LECTURE 8

X-RAY TUBES AND ITS OPERATION
Lesson Objectives

Upon completion of this lesson, the student should be able to:-

- Discuss the characteristics of x-ray tube.
- Explain the function and design of its components.
- Explain the principle operation of x-ray tube.
X-RAY TUBE
The X-ray Tube

- The x-ray tube is divided into four major components.
  1) Cathode Assembly
  2) Anode Assembly
  3) Glass Envelope
  4) Protective Housing
CATHODE ASSEMBLY
1) The Cathode Assembly

- The cathode is the negative side of the tube.
- The function of the cathode is to produce a thermionic cloud, conduct the high voltage to the gap between cathode and anode and focus the electron stream to the anode target.
- It contains two primary parts:
  a) The filaments
  b) The focusing cup
a) The Filaments

• Most tube have two filaments (dual focus) which provide a choice of quick exposures or high resolution.

• The filaments are made of thoriated tungsten.

• Tungsten is used in x-ray tube because of it’s high melting point of 3370°C.
a) The Filaments

• X-rays are produced by thermionic emission when 3-6 Amps of current is applied from the filament circuit.
• The wire: 0.1-0.2mm thick, The coil: 1-2mm wide, 7-15mm long.
• Filament materials
  – Tungsten - most widely used material
• High boiling point (3,370° C)
• It is difficult to vaporize
  – Rhenium (3,170° C)
  – Molybdenum (2,620° C)
Space Charge Effect

• When emitted by the filament, the electrons form a cloud near the filament momentarily before being accelerated to the anode. This is called a space charge.
Saturation Current

- When very high mA and very low kVp, the thermionic emission can be space charge limited.
- With high mA the cloud makes it difficult for subsequent electrons to be emitted.
- Above 1000 mA space charge limited exposure can be a major problem.
b) Focusing Cup

- The filaments are mounted within a focusing cup.
- Generally made of nickel, stainless steel, or molybdenum.
- Focuses the electrons on a smaller spot of the anode.
- This improves detail on the film.
- The focusing cup has a negative charge so that it can condense the electron beam to a small area of the anode.
Focusing Cup

Cathode

Anode

Filament emitting electrons

Strong Negative Charge

Electron Beam

Focal Spot

Strong Negative Charge
Dual Focal Spots
Fig. 7-6.  A, Without a focusing cup, the electron beam would be spread beyond the anode because of mutual electrostatic repulsion among the electrons.  B, With a focusing cup, which is negatively charged, the beam is condensed and directed to the desired area of the anode.
ANODE ASSEMBLY
The Anode Assembly

• The anode is the positive side of the tube.
• It is struck by the electron stream.
• The area struck is the anode target.
• Usually made of tungsten.
• A great deal of heat is produced at the anode.
  – Depends on the voltage, the current, and the length of time the anode is struck by electrons
The Anode Assembly

- X-ray tubes are classified by the type of anode:
  a) Stationary (top)
  b) Rotating (bottom)
a) The Stationary Anode

- **Stationary anodes** are used in dental x-ray and some portable x-ray machine where high tube current and power are not required i.e used when lower heat quantities are produced.
- Consists of a tungsten target and copper block and stem.
- Copper conducts the heat away from the tungsten target.
- The heat can damage the anode target, causing pitting
  - Results in x-ray beam of reduced intensity due to scattering and absorption in the uneven surface
b) The Rotating Anode

- The rotating anode allows the electron beam to interact with a much larger target area.
- The heat is not confined to a small area.
Rotating Anode Construction

- Tungsten-Rhenium
- Molybdenum
- Graphite
b) The Rotating Anode

- The first was made by Philips Medical Systems in Holland in 1929
- Consists of a tungsten alloy disk on a molybdenum base
- Rotating anodes range in size from about 5 cm to 12.5 cm
- Disk sizes determine the thermal load
- Anodes have an angle of about 7° to 20°
b) The Rotating Anode

• The anode serves three functions:
  – Receives the electrons emitted from the cathode.
  – It is a electrical conductor.
  – Mechanical support for the target.
b) The Rotating Anode

- The Anode must also be a good thermal conductor.
- When the electron beam strikes the anode more than 99% of the kinetic energy is converted to heat.
b) The Rotating Anode

- Consists of two main parts:

  1) Stator
  - Rests just outside of the glass tube
  - Made up of a series of electromagnets equally spaced around the neck of the tube
    - Designed to energize opposing pairs, in sequence, so that they induce the rotation of the rotor.

  2) Rotor
  - Located within the glass tube
  - Made up of copper bars & soft iron around a molybdenum shaft
    ***Mutual Induction***
Rotating Anode Induction Motor

Stator of Induction Motor

Rotor of Induction Motor

Anode Stem

Anode Disk

Filament

Glass Envelope
b) The Rotating Anode

- The rotor is an electromagnetic induction motor.
- It spins at 3400-3600 rpm.
- Latest or High speed anodes spin at 10,000 rpm.
b) The Rotating Anode

- Even with the anode rotating, some melting occurs. The heat must be rapidly dissipated.
- Molybdenum and copper are used to rapidly transfer the heat from the target.
b) The Rotating Anode

- When the exposure button is depressed, current is applied to the tube that produces a magnetic field that starts the rotation of the anode.
b) The Rotating Anode

- When the anode is spinning at the correct speed, the exposure can be made.
- After the exposure is completed, it slows by reversing the motor.
The Benefits Of Using Tungsten As A Target Material

- High melting point - 3370° C
- High Z number
- Resists vaporization at high temperatures
- Ability to conduct heat away from area of heat production
- Its density
- Ability to absorb heat without raising the temperature of the conductor
- Its availability makes it cost-effective
GLASS ENVELOPE
c) The Glass Envelope

- The glass envelope is made of Pyrex to withstand the tremendous heat produced during x-ray.
- The window is a 5 cm square with a thin section of glass where the useful beam is emitted.
c) The Glass Envelope

- Surrounds entire cathode & anode assemblies except for the stator
- Made of several layers of Pyrex w/ varying densities
- Glass is fitted to the metal of the anode & cathode ends
- Must be airtight to maintain a good vacuum
- A target window is constructed in the glass envelope to allow less scatter & attenuation of the photons
  - In most tubes - simply a thinner “cut” of glass
  - In mammography - a special metallic beryllium window prevents attenuation of lower energy photon
PROTECTIVE HOUSING
d) Protective Housing

- The tube is housed in a lead lines metal protective housing.
- The x-ray photons are generated isotropically or in all directions.
- The housing is designed to limit the beam to window.
d) Protective Housing

- The tube cannot have more than 100 mR at 1 m (26 µC/kg) / Hour when operated at its maximum output.
d) Protective Housing

- The housing also provide mechanical support and protection from damage.
- On some tubes, the housing also contains oil that provides more insulation and a thermal cushion.
d) Protective Housing

- Never hold the tube during an exposure.
- Never use the cables or terminals as handles.
d) Protective Housing

- The housing incorporates specially designed high voltage receptacles to protect against electrical shock.
- Some housing have a fan for cooling.
OPERATIONAL AND PRINCIPLE
The x-ray tube uses all three forms of cooling.

- Radiation
- Conduction
- Convection
Focal Tracks

- With a rotating anode, the electrons strike a moving target forming focal tracks on the tube.
Focal Area Available for

\[ A = 4 \text{ mm}^2 \]
Anode Area versus Disk Size
Focal Spot

- Actual focal spot - the area of the target material being bombarded by electrons from the filament.
- Effective focal spot - the imaginary geometric line that can be drawn based on the actual focal spot size vs. the angle of the anode.
- Best described by the angle of the anode
  - the smaller the angle of the anode, the smaller the effective focal spot size (any angle <45 degrees results in the effective FS being smaller than the actual FS)
  - 12 degrees target angle most common because it is the minimum that will cover a 14x17 at 40”
Anode Angle versus Focal Spot Size

Same Actual Focal Spot Size

Larger Effective Focal Spot

Central Ray

Smaller Effective Focal Spot

Central Ray
Anode Angle versus Focal Spot Size

Cath Lab: need 9" beam at 40" from FS (up to 14" for vasc)
Line-Focus Principle

• The focal spot is the area of the anode from which the x-rays are emitted.
• The focal spot impacts the geometric resolution of the x-ray image.
Line Focus Principle

1 x 1 mm

Note: effective size is larger at cathode side of beam

Apparent Size from receptor's point-of-view (effective size)

Electron Beam

Rotating Anode

15°

Focal Spot
Line-Focus Principle

• By angling the anode target, one makes the effective focal spot much smaller than the actual area of interaction.
• The angling of the target is know as the line focus principle.
Line-Focus Principle

- The **Effective Focal Spot** is the beam projected onto the patient.
- As the anode angle decreases, the effective focal spot decreases.
- Diagnostic tube target angles range from 5 to 15°.
Line-Focus Principle

• The advantage of Line focus is it provides the sharpness of the small focal spot with the heat capacity of the large focal spot.
Line-Focus Principle

• Smaller target angles will produce smaller effective focal spots and sharper images.
• To cover a 17” the angle must be 12°
• To cover 36” the angle must be 14°
Off Focal Radiation

• Remember that x-rays are produced in all directions. The electrons can rebound and interact with other areas of the anode.
• This is called Off-Focal Radiation.
Control of Off Focal Radiation

- A diaphragm is placed between the tube and the collimator to reduce off focus rays.
Anode Heel Effect

- One unfortunate consequence of the line-focus principle is that the radiation intensity on the cathode side of the x-ray tube is higher than the anode side.
Heel Effect

ANODE

17°

X-Ray Beam

10°

INCREASING INTENSITY

INCREASING INTENSITY
Heel Effect

Due to attenuation in tungsten. Exit path is longer at anode side.

Intensity is lower at anode side of field.
Anode Heel Effect

• The x-rays are emitted isotropically or in all directions.
• Some of the beam is absorbed by the target resulting in a lower intensity.
Anode Heel Effect

• The difference in the intensity can vary by as much as 45%.

• If the center is 100% the anode side of the beam can as low as 75% and the cathode as much as 120%.
Anode Heel Effect

• The heel effect should be considered when positioning areas of the body with different thickness or density.

• The cathode side should be over the area of greatest density.
Anode Heel Effect

• As the angle of the anode decreases, the anode heel effect increases.

• This can result in incomplete coverage of the film with the beam.
Anode Heel Effect on Resolution

• The sharpness of the image can be dependent upon which area of the beam coverage you are looking at.

• Similar to the shape distortion when the tube is not centered.
Anode Heel Effect

- The anode should be up and the cathode down for the full spine x-ray.
- The patient is less dense at the c-spine and more dense at the pelvis.
Causes of X-ray Tube Failure

- All causes of tube failure relate to the thermal characteristics of the tube.
- When the temperature of the anode during a single exposure is excessive, localized melting and pitting occurs.
- These surface irregularities lead to variable and reduced radiation output.
Causes of X-ray Tube Failure

- If the melting is severe, the tungsten vaporizes and can plate the port. This can cause added filtering or interference with the flow of electrons.
- If the temperature of the anode increases too rapidly, the anode can crack and then become unstable in rotation.
Causes of X-ray Tube Failure

• Maximum radiographic techniques must never be applied to a cold anode.
• These images show damage to the anode,
Causes of X-ray Tube Failure

- During long exposures (1 to 3 seconds) the anode may actually glow like a light bulb.
- The heat may cause a failure of the bearing for the anode or a crack in the glass envelope.
Filament failure

• Because of the high heat of the filament, tungsten atoms are slowly vaporized and plate the inside of the glass envelope. This will eventually lead to arcing and tube failure.

• Continuous high mA radiography will actually lead to the filament breakage.
Tube Warm-up Procedures

• By warming the anode through a series of exposures and increasing kVp settings, the anode will build up heat that is needed to avoid fracture of the anode.

• This process takes a little over one minute put will add to the life of the tube.

• Close shutters of collimator.
Sample Tube Warm-up Procedures

• Make exposure of 12 mAs @ 70 kVp
• Wait 15 seconds
• Make exposure of 12 mAs @ 80 kVp
• Wait 15 seconds
• Make exposure of 12 mAs @ 90 kVp
• Tube warm up is now complete.
RATING CHARTS AND COOLING CURVES
X-ray Tube Rating Charts

• It is essential for the radiographer to understand how to use tube rating charts.
• There are three types of charts:
  – X-ray/Radiographic Rating Chart
  – Anode Cooling Chart
  – Tube Housing Cooling Chart
X-ray/Radiographic Rating Charts

• Provide as a guide regarding max exp factors that can be used without overloading the tube.
• With careful use, the x-ray tube can provide long periods of service.
• Inconsiderate or careless operation can lead to shortened life or abrupt failure.
X-ray/Radiographic Rating Charts

• The mA is graphed as a curved line.
• Any combination of kVp and Time below the line should be safe for a single exposure.
• Example:
• Is an exposure of 80kVp and 0.1 second and 150 mA within the limits of the 1φ, 0.6mm focal-spot tube rating chart shown in the figure.
X-ray/Radiographic Rating Charts

• Tube life is extended by:
  1. Use of minimum mAs & kVp appropriate for the exam.
  2. Use of faster images receptors require lower mAs and kVp. They extend tube life.
Anode Cooling Chart

• Permit calculation of the time necessary for the anode to cool enough for additional exposures to be made.
• The anode has a limited capacity for storing heat.
• Heat is continuously dissipated to the oil bath and tube housing by conduction and radiation.
• A heat unit (HU) is calculated as kVp x mA x time x rectification constant.
• Rectification constant

<table>
<thead>
<tr>
<th>Rectification</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1φ 2 pulse (full wave)</td>
<td>= 1.00</td>
</tr>
<tr>
<td>3φ 6 pulse</td>
<td>= 1.35</td>
</tr>
<tr>
<td>3φ 12 pulse</td>
<td>= 1.41</td>
</tr>
<tr>
<td>High Frequency</td>
<td>= 1.45</td>
</tr>
</tbody>
</table>
• Example:
• How many heat units are generated by an exposure of 80kVp, 200mA and 0.2 second on a 1φ full-wave rectified unit?
• Answer:-

\[ kV \times mA \times s \times CU = HU \]
Anode Cooling Chart
• To use this chart:-

A) convert the exp factors in heat unit
B) find the total heat units applied on the vertical scale
C) Read from the heat units over to the cooling curve and then down to read the corresponding time
D) Calculate time necessary for the anode cool to any desired level and subtract the corresponding time of the initial exposure.
Anode Cooling Chart

- This chart is not dependent upon the filament size or speed of anode rotation.
- The cooling is rapid at first but slows as the anode cools. It is not uncommon for it to take 15 minutes to cool the tube.
Housing Cooling Charts

• The tube housing cooling chart is very similar to the anode cooling chart.
• Permit calculation of time necessary for the housing to cool enough for additional exposures to be made.
• The tube housing will generally have a capacity of about 1 to 1.5 million HU.
• Complete cooling may take 1 to 2 hours.
Housing Cooling Characteristics

Housing Heat Units (PKV x MA x SEC) vs. Cooling Time In Minutes

- Housing Heat Units range from 0 to 1,250,000 on the y-axis.
- Cooling time in minutes ranges from 0 to 150 on the x-axis.

The graph shows a downward trend, indicating a decrease in housing heat units as the cooling time increases.
Next lesson...

• Care and precaution of x-ray tube
• X-ray tube aging