Chapter 5

Radiography

5.1 Introduction

Source: Penetrating radiation: x-ray, gamma-rays, neutrons.

Modification: Intensity of transmitted radiation is affected by changes in density, composition and discontinuity.

Detection: Transmitted radiation is detected by a film or radiation detectors.

5.2 Basic Physics and Modification

Dealing mainly with x- and gamma-rays.

- X-rays and gamma-rays are electromagnetic radiation, with wavelength less than that of ultraviolet rays.

- Electromagnetic radiation travels at the speed of light ($c = 2.997925 \times 10^8 \approx 3 \times 10^8$m/s

- Photons are packets of radiation, each carrying an energy, $E = h\nu$, where h is Planck's constant (6.6256×10^{-34} Js) and f is radiation frequency.

- E is usually expressed in electron-volts, eV, 1 eV = 1.6021×10^{-19}J, and is the range of 1 meV to 10 MeV.

- Wavelength, $\lambda = c/\nu$ can be expressed as:

$$\lambda(\mu\text{m}) = \frac{12,400}{E(\text{eV})} \tag{5.1}$$

- Intensity of radiation, I, is the number of photons per unit time, while the energy is the energy of a single photon.

- Radiation flux, ϕ, is the number of photons per unit area per unit time, or more rigorously the number of photon tracks per unit volume per unit time.

- Radiation fluence, ψ is the time integrated flux, with units of photons per unit area.

- Law of Divergence: $4\pi R^2 \times \phi = \text{constant}$, where R is distance of travel.

- Therefore radiation intensity, flux and fluence follow the $1/R^2$ law, i.e.,

$$\frac{I_1}{I_2} = \frac{R_2^2}{R_1^2} \tag{5.2}$$

- In matter, the intensity of a *narrow beam* of radiation decreases exponentially, such that:

$$I = I_0 \exp[-\mu x] \tag{5.3}$$

  where x is distance of travel, I_0 is intensity at $x = 0$ and μ is called the linear attenuation coefficient.

- Value of μ depends on density and nature of material, as well as radiation energy.

- μ/ρ is called the mass attenuation coefficient, where ρ is the material density, μ/ρ is not too sensitive to changes in material.

- The intensity of a radiation beam transmitted though a material of thickness x will change from $I_0 \exp[-\mu x]$ to $I_0 \exp[-\mu(x - \delta) - \delta\mu\prime]$, as the radiation passes through a discontinuity of thickness δ, and attenuation coefficient $\mu\prime$; note that if $\mu\prime < \mu$, as in the case of cracks, the transmitted beam intensity will increase, while if $\mu\prime > \mu$, as in the case of dense inclusions, the transmitted beam intensity will decrease.

- Buildup Effect: for a wide beam, scattering of radiation can contribute to the measured transmitted signal, modifying Eq. (5.3) to:

  $$I = BI_0 \exp[-\mu x] \tag{5.4}$$

  where B is called the buildup factor, $B = 1 + I_s/I_D$, where I_s is the scattered component and I_D is the direct, uncollided component; B is function also of material density and photon energy.

- If buildup is not reduced, or accounted for, it can affect the interpretation of the signal, as it affects the value of the transmitted radiation.

- Note that also radiation divergence affects the intensity of the transmitted signal and consequently influences the interpretation process.

- The attenuation of photons in matter is governed by the following three main interactions:

  Photo-absorption: (photoelectric effect) dominant at low photon energies:

    - Entire photon energy is given to the inner electrons of the atom.
    - Electron may be ejected from their orbits (excited) and if fast may subsequently cause ionization of atoms.

  Compton scattering: dominates at moderate photon energies:

    - Photon interacts with free-electrons in an elastic-like manner.
    - Part of photon energy is given to the electron, electron escapes from atoms leading to ion-pair formations, fast electrons cause ionization.
    - Photon emerges with a lower energy and at a different direction.
    - Reaction responsible for the buildup effect

  Pair Production: occurs only for $E > 1.022$ MeV, mainly above 4 MeV or so:

    - Photon is disintegrated and an electron and a positron emerge in opposite directions.
    - Pair formation consumes 1.022 MeV of the reaction (2× rest mass of each particle), and remaining energy is shared between the two particles.
    - Electron and positron cause ionization.

  - Positron annihilates with an electron creating two photons, each with 0.511 MeV energy, travelling in opposite directions.
  - One of these photons may reach the transmission detector, or film, affecting the value of the transmitted radiation.
  - Reaction is not likely to occur with the source commonly used in radiography.

5.3 Sources

5.3.1 X-Rays

- Produced by high-energy electrons bombarding an electron-rich target (usually made of tungsten).
- Electrons are produced by a hot filament.
- Electrons are accelerated in vacuum (10^{-2} Pa) by a high voltage electric field, giving each electron an energy of eV_p, where e is the electronic charge and V_p is the applied voltage (20 kV to 20 MV).
- Incident neutrons excite the innermost electrons in the target atoms, when upon returning to a more stable state releases photons, the x-rays.
- A window of aluminum or beryllium (low absorption) is provided in the vacuum chamber to allow x-rays to exit.
- Photon energy can vary contniously any where from zero to the maximum possible energy of eV.
- The continuous energy spectrum is due to the deflection of electrons by the strong electromagnetic fields surrounding the nuclei of the atoms of the target (bremsstrahlung radiation).
- The photon energy spectrum contains peaks (called the line spectra) corresponding to electron transitions between the shells of the target atom.
- X-ray machines are related by the peak energy, eV_p, or simply the applied voltage V_p, called peak voltage as it corresponds to the peak energy.
- Average photon energy is about $\frac{1}{3}eV_p$.

- Increasing in V_p adds to the spectrum, photons with higher frequency (i.e. energy).
- Current intensity, measured in mA, affects the intensity of radiation emitted, but not its energy distribution.
- Efficiency of x-ray production = $ZV_p/10^7$, where Z is the atomic number of target nucleus, 3% at 300 kV for a tungsten target (effective cooling is required to remove remaining heat energy).
- 50 kV machines are used for low density materials, wood, plastics, leather, etc.
- 100 kV: light metals.
- 150 kV: thick sections of light metals and thin sections of steel or copper.
- 250 kV: heavier sections of steel and copper.
- 1 MeV to 2 MeV: thick sections of metals.
- Machine's penetrating depth is typically expressed in terms of thickness of steel that will produce an acceptable indication at the rated voltage and current.
- Conversion to other materials can be performed using the attenuation coefficients such that:

  $$\mu_1 t_1 = \mu_2 t_2 \tag{5.5}$$

  where 1 and 2 refer to the reference material and the other material, t is thickness and μ is the linear attenuation coefficient evaluated at the average energy of the x-ray machine.

5.3.2 Gamma-Rays

- Emit discrete photon energies.
- Strength is determined by source activity:

  $$\text{Activity} = \lambda N \tag{5.6}$$

  where λ here refers to the decay constant (1/s) and N is the number of radioactive nuclei, Activity measured in disintegration per second (Becquerel) or Curies (1 Ci = 3.7×10^{10} Bq), sources up to 10 Ci have been used.

- Source decays:
$$N = N_0 \exp(-\lambda t) \tag{5.7}$$
where N_0 is the number of nuclei at time, $t = 0$.

- Half-life:
$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.669}{\lambda} \tag{5.8}$$

- Iridium-192: 0.31, 0.47, 0.60 MeV, $t_{\frac{1}{2}} = 74$ days, useful in steel thicknesses of 6 to 75 mm or equivalent.

- Cesium-137: 0.66 MeV, $t_{\frac{1}{2}} = 30.1$ years, useful in steel thicknesses of 12 to 100 mm or equivalent.

- Cobalt-60: 1.33, 1.17 MeV, $t_{\frac{1}{2}} = 5.3$ years, useful in steel thicknesses of 18 to 225 mm or equivalent.

- A number of source storage-manipulation mechanisms are available.

- In calculating time of exposure of film to radiation, i.e. in effect total number of emitted photons, initial source activity, decay time and half-life of source, source-to-film distance, thickness of objects and types of film used must be taken into account.

5.4 Film Radiography

Films are made of radiation sensitive emulsion material, silver halide crystals in a binding agent (gelatin), covered on both sides by a thin sheet of polyester (film base) to protect against exposure by light.

- The Grains of the emulsion undergo a chemical reaction upon exposure to radiation.

- Upon processing, exposed grains darken, unexposed stay light.

- Film exposure:
$$\mathcal{E} = \mathcal{I} \times \sqcup \tag{5.9}$$
where $\mathcal{E}$ refers to radiation exposure, I to radiation intensity at film, and t is time of film exposure, note that I can be increased by increasing x-ray machine current.

- When the developed film is exposed to light, the *light transmission density*, D, also called optical density or darkness, is expressed as:

  $$D = \log \frac{J_o}{J_t} \tag{5.10}$$

  where J_0 is the intensity of light incident on the film and I_t is the light transmitted light intensity, light seen by a viewer at the other side looking at the unexposed side of the film, note that $D = 0$ means 100 % transmission of light through the film.

- Each type of film has its won characteristic logarithmic exposure curve (D v.s. $\log \mathcal{E}$) that defines its response rate.

- Log relative exposure, RE,

  $$\log(\mathrm{RE}) = \log \frac{\mathcal{E}}{\mathcal{E}_{\prime}} \tag{5.11}$$

  where E_0 is some reference exposure, conveniently taken as unity.

- Film contrast at a density D is defined by the slope of the film characteristic curve:

  $$G_D = \frac{dD}{d\log(\mathcal{E})} \tag{5.12}$$

  The higher the value of G_D, the better is the film contrast.

- Faster films have a larger value of D for a given RE, as grains in film begin reaction sooner, but higher speed films tend to have larger grains and may not produce the required detail.

- Film unsharpness, U_f, produced by lack of definition due to film response characteristics, i.e. sharp edges may blur, determined by measuring the distance observed on a developed film to change D in from one value to another in response to a step change in object geometry.

5.5 Indication

5.5.1 Unsharpness

Unsharpness, loss of resolution is caused by geometric effects, as well as film unsharpness.

- Penumbra is the inability to reproduce faithfully the boundary of a given object.
- Produced by radiation divergence.
- An x-ray sources is not a point source and has a finite size, called the focal spot size, F, which is the effective width of the source.
- F results in a penumbra and the corresponding Geometric Unsharpness (lack of resolution) us defined by U_g as:

  $$U_g = \frac{Fl}{L_0} \tag{5.13}$$

  where l is the film-to-object distance and L_0 is the source-to-object distance.
- Total image unsharpness, U_t:

  $$U_t = \sqrt{U_f^2 + U_g^2} \tag{5.14}$$

5.5.2 Sensitivity

Ability of system to produce a detailed image of object, also called spatial resolution, thickness sensitivity or contrast sensitivity, is measured by the detectable Δx in a thickness x:

$$\frac{\Delta x}{x} = 2.3 \frac{\Delta DB}{\mu G_D x} \tag{5.15}$$

with the usual definition of the above parameters used. Penetrameters are used to measure this in practice, note that Δx can be +ve or −ve.

Penetrameters

- These are image quality indicators placed on top or alongside of object to check ability of setup (selected source energy, current, exposure time, film, distances).
- Made of same material as test object or with an equivalent material.
- Made of a step-wedge shape plate (plaque) with drilled holes of different sizes, or a series of wires of different diameters.

- Typically placed, on the source side, on the thickest part of object to verify that radiation is able to penetrate that part and to evaluate the sensitivity and quality of the radiographic technique.
- One type of Penetrameters is defined by an identification, or lead number, which gives the maximum thickness of the object to be radiographed, has thickness, T, which is typically 2% of the object thickness, and includes holes of diameters 1T, 2T and 4T.
- With the above pentameter, 2% corresponds to the desired sensitivity $(\Delta x/x)$ and the smallest observed hole size will indicate the minimum observable size of flaw.

5.6 Calculation of X-ray Exposures

1. Select voltage, given thickness to be inspected.
2. Obtain milliampere-minute exposure from working curve.
3. Operate x-ray machine for a time and milliampere setting that equals the exposure.

Example

Design an x-ray radiography system for examining a steel plate varying in thickness from 7 to 10 mm.

- Thickness range in inches is 0.27 to 0.4.
- Graph relating kV to thickness of steel gives:
  - For 0.27 inches, about 100 kV.
  - For 0.4 inches, about 110 kV.
- Exposure graphs available for 100 kV and 120 kV, therefore these two voltages will be used, but either will do.
- For 0.27 inches, 100 kV, $\mathcal{E} \approx \in\prime$ mA- minute, i.e. 20 mA for a minute, or 10 mA for two minutes, at 100 kV.
- For 0.4 inches, 120 kV, $\mathcal{E} \approx \in\nabla$ mA- minute, i.e. 25 mA for a minute, or 12.5 mA for two minutes, at 120 kV.

- Milliampere-minute exposure will typically specify the type of film to be used, the film density, source-to- film distance and development time and process.

5.7 Safety and Protection

- Röntgen (Roentgen) is an old unit of radiation exposure, designated as R and is the quantity of x- or gamma radiation that produces in dry air, at standard pressure and temperature, ions carrying one electrostatic unit of electricity in one cm^3 of air, or the equivalent of 8.3 mJ in gram of air.

- Radiation absorbed dose is expressed in units of Gray (Gy), or the old units "rad", with 1 Gy=100 rad, and 1 Gy represents 1 J of energy deposited in kg of medium, 1 rad deposits 10 mJ (1 erg) in gram of material.

- The biological effect of radiation is defined by a radiation-type dependant "quality factor", which is equal to unity for x- and gamma-radiation. This quality factor multiplied by the absorbed dose gives the Sievert, or in the old units "rem", roentgen equivalent man or mammal, 1 Sv=100 rem.

- Occupational exposures for Atomic Radiation Workers are (jurisdiction dependant) limited to 1.25 rem per calendar quarter, 5 rem per year (100 mrem per week), and lifetime limit (above age 18) of 5 rems.

- Exposure to a member of the public is typically limited to 2 mrem in any hour, 500 mrem per year.

- Radiation exposure is monitored by personal film badges (thermoluminescent dosimeters, TLD), pocket dosimeters, or survey meters.

- To protect against radiation: minimize time of exposure, maximize distance ($1/R^2$ effect), and use shielding material.

- ALARA principle: keep radiation dose to as low as reasonably achievable.

5.8 Work Problems

1. For x-ray tubes voltages of 650, 440 and 160 kV_p, calculate the maximum and average x-ray energy levels. For each also estimate the-ray energy level at which the x- ray intensity is highest.

2. A 19 mm source is used to inspect a 30 mm thick steel plate. The distance from the source to the front of the plate is 600 mm. A 25 mm diameter flaw is located 5 mm below the plate surface, on the centre line from the source.

    (a) Sketch this inspection arrangement, indicating the image size on the film and the penumbra.

    (b) Calculate the geometric unsharpness for these conditions.

    (c) Repeat the calculations for a flaw located 23 mm below the plate surface with and compare the results.

    (d) What is the effect of using a smaller source, with a focal spot point if 5 mm, on the geometric unsharpness.

3. A weld in an aluminum pipe (20 mm ID and 2.39 mm thick) is to be radiographs. Prepare a suitable test plan for this inspection using:

    (a) An x-ray machine.

    (b) An isotopic source.

5.9 Graphs

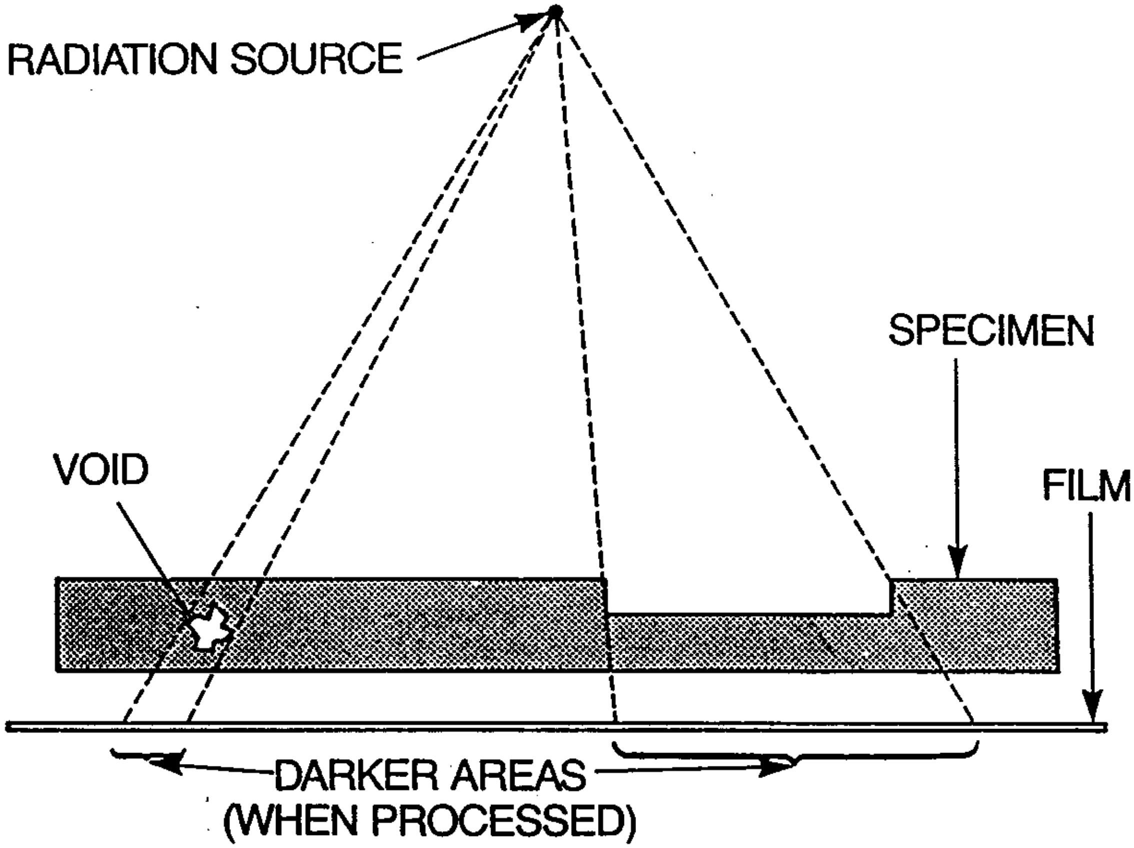


Figure 5.1: Radiography

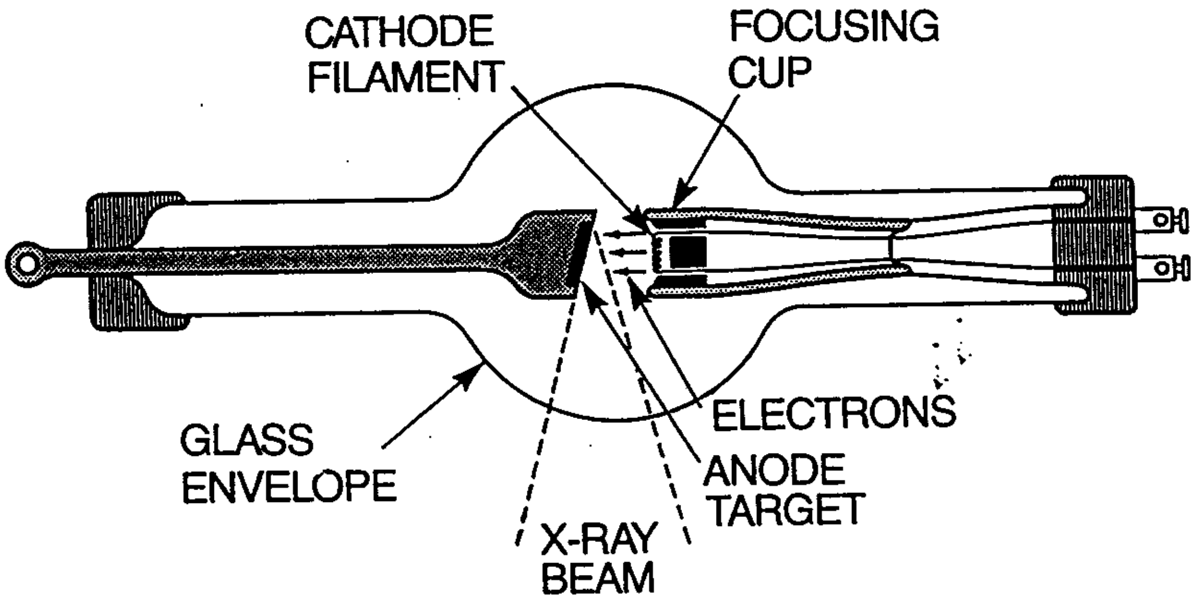


Figure 5.2: X-Ray Tube

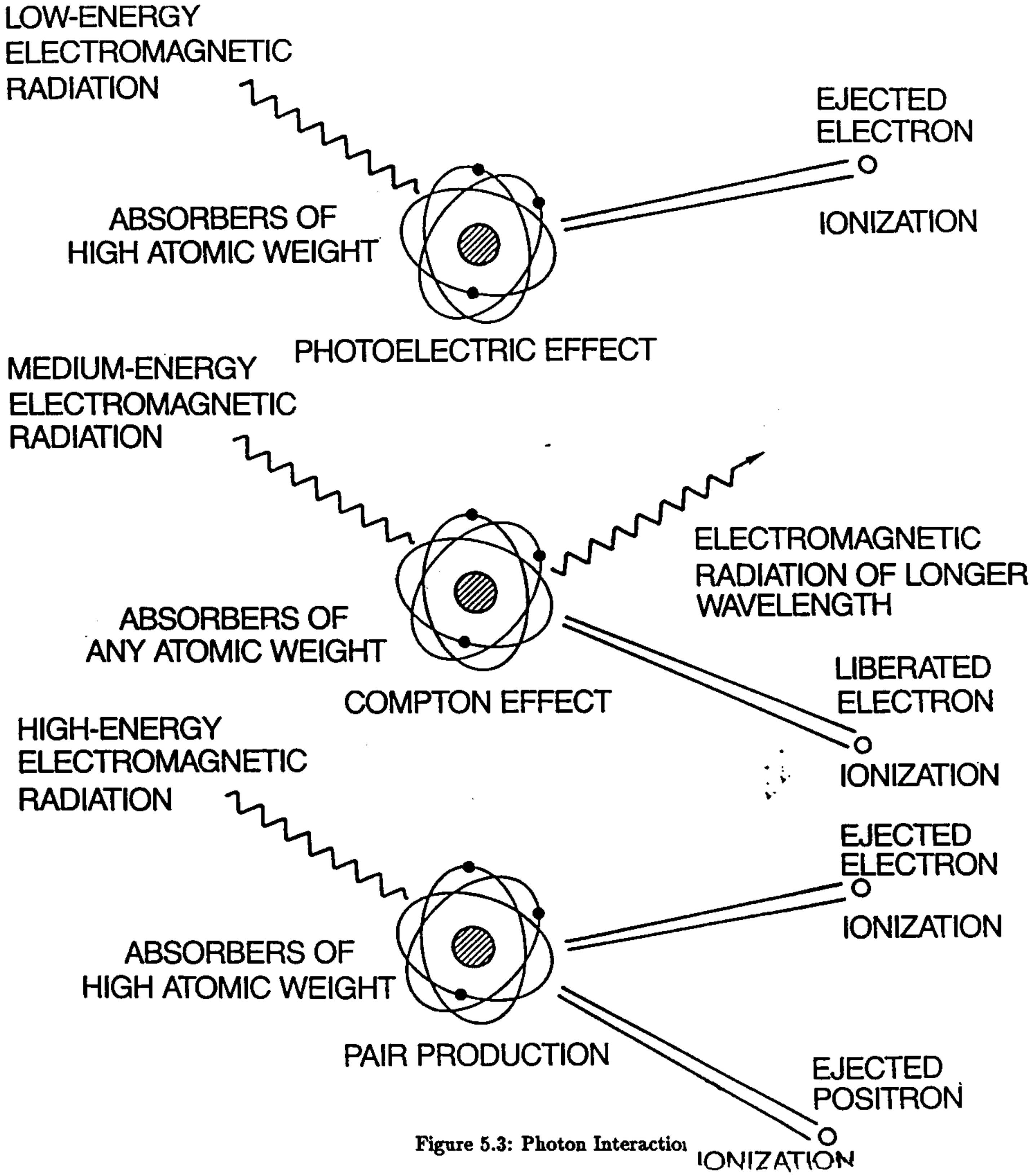


Figure 5.3: Photon Interactio

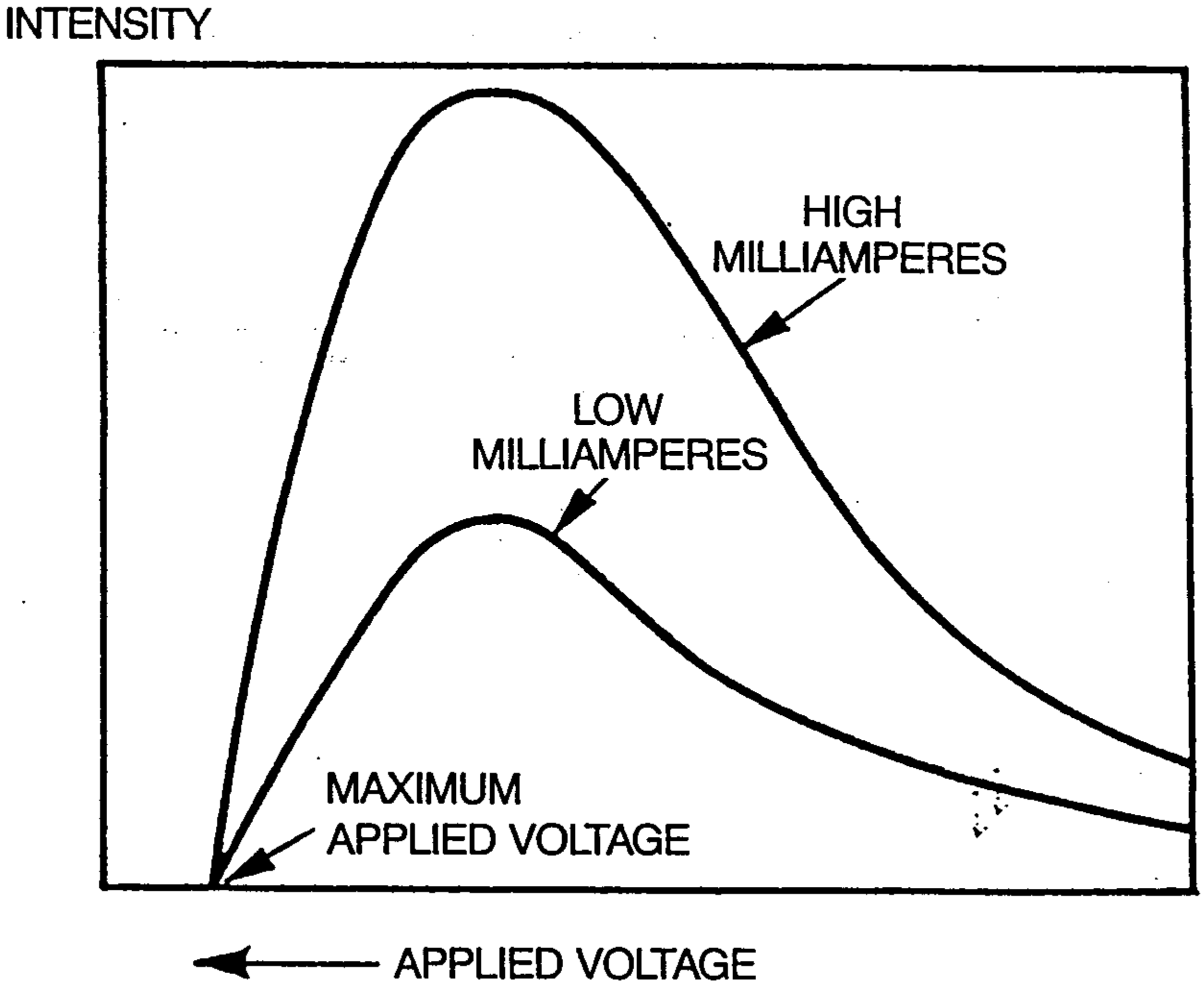


Figure 5.4: X-Ray Energy Spectrum

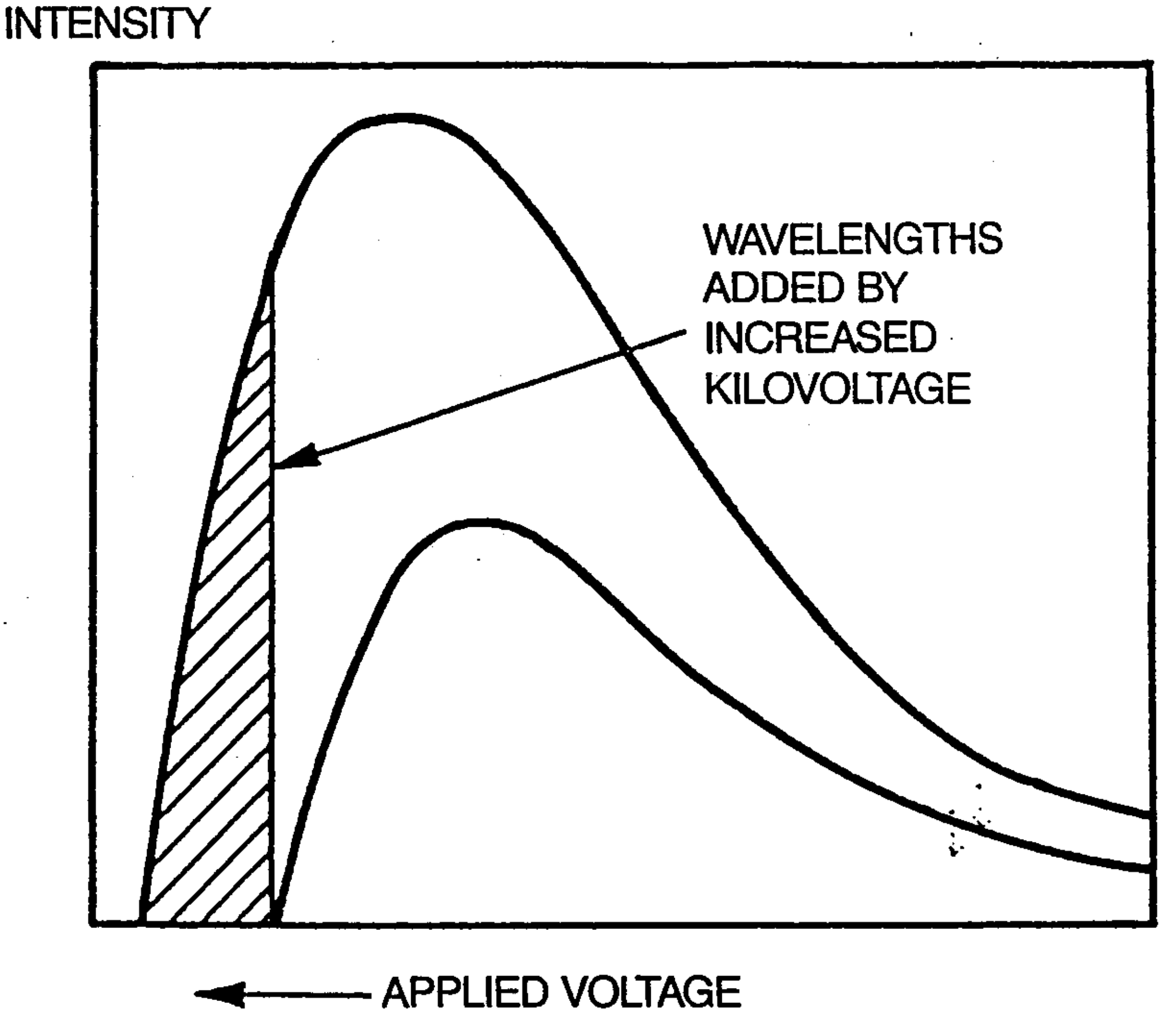


Figure 5.5: Effect of Voltage on X-Ray Energy Spectrum

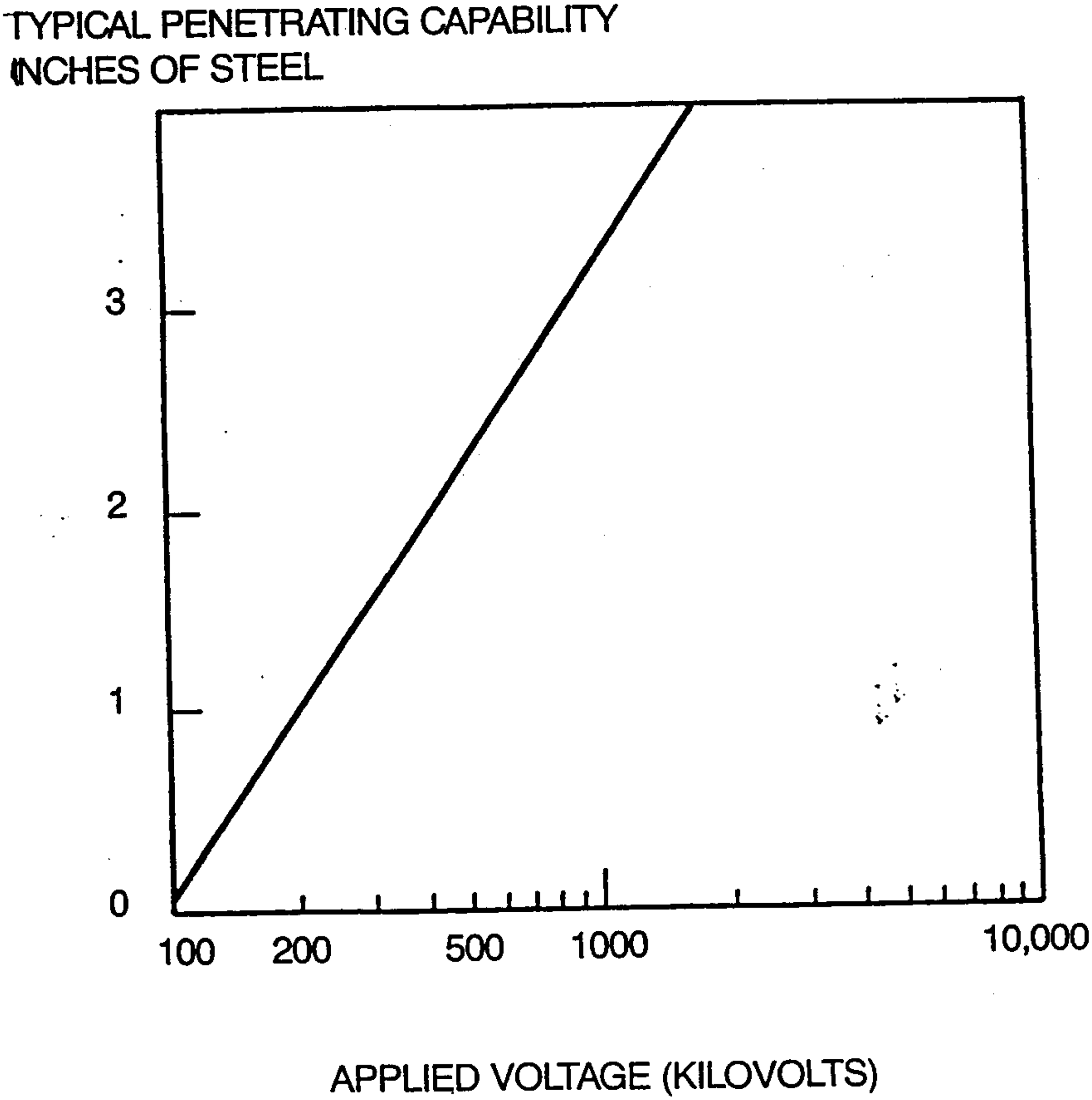


Figure 5.6: Effect of Voltage on Penetrability

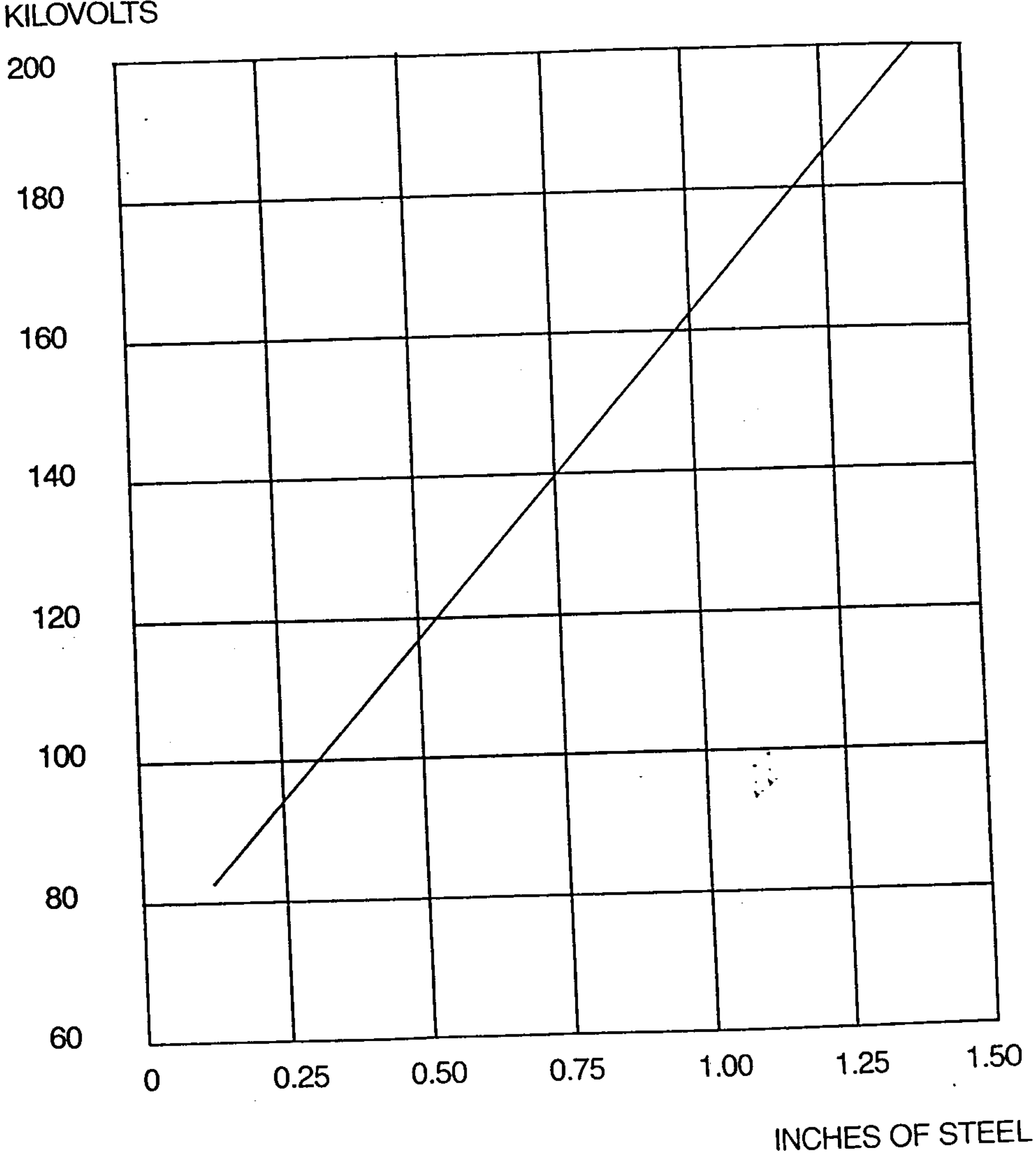


Figure 5.7: Voltage Required for Steel

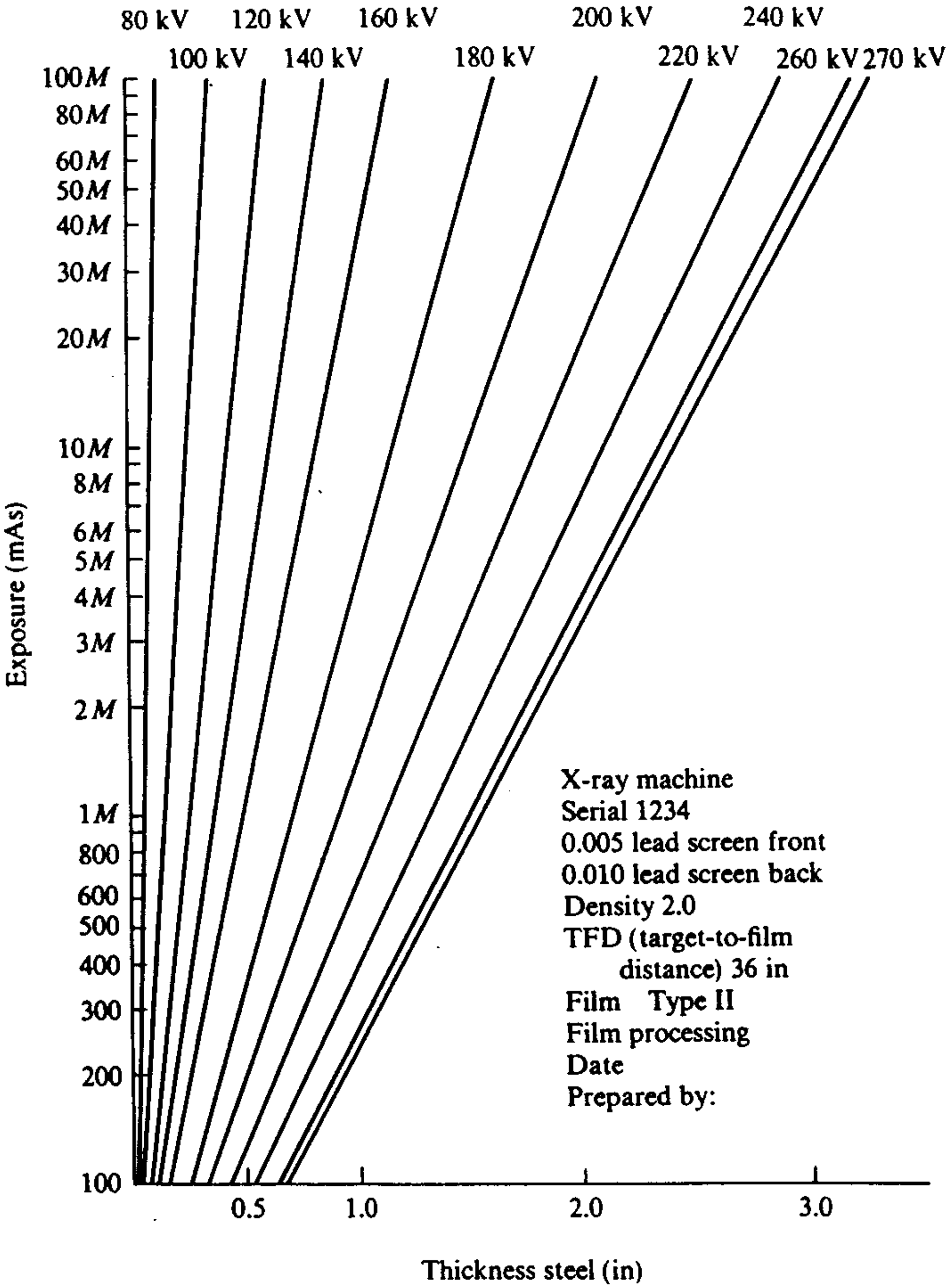


Figure 5.8: Exposure for Steel

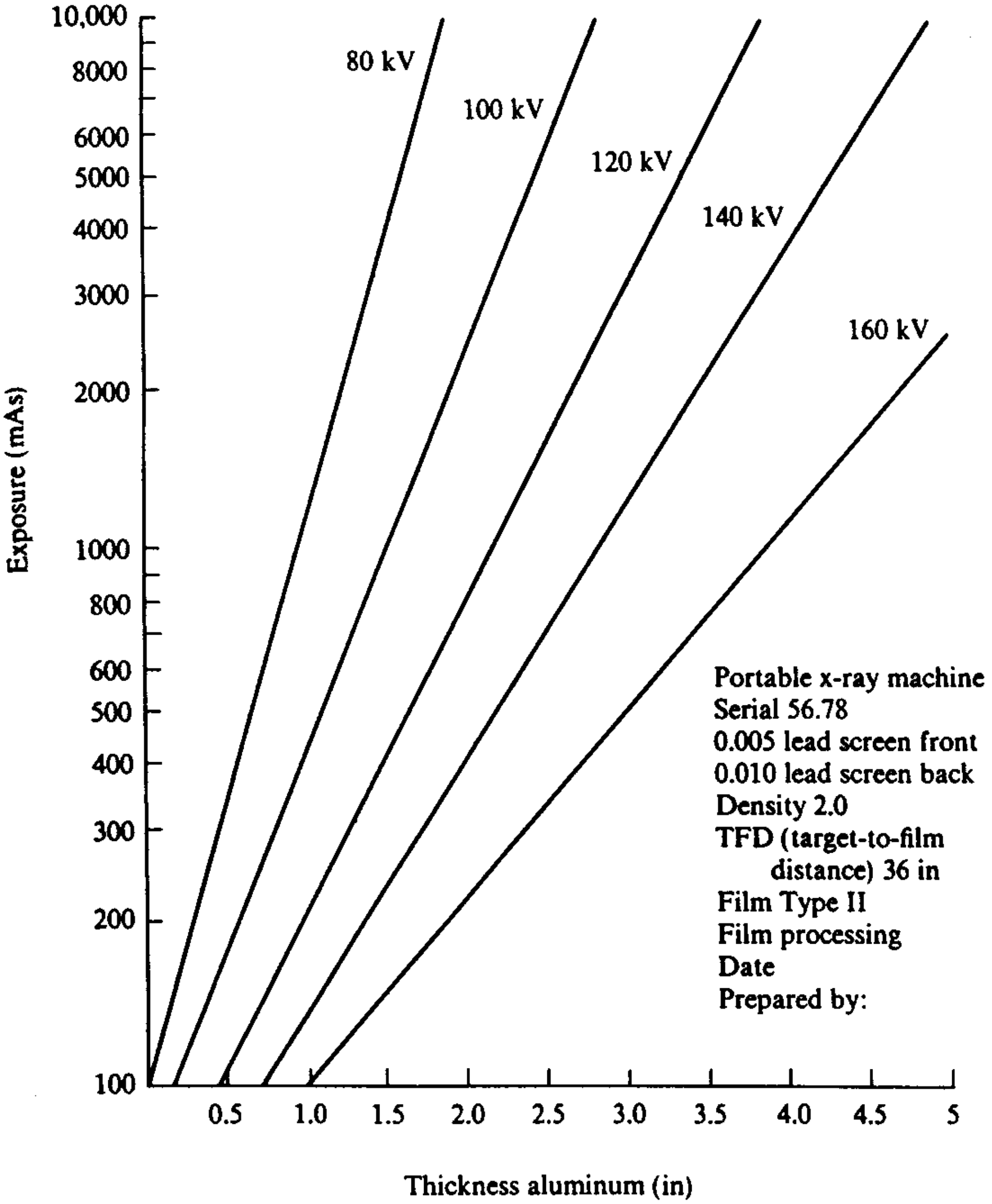


Figure 5.9: Exposure for Aluminium

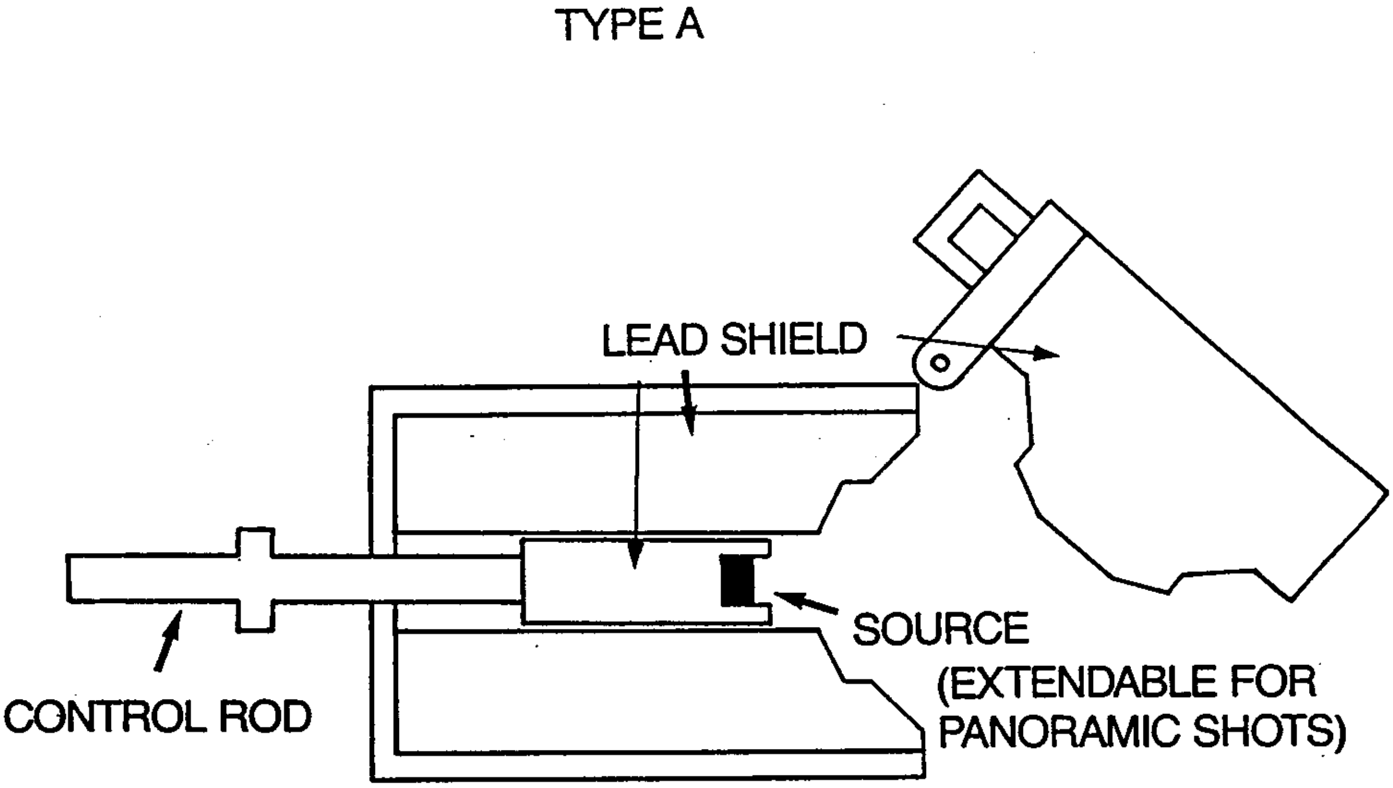
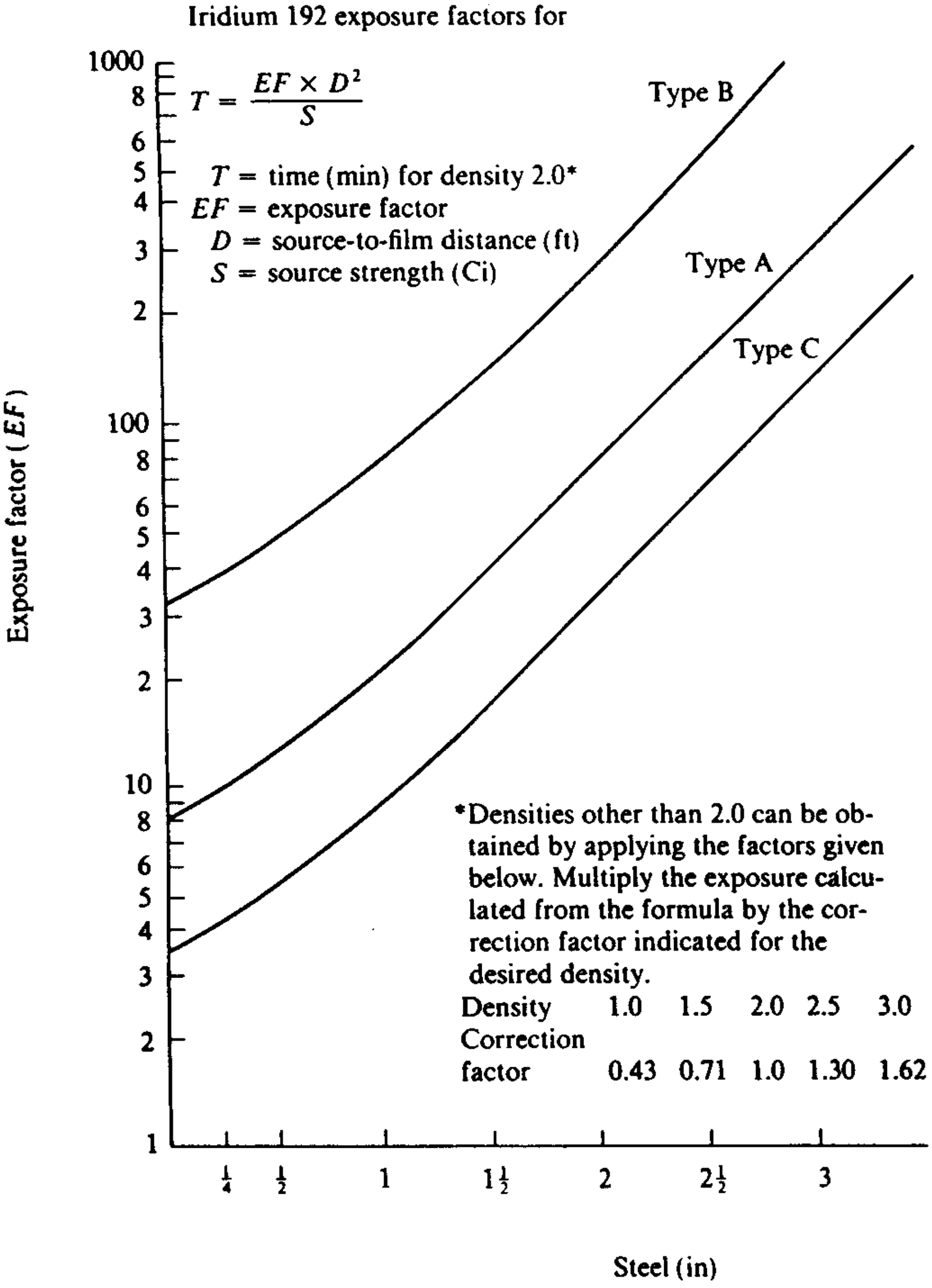


Figure 5.10: A Gamma-Ray Devices



$$T = \frac{EF \times D^2}{S}$$

T = time (min) for density 2.0*
EF = exposure factor
D = source-to-film distance (ft)
S = source strength (Ci)

*Densities other than 2.0 can be obtained by applying the factors given below. Multiply the exposure calculated from the formula by the correction factor indicated for the desired density.

Density	1.0	1.5	2.0	2.5	3.0
Correction factor	0.43	0.71	1.0	1.30	1.62

Figure 5.11: Ir-192 Exposure for Steel

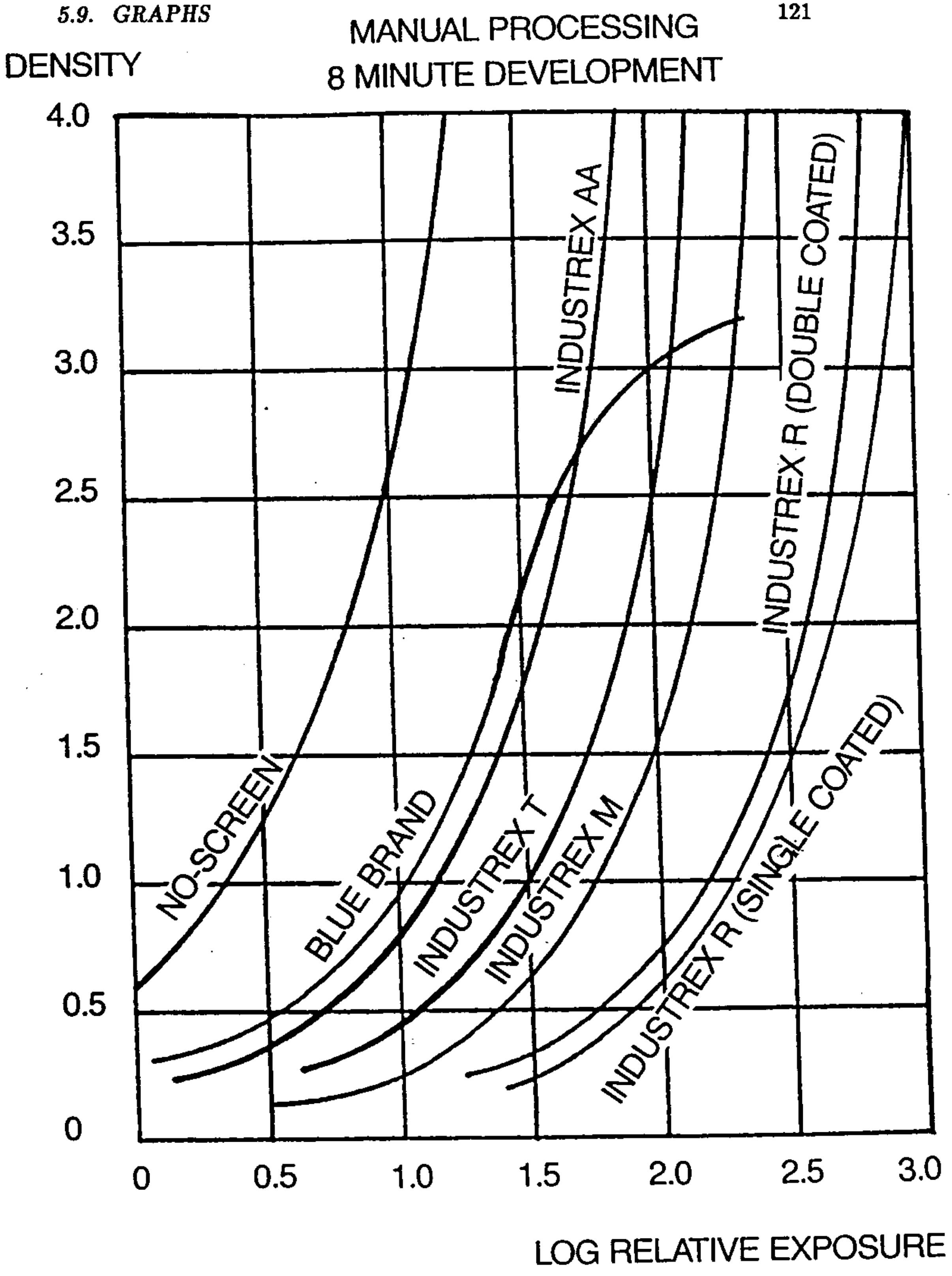


Figure 5.12: Film Characteristic Curve

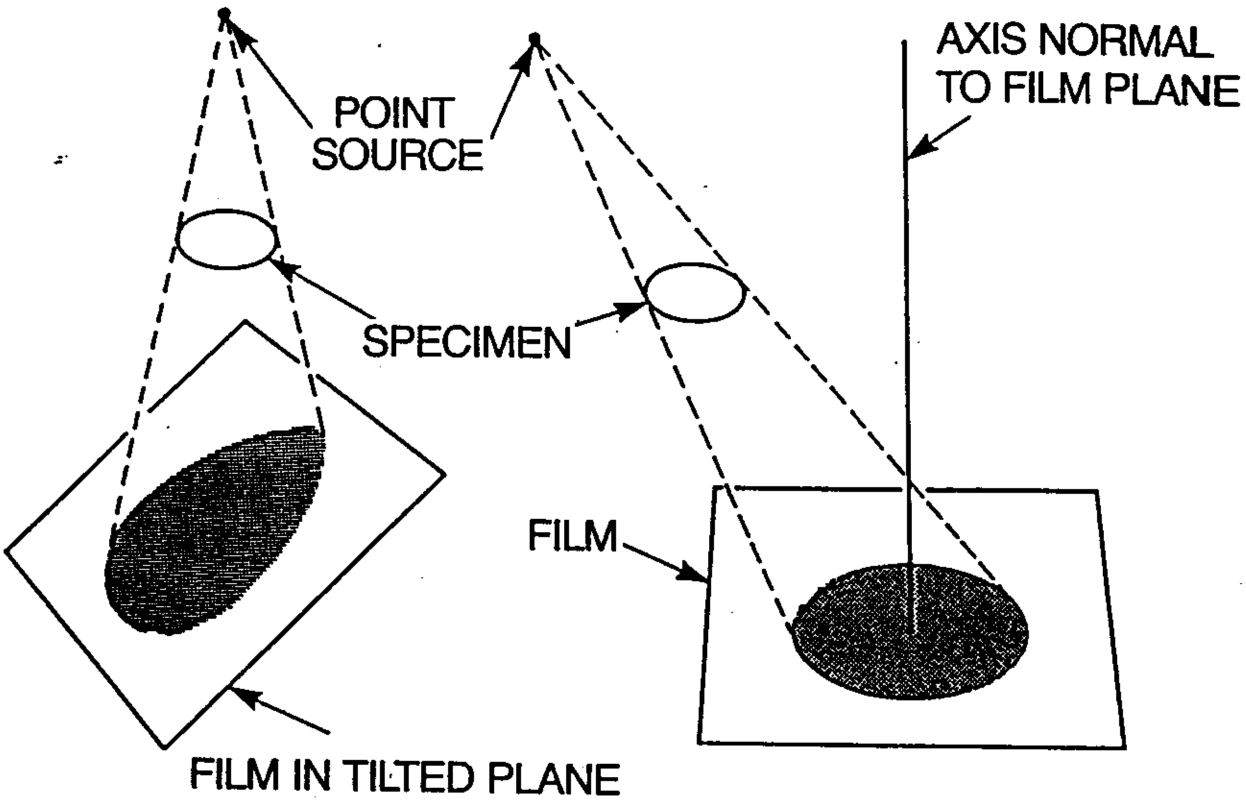


Figure 5.13: Effect of Exposure Direction on Geometry

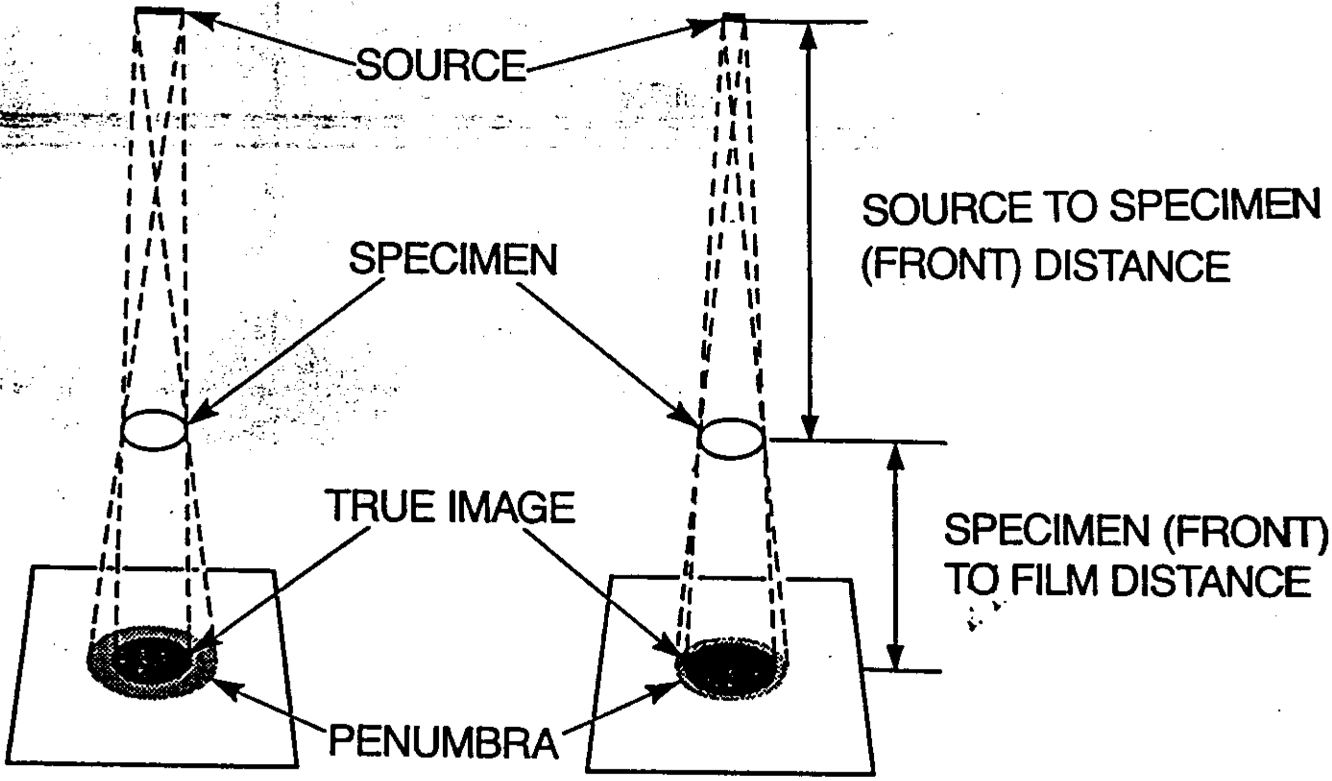


Figure 5.14: Penumbra

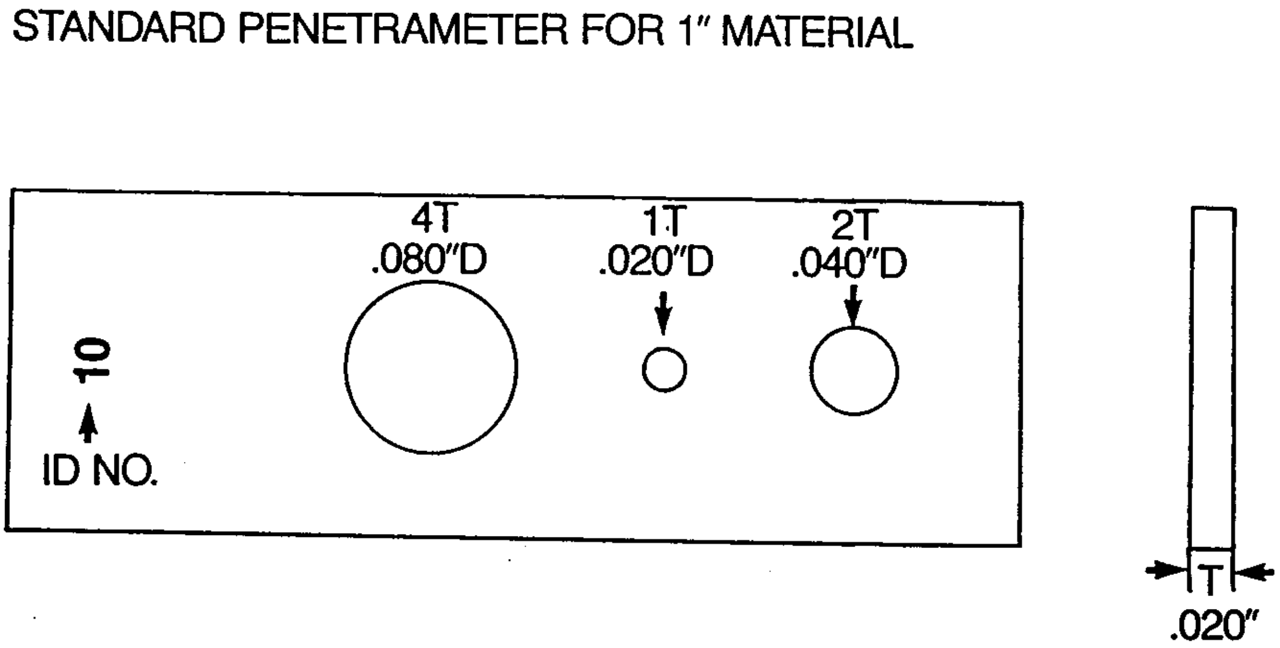


Figure 5.15: Penetrameter