X-RAY TUBE

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Radiology Equipment Technician I (X-Ray)

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Outline

X-ray tube

 - Basic Design

- Line focus principle

- Heel effect

Objectives

The student should be able to do the followings;

- Draw x-ray tube with its components
- Mention the role of x-ray components
- Explain the line focus principle.
- Define the heel effect.

X-Ray Tube

THE X-RAY tube is a component of the x-ray imaging system rarely seen by radiologic technologists. It is contained in a protective housing and therefore is inaccessible. Figure 6-1 is a schematic diagram of a rotating anode diagnostic x-ray tube. Its components are considered separately, but it should be clear that there are two primary parts: the cathode and the anode.

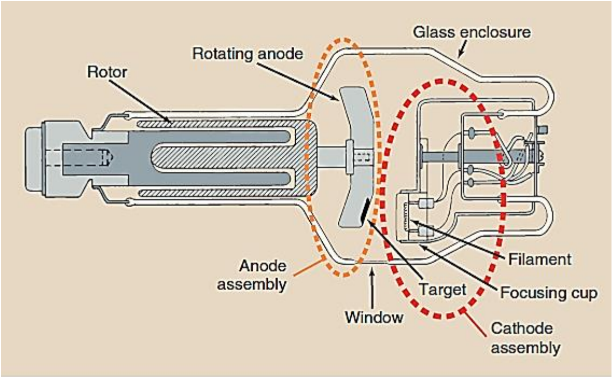
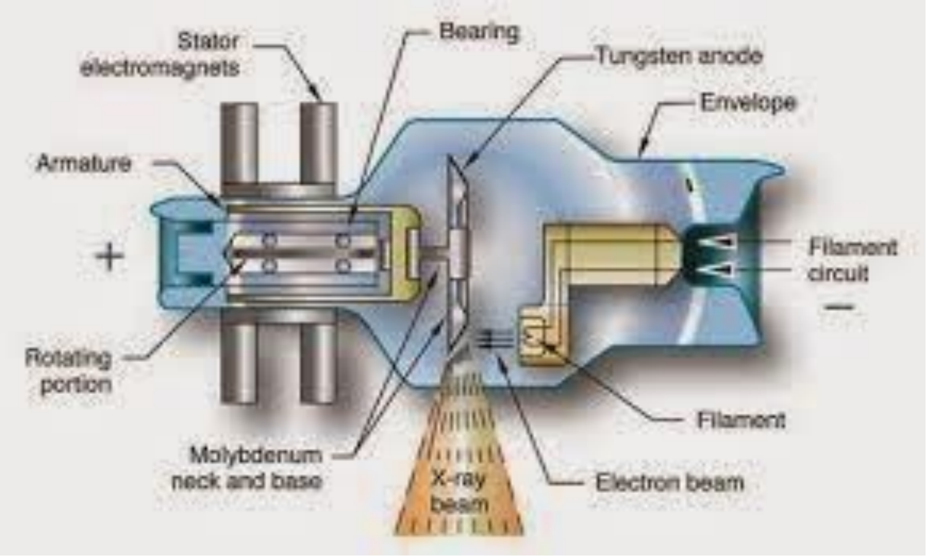


FIGURE 6-1 Principal parts of a rotating anode x-ray tube.

Each of these is an electrode, and any electronic tube with two electrodes is a diode. An x-ray tube is a special type of diode. The external structure of the x-ray tube consists of three parts: the support structure, the protective housing, and the glass or metal enclosure. The internal structures of the x-ray tube are the anode and the cathode.

X-Ray Tube

An explanation of the external components of the x-ray tube and the internal structure of the x-ray tube follows. The causes and prevention of x-ray tube failure are discussed. With proper use, an x-ray tube used in general radiography should last many years. X-ray tubes used in computed tomography (CT) and interventional radiology generally have a shorter life.



X-Ray Tube Components

EXTERNAL COMPONENTS

- The x-ray tube and housing assembly are quite heavy; therefore, they require a support mechanism so the radiologic technologist can position them. Figure 6-2 illustrates two of the three main methods of x-ray tube support.

1- the support structure:

Ceiling Support System, Floor-to-Ceiling Support System, and C-Arm Support System

video

EXTERNAL COMPONENTS

1. The Support Structure

1. Ceiling Support System

2. Floor-to-Ceiling Support System

3. C-Arm Support System

EXTERNAL COMPONENTS

2. Protective Housing

When x-rays are produced, they are emitted **isotropically,** that is, with equal intensity in all directions. We use only x-rays emitted through the special section of the x-ray tube called the **window** (Figure 6-3). The x-rays emitted through the window are called the **useful beam.** X-rays that escape through the protective housing are called **leakage radiation**; they contribute nothing in the way of diagnostic information and result in unnecessary exposure of the patient and the radiologic technologist. Properly designed protective housing reduces the level of leakage radiation to less than 1 mGy/h at 1 m when operated at maximum conditions.

Protective housing guards against excessive radiation exposure and electric shock.

EXTERNAL COMPONENTS

2. Protective Housing (cont.)

The protective housing incorporates specially designed high-voltage receptacles to protect against accidental electric shock. Death by electrocution was a very real hazard for early radiologic technologists. The protective housing also provides **mechanical support** for the x-ray tube and protects the tube from damage caused by rough handling. The protective housing around some x-ray tubes contains oil that serves as both an **insulator** against electric shock and as a thermal **cushion** to dissipate heat.

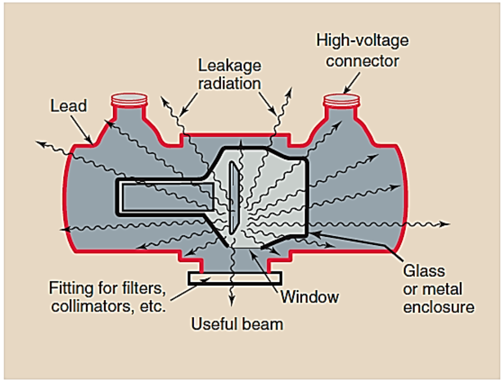


FIGURE 6-3 Protective housing reduces the intensity of leakage radiation to less than 1 mGy_a/h at 1 m.

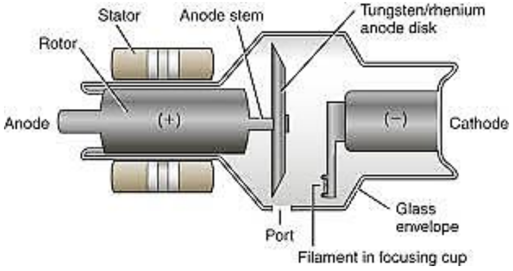
Some protective housings have a cooling fan to air cool the tube or the oil in which the x-ray tube is immersed. A bellows-like device allows the oil to expand when heated. If the expansion is too great, a microswitch is activated, so the tube cannot be used until it cools.

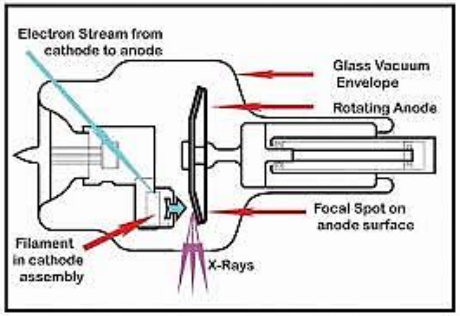
EXTERNAL COMPONENTS

3. Glass or Metal Enclosure

An x-ray tube is an electronic vacuum tube with components contained within a *glass or metal enclosure*. The x-ray tube, however, is a special type of vacuum tube that contains two electrodes: the cathode and the anode. It is relatively large, perhaps 30 to 50 cm long and 20 cm in diameter. The glass enclosure is made of Pyrex glass to enable it to withstand the tremendous heat generated. The enclosure maintains a vacuum inside the tube.

This vacuum allows for more efficient x-ray production and a longer tube life. When just a little gas is in the enclosure, the electron flow from cathode to anode is reduced, fewer x-rays are produced, and more heat is generated. Early x-ray tubes, modifications of the Crookes tube, were not vacuum tubes but rather contained controlled quantities of gas within the enclosure. The modern x-ray tube, the Coolidge tube, is a vacuum tube. If it becomes gassy, x-ray production falls, and the tube can fail.





[Crookes Tube Cathode Ray Tube]

EXTERNAL COMPONENTS

3. Glass or Metal Enclosure (cont.)

An improvement in tube design incorporates metal rather than glass as part or all of the enclosure.
As a glass enclosure tube ages, some tungsten vaporizes and coats the inside of the glass enclosure. This alters the electrical properties of the tube, allowing tube current to stray and interact with the glass enclosure; the result is arcing and tube failure.

Metal enclosure tubes maintain a constant electric /potential between the electrons of the tube current and the enclosure. Therefore, they have a longer life and are less likely to fail. Virtually all high-capacity x-ray tubes now use metal enclosures. The x-ray tube window is an area of the glass or metal enclosure, approximately 5 cm2, that is thin and through which the useful beam of x-rays is emitted. Such a window allows maximum emission of x-rays with minimum absorption.

INTERNAL COMPONENTS

1. Cathode

Figure 6-4 shows a photograph of a dual-filament cathode and a schematic drawing of its electric supply. The two filaments supply separate electron beams to produce two focal spots. The cathode is the negative side of the x-ray tube; it has two primary parts, a filament and a focusing cup. The **filament** is a coil of wire similar to that in a kitchen toaster, but it is much smaller. The filament is approximately 2 mm in diameter and 1 or 2 cm long. In the kitchen toaster an electric current is conducted through the coil, causing it to glow and emit a large quantity of heat. An x-ray tube filament emits electrons when it is heated. When the current through the filament is sufficiently high, the outer-shell electrons of the filament atoms are “boiled off” and ejected from the filament. This phenomenon is known as **thermionic emission**.

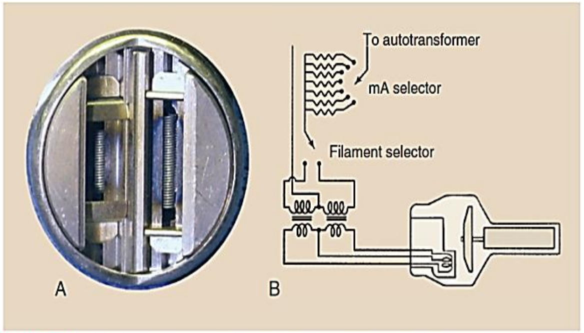
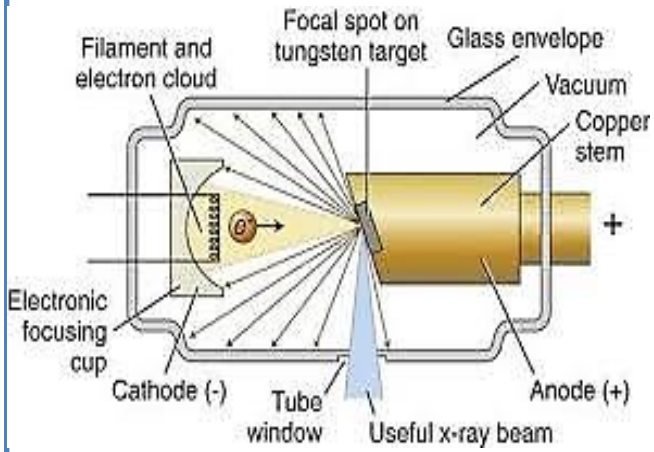


FIGURE 6-4 A, Dual-filament cathode designed to provide focal spots of 0.5 mm and 1.5 mm. B, Schematic for a dual-filament cathode.



INTERNAL COMPONENTS

1. Cathode (cont.)

Filaments are usually made of **thoriated tungsten**. Tungsten provides for higher thermionic emission than other metals. Its melting point is 3410°C; therefore, it is not likely to burn out like the filament of a light bulb.

Also, tungsten does not vaporize easily. If it did, the tube would become gassy quickly, and its internal parts would be coated with tungsten. The addition of 1% to 2% thorium to the tungsten filament enhances the efficiency of thermionic emission and prolongs tube life.

Tungsten vaporization with deposition on the inside of the glass enclosure is the most common cause of tube failure.

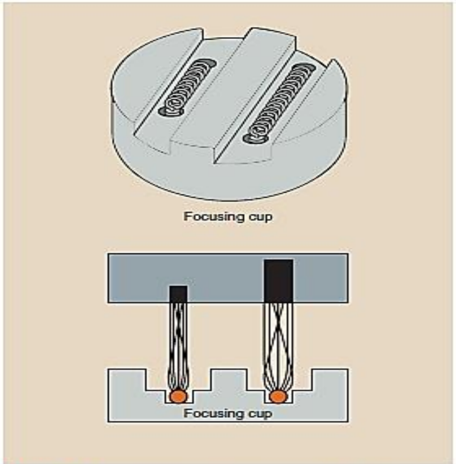


FIGURE 6-5 The focusing cup is a metal shroud that surrounds the filament.

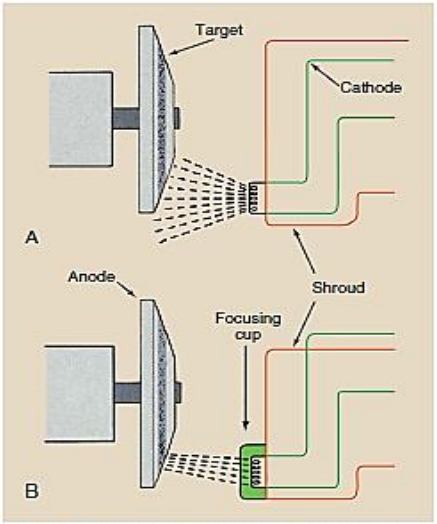


FIGURE 6-6 **A,** Without a focusing cup, the electron beam is spread beyond the anode because of mutual electrostatic repulsion among the electrons. **B,** With a focusing cup that is negatively charged, the electron beam is condensed and directed to the target.

INTERNAL COMPONENTS

1. Cathode (cont.)

Tungsten metal does vaporize and is deposited on internal components. This upsets some of the electric characteristics of the tube and can cause arcing and lead to tube failure. Such malfunction is usually abrupt The filament is embedded in a metal shroud called the **focusing cup** (Figure 6-5). Because all of the electrons accelerated from cathode to anode are electrically negative, the electron beam tends to spread out owing to electrostatic repulsion. Some electrons can even miss the anode completely.

The focusing cup is negatively charged so that it electrostatically confines the electron beam to a small area of the anode (Figure 6-6). The effectiveness of the focusing cup is determined by its size and shape, its charge, the filament size and shape, and the position of the filament in the focusing cup.

Most rotating anode x-ray tubes have two filaments mounted in the cathode assemble “side by side,” creating large and small focal spot sizes.

INTERNAL COMPONENTS

2. Anode

The anode is the positive side of the x-ray tube. There are two types of anodes, **stationary** and **rotating** (Figure 6-10). Stationary anode x-ray tubes are used in dental x-ray imaging systems, some portable imaging systems, and other special-purpose units in which high tube current and power are not required. General-purpose x-ray tubes use the rotating anode because they must be capable of producing high-intensity x-ray beams in a short time. The anode is the positive side of the x-ray tube; it conducts electricity and radiates heat and x-rays from the target. The anode serves three functions in an x-ray tube. The anode is an **electrical conductor.** It receives electrons emitted by the cathode and conducts them through the tube to the connecting cables and back to the highvoltage generator. The anode also provides *mechanical support* for the target.

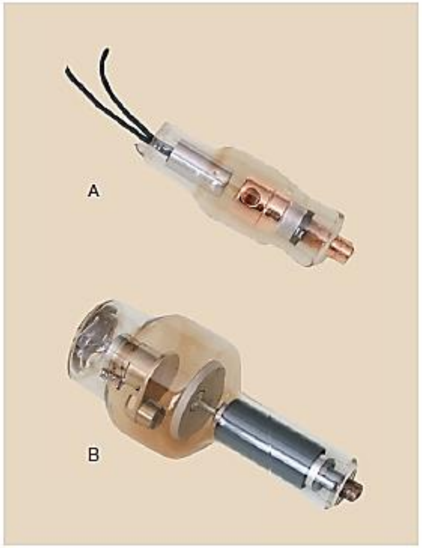


FIGURE 6-10 All diagnostic x-ray tubes can be classified according to the type of anode. **A,** Stationary anode. **B,** Rotating anode.

INTERNAL COMPONENTS

2. Anode (cont.)

The anode also must be a good **thermal dissipater**. When the projectile electrons from the cathode interact with the anode, more than 99% of their kinetic energy is converted into heat. This heat must be dissipated quickly. Copper, molybdenum, and graphite are the most common anode materials. Adequate heat dissipation is the major engineering hurdle in designing higher capacity x-ray tubes. Tungsten is the target material of choice for general radiography for three main reasons:

1. **Atomic number**—Tungsten's high atomic number, 74, results in high-efficiency x-ray production and in high-energy x-rays.
2. 2. **Thermal conductivity**—Tungsten has a thermal conductivity nearly equal to that of copper. It is therefore an efficient metal for dissipating the heat produced.

3. **High melting point**—Any material, if heated sufficiently, will melt and become liquid. Tungsten has a high melting point (3400°C compared with 1100°C for copper) and therefore can stand up under high tube current without pitting or bubbling.

INTERNAL COMPONENTS

2. Anode (cont.)

The *rotating anode* x-ray tube allows the electron beam to interact with a much larger target area; therefore, the heating of the anode is not confined to one small spot, as in a stationary anode tube. Figure 6-13 compares the target areas of typical stationary anode (4 mm^2) and rotating anode (1800 mm^2) x-ray tubes with 1-mm focal spots. Thus the rotating anode tube provides nearly 500 times more area to interact with the electron beam than is provided by a stationary anode tube.

Higher tube currents and shorter exposure times are possible with the rotating anode. The stem of the anode is the shaft between the anode and the rotor. It is narrow so as to reduce its thermal conductivity. The stem usually is made of molybdenum because molybdenum is a poor heat conductor.

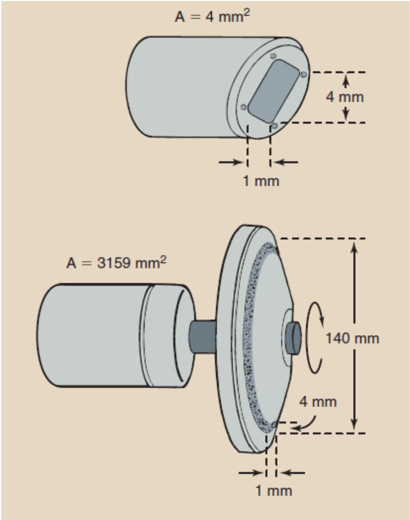


FIGURE 6-13 Stationary anode tube with a 1-mm focal spot may have a target area of 4 mm^2. A comparable 15-cm diameter rotating anode tube can have a target area of approximately 1800 mm^2, which increases the heating capacity of the tube by a factor of nearly 500.

LINE FOCUS PRINCIPLE

The **line focus principle** in radiography explains the relationship between the actual focal spot on the anode surface and the effective focal spot size.

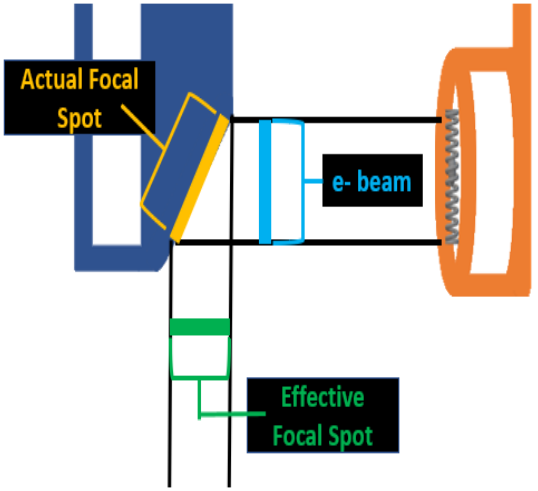
The focal spot is the area of the target upon which the electron beam strikes. The energy of the electrons in the electron beam is mostly converted into heat (approximately 99%, which is why materials such as tungsten are used due to their high melting-points) and dissipated uniformly across the focal spot and anode surface.

The x-rays produced at the anode comprise less than one percent of the energy of the electrons in the electron beam.

A large focal spot is therefore useful to protect the tungsten target as the heat accumulates and dissipates within the larger area of focal spot when compared to a small focal spot. However, a small focal spot is required to achieve good radiographic image quality.

Focal Spot

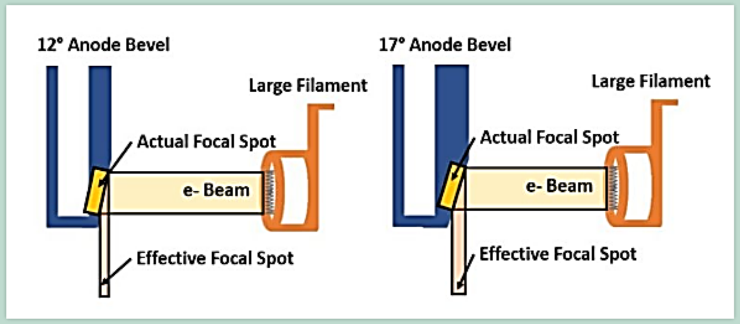
Focal spot is the area of the anode surface which receives the beam of electrons from the cathode. It is the apparent source of x-rays. Size and shape of the focal spot is determined by the size and shape of the electron beam when it strikes the anode.
To produce sharp images, focal spots need to be small but able to withstand heat loading without melting the anode target. A small focal spot is used when spatial resolution is important, while a large focal spot is employed when a short exposure time is the priority.



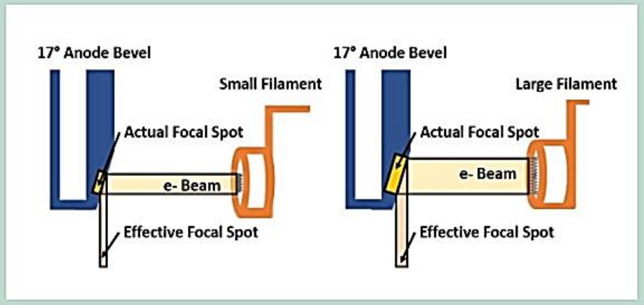
The actual focal spot is always larger than the effective focal spot because of the angle or bevel of the anode face.

The term focal spot is used to describe the area on the anode from which the x-rays are emitted, but the term focal spot can also be used to describe the source of the x-ray photons from the viewpoint of the image receptor. We can distinguish between these two uses of the term by adding “actual” or “effective” to the term.

Focal Spot (cont.)



Steeper anode angles result in smaller effective focal spots.



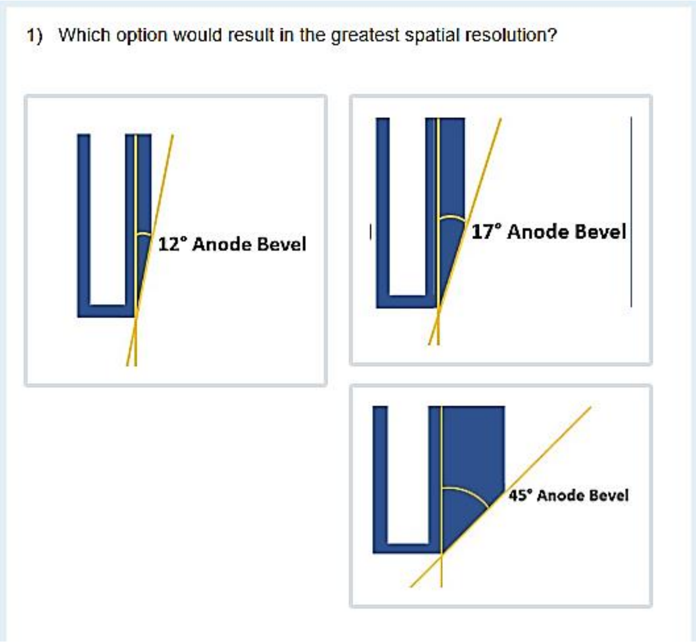
Smaller filaments produce smaller electron beams and smaller actual and effective focal spots. Larger filaments produce larger electron beams and larger actual and effective focal spots.

The **actual focal spot** describes the physical area of the focal track that is impacted by the electrons. The **effective focal spot** is the area of the focal spot that is projected toward the object being imaged and the image receptor. Because the edge of the anode where the electrons interact is beveled, or angled, the effective focal spot is always smaller than the actual focal spot. The effective focal spot size is determined by the size of the filament selected and the angle of the target bevel.

- Smaller filaments produce smaller effective focal spots. Larger filaments produce larger effective focal spots.
- Target bevels closer to vertical (0°) create smaller effective focal spots. Target bevels closer to parallel (90°) will produce larger effective focal spots.

Focal Spot (cont.)

As with many factors in the selection of radiographic techniques, the smaller effective focal spot produced by the target angle must be balanced with the variation in exposure across the image receptor caused by the anode-heel effect.

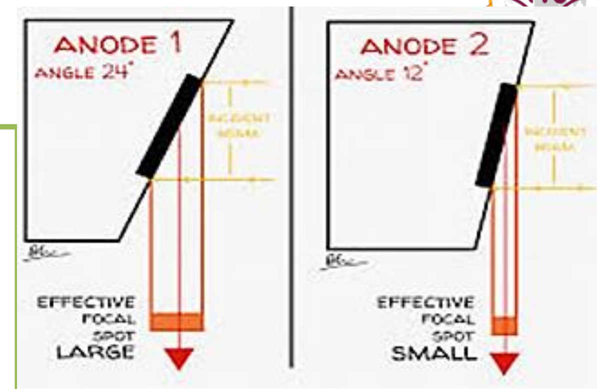


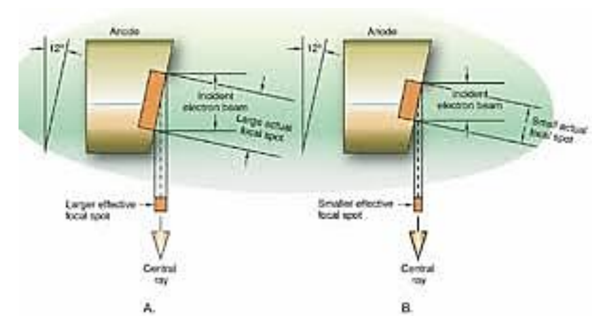
Focal Spot (cont.)

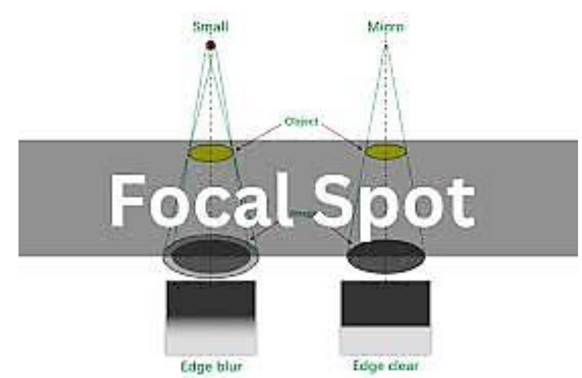
To produce sharp images, focal spots need to be small but able to withstand heat loading without melting the anode target. A small focal spot is used when spatial resolution is important, while a large focal spot is employed when a short exposure time is the priority.

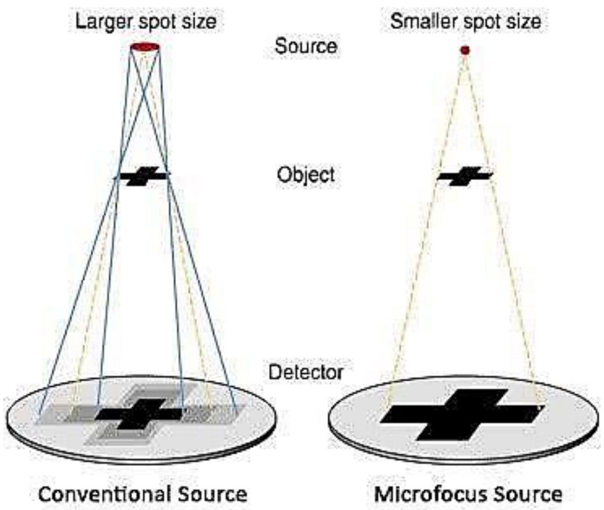
The focal spot sizes commonly employed are:
0.3 mm and 0.6 mm, usually for mammography
1.0 mm and 1.2 mm, usually for general radiography

The effective focal length of a focal spot can be calculated using:
Effective focal length = Actual focal length x sin θ
where **θ** is the anode angle



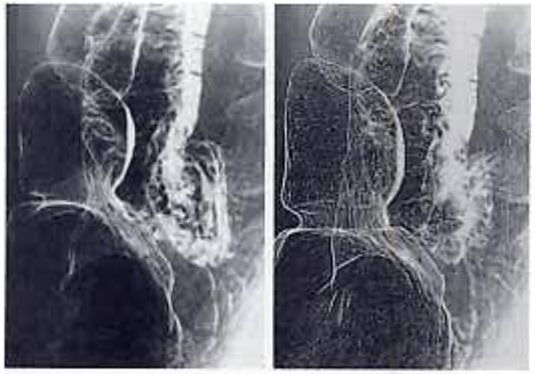




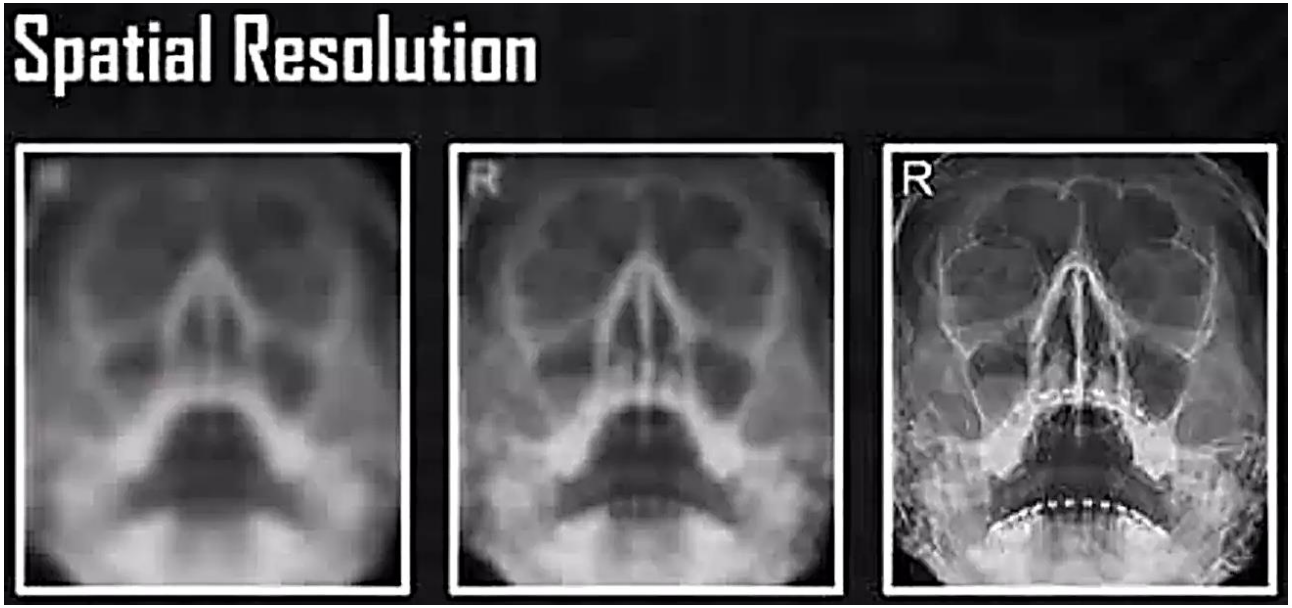

Larger spot size
Smaller spot size
Source
Object
Detector
Conventional Source
Microfocus Source


High Det Resolution
Medium Det Resolution
Low Det Resolution


Small
Large
eXtra Large




B
Small focal spot
Large focal spot-
Reduction in sharpness


Spatial Resolution
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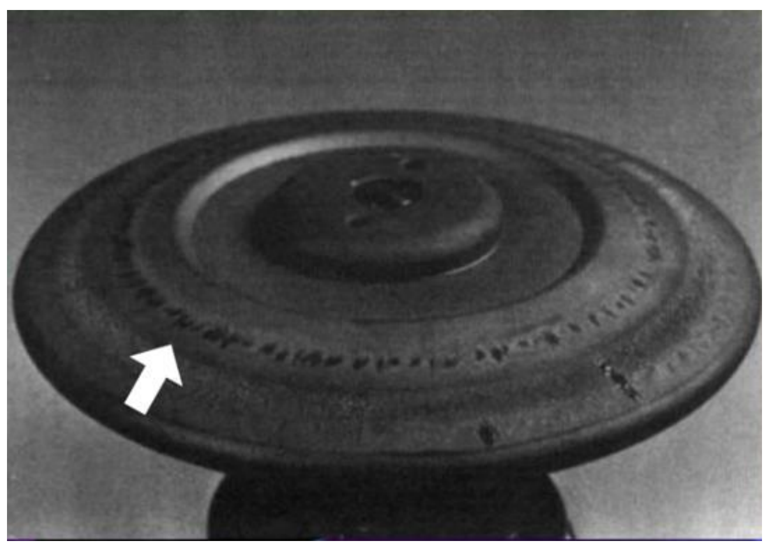
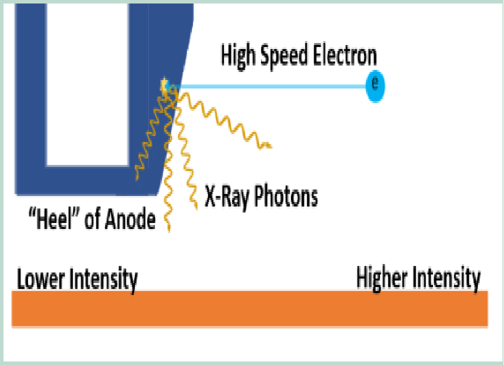


Heel Effect

ANODE-HEEL EFFECT: The anode-heel effect is a variation in x-ray intensity along the length of the x-ray tube caused by absorption of x-ray photons by the anode. We know that tungsten has a high atomic number and, while that makes it a good target for the production of x-rays, it also makes it a good absorber of x-rays.



X-rays that exit the site of interaction in a direction toward the anode end of the x-ray tube travel through a much thicker amount of metal and are much more likely to be absorbed before leaving the anode. This means that the x-ray intensity is greater on the side of the image receptor positioned under the cathode and lower on the end under the anode.

Interventional radiology (IR) is the use of medical imaging techniques to guide doctors as they diagnose and treat certain problems with blood vessels and lymph vessels throughout the body. IR is also called image-guided therapy

Heel Effect

IR exposure varies across the length of the IR due to the anode-heel effect.
Exposure is higher on the cathode side of the image, because x-rays reaching this side of the IR travel through less metal.
Exposure is lower on the anode side of the image, because x-rays reaching this side of the IR travel through more metal and are more likely to be absorbed before leaving the tube.

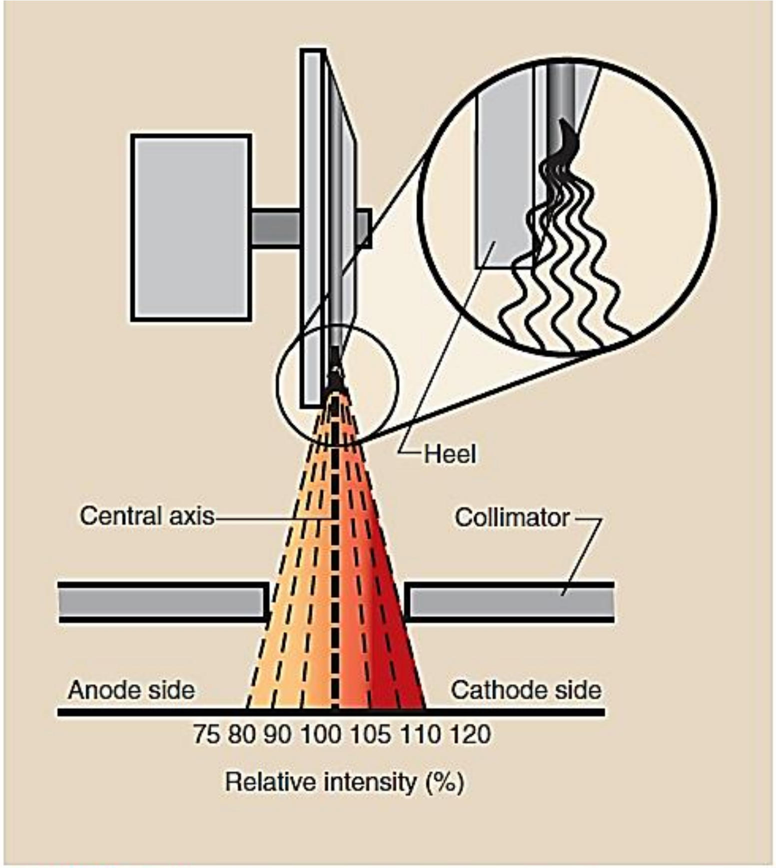


FIGURE 6-20 The heel effect results in reduced x-ray intensity on the anode side of the useful beam caused by absorption in the "heel" of the target.

X-RAY TUBE FAILURE

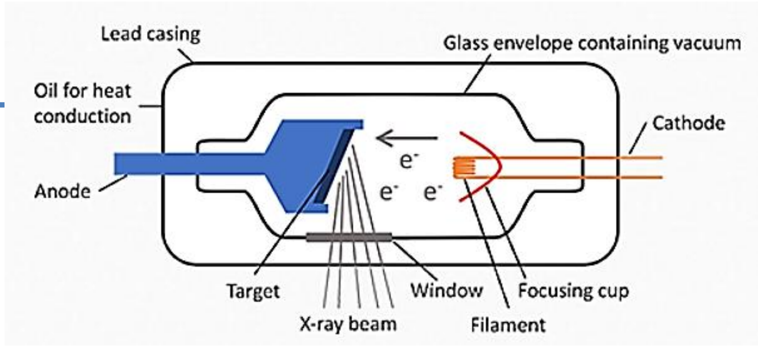
With careful use, x-ray tubes can provide many years of service. With inconsiderate use, x-ray tube life may be shortened substantially. The length of x-ray tube life is primarily under the control of radiologic technologists. Basically, x-ray tube life is extended by using the minimum radiographic factors of mA, kVp, and exposure time that are appropriate for each examination. The use of faster image receptors results in longer tube life.

X-ray tube failure has several causes, most of which are related to the thermal characteristics of the x-ray tube. Enormous heat is generated in the anode of the x-ray tube during x-ray exposure. This heat must be dissipated for the x-ray tube to continue to function. This heat can be dissipated in one of three ways: radiation, conduction, or convection. **Radiation** is the transfer of heat by the emission of infrared radiation. Heat lamps emit not only visible light but also infrared radiation. **Conduction** is the transfer of energy from one area of an object to another. The handle of a heated iron skillet becomes hot because of conduction.

Convection is the transfer of heat by the movement of a heated substance from one place to another. Many homes and offices are heated by the convection of hot air.

Overview

- A current is passed through the tungsten filament and heats it up.
- As it is heated up the increased energy enables electrons to be released from the filament through thermionic emission.
- The electrons are attracted towards the positively charged anode and hit the tungsten target with a maximum energy determined by the tube potential (voltage).
- As the electrons bombard the target they interact via Bremsstrahlung and characteristic interactions which result in the conversion of energy into heat (99%) and x-ray photons (1%).
- The x-ray photons are released in a beam with a range of energies (x-ray spectrum) out of the window of the tube and form the basis for x-ray image formation.



Overview

Target, focus, focal point, focal spot: where electrons hit the anode
Actual focal spot: physical area of the focal track that is impacted
Focal track: portion of the anode the electrons bombard. On a rotating anode this is a circular path
Effective focal spot: the area of the focal spot that is projected out of a tube
Window: made of beryllium with aluminium or copper to filter out the soft x-rays. Softer (lower energy) x-ray photons contribute to patient dose but not to the image production as they do not have enough energy to pass through the patient to the detector. To reduce this redundant radiation dose to the patient these x-ray photons are removed.
Glass envelope: contains vacuum so that electrons do not collide with anything other than target.
Insulating oil: carries heat produced by the anode away via conduction.
Filter: Total filtration must be >2.5 mm aluminium equivalent (meaning that the material provides the same amount of filtration as a >2.5 mm thickness of aluminium) for a >110 kV generator

References

- Bushong S. C., . (2017). *Radiologic science for technologists*. St. Louis, Missouri: Elsevier.
- Guy C. and Ffytche D. (2005). *An Introduction to The Principles of Medical Imaging*. Imperial College Press