

Figure 4.48. Schematic illustration of a line-trace display of a signal with characteristics that can produce a good image for an observer. The image is perceived as filling out the dynamic range of the display, from near full black to near full white, with no saturation.

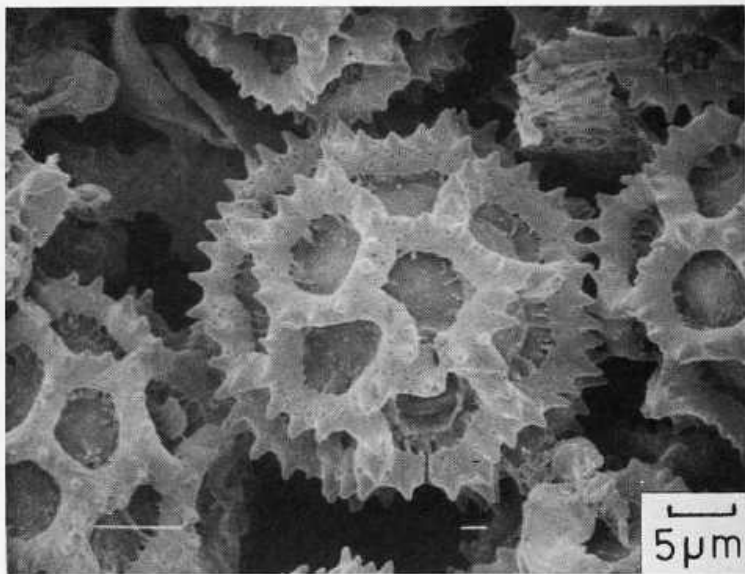
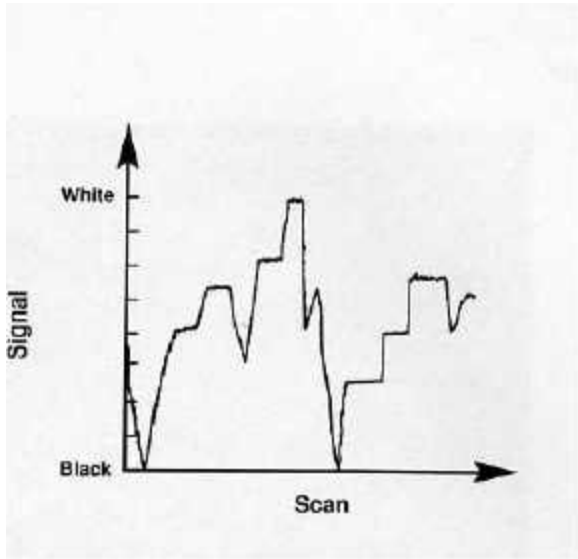
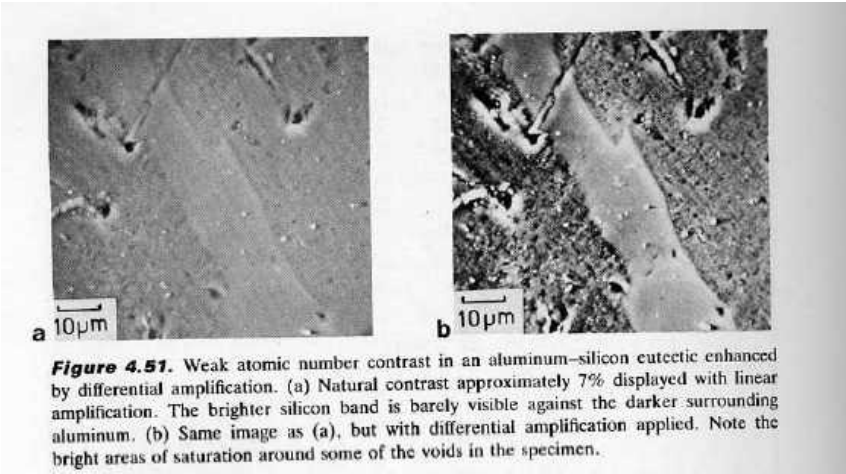
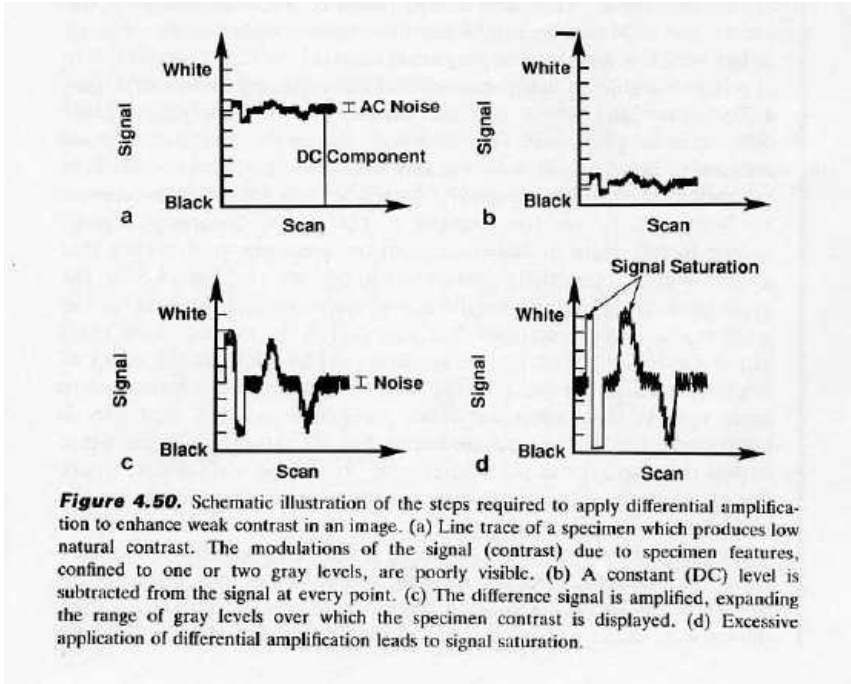


Figure 4.49. Example of linear amplification applied to a sample which produces high natural contrast by the topographic contrast mechanism. Positively biased E-T detector. (Specimen: pollen grains; courtesy JEOL.)





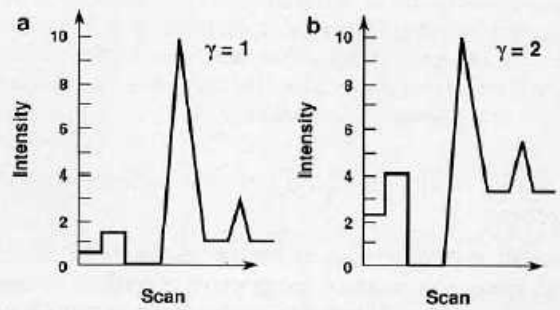


Figure 4.52. (a) Schematic illustration of a line trace for which the signal spans the full dynamic range of the display, but the information of interest lies in a narrow gray-scale range near the zero of signal (dark regions). (b) Same signal trace, but with nonlinear amplification applied ($\gamma = 2$).

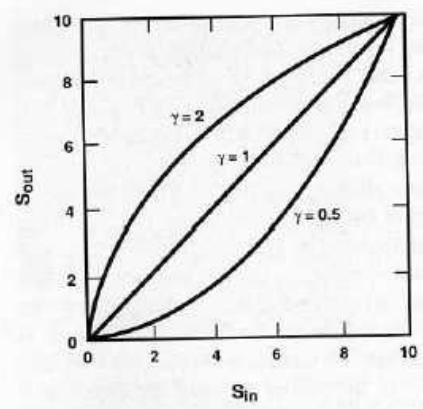


Figure 4.53. Signal response functions for nonlinear amplification (gamma processing). For $\gamma = 2$, the contrast at the dark end of the gray scale is expanded, improving the visibility of dark objects. For $\gamma = 0.5$, the expansion of contrast occurs at the bright end of the gray scale.

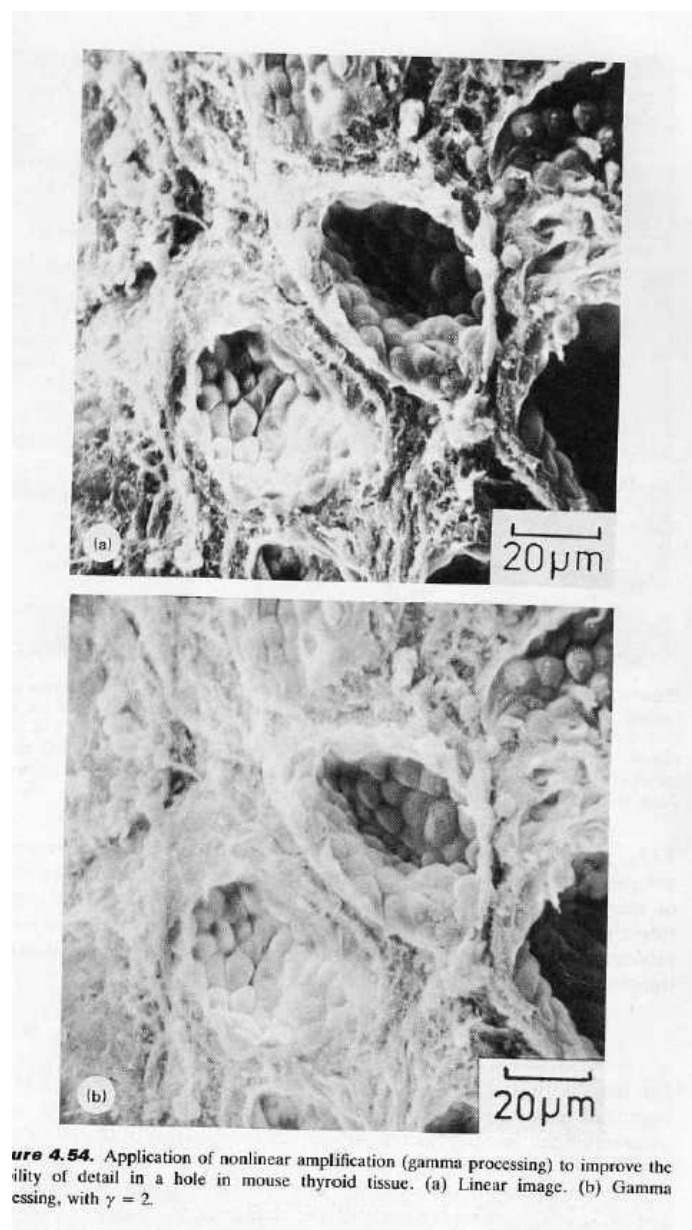


Figure 4.54. Application of nonlinear amplification (gamma processing) to improve the visibility of detail in a hole in mouse thyroid tissue. (a) Linear image. (b) Gamma processing, with $\gamma = 2$.

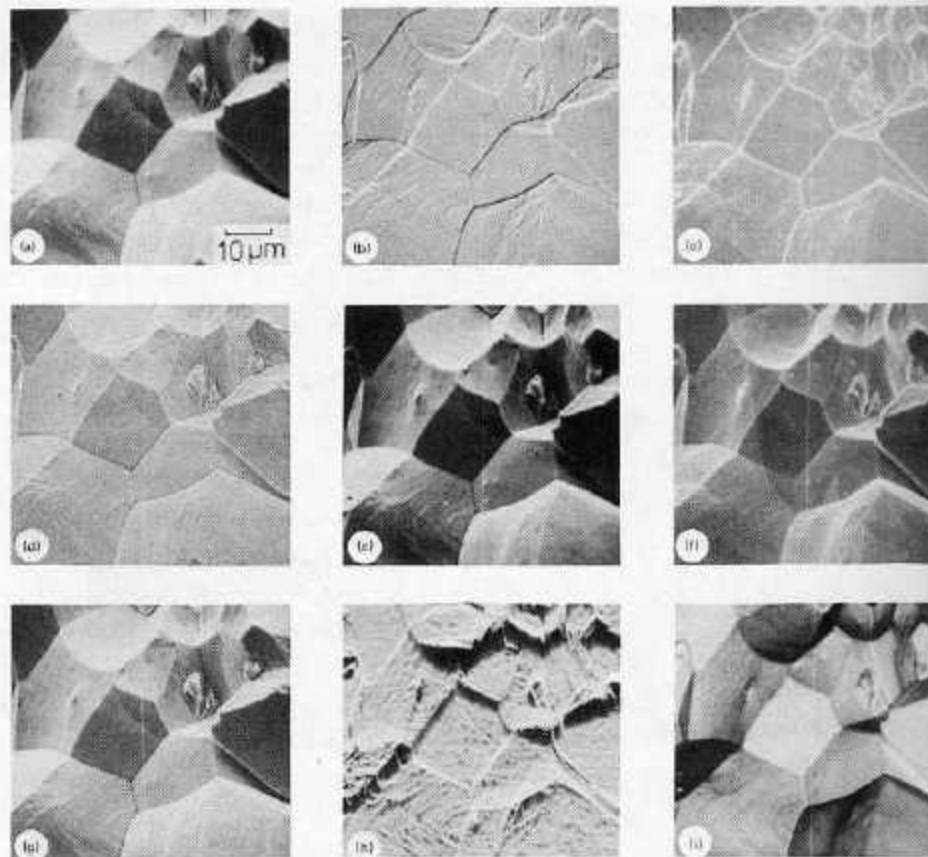
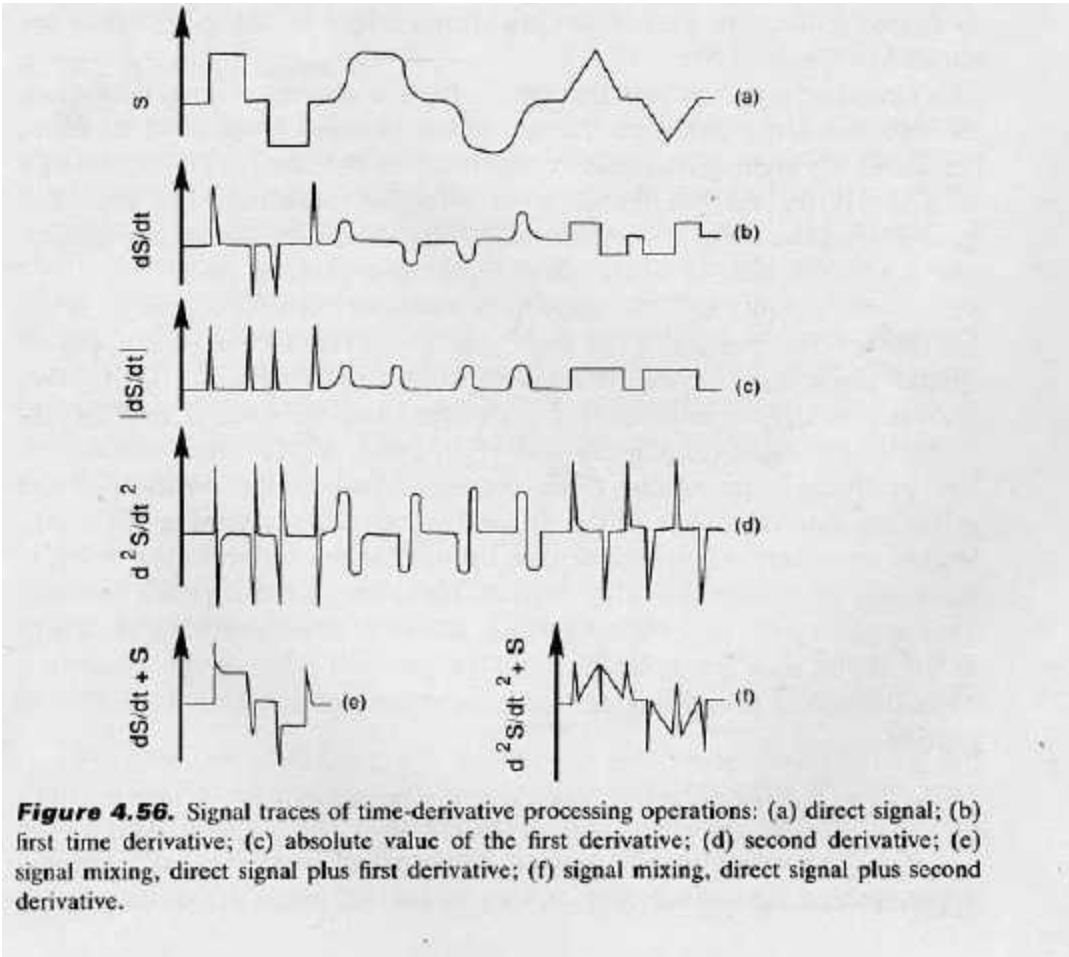


Figure 4.55. Images of an iron fracture surface with various types of signal processing applied: (a) direct + E-T image; (b) first time derivative; (c) absolute value of the first time derivative; (d) second time derivative; (e) 50% direct image plus 50% first time derivative; (f) 50% direct image plus 50% absolute first time derivative; (g) 50% direct image plus 50% second time derivative; (h) Y-modulation image; (i) reversed contrast. Beam energy 20 keV.



RESOLUTION

Beam Size : Aberrations, Working Distance

Type of Signal : Back Scattered, Secondary X-ray

Beam Spreading : Voltage, Atomic No. (Z)

Contrast : Specimen,	Beam Current
↓	↓
Z, Topography	Voltage Current

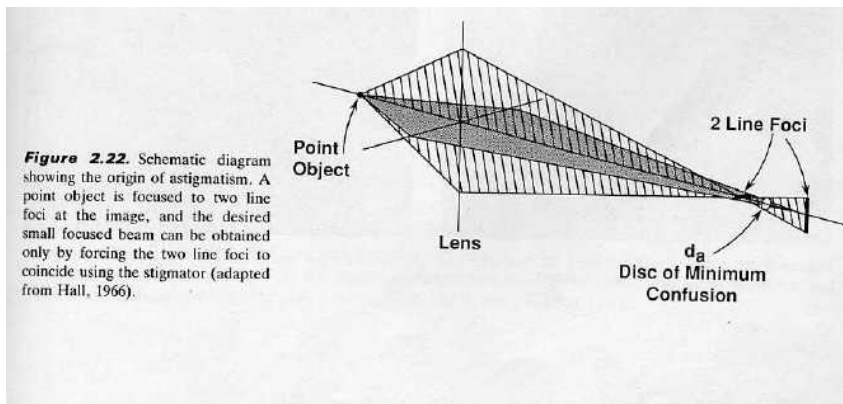
Limit of diffraction = $0.61 \lambda/2$

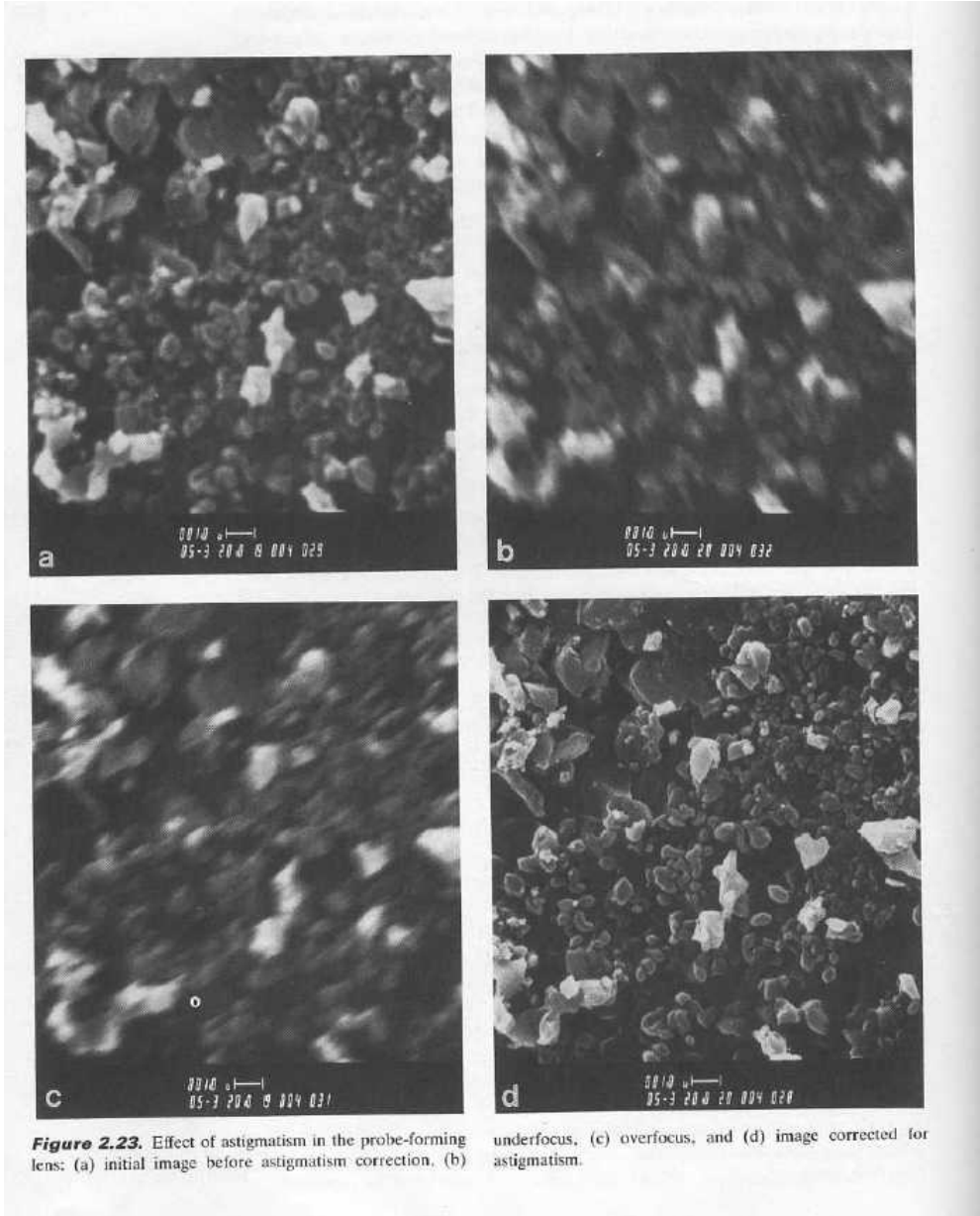
$$d_{\text{spherical}} = 0.68 C_s^{1/4} \lambda^{3/4}$$

$$d_{\text{chromatic}} = 1.1 \lambda^{1/2} (C_c \delta E/E)^{1/2}$$

$$d_{\text{total}}^2 = \sum_i d_i^2$$

Figure 2.21. Schematic drawings showing how (a) spherical aberration, (b) aperture diffraction, and (c) chromatic aberration in a lens cause a point object at P to





LIMITS ON PROBE SIZE AND APERTURES DUE TO ABERRATIONS AND DIFFRACTION

In general, $d^2_{\text{tot}} = P/\alpha^2 + Q\alpha^2 + R\alpha^6$

$P = 4i_{\text{beam}}/\pi^2\beta + (0.61\lambda)^2$ Finite Beam Size and Diffraction

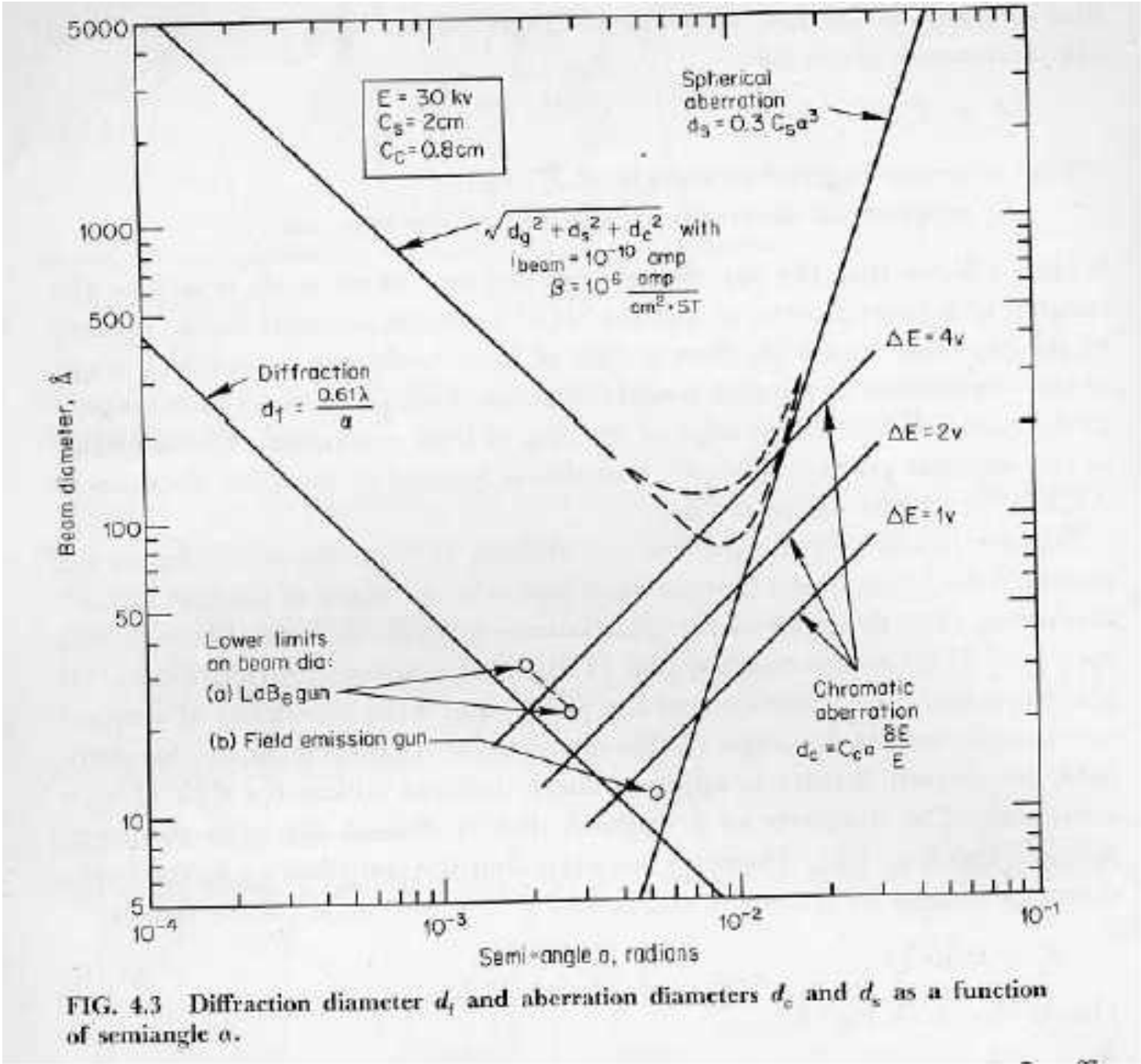
$Q = (C_c\delta E/E)^2 + C_a^2$ Chromatic

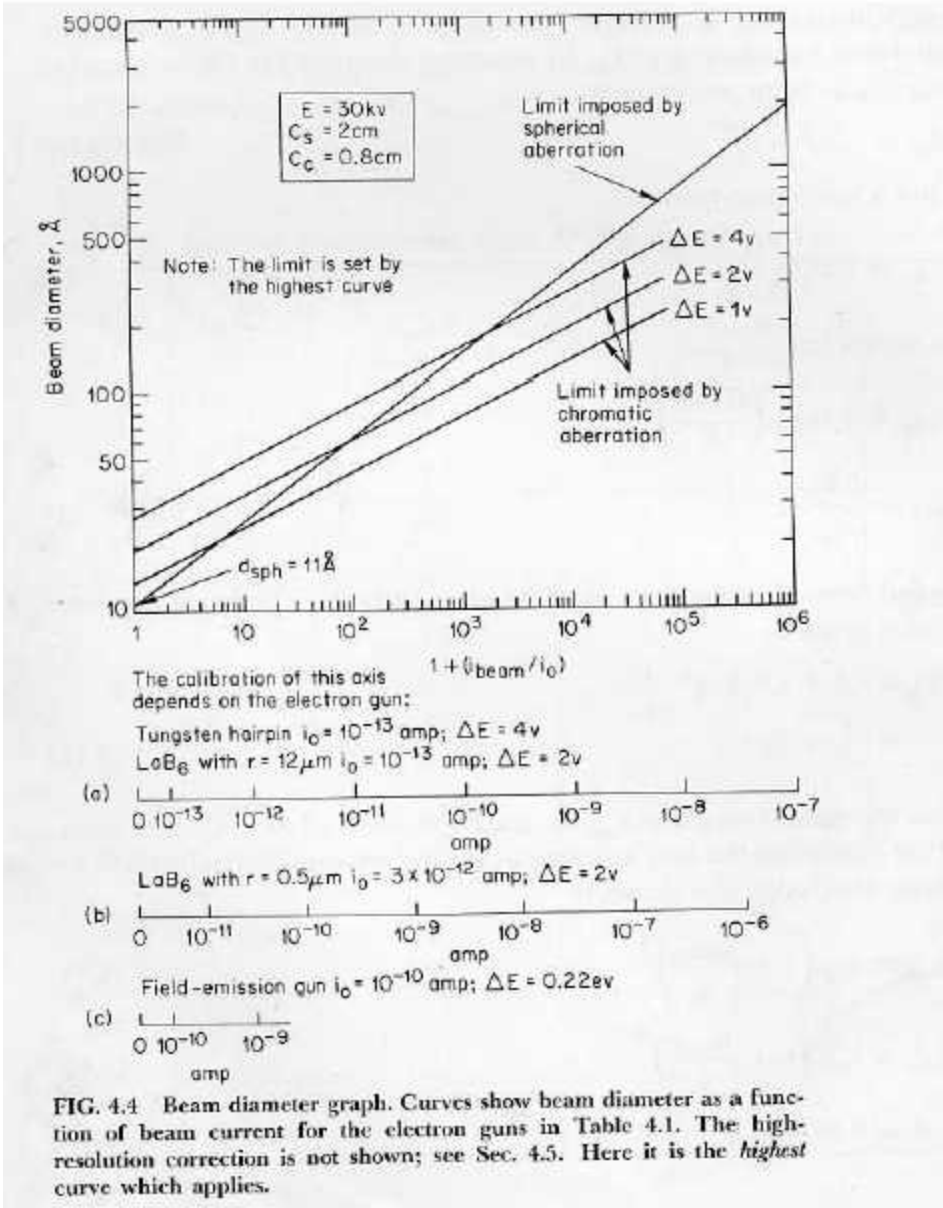
$R = (0.3C_s)^2$ Spherical

Considering ONLY *spherical aberration* (with diffraction and beam current) one can derive minimum spot sizes for a particular beam current. This also specifies an *optimum aperture size*. Below this size you are *losing brightness with no benefit in resolution*. Above this size, you *lose resolution for that beam current*.

Similarly, one can derive optimal conditions when ONLY *chromatic aberration* is present.

At high beam currents, resolution is largely limited by spherical aberration. At low voltages and low beam currents, chromatic aberration becomes important. The above information is shown in figures 4.3 – 4.5 in the transparencies. *Note : i_0 is brightness, normalised by the accelerating voltage.*





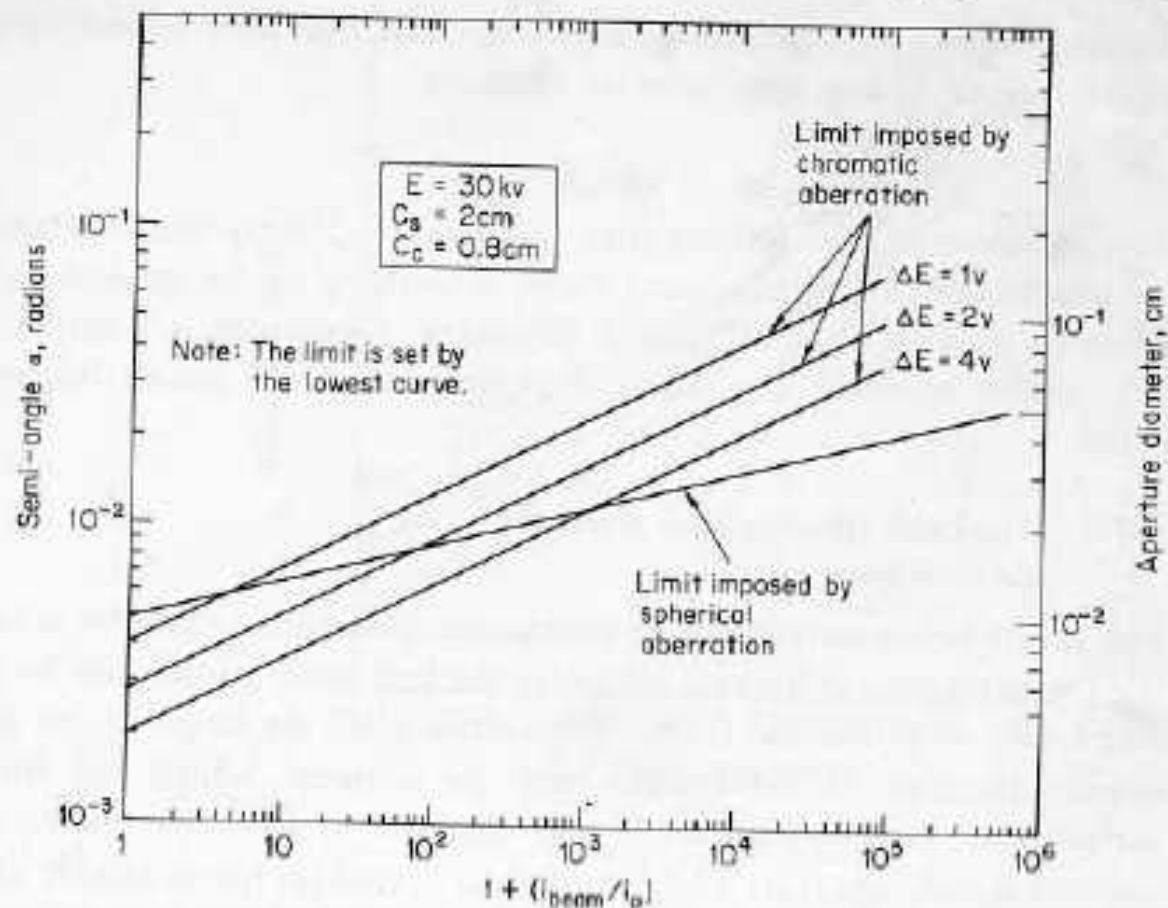


FIG. 4.5 Aperture size graph. Curves show the optimum beam aperture as a function of beam current. Here it is the *lowest* curve which applies.

TABLE 4.1 *Electron-gun data*

Gun	Lifetime, hr	Brightness β at 25 kv, amps/cm ² sterad	i_0 , amps (See Eq. 4.29)	Energy spread δE , ev
Tungsten hairpin	80	2.9×10^{10a}	1.2×10^{-13}	?
	40	4.8×10^9	1.9×10^{-14}	1.6 ^b
	16	9×10^8	3.6×10^{-14}	2.0
	8	1.5×10^8	6.2×10^{-14}	3.0
LaB ₆ with tip radius = 10 to 12 μm	300-500 at 10^{-5} torr ^c	$1-2 \times 10^{10d}$	1.1×10^{-13}	2-3 ^f
LaB ₆ with tip radius = 1 μm	50-100 at 10^{-6} torr ^g	$5-6 \times 10^9$	3.3×10^{-12}	2-3 ^f
Tungsten field emission	See footnote g	2×10^8	1.1×10^{-10}	0.22 ^g

^aScaled from theoretical figures from Haine and Cosslett (1961, p. 134).

^bEstimated from Pfeiffer (1971).

^cLaB₆ rod must be cleaned at intervals of 100 hr.

^dScaled from Broers (1969a).

^eThe high brightness is contained within narrow lobes which can be located with the help of scanning coils below the gun (Fig. 5.5).

^fData provided by A. N. Broers.

^gAfter Crewe, Isaacson, and Johnson (1971). Field-emission points must be re-formed at intervals of approximately 1 hr.

Table 4.2. Size of Picture Element as a Function of Magnification^a

Magnification	Edge of picture element
10X	10 μm
100X	1 μm
1,000X	0.1 μm (100 nm)
10,000X	0.01 μm (10 nm)
100,000X	1 nm

^a 1000 \times 1000 scan matrix; 10 cm \times 10 cm display on CRT.

scan-control module). Table 4.2 shows the length of the picture element's edge as a function of magnification for the case of a high-resolution (1000 \times 1000) image.

For a given choice of magnification, images are considered to be in sharpest focus if the signal measured when the beam is addressed to a given picture element comes only from that picture element. From Table 4.2, the picture element decreases to nanometers at high magnification. Overlap of information from adjacent picture elements must eventually occur as the magnification is increased, because of the finite size of the interaction volume. This overlap of pixel information is manifested as blurring in the image, as illustrated in Fig. 4.8.

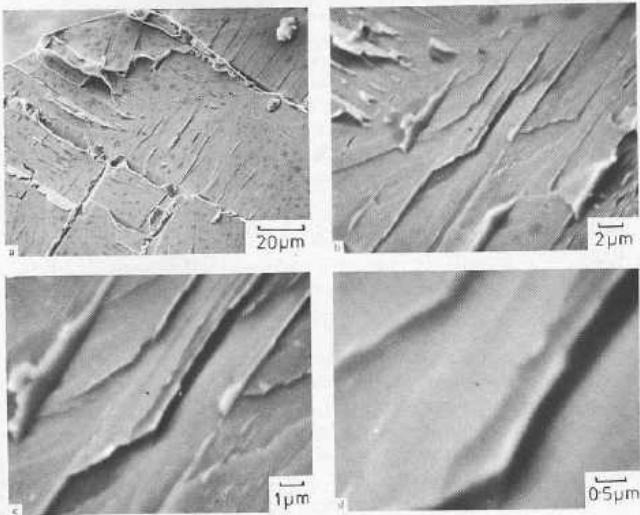
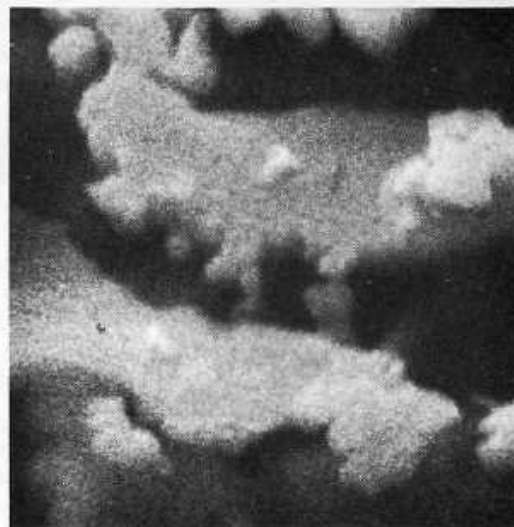
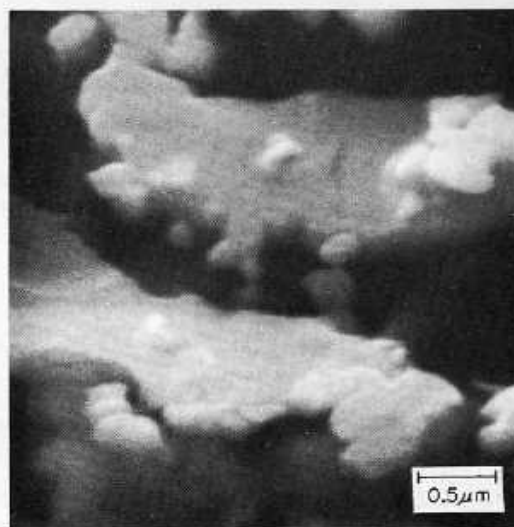


Figure 4.8. Images of a fracture surface illustrating the effects of pixel overlap (hollow magnification). The finest details in the image at low magnification appear sharp, while at the highest magnification, blurring can be observed.



(a)



(b)

FIG. 2.1 Illustrating the effect of beam current and recording time on secondary electron image of silver mesh ($\theta = 30^\circ$). (a) 3×10^{-12} amp, 40 sec, 20 kv; (b) 10^{-11} amp, 100 sec, 20 kv.

SIGNAL – NOISE, ETC.,

S = Signal, N = Noise,
 $\Delta S > 5 N$ to see anything
Contrast $C = \Delta S/S$

i_B = Beam Current must be greater than
(1000x1000 pixels) $\frac{4 \times 10^{-12}}{\epsilon C^2 \tau_f}$ Ampere

ϵ = detector efficiency

τ_f = time probe sits on one pixel

Low Contrast \Rightarrow large i_B /Long τ_f

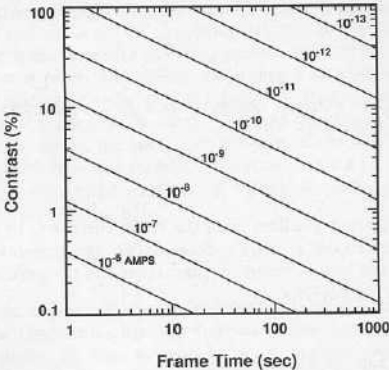


Figure 4.41. Graphical representation of the relationship of parameters of contrast, frame time, and beam current in the threshold equation. Assumptions: the signal production/collection efficiency $\epsilon = 0.25$, and the scan is 1000×1000 picture elements.

Table 4.6. Gaussian Probe Size for Various Contrast Values (tungsten filament, 20 keV)

Contrast	d_{\min} (nm)	Contrast	d_{\min} (nm)
1.0	2.3	0.025	91
0.5	4.6	0.01	230
0.25	9.1	0.005	460
0.10	23	0.0025	911
0.05	46	0.001	2,300

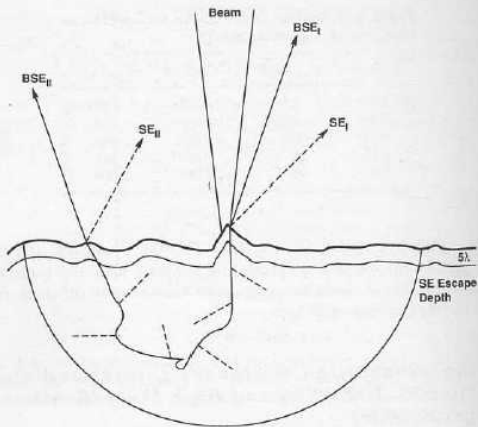


Figure 4.42. Backscattered- and secondary-electron signals emitted with a finely focused high-resolution beam.

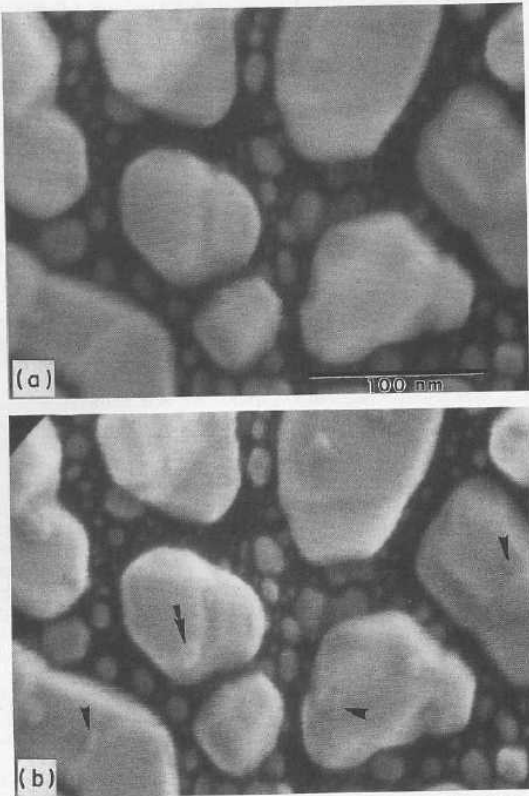


Figure 4.46. Improved contrast by separation of SE_{II} from the SE_i + SE_{II}. (a) Image of gold islands on graphite with SE_i + SE_{II} + SE_{II} obtained with conventional E-T operation. (b) SE_i + SE_{II} only, with SE_{II} suppressed by the use of a low secondary-yield shield. Note improved contrast of small features indicated by arrows (Peters, 1984; micrographs courtesy of K.-R. Peters).

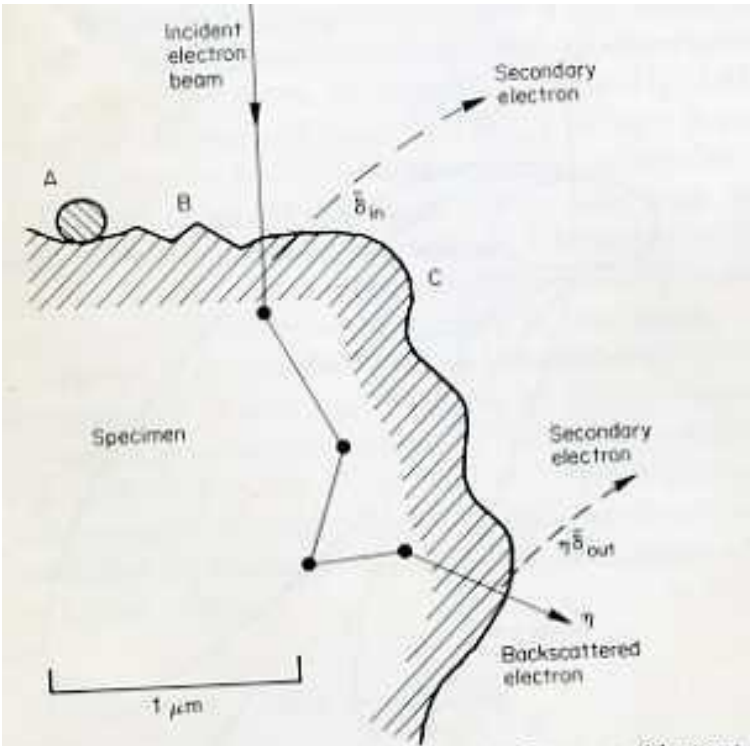
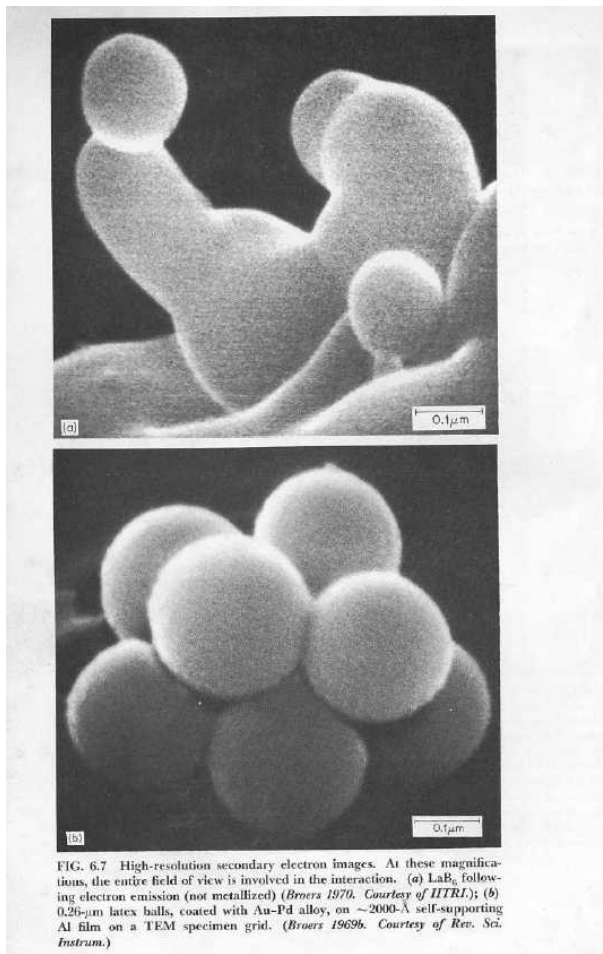


FIG. 3.17 Secondary electron emission from a solid target.

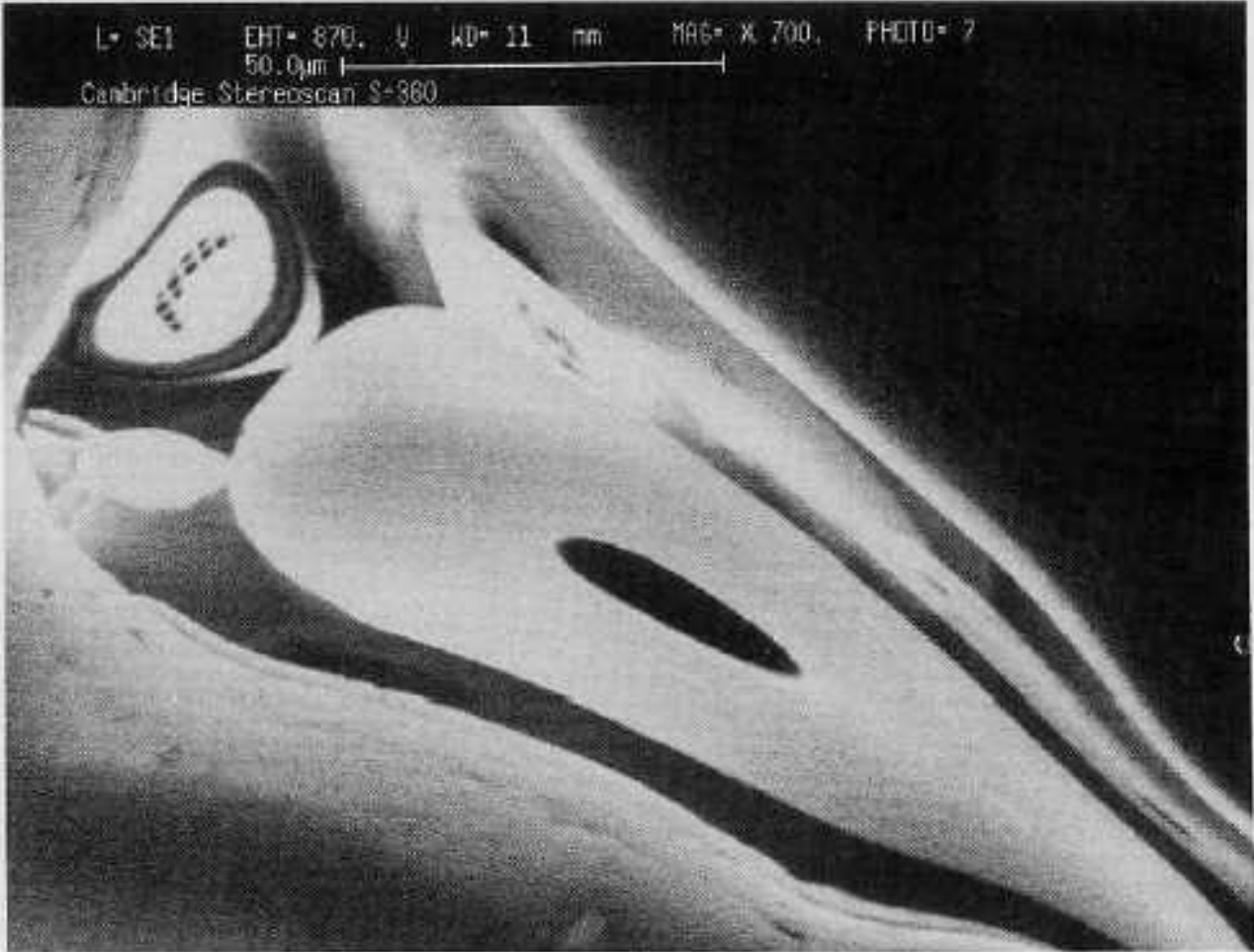


Figure 4.62. Extreme specimen charging, in which the beam is reflected off the specimen and scans the specimen chamber, producing a highly distorted “fisheye lens” view of the polepiece, the Faraday cage of the E-T detector, and the chamber walls.

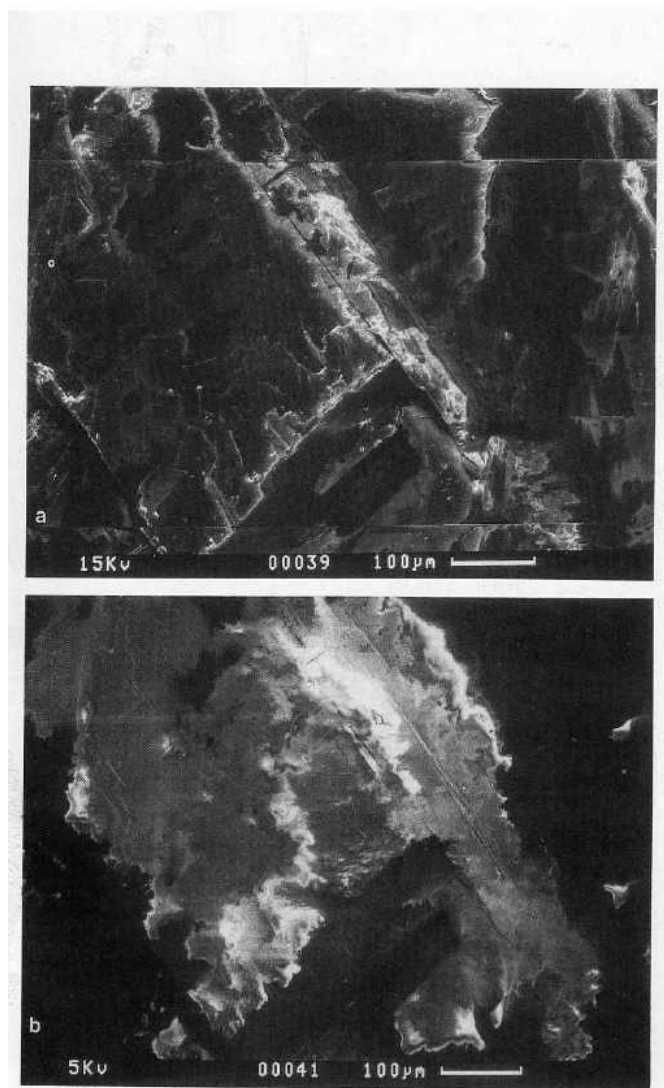
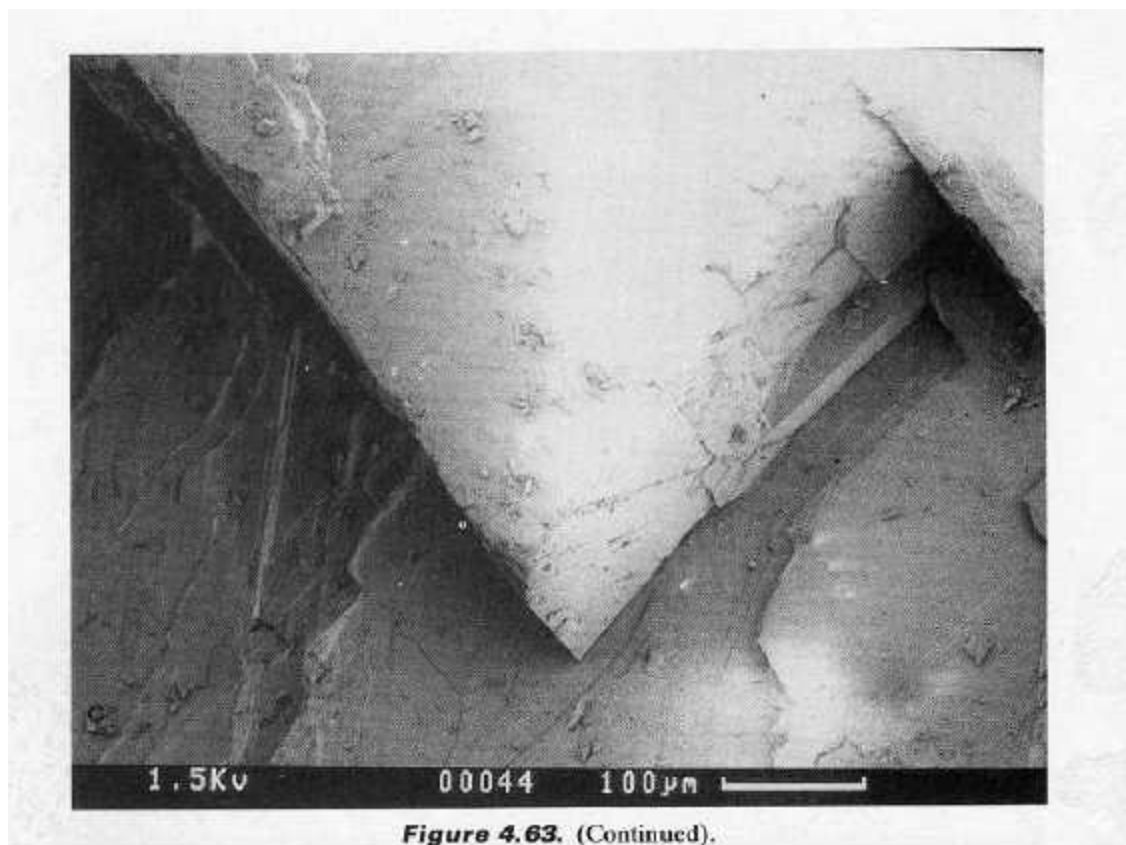
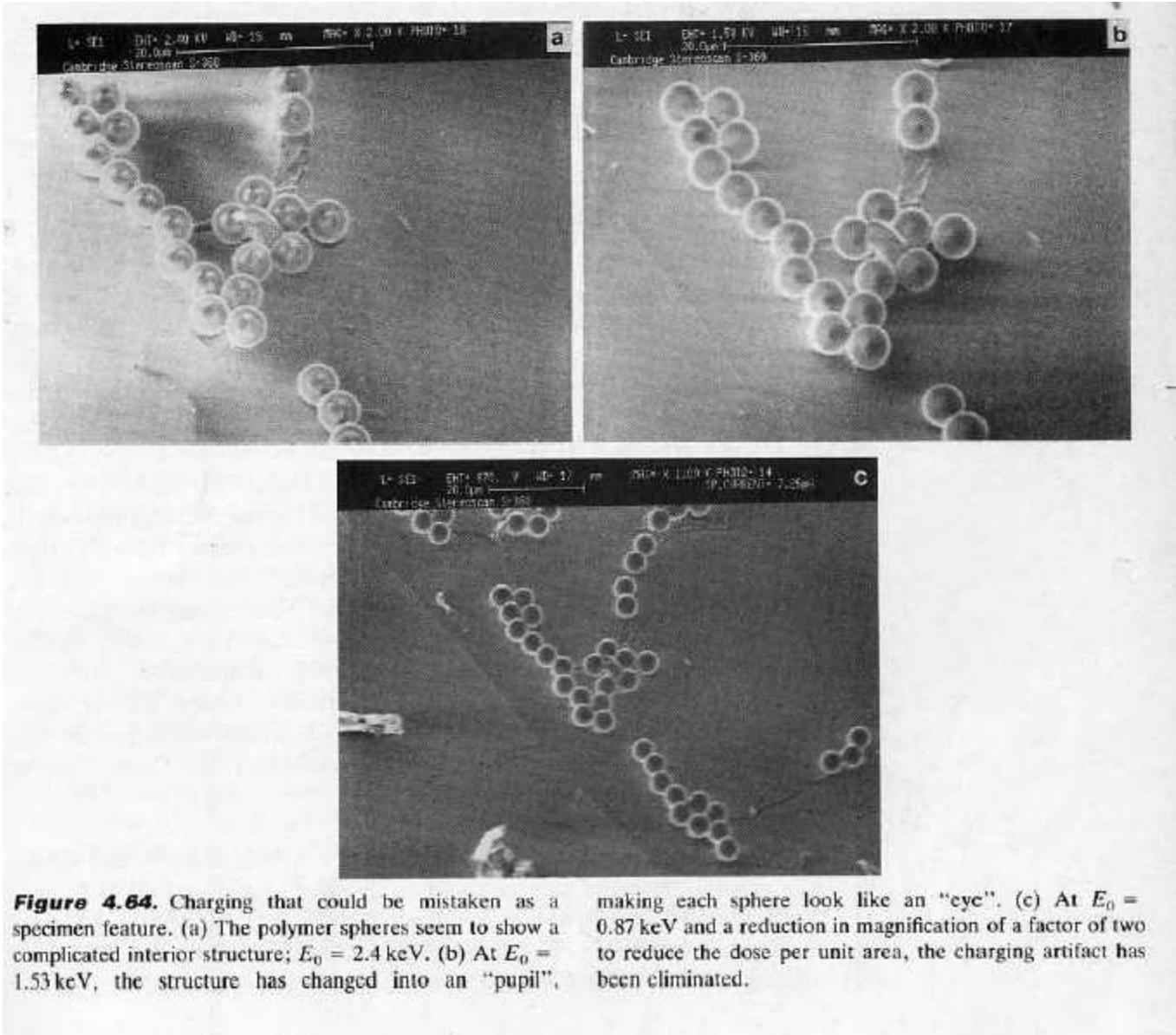


Figure 4.63. Charging observed during SEM imaging of an uncoated calcite crystal. (a) $E_0 = 15$ keV; note the bright/dark regions and the scan discontinuities. (b) $E_0 = 5$ keV; the scanned image is now stable, but the bright/dark voltage contrast dominates the true features of the image. (c) $E_0 = 1.5$ keV; operation at the E_2 crossover point produces a stable image in which topographic contrast showing the true features of the specimen is evident. The bright area on the tilted top surface shows that not all regions of charging can be simultaneously controlled.





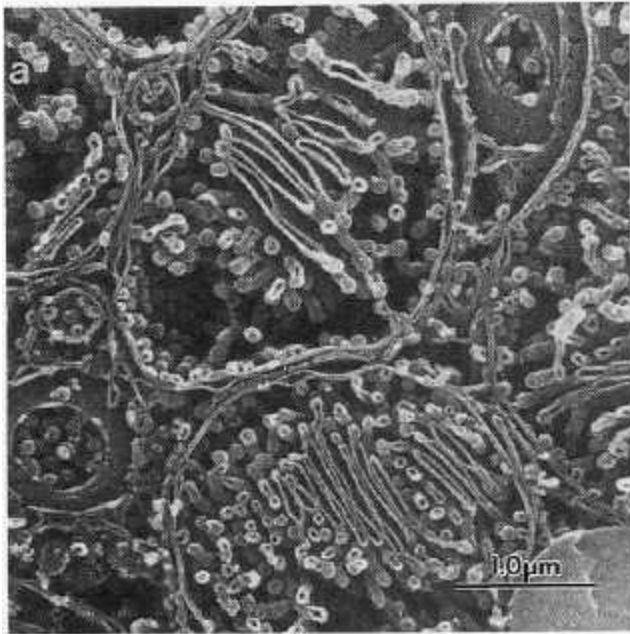
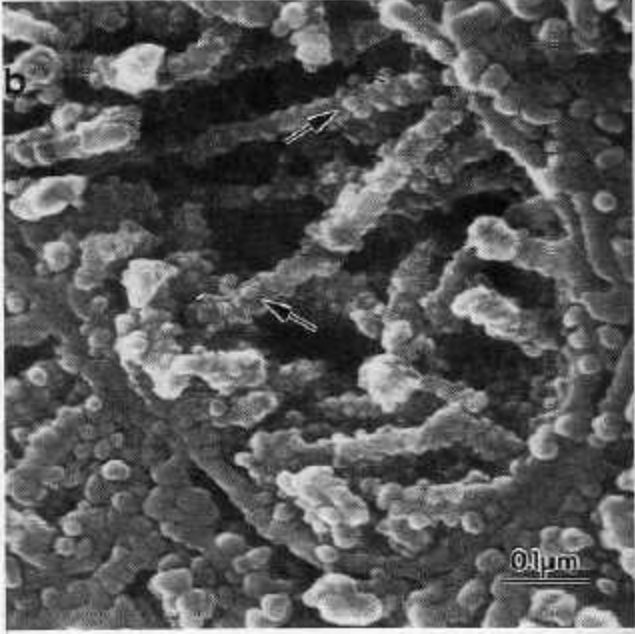


Figure 13.4. Conductive staining methods. (a) Mitochondria of a rat suprarenal gland cell. Lamellar, tubular, and vesicular cristae are present (Hanaki *et al.*, 1985). (b) Inner



membrane particles on mitochondrial tubules (arrows) from a rat liver cell (Osatake *et al.*, 1985).

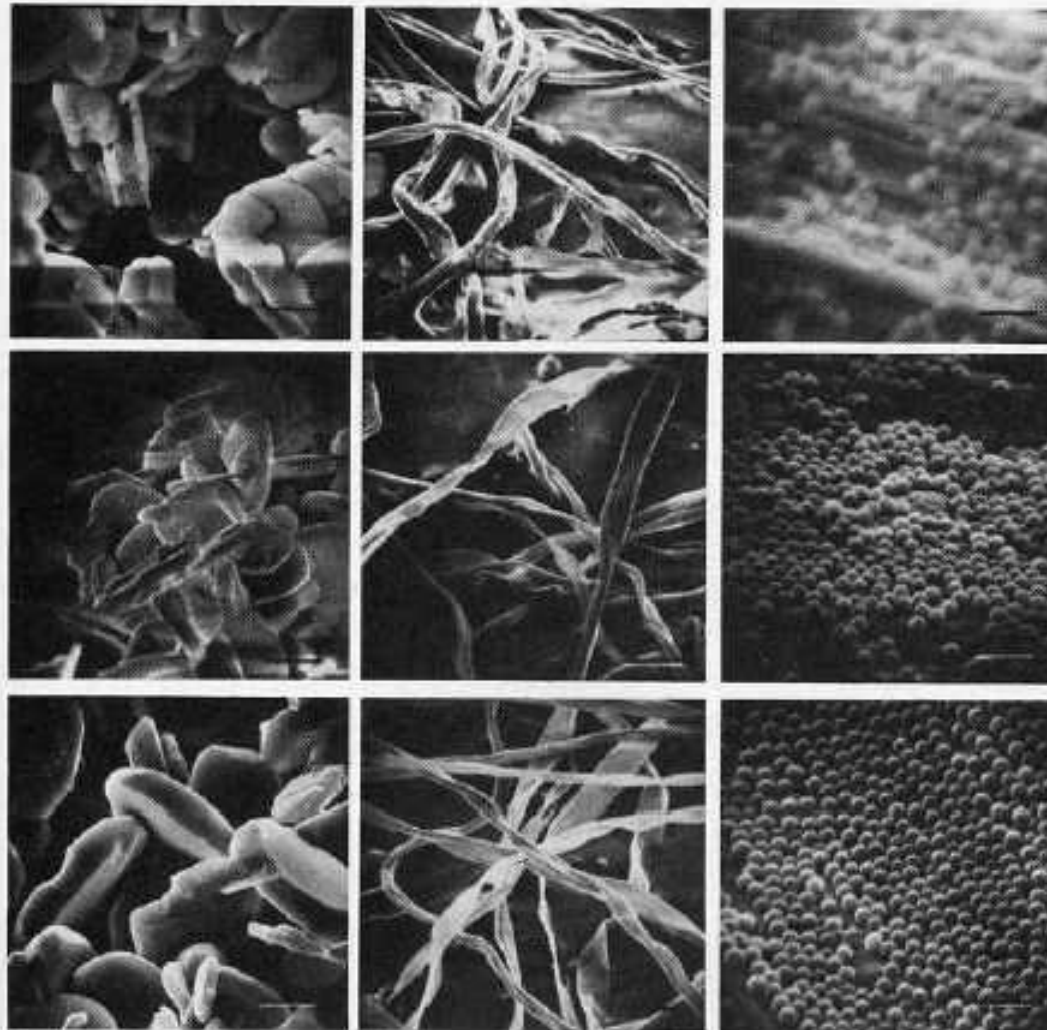
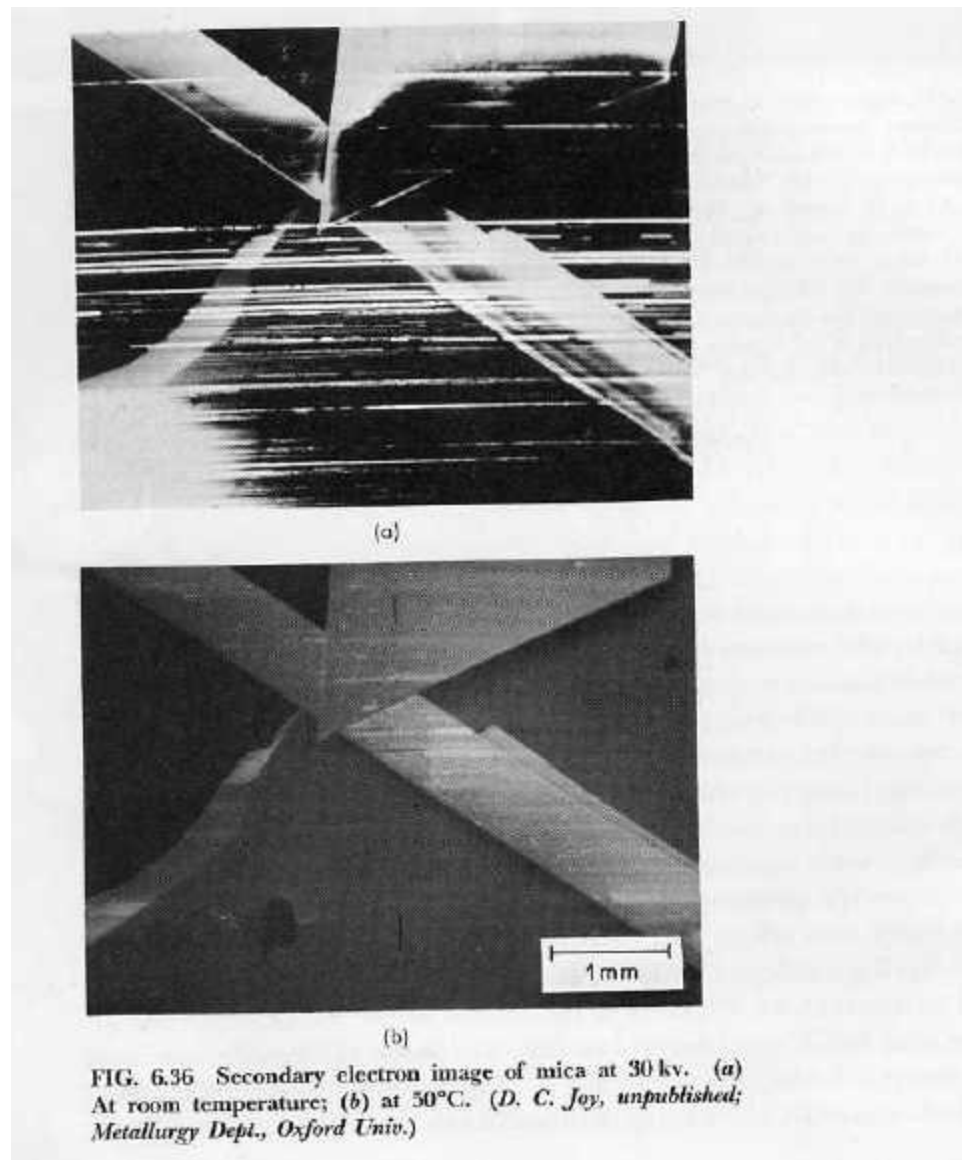
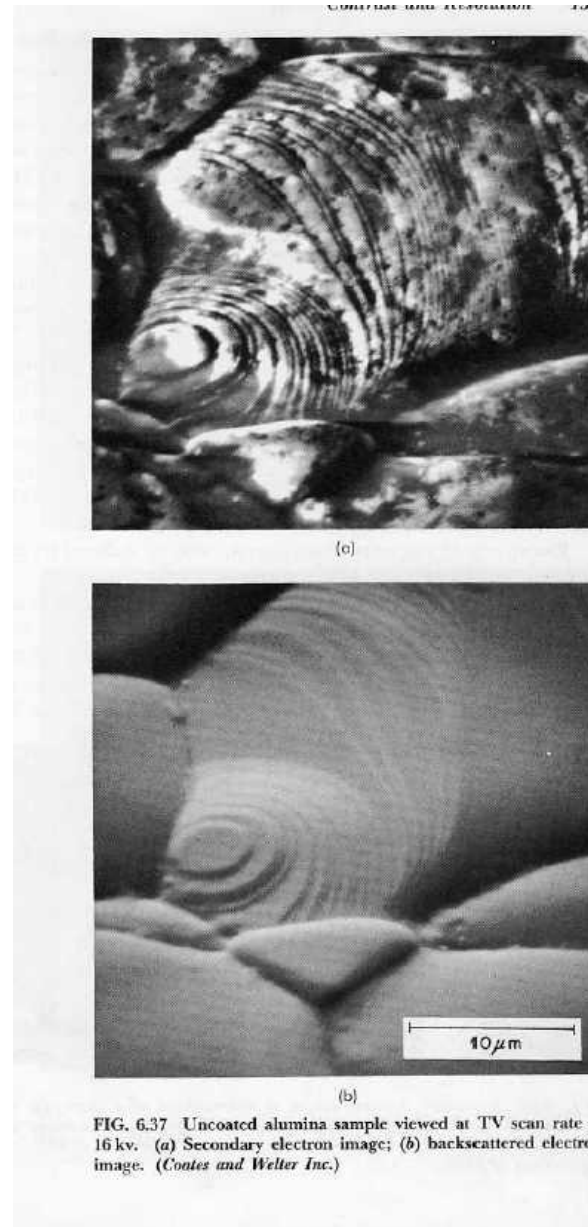


Figure 13.25. Comparison of uncoated, evaporative-coated, and sputter-coated non-conductors. Left, Al_2O_3 ; center, cotton wool; right, polystyrene latex spheres. Top row, uncoated; center row, evaporative-coated with 10 nm of gold; bottom row, sputter-coated with 10 nm of gold. Magnification bar = 1 μm .





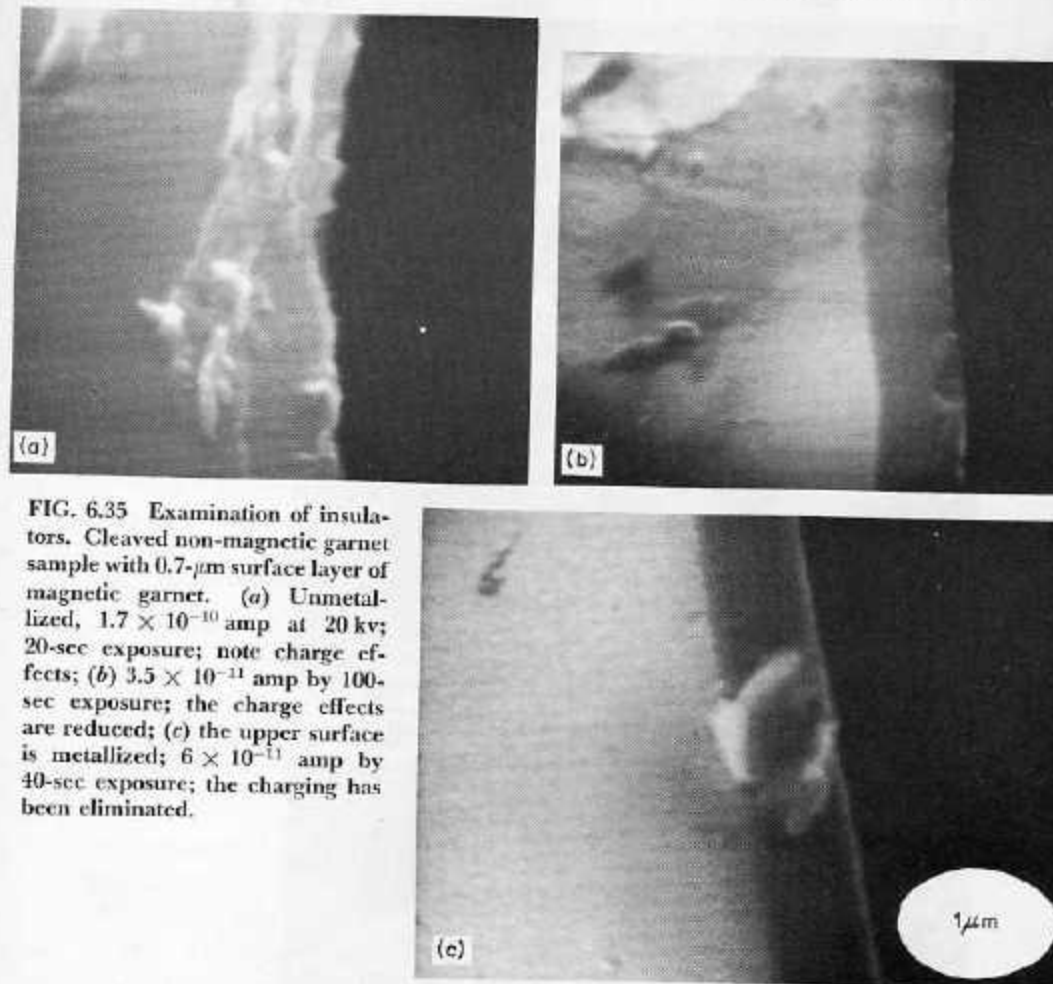


FIG. 6.35 Examination of insulators. Cleaved non-magnetic garnet sample with $0.7\text{-}\mu\text{m}$ surface layer of magnetic garnet. (a) Unmetallized, 1.7×10^{-10} amp at 20 kv; 20-sec exposure; note charge effects; (b) 3.5×10^{-11} amp by 100-sec exposure; the charge effects are reduced; (c) the upper surface is metallized; 6×10^{-11} amp by 40-sec exposure; the charging has been eliminated.

STEREO IMAGING

Measure X, Y coordinates of 2 points
relative to some feature in both pictures
[rotated by α about Y-axis]

$$Z = P/2M \sin \alpha/2$$

Where

M = Magnification

$$M_x = X_L - P/2 = X_R + P/2$$

$$M_y = Y_L = Y_R \quad L = \text{Left}$$

$$P = X_L - X_R \quad R = \text{Right}$$

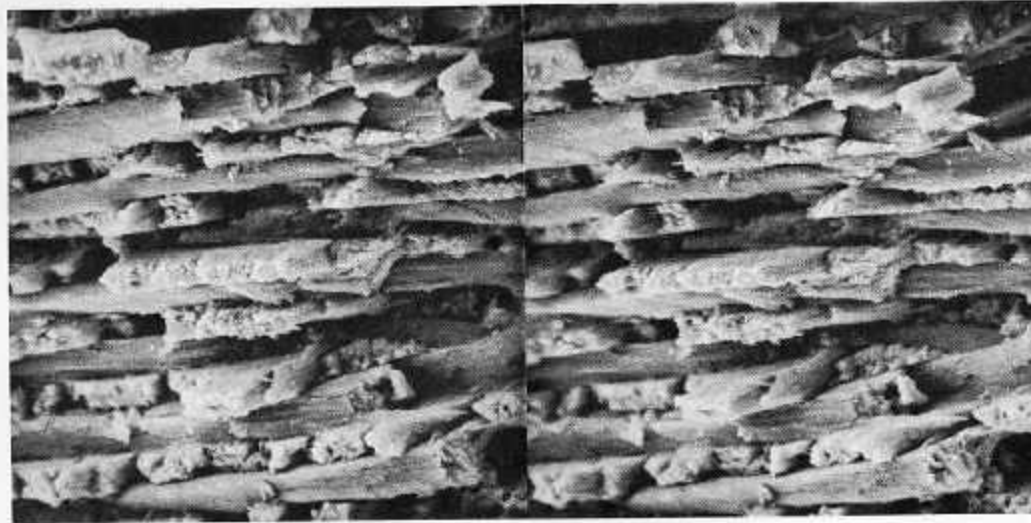


FIG. 11.4 Fractured sheep dental enamel showing prismatic bundles (emerging) and inter-row sheet regions horizontal. Very little concept of the topography of this rough surface can be gained from examination of one image.

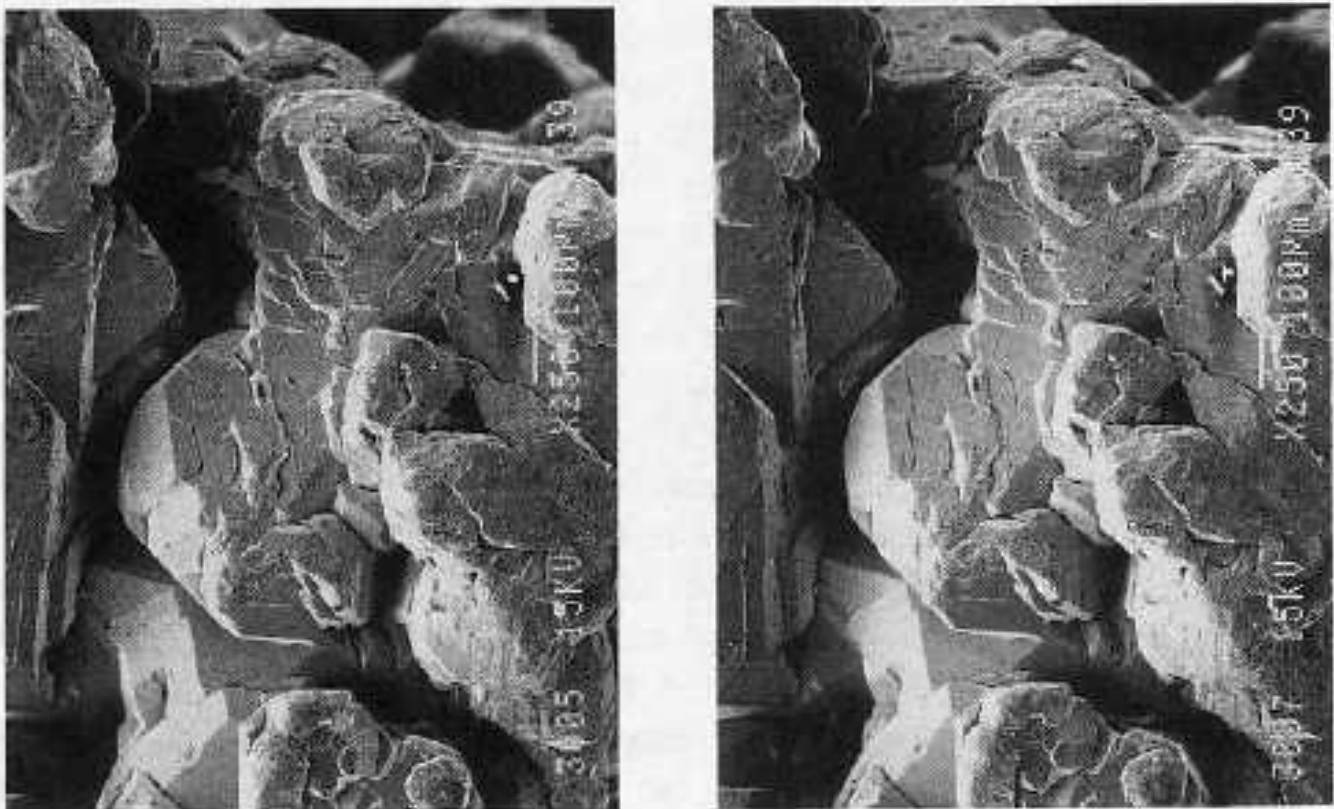


Figure 4.67. Stereo pair of native silver. A typical application of qualitative stereo imaging to view a complicated three-dimensional structure. Illumination is from the left.

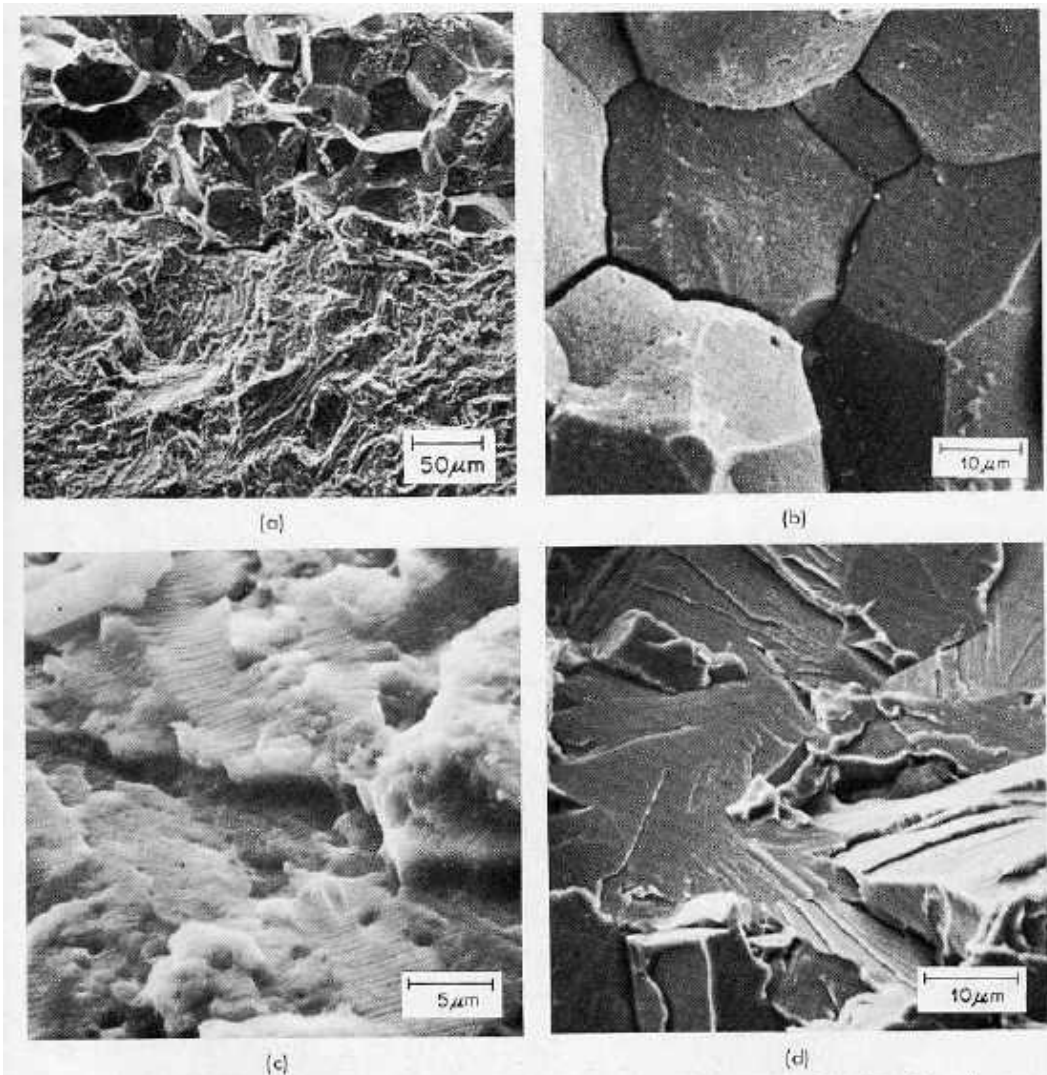
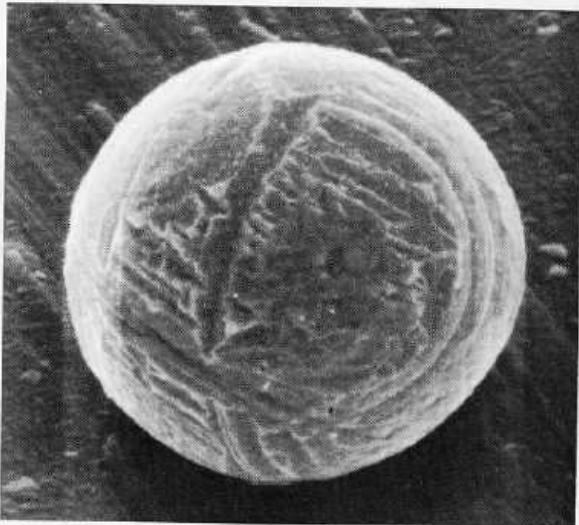
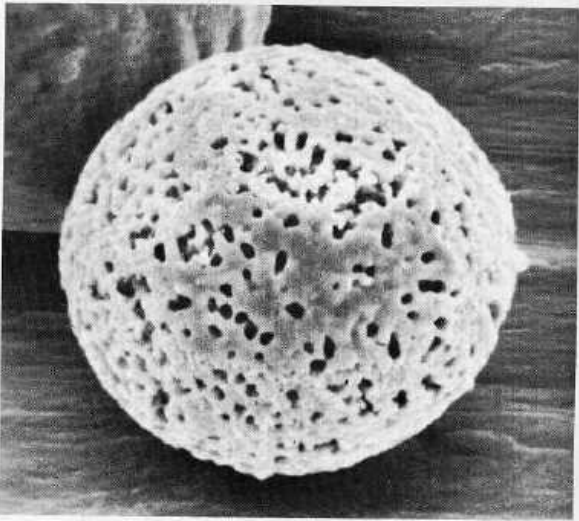


FIG. 9.9 Examples of the SEM applied to the study of fractures. (a) Boundary between a fatigue crack and an intergranular fracture in steel; (b) detail from (a); (c) fatigue fracture surface of an Al-Zn-Mg alloy showing striations; (d) brittle fracture (at liquid N₂ temperature) of C-Mn semikilled steel. (Reproduced by permission of the Welding Institute, Abington Hall, Cambridge, Eng.)



(a)



(b)

FIG. 9.10 Iron oxide particles of 20 μm diameter (a) unreduced; (b) reduced at 700°C. (Themelis and Gauvin 1962. Courtesy of Am. Inst. Chem. Eng. J.)

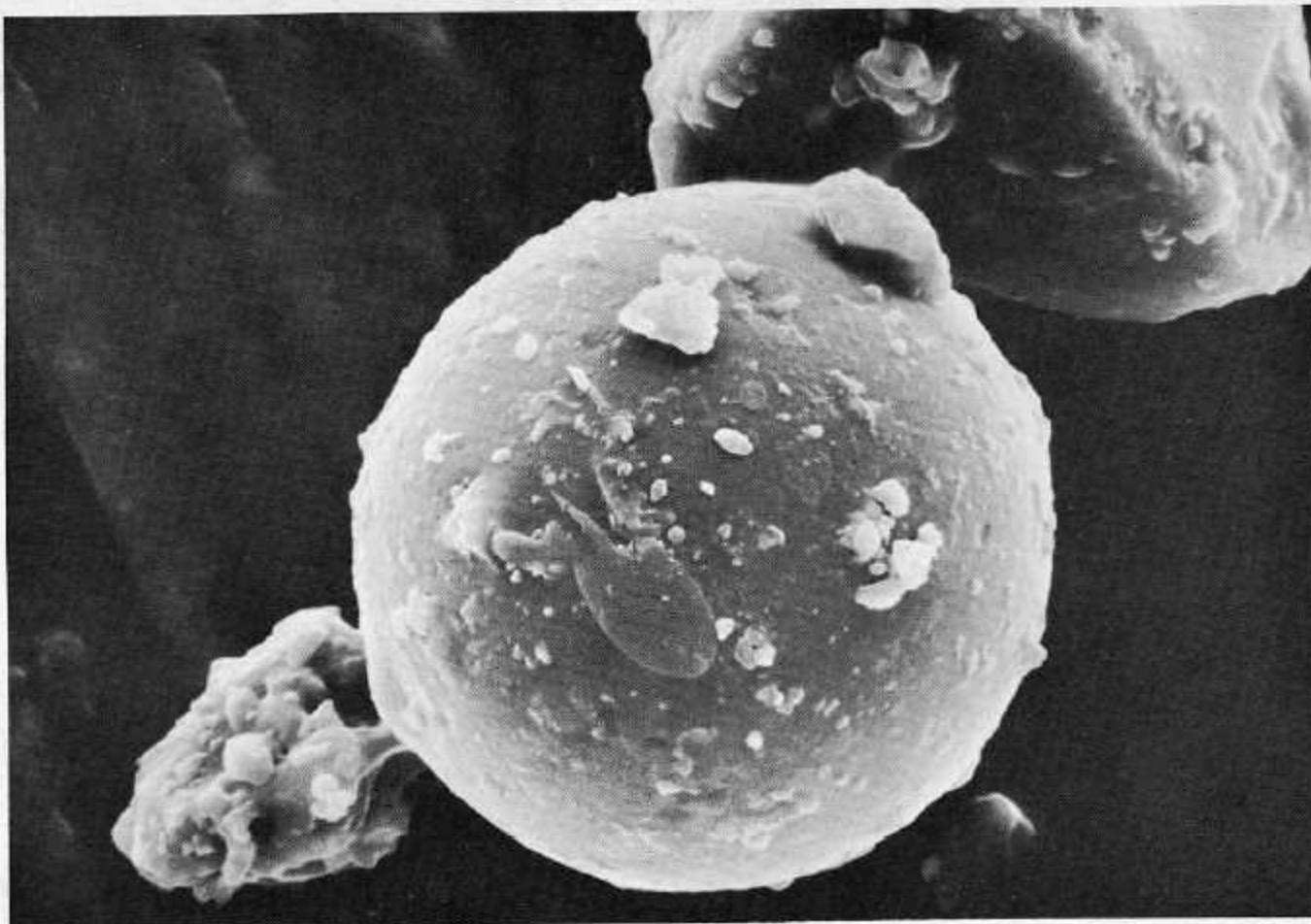
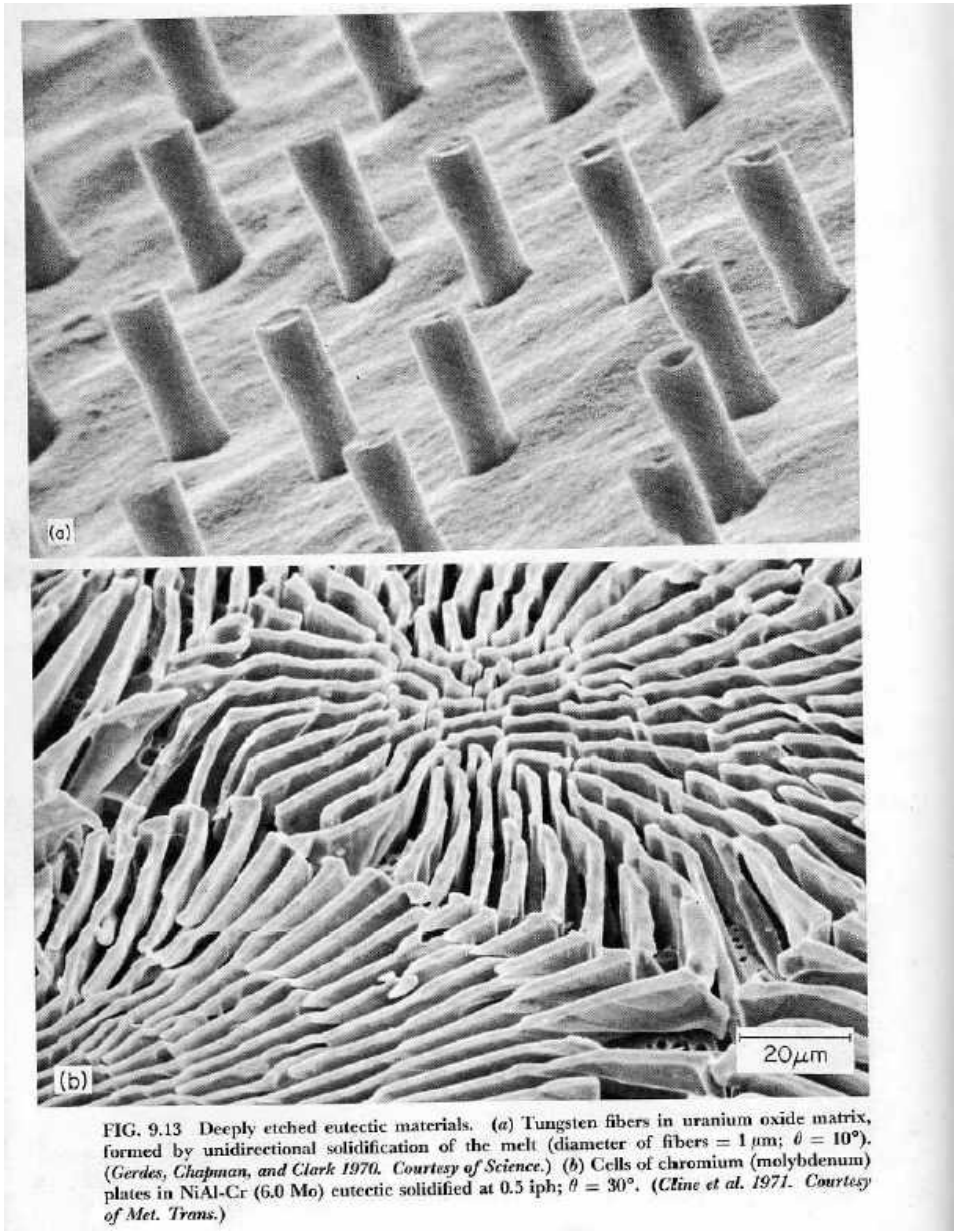


FIG. 9.11 Glass particle of diameter $19\text{ }\mu\text{m}$ from Apollo 11. (Moon dust was sprinkled onto collodion-covered stub and then coated with $300\text{-}\text{\AA}$ Au using rotating shadowing unit.)
(*R. B. Bolon, General Electric Co. Corporate Research and Development.*)



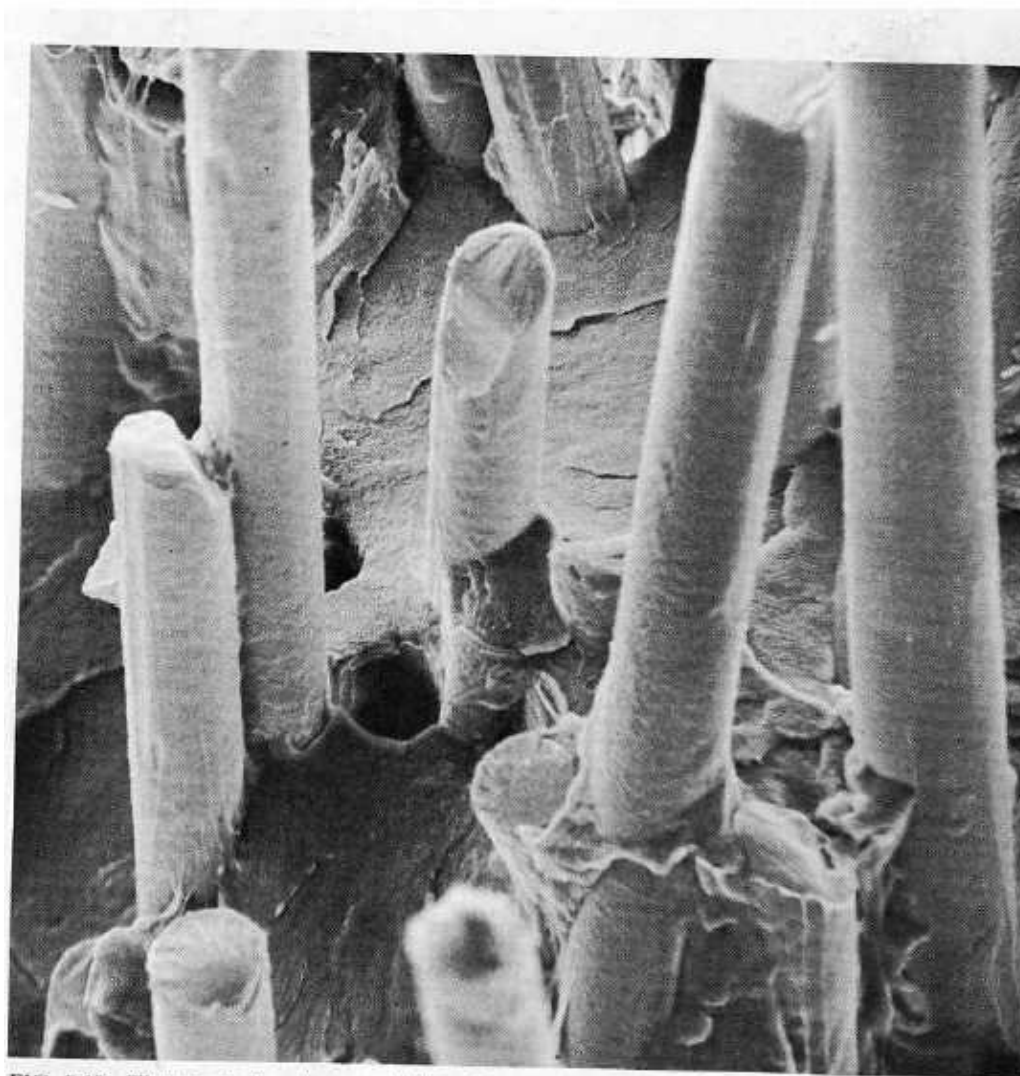


FIG. 9.12 Thermoplastic polyester reinforced with glass fibers. Diameter of glass fiber = $5\text{ }\mu\text{m}$. (E. H. Christopherson, General Electric Co. Corporate Research and Development.)

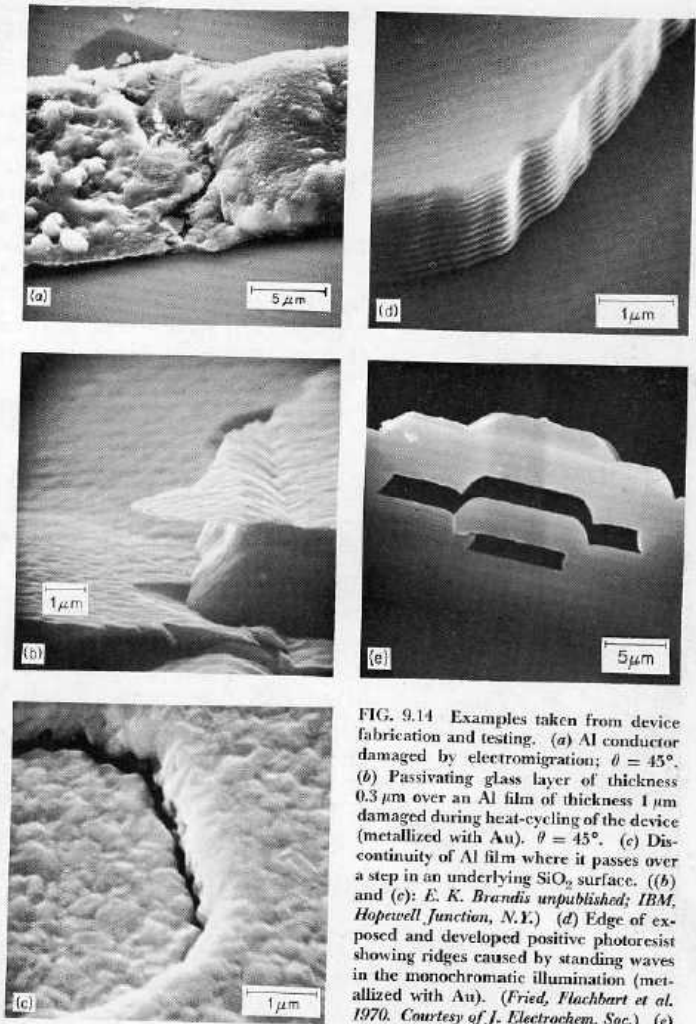
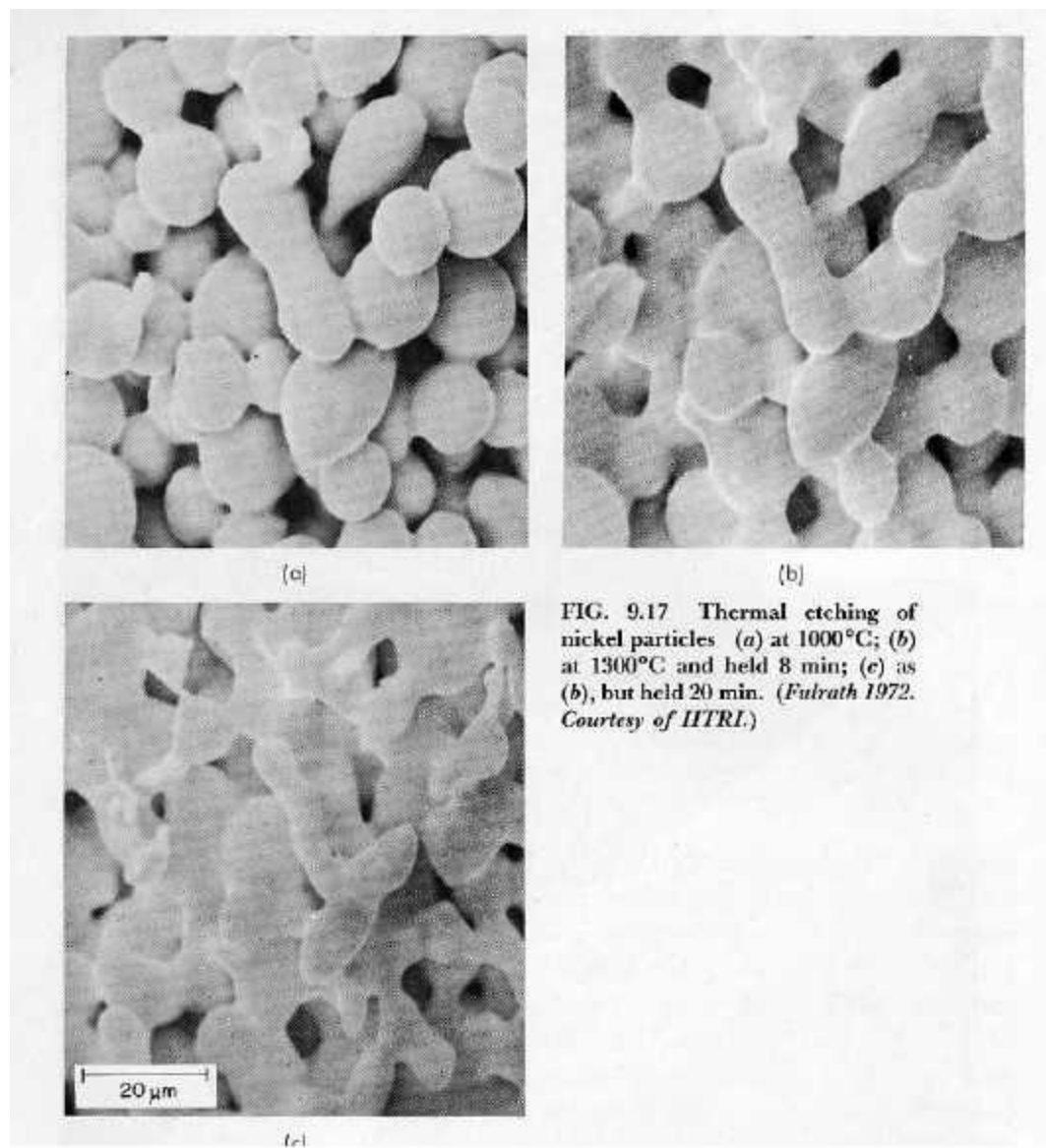
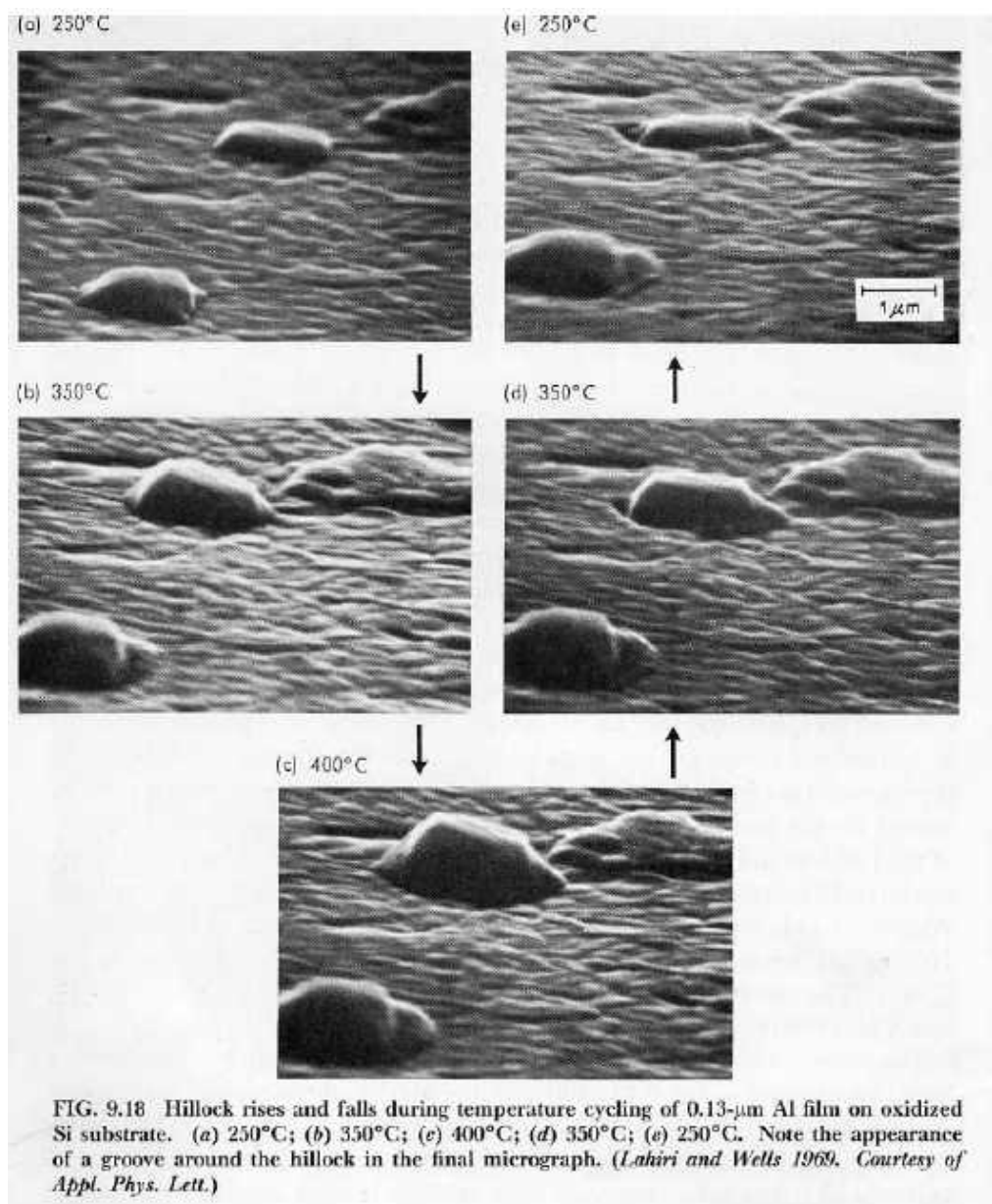
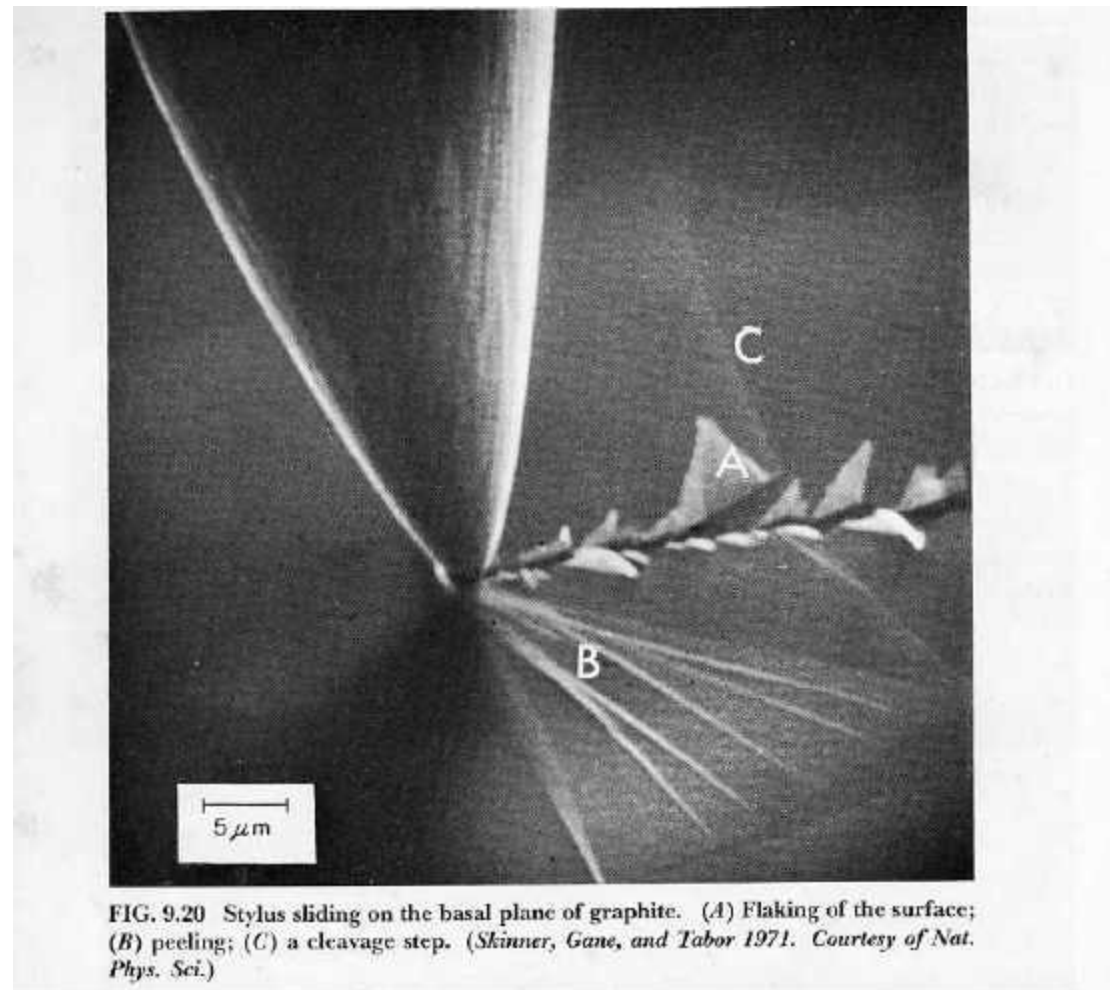


FIG. 9.14 Examples taken from device fabrication and testing. (a) Al conductor damaged by electromigration; $\theta = 45^\circ$. (b) Passivating glass layer of thickness $0.3 \mu\text{m}$ over an Al film of thickness $1 \mu\text{m}$ damaged during heat-cycling of the device (metallized with Au). $\theta = 45^\circ$. (c) Discontinuity of Al film where it passes over a step in an underlying SiO_2 surface. ((b) and (c): E. K. Brandis unpublished; IBM, Hopewell Junction, N.Y.) (d) Edge of exposed and developed positive photoresist showing ridges caused by standing waves in the monochromatic illumination (metallized with Au). (Fried, Flachbart et al. 1970. Courtesy of J. Electrochem. Soc.) (e) Multi layer integrated circuit which was cleaved to show the internal structure. The voids are where the aluminum conductors were etched away, to leave the quartz insulating layers; $\theta = 90^\circ$. (P. Beaufre; IBM Essoannes Plant, France.)

FIG. 9.14 Examples taken from device fabrication and testing. (a) Al conductor damaged by electromigration; $\theta = 45^\circ$. (b) Passivating glass layer of thickness $0.3 \mu\text{m}$ over an Al film of thickness $1 \mu\text{m}$ damaged during heat-cycling of the device (metallized with Au). $\theta = 45^\circ$. (c) Discontinuity of Al film where it passes over a step in an underlying SiO_2 surface. ((b) and (c): E. K. Brandis unpublished; IBM, Hopewell Junction, N.Y.) (d) Edge of exposed and developed positive photoresist showing ridges caused by standing waves in the monochromatic illumination (metallized with Au). (Fried, Flachbart et al. 1970. Courtesy of J. Electrochem. Soc.) (e) Multi layer integrated circuit which was cleaved to show the internal structure. The voids are where the aluminum conductors were etched away, to leave the quartz insulating layers; $\theta = 90^\circ$. (P. Beaufre; IBM Essoannes Plant, France.)







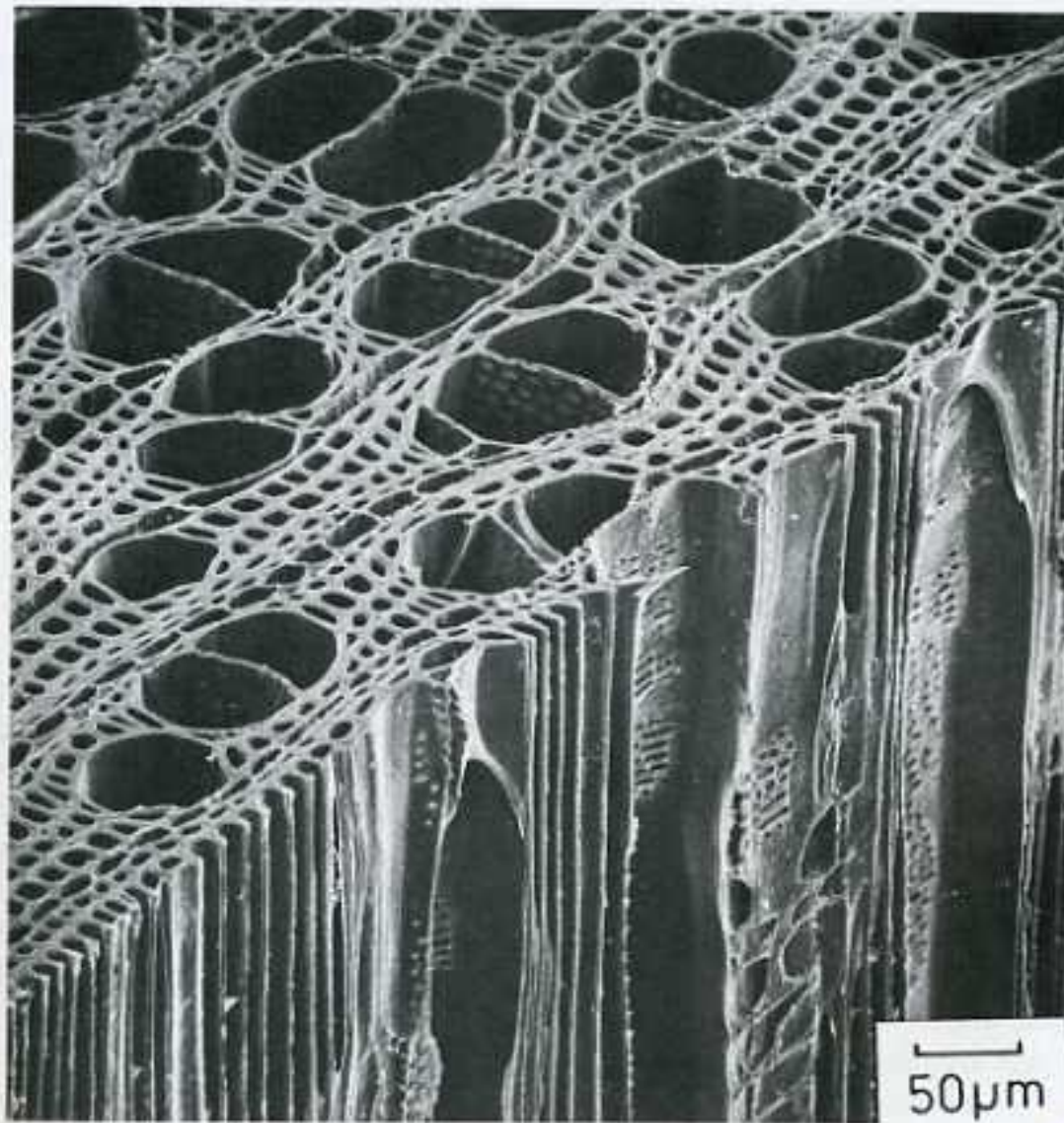


Figure 12.12. Transverse and radial longitudinal surfaces of the wood of *Notofagus fusca* (Exley *et al.*, 1974).



CHAPTER 2

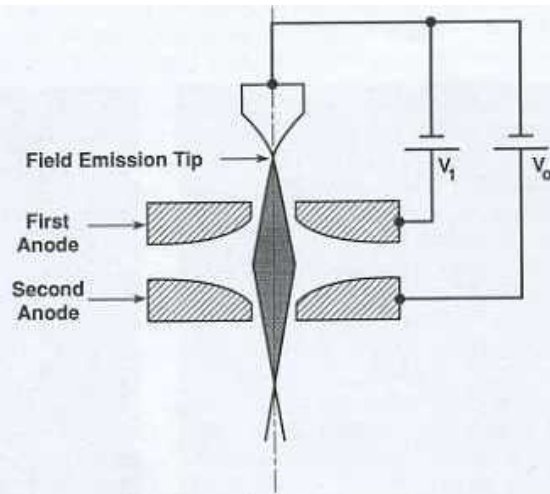


Figure 2.12. Schematic diagram of the Butler triode field emission source. V_1 is the extraction voltage, typically a few kV, and V_0 is the accelerating voltage (adapted from Crewe, 1969).

Brightness and Probe Current. The cathode current density J_c for a cold field emission source strongly depends on the applied field strength, similar to the way thermionic emission is dependent upon temperature. Expressions derived to calculate J_c (Fowler and Nordheim, 1928; Good and Muller, 1956) yield values in the range $J_c = 10^4$ –

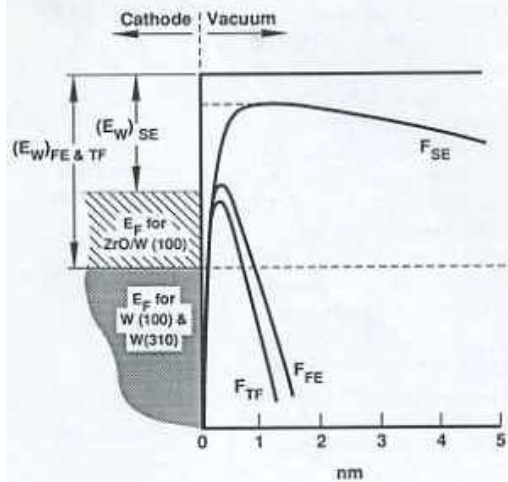


Figure 2.13. Energy-level diagram for cold field emission (FE), thermal field emission (TF), and Schottky emission (SE). Electrons tunnel through the narrow barriers in the FE and TF cases. For the SE case, the sharp tip covers the barrier and the zirconium oxide coating reduces the work function so that electrons can escape over the barrier (adapted from Tuggle *et al.*, 1985).

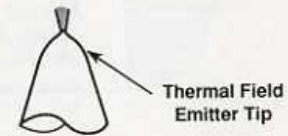
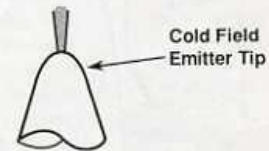
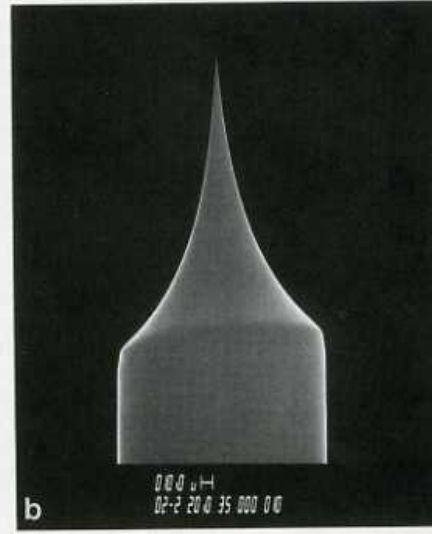


Figure 2.11. Examples of field emission sources. (a) SEM micrograph of (310) single crystal wire spot welded to a tungsten wire. (b) Higher-magnification image of the tip. (c) Schematic diagram comparing tip shapes for the Schottky emitter, cold field emitter, and thermal field emitter (adapted from Tuggle *et al.*, 1985).

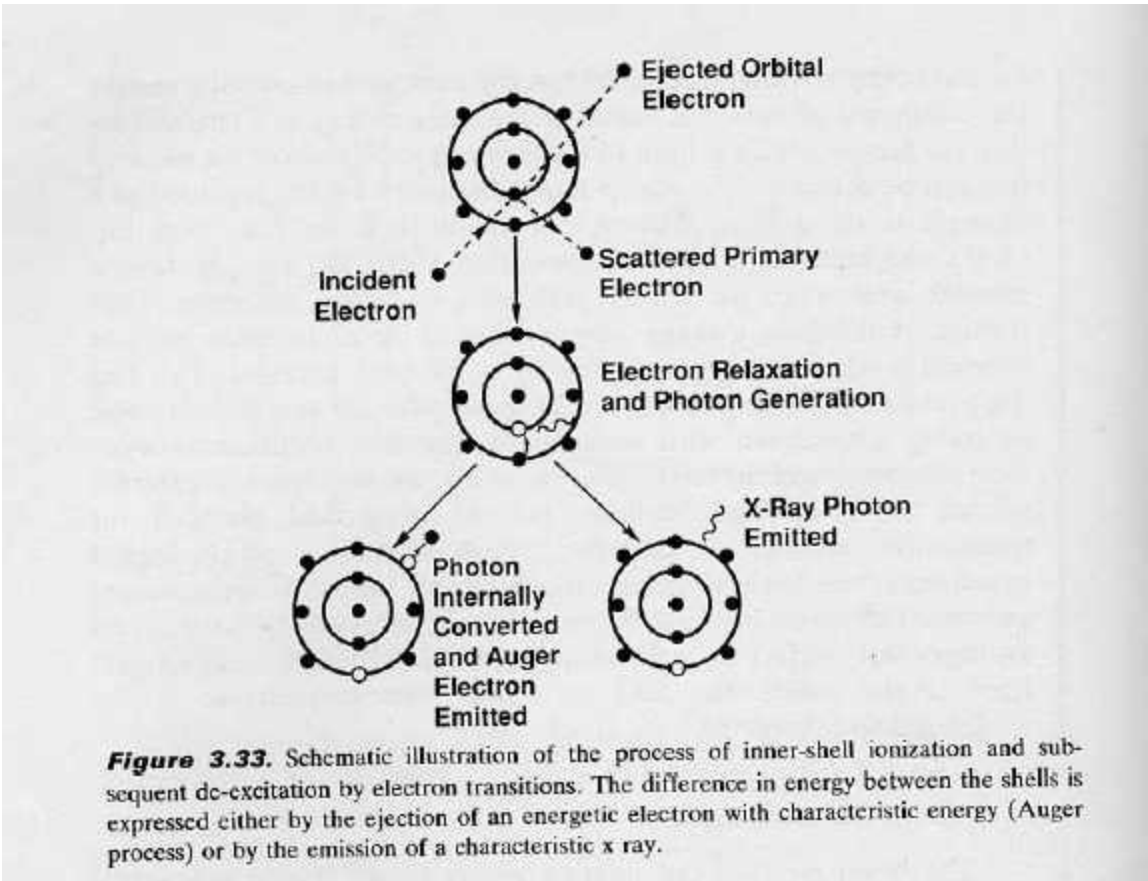


Figure 3.33. Schematic illustration of the process of inner-shell ionization and subsequent de-excitation by electron transitions. The difference in energy between the shells is expressed either by the ejection of an energetic electron with characteristic energy (Auger process) or by the emission of a characteristic x ray.

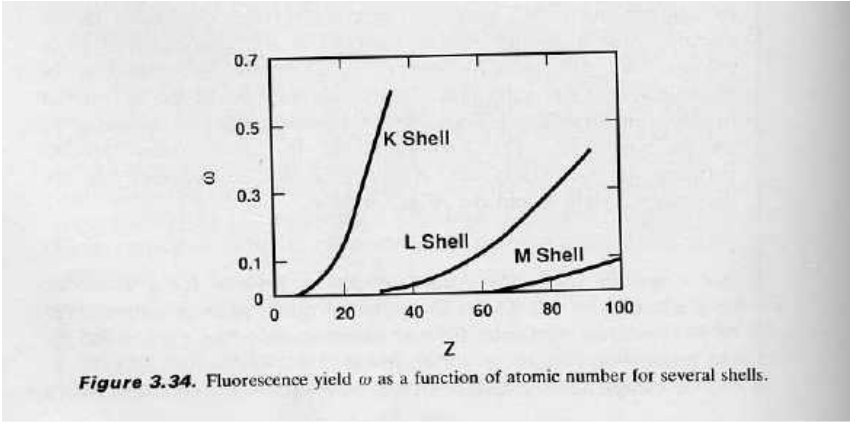
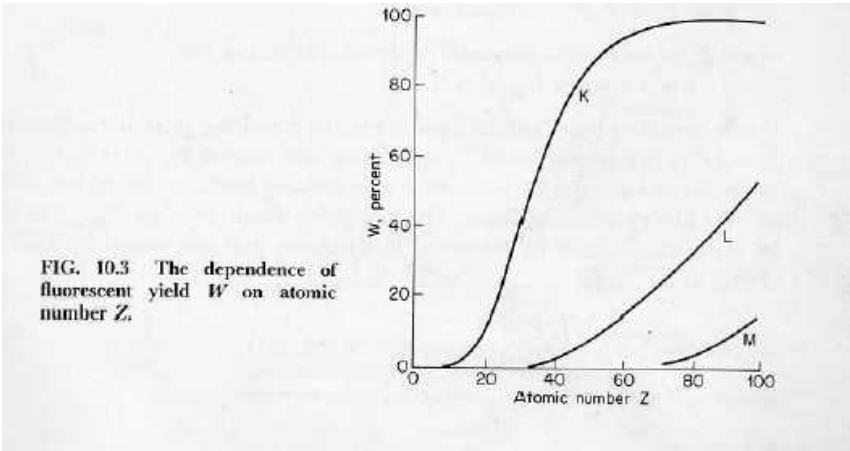
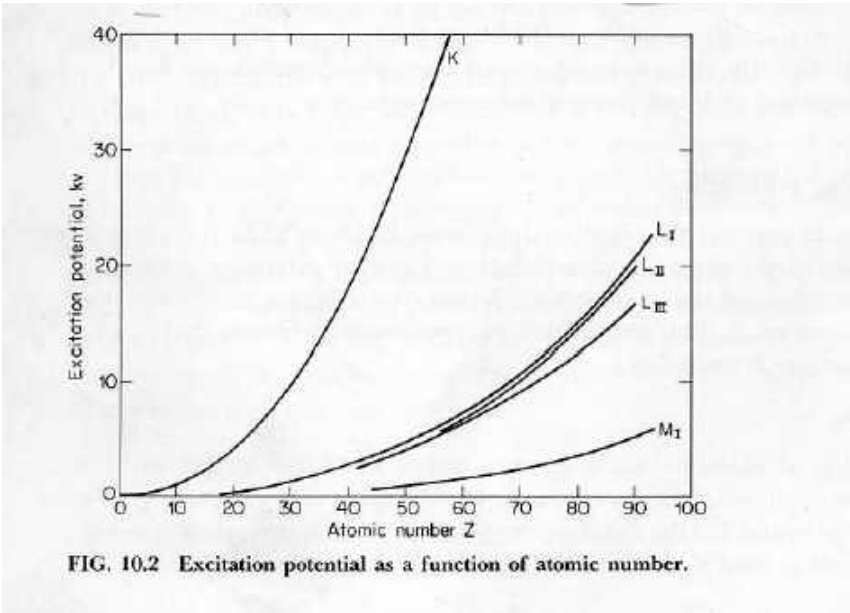
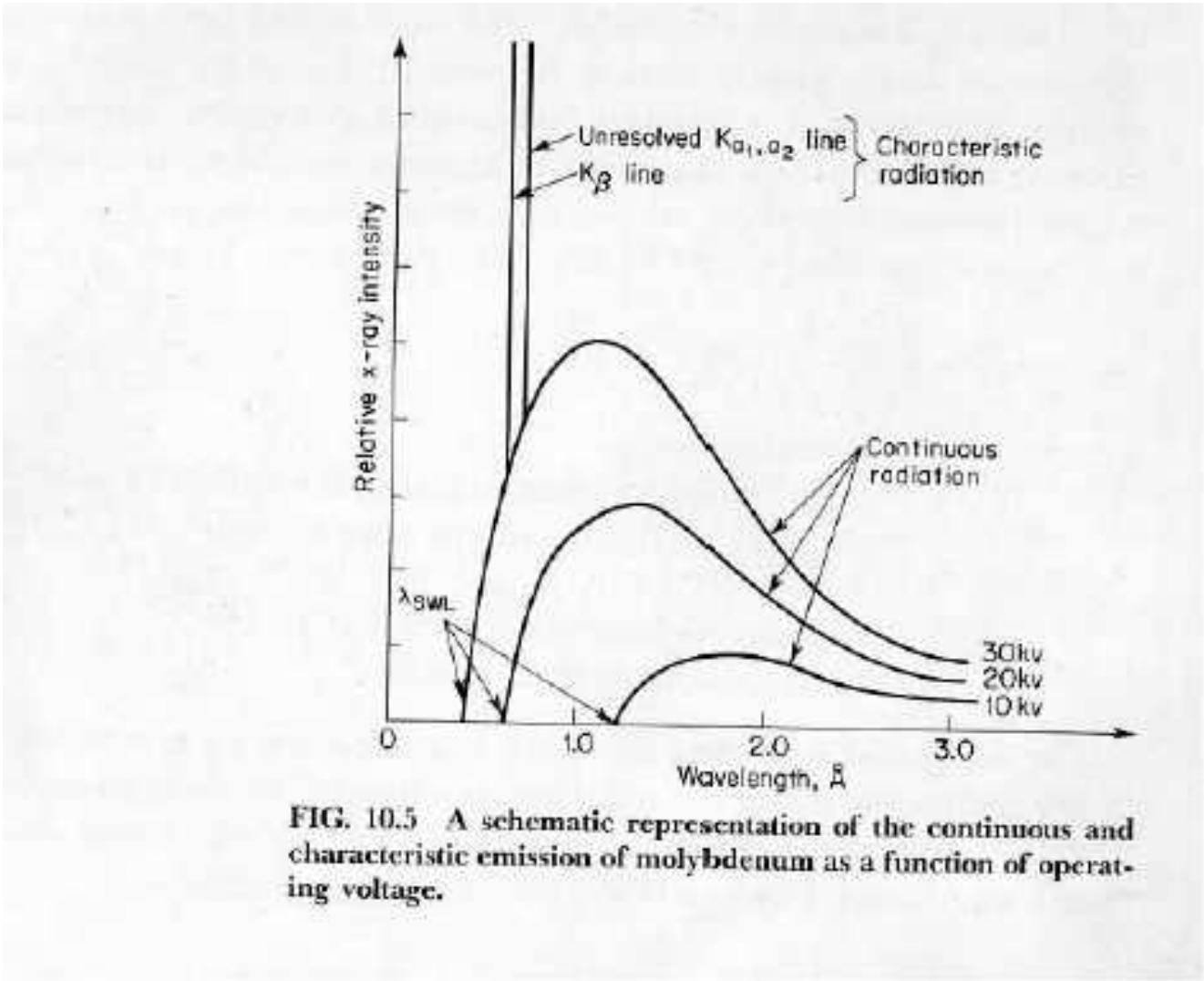


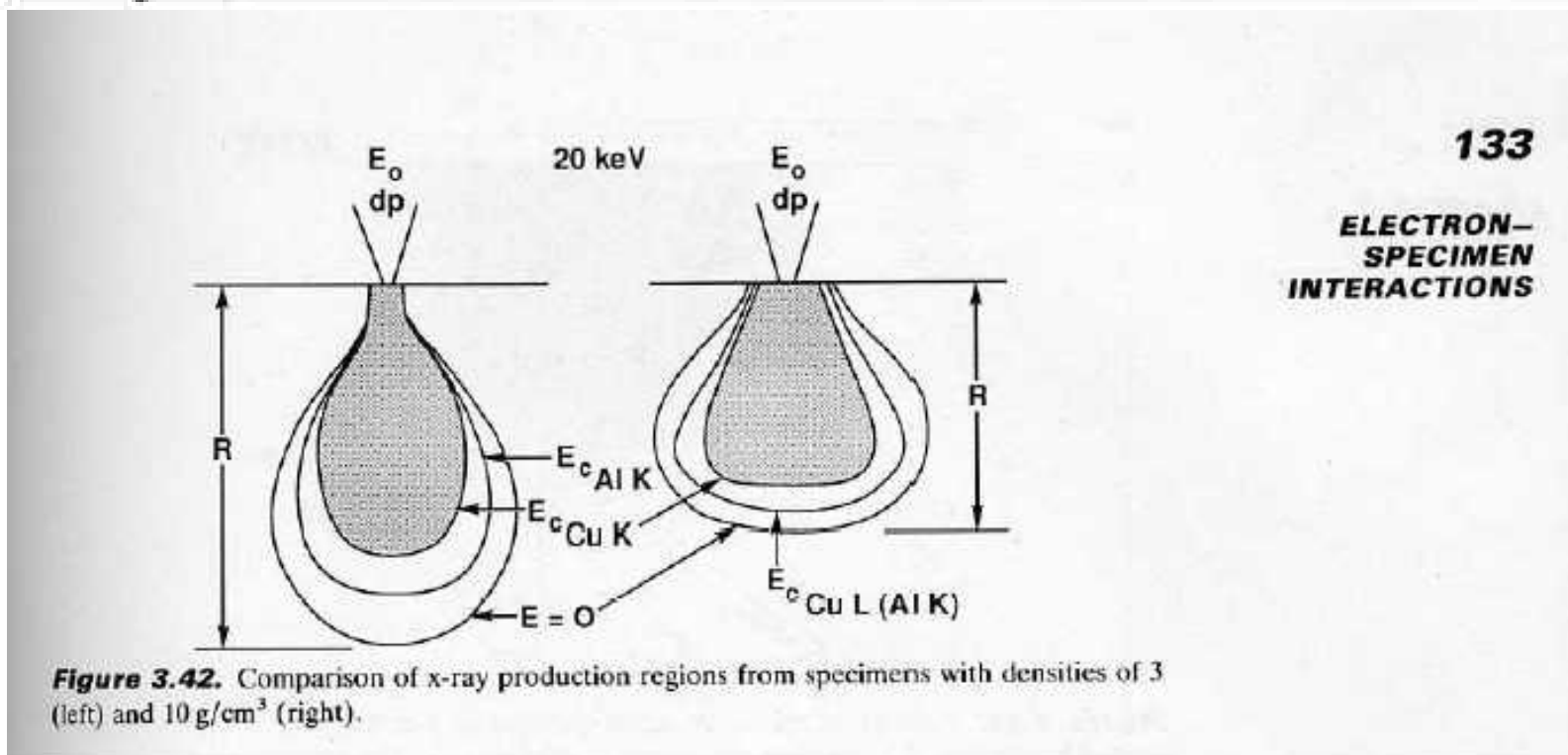
Figure 3.34. Fluorescence yield ω as a function of atomic number for several shells.





$$K = \frac{0.0276A}{Z^{0.889}}, \quad (3.44)$$

$$\rho R = 0.064(E_0^{1.68} - E_c^{1.68}), \quad (3.45)$$



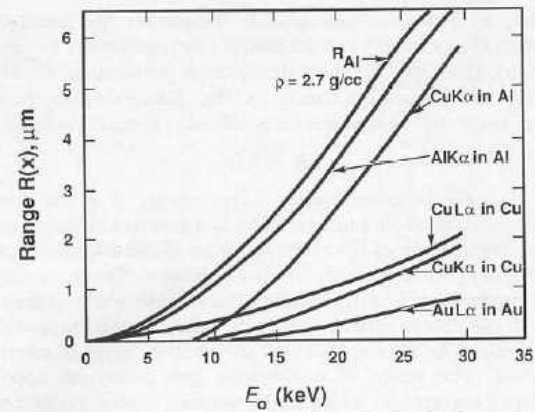


Figure 3.40. X-ray generation range for the Al $K\alpha$, Cu $K\alpha$, Cu $L\alpha$, and Au $L\alpha$ lines generated within aluminum, copper, and gold as a function of incident beam energy.

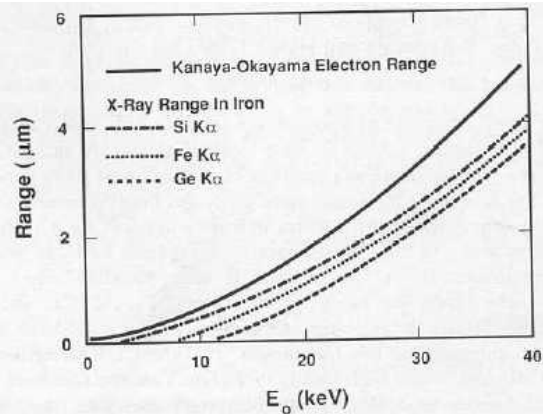


Figure 3.41. X-ray generation range (Andersen-Hasler) for Si $K\alpha$, Fe $K\alpha$, and Ge $K\alpha$ in an iron matrix as a function of beam energy.

Table 3.13. X-Ray Energy and Mass Absorption Coefficients for Ni $K\alpha$ in Several Elements

Element (atomic number)	$K\alpha$	$K\beta$	E_{edge}	(μ/ρ) Ni $K\alpha$ (cm ² /g)
Mn (25)	5.895	6.492	6.537	344
Fe (26)	6.400	7.059	7.111	380
Co (27)	6.925	7.649	7.709	53
Ni (28)	7.472	8.265	8.331	59
Cu (29)	8.041	8.907	8.980	65.5

propagating through a slab of thickness t and density ρ , the intensity on the exit surface is attenuated according to the expression

$$\frac{I}{I_0} = \exp - (\mu/\rho)(\rho t), \tag{3.46}$$

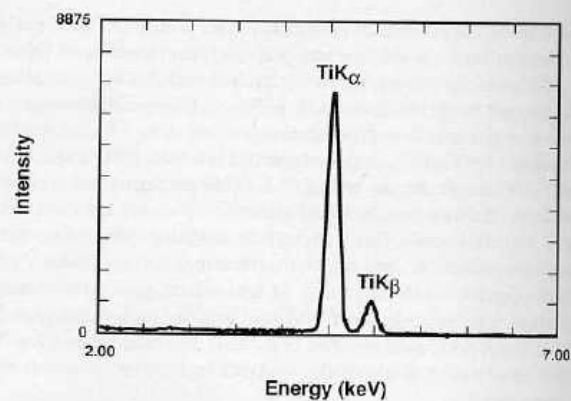


Figure 6.2. Titanium $K\alpha$ and $K\beta$ peaks. $K\alpha = 4.51$ keV. [Ultrathin window (diamond) Si(Li) EDS, 145 eV FWHM at Mn $K\alpha$.]

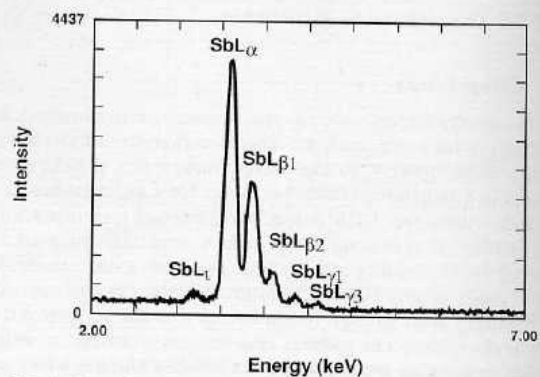


Figure 6.3. Antimony L -family x-ray peaks. $L\alpha_1 = 3.61$ keV. [Ultrathin window (diamond) Si(Li) EDS, 145 eV FWHM at Mn $K\alpha$.]

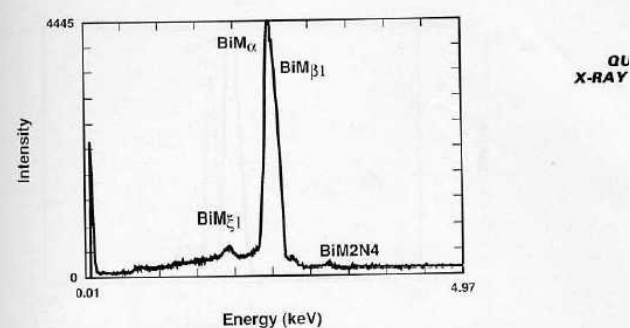
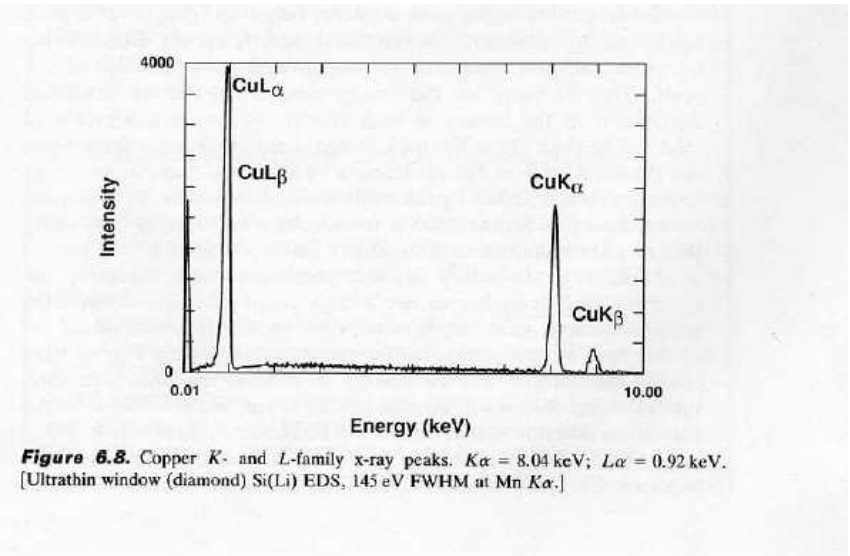
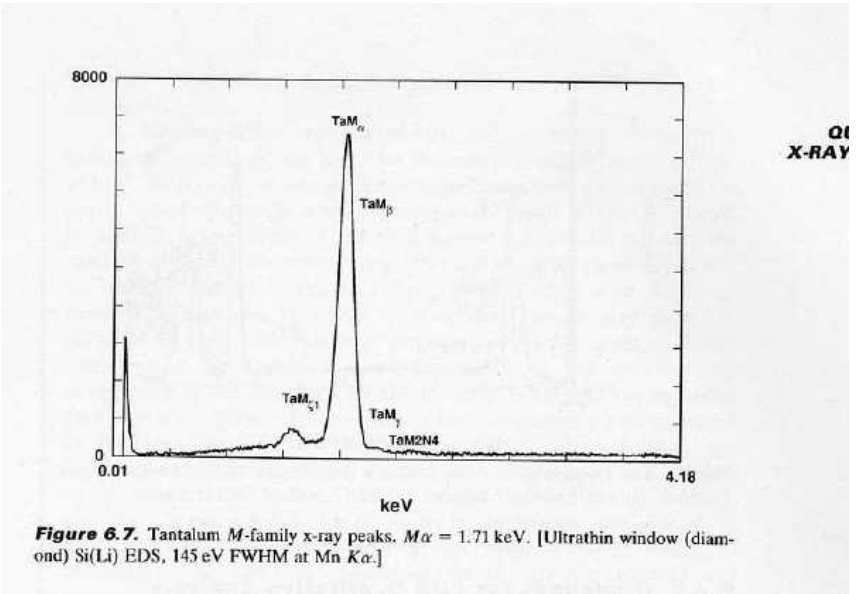
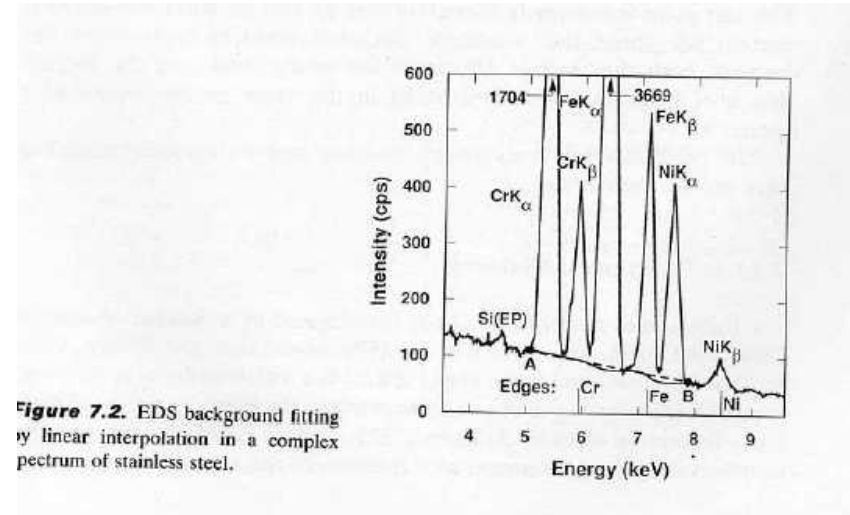
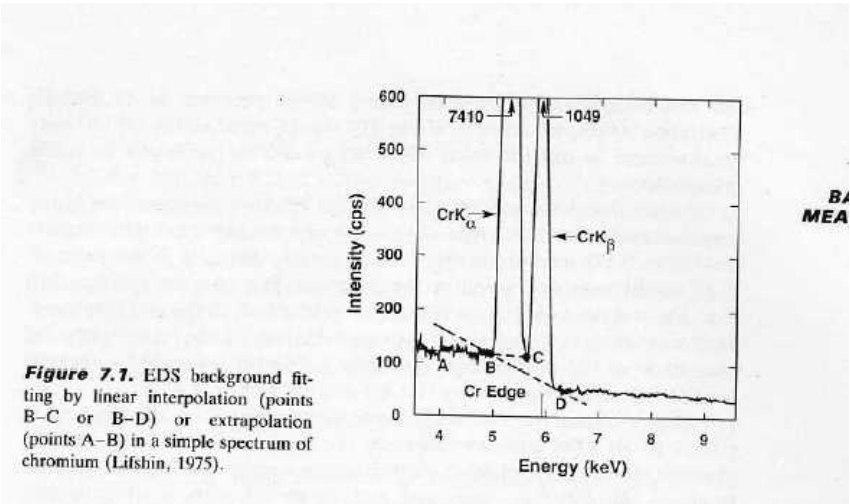
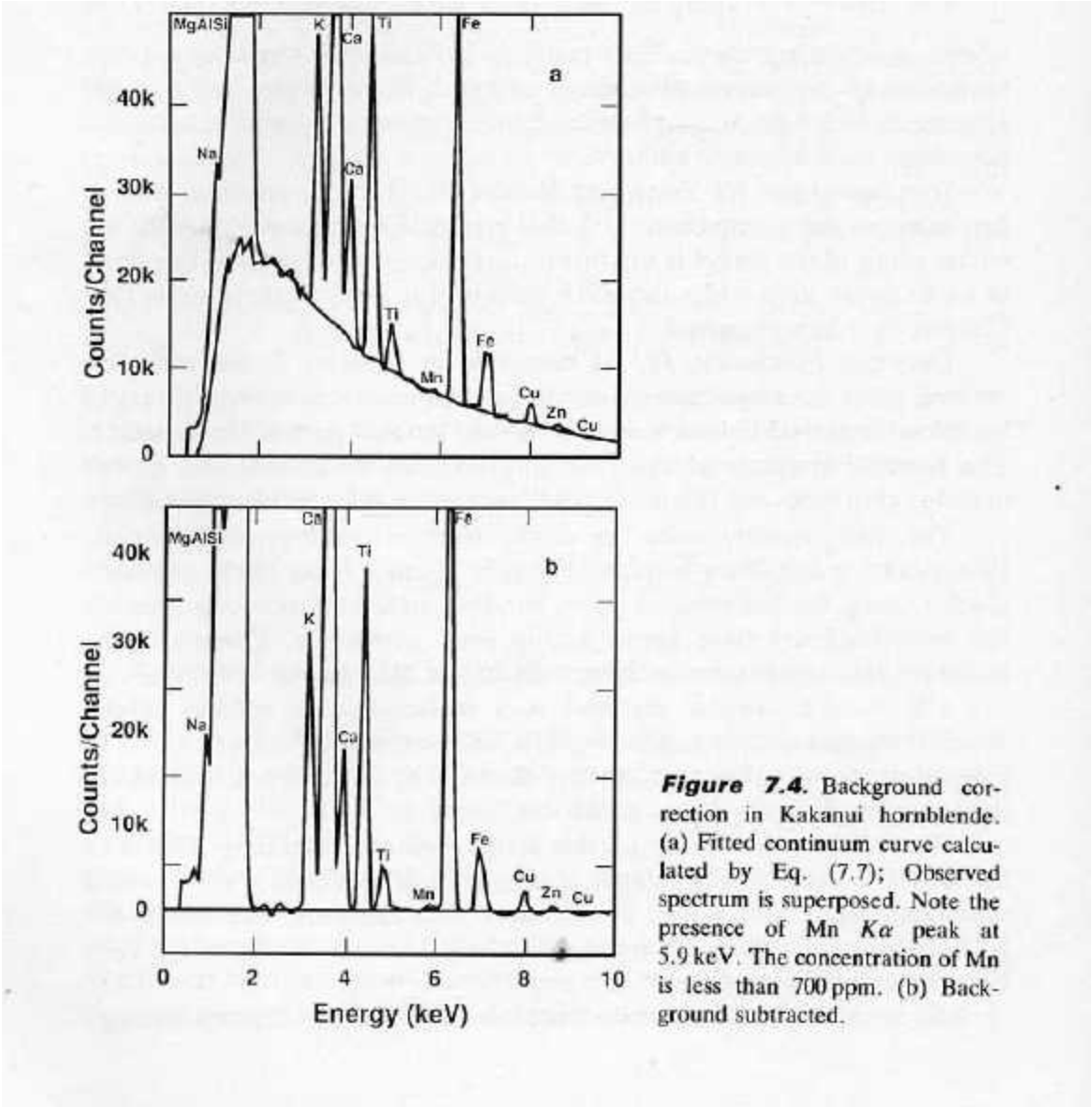


Figure 6.4. Bismuth M -family x-ray peaks. $M\alpha = 2.42$ keV. [Ultrathin window (diamond) Si(Li) EDS, 145 eV FWHM at Mn $K\alpha$.]







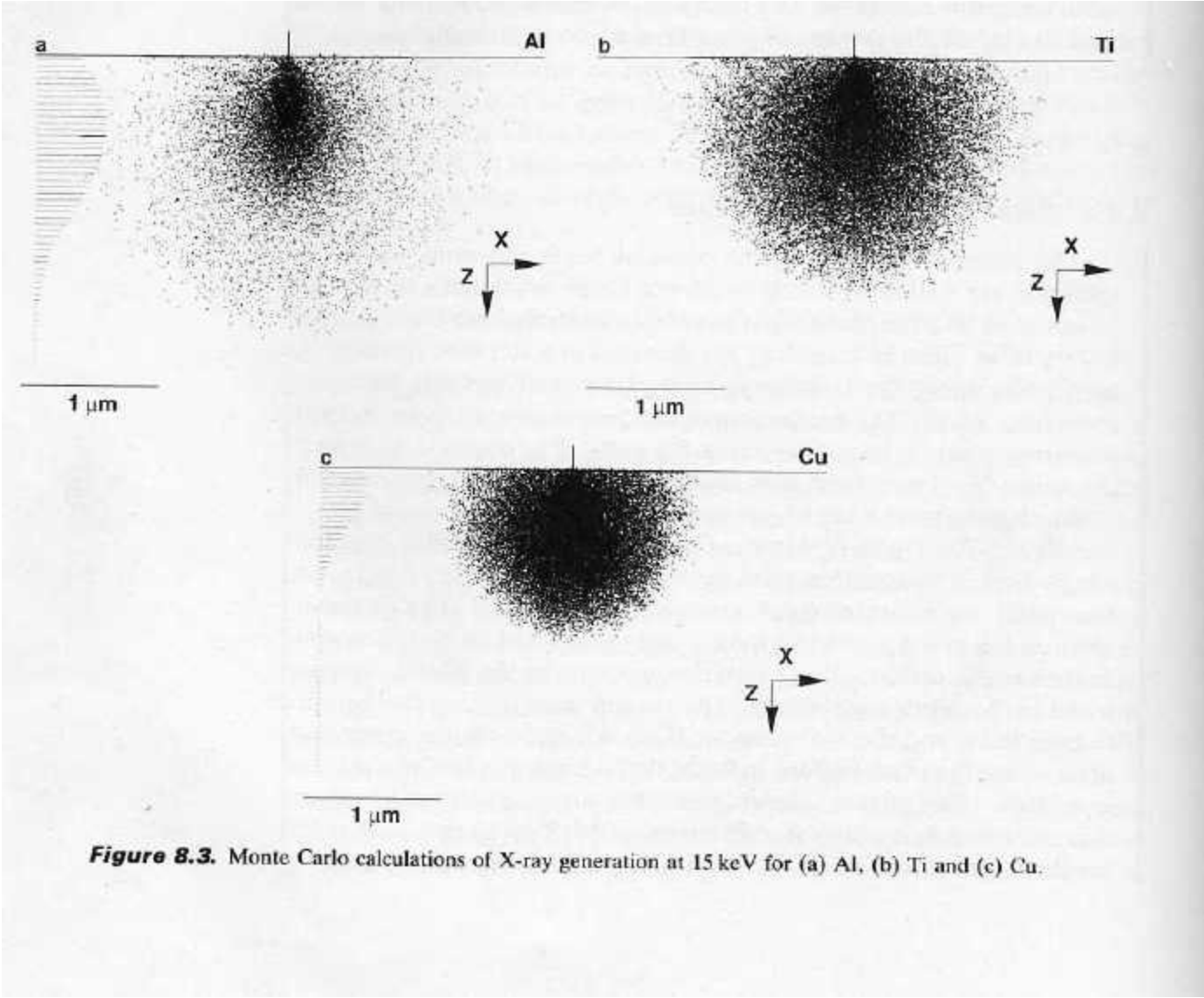
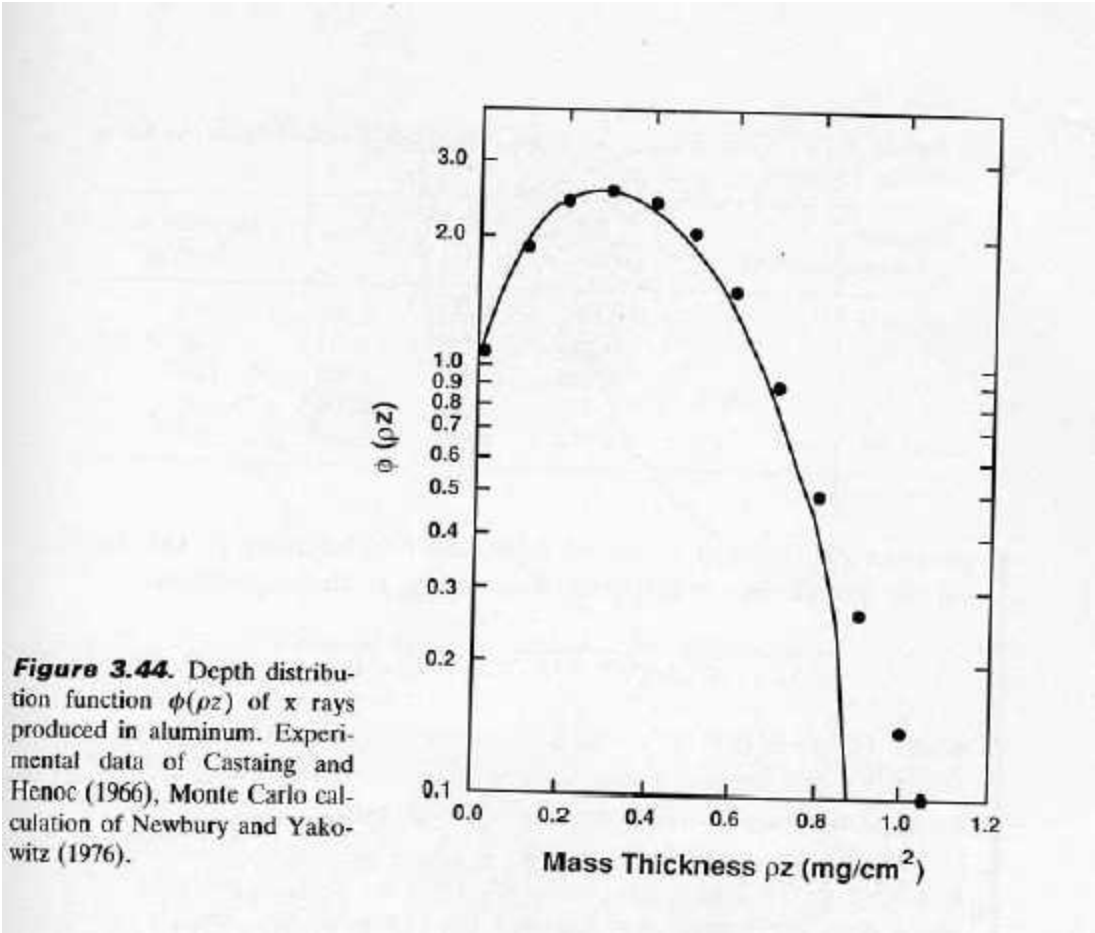


Figure 8.3. Monte Carlo calculations of X-ray generation at 15 keV for (a) Al, (b) Ti and (c) Cu.



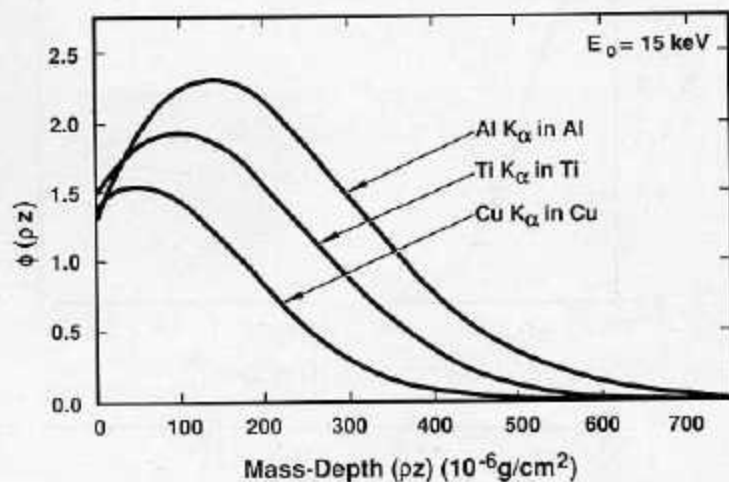


Figure 8.5. Calculated $\phi(\rho z)$ curves for Al $K\alpha$ in Al, Ti $K\alpha$ in Ti, and Cu $K\alpha$ in Cu at 15 keV.

