fig. 6.23 Tube rating chart. Any combination of kilovolts peak *(kVp)* and exposure time below the curved milliamperes *(mA)* line in the chart will be safe.

set. However, tube rating charts are used when creating exposure technique charts or when programming the APR system. The chart is read by noting the point on the graph at which the horizontal line representing the kVp setting intersects with the vertical line representing the exposure time. If this point is below the curved line that represents the mA setting, the exposure is *safe*. If it is above the mA line, the exposure *exceeds* tube capacity.

The maximum heat capacity of the anode is rated in **heat units (HU)**. The HU produced by an exposure are determined by multiplying the kVp × mA × time. The heat unit formula varies depending on the design of the generator. Note there is an added multiplication factor for the three-phase and the high-frequency generators. The high-frequency generator will produce the most heat for the same technical factors. Specifically, it will produce 40% more heat than a single-phase. The HU factors are:

Single phase:

$$HU = mA \times Time \times kVp$$

Three phase:

$$HU = mA \times Time \times kVp \times 1.35$$

High frequency:

$$HU = mA \times Time \times kVp \times 1.40$$

An exposure of 70 kVp, 0.15 second, 300 mA using a three-phase generator would produce 4253 HU.

HU are used to calculate tube cooling time using a cooling chart (Fig. 6.24). Cooling charts also are provided by the tube manufacturer and are specific for each tube model. You will note that the chart in Fig. 6.24 was made for a tube with an anode heat capacity of 250,000 HU. If this tube were heated to its maximum capacity, half of the

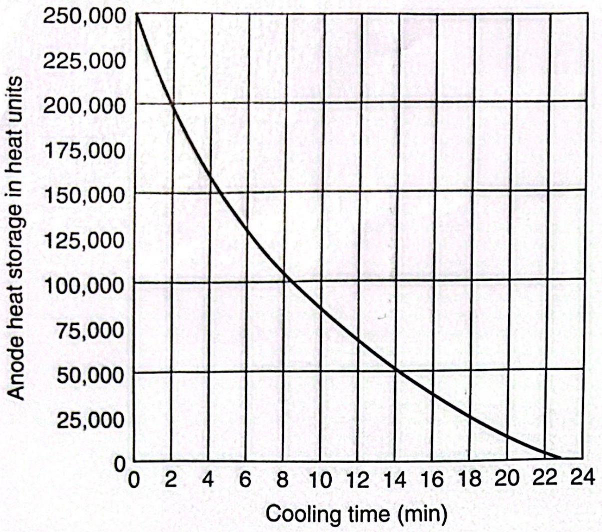

Fig. 6.24 Anode cooling chart.

HU would be dissipated within a period of 6 minutes. Cooling charts are used by service engineers, but they are seldom needed by limited operators.

It is important to note that tubes that are never overheated will eventually fail. With moderate use, an x-ray tube can last up to 8 years. The reason for failure is usually related to the events that occur when the rotor switch is activated. The anode rotor turns on precision ball bearings that are essential to its operation. These bearings wear out with use, and when this occurs, the tube must be replaced. During rotor activation, the filament is maintained at a high heat, resulting in tiny amounts of vaporization of the filament material. Over time, the diameter of the filament decreases until it is so thin that it breaks, similar to the failure of a light bulb filament that "burns out." The filaments are under greatest stress when used at the highest mA station to which they are connected. Using these settings only when needed will reduce filament wear and prolong tube life.

The life of rotor bearings and filaments can be greatly extended by minimizing the time that the rotor switch is activated. *Do not activate the rotor switch before you are completely ready to make the exposure.* Continuing to hold this switch, rather than proceeding with the exposure as soon as the tube is ready, increases wear on both bearings and filament, shortening tube life. Many radiographers develop the bad habit of starting the rotor switch before they begin to give breathing instructions to the patient. These instructions and their implementation take more time than is needed by the rotor, so this practice results in unnecessarily prolonged rotor time for every exposure. Most patients can easily hold their breath for the few seconds of preliminary rotor time, so it is best to start the rotor *after* the patient is ready. An exception to this rule is made when the patient is unable to cooperate and the radiographer must have instantaneous control over the timing of the exposure. This is often the case when performing radiography on infants and children. Box 6.2 gives recommendations for prolonging tube life.

Box 6.2

Extending X-Ray Tube Life

- Warm up the anode according to the manufacturer's instructions.
- Do not hold down the rotor switch for long periods of time.
- Use low mA settings whenever possible.
- Use the low-speed rotor whenever possible.
- Do not make repeated exposures near the tube limits.
- Do not use a tube when you can hear the rotor bearings (call a service engineer).

SUMMARY

A simplified x-ray circuit diagram provides a means for studying the devices that make up the x-ray generator and the way they work together to meet the requirements of radiography. The limited operator controls the function of these devices by means of a conventional or computerized control console. The control console provides the means for selecting the kVp and mAs and for making the x-ray exposure.

Rectification of AC is necessary for x-ray production. Although x-ray tubes tend to be self-rectifying, diodes in the high-voltage circuit provide more reliable rectification, preventing tube damage and increasing the efficiency of x-ray production. X-ray production is most efficient when the voltage waveform is nearly constant, as provided by three-phase and high-frequency generators.

The limited operator is responsible for implementing good practices to prolong x-ray tube life. These practices involve protecting the tube from sudden or excessive heating and minimizing the time that the rotor switch is activated.