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E 94-00, *Standard Guide for Radiographic Examination*
E 155-00, *Standard Reference Radiographs for Inspection of Aluminum and Magnesium Castings*
E 170-99e1, *Standard Terminology Relating to Radiation Measurements and Dosimetry*
E 186-98, *Standard Reference Radiographs for Heavy-Walled (2 to 4 1/2-in. [51 to 114-mm]) Steel Castings*
E 192-95 (1999), *Standard Reference Radiographs for Investment Steel Castings of Aerospace Applications*
E 242-95 (2000), *Standard Reference Radiographs for Appearances of Radiographic Images as Certain Parameters Are Changed*
E 272-99, *Standard Reference Radiographs for High-Strength Copper-Base and Nickel-Copper Alloy Castings*
E 280-98, *Standard Reference Radiographs for Heavy-Walled (4 1/2 to 12-in. [(114 to 305-mm]) Steel Castings*
E 310-99, *Standard Reference Radiographs for Tin Bronze Castings*
E 390-95, *Standard Reference Radiographs for Steel Fusion Welds*
E 431-96, *Standard Guide to Interpretation of Radiographs of Semiconductors and Related Devices*
E 446-98, *Standard Reference Radiographs for Steel Castings Up to 2 in. (51 mm) in Thickness*
E 505-96, *Standard Reference Radiographs for Inspection of Aluminum and Magnesium Die Castings*
E 592-99, *Standard Guide to Obtainable ASTM Equivalent Penetrameter Sensitivity for Radiography of Steel Plates 1/4 to 2 in. (6 to 51 mm) Thick with X Rays and 1 to 6 in. (25 to 152 mm) Thick with Cobalt-60*
E 666-97, *Standard Practice for Calculating Absorbed Dose from Gamma or X Radiation*
E 689-95 (1999), *Standard Reference Radiographs for Ductile Iron Castings*
E 746-02, *Standard Test Method for Determining Relative Image Quality Response of Industrial Radiographic Film*
E 747-97, *Standard Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology*
E 748-95, *Standard Practices for Thermal Neutron Radiography of Materials*
E 801 (2001), *Standard Practice for Controlling Quality of Radiological Examination of Electronic Devices*
E 802-95 (1999), *Standard Reference Radiographs for Gray Iron Castings Up to 4 1/2 in. [114 mm]) in Thickness*
E 803, *Standard Test Method for Determining the L/D Ratio of Neutron Radiography Beams*
E 975-00, *Standard Practice for X-Ray Determination of Retained Austenite in Steel with Near Random Crystallographic Orientation*
E 999-99, *Standard Guide for Controlling the Quality of Industrial Radiographic Film Processing*
E 1000-98, *Standard Guide for Radioscopy*
E 1025-98, *Standard Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology*
E 1030-00, *Standard Test Method for Radiographic Examination of Metallic Castings*
E 1032-95, *Standard Test Method for Radiographic Examination of Weldments*
E 1114-92 (1997), *Standard Test Method for Determining the Focal Size of Iridium-192 Industrial Radiographic Sources*
E 1161-95, *Standard Test Method for Radiologic Examination of Semiconductors and Electronic Components*
E 1165-92 (2002), *Standard Test Method for Measurement of Focal Spots of Industrial X-Ray Tubes by Pinhole Imaging*
E 1254-98, *Standard Guide for Storage of Radiographs and Unexposed Industrial Radiographic Films*
E 1255-96, *Standard Practice for Radioscopy*
E 1320-00, *Standard Reference Radiographs for Titanium Castings*
E 1390-90 (2000), *Standard Guide for Illuminators Used for Viewing Industrial Radiographs*
E 1411-95, *Standard Practice for Qualification of Radioscopic Systems*
E 1441-00, *Standard Guide for Computed Tomography (CT) Imaging*
E 1453-93 (1996), *Standard Guide for Storage of Media That Contains* [sic] *Analog or Digital Radioscopic Data*
E 1475-97, *Standard Guide for Data Fields for Computerized Transfer of Digital Radiological Test Data*
E 1496-97, *Standard Test Method for Neutron Radiographic Dimensional Measurements*
E 1570-00, *Standard Practice for Computed Tomographic (CT) Examination*
E 1647-98a, *Standard Practice for Determining Contrast Sensitivity in Radioscopy*
E 1648-95 (2001), *Standard Reference Radiographs for Examination of Aluminum Fusion Welds*
E 1672-95 (2001), *Standard Guide for Computed Tomography (CT) System Selection*
E 1734-98, *Standard Practice for Radioscopic Examination of Castings*
E 1735, *Standard Test Method for Determining Relative Image Quality of Industrial Radiographic Film Exposed to X-Radiation from 4 to 25 MV*
E 1742-00, *Standard Practice for Radiographic Examination*
E 1814-96, *Standard Practice for Computed Tomographic (CT) Examination of Castings*
E 1815-96 (2001), *Standard Test Method for Classification of Film Systems for Industrial Radiography*
E 1894-97, *Standard Guide for Selecting Dosimetry Systems for Application in Pulsed X-Ray Sources*
E 1931-97, *Standard Guide for X-Ray Compton Scatter Tomography*
E 1936-97, *Standard Reference Radiograph for Evaluating the Performance of Radiographic Digitization Systems*
E 1955-98, *Standard Radiographic Examination for Soundness of Welds in Steel by Comparison to Graded ASTM E 390 Reference Radiographs*
E 2002-98, *Standard Practice for Determining Total Image Unsharpness in Radiology*
E 2033-99, *Standard Practice for Computed Radiology (Photostimulable Luminescence Method)*
E 2116-00, *Standard Practice for Dosimetry for a Self-Contained Dry-Storage Gamma-Ray Irradiator*
F 629-97, *Standard Practice for Radiography of Cast Metallic Surgical Implants*
F 947-85 (1996), *Standard Test Method for Determining Low-Level X-Radiation Sensitivity of Photographic Films*
F 1035-91 (1997), *Standard Practice for Use of Rubber-Cord Pie Disk to Demonstrate the Discernment Capability of a Tire X-Ray Imaging System*

These terms imply an exponential function for transmitted radiation in terms of shield thickness. Figures 9 and 10, however, show that the transmission curves are not completely linear on a semilogarithmic plot.[1,3] Hence, the listed half value layers and tenth value layers in Tables 5 and 6 are approximate, obtained with large attenuation.

Table 7 lists densities of commercial building materials. For X-radiation and gamma radiation, the absorption process depends largely on compton absorption and scattering, which in turn increase with the atomic electron density. As a first approximation, electron density varies directly with the mass density of a material. Hence, the denser building materials are usually better shielding materials for a given thickness of material. On a mass basis, shielding materials are much the same above about 500 keV. Where space is a problem, lead is often used to achieve the desired shield attenuation. Lead, however, requires extra structural support because it is not self-supporting. Concrete is by far the most commonly used shielding material for economic, structural and local availability reasons — in addition to desirable shielding characteristics. Where space considerations are important depleted uranium shields are expensive but offer excellent solutions to difficult problems.

Table 5 lists half value layers and tenth value layers for several commonly used gamma ray emitting radionuclides. Table 6 lists similar information for X-ray peak voltages. Figures 9 and 10 show actual transmission through lead and concrete for the gamma ray emitting radionuclides. Figure 11 shows a representative transmission through concrete. Similar charts are available for steel, lead and other materials for X-ray beams of various peak energies.[1,28]

Table 5. Shielding equivalents: approximate half (HVL) and tenth value (TVL) layer thicknesses in lead and concrete for several gamma ray sources.[3,27]

	Lead				Concrete			
	Half Value Layers		Tenth Value Layers		Half Value Layers		Tenth Value Layers	
Source	mm	(in.)	mm	(in.)	mm	(in.)	mm	(in.)
Radium-226	16	(0.65)	56	(2.20)	69	(2.7)	234	(9.2)
Cobalt-60	12	(0.49)	41	(1.60)	66	(2.6)	218	(8.6)
Cesium-137	6	(0.25)	21	(0.84)	48	(1.9)	157	(6.2)
Iridium-192	6	(0.24)	20	(0.79)	41	(1.6)	140	(5.5)
Gold-198	3	(0.13)	11	(0.43)	41	(1.6)	140	(5.5)

Table 6. Shielding equivalents: approximate half value layers (HVL) and tenth value layers (TVL) for lead and concrete for various X-ray tube potentials.[3,27]

Peak	Lead				Concrete			
Voltage	Half Value Layers		Tenth Value Layers		Half Value Layers		Tenth Value Layers	
(kV)	mm	(in.)	mm	(in.)	mm	(in.)	mm	(in.)
50	0.05	(0.002)	0.16	(0.006)	4.32	(0.170)	15.10	(0.594)
70	0.15	(0.006)	0.50	(0.020)	8.38	(0.330)	27.95	(1.100)
100	0.24	(0.009)	0.80	(0.031)	15.10	(0.594)	50.80	(2.000)
125	0.27	(0.011)	0.90	(0.035)	20.30	(0.799)	66.00	(2.598)
150	0.29	(0.011)	0.95	(0.037)	22.35	(0.880)	73.60	(2.898)
200	0.48	(0.019)	1.60	(0.063)	25.40	(1.000)	83.80	(3.299)
250	0.90	(0.035)	3.00	(0.118)	27.95	(1.100)	94.00	(3.701)
300	1.40	(0.055)	4.60	(0.181)	31.21	(1.229)	104.00	(4.094)
400	2.20	(0.087)	7.30	(0.287)	33.00	(1.299)	109.10	(4.295)
500	3.60	(0.142)	11.90	(0.469)	35.55	(1.400)	116.80	(4.598)
1000	7.90	(0.311)	26.00	(1.024)	44.45	(1.750)	147.10	(5.791)
2000	12.70	(0.500)	42.00	(1.654)	63.50	(2.500)	210.40	(8.283)
3000	14.70	(0.579)	48.50	(1.909)	73.60	(2.898)	241.20	(9.496)
4000	16.50	(0.650)	54.80	(2.157)	91.40	(3.598)	304.48	(11.987)
6000	17.00	(0.669)	56.60	(2.228)	104.00	(4.094)	348.00	(13.701)
1000	16.50	(0.650)	55.00	(2.165)	116.80	(4.598)	388.50	(15.295)

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When a series of projections are taken from many angles about a part, the projection data can be backprojected as shown in Fig. 10b to create an image. As the number of projections increase, the ability to more exactly reconstruct the object increases. In a computed tomographic system, the projections are actually subjected to an incredible amount of mathematical massaging but the steps are effectively the same as involved in the manual triangulation.

The computed tomography image, the cross sectional representation of the densities within an object, depends on the three basic processes: (1) convolution or filtering of the data with special mathematical operators; (2) correlation of the projection data in an absolute space; (3) backprojecting the convolved attenuation data along its original spatial vectors. The mathematics of the image reconstruction can be found in a number of references.[4,16-18]

The intensity of an attenuated X-ray beam passing through an object is given by the line integral:

$$\textbf{(25)} \quad I = \int\int \left\{ I_o(E) \exp\left[-\mu(E,x)\,dx\right] \right\} dE$$

where I is the beam intensity at the detector, $I_o(E)$ is the beam intensity with no object, E is energy of the X-rays, $\mu(E,x)$ is the linear attenuation coefficient and x is the transmitted distance through the object. Most computed tomographic systems use X-rays generated by a bremstrahlung source that creates a broad spectrum defined here as $I_O(E)$. The transmitted intensity is an integration over the energy spectrum and along the ray path through the object as a function of the distribution of linear attenuation coefficient $\mu(E,x)$. For predictive purposes, it is useful to change Eqs. 25 to 26:

$$\textbf{(26)} \quad I = I_o \exp\left[-\mu(E_{\text{eff}})x\right]$$

where E_{eff} is an effective energy and a uniform material is assumed. The effective energy is that specific energy, where the transmitted intensity of a monoenergetic beam would be equivalent to that of an integrated spectrum. The effective energy is influenced by the type and amount of material penetrated because, as the attenuation or path length increases, the lower energy photons are preferentially attenuated, resulting in higher effective energies or *harder* beams. In computed tomographic applications, attenuations of 10^4 and higher are not uncommon, although attenuations of 10^1 to 10^2 are preferred.

The measured intensity at the detector is normalized based on the calibration of the detector array and the measured intensity for no object in the beam. By taking the logarithm of the normalized intensity, the value of the projection $P_q(r)$ is proportional to the linear attenuation coefficient:

$$\textbf{(27)} \quad P_q(R) = \ln \frac{I}{I_o} \propto \mu$$

where P_q is the projection at angle q and R is the position of the ray along that projection (see Fig. 10b).

The backprojection of the data will therefore create an image distribution where the values in the image are proportional to the linear attenuation coefficient. The backprojection is given by Eq. 28:

$$\textbf{(28)} \quad b_q(x,y) = \int P_q(R) \times \delta(x\cos q + y\sin q - R)\,dR$$

where δ is the dirac delta function. This equation effectively distributes the values of the projections $P_q(R)$ to all points (X,Y) that lie on the projection line. By integrating over angle q the total reconstructed image will be formed:

$$\textbf{(29)} \quad f(x,y) = \int\int P_q(R) \times \delta(x\cos q + y\sin q - R)\,dR\,dq$$

This reconstruction is crude because, intuitively, a point object (or delta function) will be reconstructed with the crossing of radial lines creating a star effect. This is evident in Fig. 10b and is shown in Fig. 11. This point response can be shown to be a $1{\cdot}r^{-1}$ blurring of the image points (where r is the distance from the point). Reconstructions must therefore use filtering to remove this effect.

The filtering is usually performed by a convolution function $C(R)$ such that:

$$\textbf{(30)} \quad f(x,y) = \int\int P_q(R) * CR \times \delta(x\cos q + y\sin q - R)\,dR\,dq$$

Each projection is convolved with a function and the result is backprojected. Figure 11 demonstrates the benefit of the filtering. The convolution function $C(R)$ is a filtering operation that can be selected to enhance various characteristics of the image. Innumerable filters are possible for use in the convolution. The two most popular (and extreme) filters are the ramachandran filter, used to emphasize sharpness, and the shepp and logan filter,