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Standard Test Method for Calibrating and Measuring CT Density[1]

This standard is issued under the fixed designation E1935; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers instruction for determining the density calibration of X- and γ-ray computed tomography (CT) systems and for using this information to measure material densities from CT images. The calibration is based on an examination of the CT image of a disk of material with embedded specimens of known composition and density. The measured mean CT values of the known standards are determined from an analysis of the image, and their linear attenuation coefficients are determined by multiplying their measured physical density by their published mass attenuation coefficient. The density calibration is performed by applying a linear regression to the data. Once calibrated, the linear attenuation coefficient of an unknown feature in an image can be measured from a determination of its mean CT value. Its density can then be extracted from a knowledge of its mass attenuation coefficient, or one representative of the feature.

1.2 CT provides an excellent method of nondestructively measuring density variations, which would be very difficult to quantify otherwise. Density is inherently a volumetric property of matter. As the measurement volume shrinks, local material inhomogeneities become more important; and measured values will begin to vary about the bulk density value of the material.

1.3 All values are stated in SI units.

1.4 *This standard does not purport to address the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1316 Terminology for Nondestructive Examinations
E1441 Guide for Computed Tomography (CT) Imaging
E1570 Practice for Computed Tomographic (CT) Examination

3. Terminology

3.1 *Definitions:*

3.1.1 The definitions of terms relating to CT, that appear in Terminology E1316 and Guide E1441, shall apply to the terms used in this test method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *density calibration*—calibration of a CT system for accurate representation of material densities in examination objects.

3.2.2 *effective energy*—the equivalent monoenergetic energy for a polyenergetic CT system. Thus, the actual, polyenergetic CT system yields the same measured attenuation coefficient for an examination object as a theoretical, monoenergetic CT system at the effective energy.

3.2.3 *phantom*—a part or item being used to calibrate CT density.

3.2.4 *examination object*—a part or specimen being subjected to CT examination.

4. Basis of Application

4.1 The procedure is generic and requires mutual agreement between purchaser and supplier on many points.

5. Significance and Use

5.1 This test method allows specification of the density calibration procedures to be used to calibrate and perform material density measurements using CT image data. Such measurements can be used to evaluate parts, characterize a particular system, or compare different systems, provided that observed variations are dominated by true changes in object density rather than by image artifacts. The specified procedure may also be used to determine the effective X-ray energy of a CT system.

5.2 The recommended test method is more accurate and less susceptible to errors than alternative CT-based approaches, because it takes into account the effective energy of the CT system and the energy-dependent effects of the X-ray attenuation process.

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[1] This test method is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

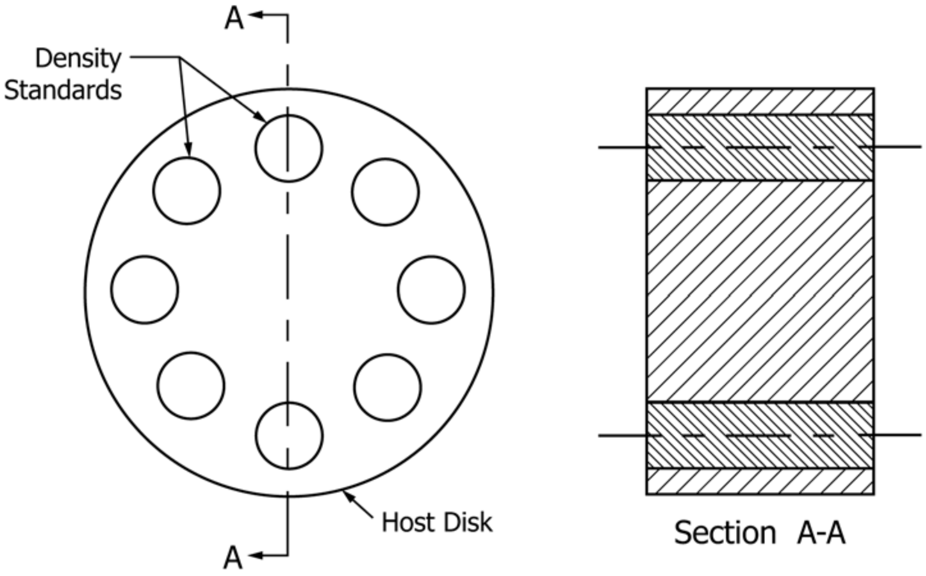

FIG. 1 Density Calibration Phantom

5.3 This (or any) test method for measuring density is valid only to the extent that observed CT-number variations are reflective of true changes in object density rather than image artifacts. Artifacts are always present at some level and can masquerade as density variations. Beam hardening artifacts are particularly detrimental. It is the responsibility of the user to determine or establish, or both, the validity of the density measurements; that is, they are performed in regions of the image which are not overly influenced by artifacts.

5.4 Linear attenuation and mass attenuation may be measured in various ways. For a discussion of attenuation and attenuation measurement, see Guide E1441 and Practice E1570.

6. Apparatus

6.1 Unless otherwise agreed upon between the purchaser and supplier, the density calibration phantom shall be constructed as follows (see Fig. 1):

6.1.1 A selection of density standards bracketing the range of densities of interest shall be chosen. For best results, the materials should have known composition and should be physically homogeneous on a scale comparable to the spatial resolution of the CT system. It is a good idea to radiographically verify homogeneity and to independently verify chemical composition. All materials should be manufactured to reproducible standards. Solids should be readily machinable and not susceptible to surface damage.

6.1.2 One or more cylinders of each density standard shall be machined or prepared, or both. Selecting cylinders over rectangles reduces the uncertainties and streaks that sharp corners have on volumetric determination and verification methods. The cylinders should be large enough that the mean CT number corresponding to each standard can be computed over a hundred or more uncorrupted (see 8.1.3) pixels but small enough relative to the dimensions of the host disk that radial effects are minimal.

6.1.3 The physical density of each density standard shall be determined empirically by weighing and measuring the specimens as accurately as possible. It is a good idea to independently verify the measured densities using volumetric displacement methods.

6.1.4 The mass attenuation coefficient, μ/ρ, at the effective energy of the system (see 8.3) shall be determined from a reference table. For compounds, μ/ρ can be obtained by taking the weighted sum of its constituents, in accordance with the following equation:

$$\mu_m = \mu/\rho = \sum_i w_i(\mu/\rho)_i \tag{1}$$

where:

w_i = the weight fraction of the ith elemental component.

6.1.5 For each density standard, the measured density, ρ, shall be multiplied by its corresponding mass attenuation coefficient, μ/ρ, as determined in 6.1.4. The linear attenuation coefficient, μ, thus obtained shall be permanently recorded for each density calibration standard.

6.1.6 A host disk to hold the density standards shall be fabricated. The opacity of the disk should approximate the attenuation range of the examination objects. If possible, the host disk should be of the same material as the examination objects, but other requirements take precedence and may dictate the selection of another material.

6.2 In general, it is very difficult to find acceptable materials for density standards. Published density data are generally not reliable enough for calibration purposes. Homogeneity often varies on a local scale and negatively influences the calibration procedure. Machine damage can increase the density at the surface of a sample, making it difficult to determine the density of the interior material crucial to the calibration process. Lot-to-lot variations in composition or alloy fraction can make it difficult to compute mass attenuation coefficients. For these and other reasons, development of a good density calibration phantom takes effort, resources and a willingness to iterate the selection and production of standards until acceptable results are obtained.

6.2.1 Liquids make the best standards, because they can be precisely controlled and measured. However, liquids require special handling considerations, are sensitive to temperature variations, and often tend to precipitate, especially high-concentration aqueous solutions. It is hard to find organic liquids with densities above 1.5 g/cm^3 or inorganic liquids above 4.0 g/cm^3; but for many purposes, they offer a suitable choice.

6.2.2 Plastics are popular but in general make the worst standards. Most plastics have at best an approximately known polymerization and often contain unknown or proprietary additives, making them poor choices for calibration standards. They also tend to vary more than other materials from batch to batch. Notable exceptions to these generalizations are brand-name acrylics and brand-name fluorocarbons.

6.2.3 Metals are also popular, but they are generally available only in a limited number of discrete densities. They can exhibit important lot-to-lot variations in alloy fractions; but with careful selection or characterization, they can make good density calibration standards. Pure elements or very well known specimens offer an excellent option when they can be obtained in the density range of interest.

6.2.4 Each material must be treated on a case-by-case basis. Reactor-grade graphite provides a good case study. Reactor-grade graphite is available in a variety of shapes, in very pure form, and in a number of densities. At first glance, it appears to offer an attractive choice in a density range without many viable alternatives. However, upon closer examination, the material is found to be susceptible to surface damage during machining and to exhibit important inhomogeneities in density on linear scales of about 1 mm. Surface damage makes it nearly impossible to determine the core density of the sample gravimetrically, because the total weight is biased by a denser outer shell. Inhomogeneities make it difficult to extract accurate mean CT numbers from an image of a sample that is not large in diameter compared to 1 mm.

7. Procedure

7.1 Unless otherwise agreed upon between the purchaser and supplier, the density calibration phantom shall be scanned as follows:

7.1.1 The phantom shall be mounted on the CT system with the orientation of its axis of revolution normal to the scan plane.

7.1.2 The phantom shall be placed at the same location used for examination object scans.

7.1.3 The slice plane shall be adjusted to intercept the phantom approximately midway between the flat faces of the disk.

7.1.4 The phantom shall be scanned using the same data acquisition parameters, and the data shall be processed using the same steps (for example, beam-hardening corrections) applied to examination objects.

8. Interpretation of Results

8.1 Unless otherwise agreed upon between the purchaser and supplier, the image of the density calibration phantom shall be analyzed as follows:

8.1.1 The phantom scan data shall be reconstructed using the same reconstruction parameters and post-processing steps, if any, used for examination object data.

8.1.2 The phantom image shall be displayed using the same display parameters used for viewing examination object images.

8.1.3 The mean CT numbers of the density standards in the CT image shall be measured. Special attention needs to be paid to this part of the measurement process. As much of the area of each specimen as practical should be used, but care must be taken to insure that only valid pixels are included. For example, a square region of interest in a round sample could yield biased results if there are significant radial effects, such as from beam hardening or a higher density around the perimeter due to surface damage caused by machining or compression. Ideally, a circular region of interest should be used that includes a hundred or more pixels but avoids the boundary region around each density standard, especially if edge effects of any type are clearly visible.

8.1.4 A table of linear attenuation coefficients versus mean CT numbers shall be prepared.

8.1.5 A least-squares fit to the equation $N_{CT} = a \cdot \mu + b$ shall be performed on the data stored in the table, where μ is the linear attenuation coefficient and N_{CT} is the CT number.

8.1.6 The resulting linear curve shall be used as the density calibration. Using the inferred linear relationship between CT number and linear attenuation coefficient, the measured CT value, N_{CT}, of any material can be used to calculate a best estimate of its associated linear attenuation coefficient, μ.

8.2 Unless otherwise agreed upon between the purchaser and supplier, the density of a region of interest in an examination object shall be determined as follows:

8.2.1 The mean CT number in the region of interest shall be measured.

8.2.2 From the known calibration parameters, the linear attenuation coefficient of the region of interest shall be obtained using the equation $N_{CT} = a \cdot \mu + b$.

8.2.3 The density of the region of interest shall be calculated by dividing the obtained linear attenuation by the appropriate tabulated value of μ/ρ at the effective energy of the system (see 8.3). If μ/ρ is not known for the feature of interest, a nominal value for μ/ρ may be used. Variations in μ/ρ are minor, and basically independent of material in the energy range of about 200 keV to about 2 MeV. Outside this range, the selection of a nominal value is more sensitive. Adoption of an appropriate nominal value is a matter of agreement between purchaser and supplier.

8.3 Unless otherwise agreed upon between the purchaser and supplier, the effective energy of the CT system shall be determined as follows:

8.3.1 A table of linear attenuation coefficients versus mean CT numbers shall be prepared for several X-ray energies bracketing the effective energy of the CT system, as shown in 8.4.1.

8.3.2 For each X-ray energy, a least-squares fit to the equation $N_{CT} = a \cdot \mu + b$ shall be performed and the correlation coefficient recorded.

8.3.3 The energy value in the table that yields the best fit (that is, the largest value of the correlation coefficient) shall be selected as the effective energy of the CT system.

8.3.4 If the effective energy has been determined previously under the same or similar conditions, this step may be skipped with the consent of the buyer.

8.4 *Illustrative Examples:*

8.4.1 *Effective Energy Determination*—The process of determining the effective X-ray energy of a CT system is illustrated with the following example taken from actual practice. The data presented were acquired with a 9-MV industrial CT system. Three materials (see Table 1) were used: methyl methacrylate, tetrafluoroethylene, and aluminum. The empirical densities of the specimens, not the published values, were determined by accurately measuring and weighing each one (see Table 2). The CT values were measured from an image of a calibration phantom constructed as described in Section 6. The mass attenuation coefficients associated with each material were determined from the literature for several X-ray energies bracketing the effective energy of the system. (In actuality, the effective energy was only approximately known, and it was necessary to perform the indicated calculation over a much greater range of energies than shown in Table 1.) For methyl methacrylate ($H_8C_5O_2$) and tetrafluoroethylene (C_2F_4), a weighted sum of their elemental components was used (see Eq 1). The semi-empirical values of μ were calculated by multiplying the empirical density by the theoretical mass attenuation coefficient. [The processing steps are illustrated in more detail in the next example.] A least-squares fit to μ versus CT number was performed for each energy. The correlation coefficient of the fit is shown at the bottom of each column of data. As can be seen, the maximum value of the correlation coefficient occurs at 3800 keV. A more refined search using smaller energy increments reveals that the effective energy is much closer to 3800 keV than an interpolation based on the correlation coefficient would seem to indicate, and this value has therefore been adopted. Pushing the determination of effective energy beyond this does not materially improve the accuracy of the density calibration procedure.

8.4.2 *Density Calibration*—The process of implementing the density calibration standard test method is illustrated in the following example. The same materials used to determine effective energy were used to perform the density calibration (see Table 2). The 3800-keV data was extracted from Table 1 and reorganized, along with the empirical density values, as shown. Each empirically-determined density (second column) was multiplied by the appropriate theoretical attenuation coefficient (third column) to obtain the semi-empirical linear attenuation coefficient (fourth column). The CT values (fifth column) were measured from an image of a calibration phantom constructed as described in Section 6. For comparative purposes, a density calibration was then performed in two ways: the measured densities were correlated against the measured CT values; and the semi-empirical linear attenuation coefficients were correlated against the measured CT values. The correlation coefficient obtained by the first method was 0.996, a respectable result. The correlation coefficient obtained by the second method was 0.9999996, a nearly perfect result. The first approach is less accurate but easier to implement; since it does not require a knowledge of effective energy or mass attenuation coefficients. For some applications, this method will yield acceptable results. However, for assured accuracy, the second method is more generally applicable and is the one recommended by this standard for optimal results (see 8.4.4).

TABLE 1 Effective-Energy Calibration Data

Material	CT Value	Semi-Empirical μ (cm^{-1}) 3700 keV	3800 keV	3900 keV	4000 keV
Methyl methacrylate	1286	0.0404	0.0399	0.0393	0.0388
Tetrafluoroethylene	2119	0.0670	0.0661	0.0652	0.0644
Aluminum	2756	0.0870	0.0862	0.0851	0.0843
Correlation Coefficient		0.9999887	0.9999996	0.9999991	0.9999893

TABLE 2 Density Calibration Data at an Effective Energy of 3800 keV

Material	Empirical ρ (g/cm^3)	Theoretical μ/ρ (cm^2/g)	Semi-Empirical μ (cm^{-1})	CT Value
Methyl methacrylate	1.18	0.0338	0.0399	1286
Tetrafluoroethylene	2.16	0.0306	0.0661	2119
Aluminum	2.71	0.0318	0.0862	2756

8.4.3 *Density Measurement*—The process of measuring densities from an image is illustrated in the following examples. The first involves a pair of test materials, polyamide ($H_{11}NC_6O$) and a polycarbonate ($H_6C_{16}O_3$). The results are shown in Table 3. The measured CT values (second column) are virtually identical. The densities of the two materials were then determined using the two calibration procedures from the previous example. The first method, based on correlating CT values with physical density, produces the uncorrected density values in the third column. By definition, the uncorrected densities are the same, to the accuracy shown. The second method, based on correlating CT values with linear attenuation coefficient, produces the corrected density values in the sixth column. The CT values were used to determine the linear attenuation coefficients (fourth column), and densities were obtained by dividing the results by the computed mass attenuation coefficients (fifth column), obtained as before from weighted sums of published values at the effective energy of the system. Results obtained by the two methods can be compared with the manufacturer's published densities of 1.14 g/cm^3 for the polyamide and 1.21 g/cm^3 for the polycarbonate. The density of polyamide determined by the first method, that

TABLE 3 Measurement of CT-Derived Densities

Material	CT Value	Uncorrected ρ (g/cm^3)	Measured μ (cm^{-1})	Theoretical μ/ρ (cm^2/g)	Corrected ρ (g/cm^3)	Published ρ (g/cm^3)
Polyamide	1272	1.20	0.0394	0.0342	1.15	1.14
Polycarbonate	1273	1.20	0.0395	0.0321	1.23	1.21
Copper	9679	10.00	0.304	0.0335	9.08	8.98

ignores mass attenuation effects, is off by 5 %; due to the high hydrogen content of the polyamide. The densities determined by the second method, that explicitly takes mass attenuation effects into account, agree with the published data to 1 %, which is better than the known batch-to-batch uniformity of these particular materials.

8.4.3.1 This example illustrates the importance of using the recommended approach. In the case study shown in Table 3, the measured CT value of copper was found to be 9679. Using the recommended calibration method, the corrected density of copper is found to be 9.08 g/cm ^{3}, that agrees to 1 % with the manufacturer's published value of 8.98 g/cm^3, despite the fact that the highest-Z material used in the density calibration was aluminum. The uncorrected density is found to be 10.00 g/cm^3, a discrepancy of 11 %. The error is caused by the neglect of pair-production effects, which at these energies are significant in higher-Z materials, like copper.

8.4.4 *Discussion*—These simple examples illustrate an important aspect of CT density calibration. For accurate results, chemical composition must be taken into account. When dealing with compounds, two materials with the same or similar CT values may have different physical densities (see 8.4.3). The measured values must be adjusted for differences in chemical composition, even if these differences are only approximately known. With lower effective energies or higher atomic-number materials, the effects of chemical composition become more important and must be included for most applications.

9. Reporting Requirements

9.1 A report documenting the density calibration procedure shall be prepared. The report should include all relevant data acquisition, reconstruction and display parameters. The specific parameters to be documented are a matter of agreement between the purchaser and the supplier. At a minimum, the report shall contain the measured mean CT values of the density standards, their tabulated mass attenuation coefficients, the results of the least-squares fit to the data (that is, *a, b* and the correlation coefficient), and a graph of CT value versus linear attenuation coefficient.

10. Precision and Bias

10.1 Conformance to the requirements specified herein will produce results that are within the following tolerances:

10.1.1 *Precision*—The precision of results will be limited by the uncertainty in the density of the density standards, the uncertainty in the mean CT value of each density standard, and the relative uncertainty in the tabulated mass attenuation coefficients. Achievable precision is estimated to be better than 1 %.

10.1.2 *Bias*—The accuracy of results may be influenced by the accuracy of the mass attenuation coefficients used. However, if a reputable table such as Cullen[3] is used, the effect should be small. The absolute accuracy using the above density calibration method is estimated to be better than 1 %. The relative accuracy is estimated to be better than 0.1 %.

11. Keywords

11.1 computed tomography; contrast sensitivity; CT density resolution; density calibration; linear attenuation coefficient; mass attenuation coefficient

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[3] Cullen, D.E. et al., "Tables and Graphs of Photon-Interaction Cross Sections from 10 keV to 100 GeV Derived from the LLNL Evaluated Photon Data Library (EPDL)," Prepared for Dept. of Commerce UCRL-50500, Vol 6, Rev. 4, 1989.