Designation: ~~E1441 – 11~~ E1441 – 19

Standard Guide for
Computed Tomography (CT) ~~Imaging~~[1]

This standard is issued under the fixed designation E1441; 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.

This standard has been approved for use by agencies of the U.S. Department of Defense.

1. Scope*

1.1 ~~Computed tomography (CT)~~ CT is a radiographic ~~method that provides an ideal examination technique whenever the primary goal is to locate and size planar and volumetric detail in three dimensions.~~ examination technique that generates digital images in three dimensions of an object, including the interior structure. Because of the relatively good penetrability of X-rays, ~~as well as the sensitivity of absorption cross sections to atomic chemistry,~~ CT permits the nondestructive physical and, to a limited extent, chemical characterization of the internal structure of materials. Also, since the method is X-ray based, it applies equally well to metallic and non-metallic specimens, solid and fibrous materials, and smooth and irregularly surfaced objects. ~~When used in conjunction with other nondestructive evaluation (NDE) methods, such as ultrasound, CT data can provide evaluations of material integrity that cannot currently be provided nondestructively by any other means.~~

1.2 This guide is intended to satisfy two general needs for users of industrial CT equipment: ~~(~~(1)~~1)~~ the need for a tutorial guide addressing the general principles of X-ray CT as they apply to industrial imaging; and ~~(~~(2)~~2)~~ the need for a consistent set of CT performance parameter definitions, including how these performance parameters relate to CT system specifications. ~~Potential users and buyers, as well as experienced CT inspectors, will find this guide a useful source of information for determining the suitability of CT for particular examination problems, for predicting CT system performance in new situations, and for developing and prescribing new scan procedures.~~

1.3 This guide does not specify ~~test objects and test procedures for comparing the relative performance of different CT systems; nor does it treat CT inspection~~ CT examination techniques, such as the best selection of scan parameters, the preferred implementation of scan procedures, ~~the analysis of image data to extract densitometric information,~~ or the establishment of accept/reject criteria for a new object.

~~1.4 Standard practices and methods are not within the purview of this guide. The reader is advised, however, that examination practices are generally part and application specific, and industrial CT usage is new enough that in many instances a consensus has not yet emerged. The situation is complicated further by the fact that CT system hardware and performance capabilities are still undergoing significant evolution and improvement. Consequently, an attempt to address generic examination procedures is eschewed in favor of providing a thorough treatment of the principles by which examination methods can be developed or existing ones revised.~~

~~1.5 The principal advantage of CT is that it nondestructively provides quantitative densitometric (that is, density and geometry) images of thin cross sections through an object. Because of the absence of structural noise from detail outside the thin plane of inspection, images are much easier to interpret than conventional radiographic data. The new user can learn quickly (often upon first exposure to the technology) to read CT data because the images correspond more closely to the way the human mind visualizes three-dimensional structures than conventional projection radiography. Further, because CT images are digital, they may be enhanced, analyzed, compressed, archived, input as data into performance calculations, compared with digital data from other NDE modalities, or transmitted to other locations for remote viewing. Additionally, CT images exhibit enhanced contrast discrimination over compact areas larger than 20 to 25 pixels. This capability has no classical analog. Contrast discrimination of better than 0.1 % at three-sigma confidence levels over areas as small as one-fifth of one percent the size of the object of interest are common.~~

~~1.6 With proper calibration, dimensional inspections and absolute density determinations can also be made very accurately. Dimensionally, virtually all CT systems provide a pixel resolution of roughly 1 part in 1000 , and metrological algorithms can often measure dimensions to one-tenth of one pixel or so with three-sigma accuracies. For small objects (less than 100 mm (4 in.) in~~

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[1] This guide 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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***A Summary of Changes section appears at the end of this standard**

~~diameter), this translates into accuracies of approximately 0.1 mm (0.003 to 0.005 in.) at three-sigma. For much larger objects, the corresponding figure will be proportionally greater. Attenuation values can also be related accurately to material densities. If details in the image are known to be pure homogeneous elements, the density values may still be sufficient to identify materials in some cases. For the case in which no *a priori* information is available, CT densities cannot be used to identify unknown materials unambiguously, since an infinite spectrum of compounds can be envisioned that will yield any given observed attenuation. In this instance, the exceptional density sensitivity of CT can still be used to determine part morphology and highlight structural irregularities.~~

~~1.7 In some cases, dual energy (DE) CT scans can help identify unknown components. DE scans provide accurate electron density and atomic number images, providing better characterizations of the materials. In the case of known materials, the additional information can be traded for improved conspicuity, faster scans, or improved characterization. In the case of unknown materials, the additional information often allows educated guesses on the probable composition of an object to be made.~~

~~1.8 As with any modality, CT has its limitations. The most fundamental is that candidate objects for examination must be small enough to be accommodated by the handling system of the CT equipment available to the user and radiometrically translucent at the X-ray energies employed by that particular system. Further, CT reconstruction algorithms require that a full 180 degrees of data be collected by the scanner. Object size or opacity limits the amount of data that can be taken in some instances. While there are methods to compensate for incomplete data which produce diagnostically useful images, the resultant images are necessarily inferior to images from complete data sets. For this reason, complete data sets and radiometric transparency should be thought of as requirements. Current CT technology can accommodate attenuation ranges (peak-to-lowest-signal ratio) of approximately four orders of magnitude. This information, in conjunction with an estimate of the worst-case chord through a new object and a knowledge of the average energy of the X-ray flux, can be used to make an educated guess on the feasibility of scanning a part that has not been examined previously.~~

~~1.9 Another potential drawback with CT imaging is the possibility of artifacts in the data. As used here, an artifact is anything in the image that does not accurately reflect true structure in the part being inspected. Because they are not real, artifacts limit the user's ability to quantitatively extract density, dimensional, or other data from an image. Therefore, as with any technique, the user must learn to recognize and be able to discount common artifacts subjectively. Some image artifacts can be reduced or eliminated with CT by improved engineering practice; others are inherent in the methodology. Examples of the former include scattered radiation and electronic noise. Examples of the latter include edge streaks and partial volume effects. Some artifacts are a little of both. A good example is the cupping artifact, which is due as much to radiation scatter (which can in principle be largely eliminated) as to the polychromaticity of the X-ray flux (which is inherent in the use of bremsstrahlung sources).~~

~~1.10 Depending on the technology of the CT system, complete three-dimensional CT examinations can be time consuming. Thus, less than 100 % CT examinations are often necessary or must be accommodated by complementing the inspection process with digital radiographic screening. One partial response to this problem is to use large slice thicknesses. This leads to reduced axial resolution and can introduce partial volume artifacts in some cases; however, this is an acceptable tradeoff in many instances. In principle, this drawback can be eliminated by resorting to full volumetric scans using planar detectors instead of linear detectors (see (*1*) under 6.5.1.5).~~

~~1.11 Complete part examinations demand large storage capabilities or advanced display techniques, or both, and equipment to help the operator review the huge volume of data generated. This can be compensated for by state-of-the-art graphics hardware and automatic examination software to aid the user. However, automated accept/reject software is object dependent and to date has been developed and employed in only a limited number of cases.~~

1.4 *Units*—~~The values~~ No units are mentioned in this document. However, for CT, values are typically stated in SI units and are ~~to be~~ regarded as standard. ~~The values given in parentheses are mathematical conversions to inch-pound units that are provided for information only and are not considered standard.~~

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

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E746 Practice for Determining Relative Image Quality Response of Industrial Radiographic Imaging Systems
E1316 Terminology for Nondestructive Examinations

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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.

E1570 Practice for Fan Beam Computed Tomographic (CT) Examination
E1695 Test Method for Measurement of Computed Tomography (CT) System Performance
E1935 Test Method for Calibrating and Measuring CT Density
E2698 Practice for Radiographic Examination Using Digital Detector Arrays
E2736 Guide for Digital Detector Array Radiography

2.2 *ISO Standards:*[3]
ISO 15708-1:2017-02 International Standard for Non-destructive Testing - Radiation Methods for Computed Tomography - Part 1: Terminology
ISO 15708-2:2017-02 International Standard for Non-destructive Testing - Radiation Methods for Computed Tomography - Part 2: Principles, Equipment and Samples
ISO 15708-3:2017-02 International Standard for Non-destructive Testing - Radiation Methods for Computed Tomography - Part 3: Operation and Interpretation
ISO 15708-4:2017-02 International Standard for Non-destructive Testing - Radiation Methods for Computed Tomography - Part 4: Qualification

3. Terminology

3.1 *Definitions*—~~CT, being a radiographic modality, uses much the same vocabulary as other X-ray techniques. A number of terms are not referenced, or are referenced without discussion,~~ In addition to terms defined in Terminology E1316~~. Because they have meanings or carry implications unique to CT, they appear with explanation in~~ , ~~Appendix X1. Throughout this guide, the term "X-ray" is used to denote penetrating electromagnetic radiation; however, electromagnetic radiation may be either X-rays or gamma rays.~~the following terms are specific to this standard.

3.1.1 Throughout this guide, the term "*X-ray*" is used to denote penetrating electromagnetic radiation; however, electromagnetic radiation may be either X-rays or gamma rays.

3.2 *~~Acronyms:~~Definitions of Terms Specific to This Standard:*

3.2.1 *~~BW~~—CT detectability, n—*~~beam width.~~the extent to which the presence of a feature or indication can be reliably inferred from a tomographic examination image.

3.2.1.1 *Discussion—*

CT detectability is dependent on the spatial resolution and contrast resolution of the image. Features may be detectable even if they are too small to be resolved, provided their contrast after blurring is still sufficient.

3.2.2 *~~CDD~~—CT slice, n—*~~contrast-detail-dose.~~a tomogram or the object cross-section corresponding to it.

3.2.2.1 *Discussion—*

The slice plane is the plane, determined by the focal spot and linear array of detectors or a single line of an area array, around which each measurement of a planar tomographic scan is centered. Each such scan also has a slice thickness, which is the distance normal to the slice plane over which changes in object opacity will significantly influence the measurements; typically, an average value based on the aperture function is used to characterize this parameter. When three-dimensional CT-density maps have been reconstructed, a slice may be formed on an arbitrary plane or other surface, not just on slice planes.

3.2.3 *~~CT~~—CT view/projection, n—*~~computed tomography.~~a set of X-ray opacity projection values (derived from measurements or by simulation) grouped together for processing purposes, especially for the convolution and backprojection steps of computing a tomograph.

3.2.3.1 *Discussion—*

The set of line integrals resulting from a scan of an object can be grouped conceptually into subsets referred to as views. Each view corresponds to a set of ray paths through the object from a particular direction. The views are also referred to as projections or profiles, while each individual datum within a given projection is referred to as a sample or often simply a data point

3.2.4 *~~CAT~~—detector aperture function, n—*~~computerized axial tomography.~~a three-dimensional function centered on the axis from the radiation source to a detector element, giving the sensitivity of the detector to the presence of attenuating material at each position.

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[3] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

3.2.4.1 *Discussion—*

The detector aperture function gives the extent and intensity distribution of each ray around and along the length of its central line. The function is determined by the size and shape of the radiation source and of the active region of the detector, and by relative distance to the source and the detector. The average width of this function in the region of the object being examined is an important limit on the spatial resolution of a CT scan.

3.2.5 ~~*DR*—~~*sinogram, n—*~~digital radiography.~~a two-dimensional array of position within view versus view angle, which can be stacked into a volume for volumetric reconstruction techniques.

~~3.2.6 *ERF*—edge response function.~~

~~3.2.7 *LSF*—line spread function.~~

~~3.2.8 *MTF*—modulation transfer function.~~

~~3.2.9 *NDE*—nondestructive evaluation.~~

~~3.2.10 *PDF*—probability distribution function.~~

~~3.2.11 *PSF*—point spread function.~~

4. Summary of Guide

~~4.1 This guide provides a tutorial introduction to the technology and terminology of CT. It deals extensively with the physical and mathematical basis of CT, discusses the basic hardware configuration of all CT systems, defines a comprehensive set of fundamental CT performance parameters, and presents a useful method of characterizing and predicting system performance. Also, extensive descriptions of terms and references to publications relevant to the subject are provided.~~

4.1 This guide provides a tutorial introduction to the technology and principles of CT and is divided into ~~three~~six main sections. ~~Sections~~Section 5 ~~and~~ discusses the significance of CT compared to conventional radiography. Section 6 ~~provide an~~ provides a brief overview of ~~CT: defining~~CT. Section 7~~the process, discussing the performance characteristics of CT systems, and describing the basic elements of all~~ describes the basic hardware elements of CT systems. Section 8 ~~addresses the physical and mathematical basis~~ outlines the general principles of CT imaging. Section ~~8~~9 ~~addresses in more detail a number of important performance parameters as well as their characterization and verification. This section~~outlines CT system performance factors used in characterizing the system performance and images. Section 10 ~~is more technical than the other sections, but it is probably the most important of all. It establishes a single, unified set of performance definitions and relates them to more basic system parameters with a few carefully selected mathematical formulae.~~identifies some CT system processes for quantitative measurements to compare the relative performance of different CT systems and calibrate for densitometric information. Note that ISO 15708 Parts 1-4 have been updated and this guide has been harmonized with the recent publications.

5. Significance and Use

~~5.1 This guide provides a tutorial introduction to the theory and use of computed tomography. This guide begins with a overview intended for the interested reader with a general technical background. Subsequent, more technical sections describe the physical and mathematical basis of CT technology, the hardware and software requirements of CT equipment, and the fundamental measures of CT performance. This guide includes an extensive glossary (with discussion) of CT terminology and an extensive list of references to more technical publications on the subject. Most importantly, this guide establishes consensus definitions for basic measures of CT performance, enabling purchasers and suppliers of CT systems and services to communicate unambiguously with reference to a recognized standard. This guide also provides a few carefully selected equations relating measures of CT performance to key system parameters.~~

5.1 ~~*General Description of Computed Tomography*—CT~~ Computed tomography (CT) is a radiographic ~~inspection~~reconstruction method that ~~uses a computer to reconstruct an image of a cross-sectional plane (slice) through an object. The resulting cross-sectional image is a quantitative map of the linear X-ray attenuation coefficient, μ, at each point in the plane. The linear attenuation coefficient characterizes the local instantaneous rate at which X-rays are removed during the scan, by scatter or absorption, from the incident radiation as it propagates through the object (See~~ provides a sensitive technique whenever the primary goal ~~7.5). The attenuation of the X-rays as they interact with matter is a well-studied problem~~ is ~~(1) and is the result of several different interaction mechanisms. For industrial CT systems with peak X-ray energy below a few MeV, all but a few minor effects can be accounted for in terms of the sum of just two interactions: photoelectric absorption and Compton scattering (1). The photoelectric interaction is strongly dependent on the atomic number and density of the absorbing medium; the Compton scattering is predominantly a function of the electron density of the material. Photoelectric attenuation dominates at lower energies and becomes more important with higher atomic number, while Compton scattering dominates at higher energies and becomes more important at lower atomic number. In special situations, these dependencies can be used to advantage (see~~ to locate ~~7.6.2~~and ~~references therein).~~size planar and volumetric detail in three dimensions.

~~5.2.1 One particularly important property of the total linear attenuation coefficient is that it is proportional to material density, which is of course a fundamental physical property of all matter. The fact that CT images are proportional to density is perhaps~~

~~the principal virtue of the technology and the reason that image data are often thought of as representing the distribution of material density within the object being inspected. This is a dangerous oversimplification, however. The linear attenuation coefficient also carries an energy dependence that is a function of material composition. This feature of the attenuation coefficient may or may not (depending on the materials and the energies of the X-rays involved) be more important than the basic density dependence. In some instances, this effect can be detrimental, masking the density differences in a CT image; in other instances, it can be used to advantage, enhancing the contrast between different materials of similar density.~~

~~5.2.2 The fundamental difference between CT and conventional radiography is shown in Fig. 1. In conventional radiography, information on the slice plane "P" projects into a single line, "A-A;" whereas with the associated CT image, the full spatial information is preserved. CT information is derived from a large number of systematic observations at different viewing angles, and an image is then reconstructed with the aid of a computer. The image is generated in a series of discrete picture elements or pixels. A typical CT image might consist of a 512 by 512 or 1024 by 1024 array of attenuation values for a single cross-sectional slice through a test specimen. This resultant two-dimensional map of the slice plane is an image of the test article. Thus, by using CT, one can, in effect, slice open the test article, examine its internal features, record the different attenuations, perform dimensional inspections, and identify any material or structural anomalies that may exist. Further, by stacking and comparing adjacent CT slices of a test article, a three dimensional image of the interior can be constructed.~~

~~5.2.3 From Fig. 1, it can be appreciated readily that if an internal feature is detected in conventional projection radiography, its position along the line-of-sight between the source and the film is unknown. Somewhat better positional information can be determined by making additional radiographs from several viewing angles and triangulating. This triangulation is a rudimentary, manual form of tomographic reconstruction. In essence, a CT image is the result of triangulating every point in the plane from many different directions.~~

~~5.2.4 Because of the volume of data that must be collected and processed with CT, scans are usually made one slice at a time. A set of X-ray attenuation measurements is made along a set of paths projected at different locations around the periphery of the test article. The first part of Fig. 2 illustrates a set of measurements made on a test object containing two attenuating disks of different diameters. The X-ray attenuation measurement made at a particular angle, φ_1, is referred to as a single view. It is shown as $f_{\varphi 1}(x')$, where x' denotes the linear position of the measurement. The second part of Fig. 2 shows measurements taken at several other angles $f_{\varphi i}(x')$. Each of the attenuation measurements within these views is digitized and stored in a computer, where it is subsequently conditioned (for example, normalized and corrected) and filtered (convolved), as discussed in more detail in Section 7. The next step in image processing is to backproject the views, which is also shown in the second part of Fig. 2. Backprojection consists of projecting each view back along a line corresponding to the direction in which the projection data were collected. The backprojections, when enough views are employed, form a faithful reconstruction of the object. Even in this simple example, with only four projections, the concentration of backprojected rays already begins to show the relative size and position of features in the original object.~~

5.2 ~~*System Capabilities*—The ability of a CT system to image thin cross-sectional areas of interest through an object makes it a powerful complement to conventional radiographic inspections. Like any imaging system, a CT system can never duplicate exactly the object that is scanned. The extent to which a CT image does reproduce the object is dictated largely by the competing influences of the spatial resolution, the statistical noise, and the artifacts of the imaging system. Each of these aspects is discussed briefly here. A more complete discussion will be found in Sections~~CT provides quantitative volume images as a function of density

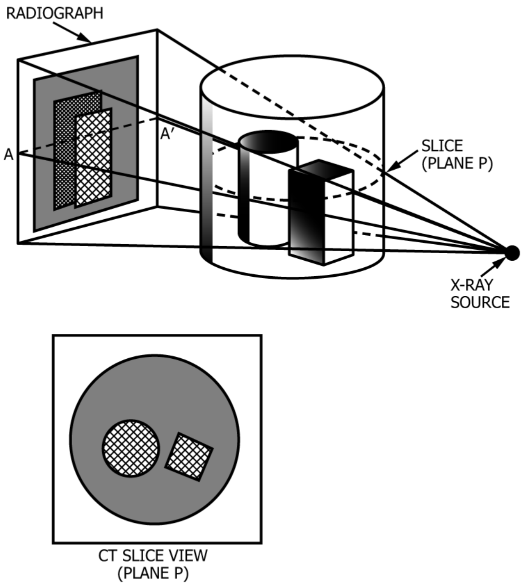


FIG. 1 A CT Image Versus a Conventional Radiograph

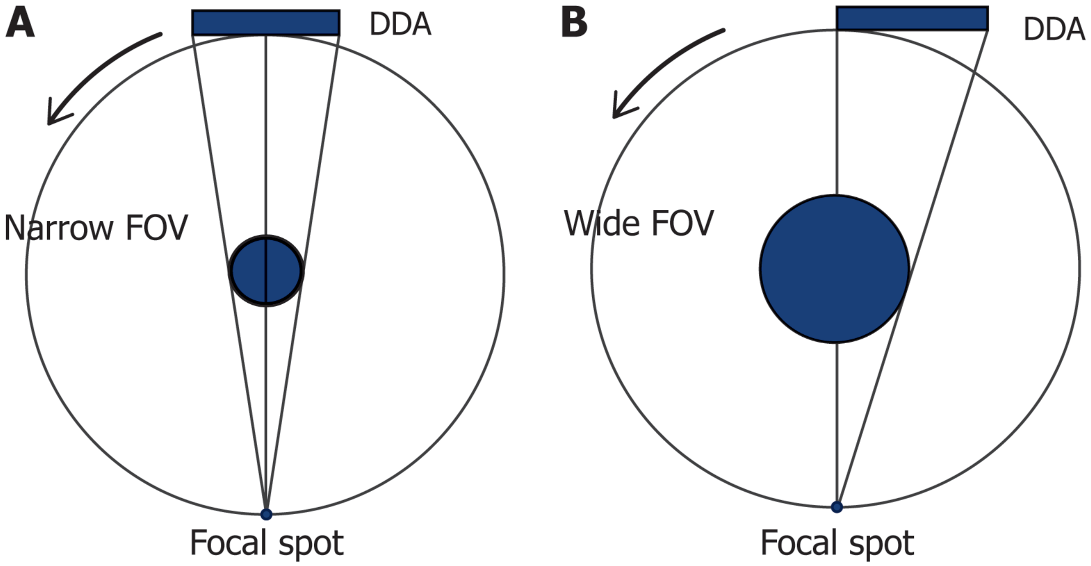


FIG. 2 ~~Schematic Illustrations of How CT Works~~Method of Acquiring an Extended FOV Using a DDA; (A) Conventional Geometric Arrangement Whereby the Central Ray of the X-ray Beam From the Focal Source is Directed Through the Middle of the Object to the Center of the DDA; (B) Alternate Method of Shifting the Location of the DDA (Multiple Positions Can be Used) and Collimating the X-ray Beam Laterally to Extend the FOV Object

and element number (attenuation coefficient) by means of computer-processed combinations of many X-ray measurements taken from different angles to produce cross-sectional images of specific areas of a scanned object, allowing the user to see inside the object without cutting. CT is considered much easier to interpret than conventional radiographic data due to the elimination of overlapping structures. The new user can learn quickly to read CT data because the images correspond more closely to the way the human mind visualizes three-dimensional structures than conventional projection radiography. Further, because CT slices and volumes are digital, they may be enhanced, analyzed, compressed, archived, input as data into performance calculations, compared with digital data from other NDE ~~8 and~~modalities, or ~~9.~~transmitted to other locations for remote viewing.

~~5.3.1 *Spatial Resolution*—Radiographic imaging is possible because different materials have different X-ray attenuation coefficients. In CT, these X-ray coefficients are represented on a display monitor as shades of gray, similar to a photographic image, or in false color. The faithfulness of a CT image depends on a number of system-level performance factors, with one of the most important being spatial resolution. Spatial resolution refers to the ability of a CT system to resolve small details or locate small features with respect to some reference point.~~

~~5.3.1.1 Spatial resolution is generally quantified in terms of the smallest separation at which two points can be distinguished as separate entities. The limiting value of the spatial resolution is determined by the design and construction of the system and by the amount of data and sampling scheme used to interrogate the object of interest. The precision of the mechanical system determines how accurately the views can be backprojected, and the X-ray optics determine the fineness of the detail that can be resolved. The number of views and the number of single absorption measurements per view determine the size of the reconstruction matrix that can be faithfully reconstructed. Reducing pixel size can improve spatial resolution in an image until the inherent limit set by these constraints is reached. Beyond this limit, smaller pixels do not increase the spatial resolution and can induce artifacts in the image. However, under certain circumstances, reconstructing with pixels smaller than would otherwise be warranted can be a useful technique. For instance, when performing dimensional inspections, working from an image with pixels as small as one-fourth the sample spacing can provide measurable benefit.~~

~~5.3.1.2 It can also be shown that a given CT image is equivalent to the blurring (convolution) of the ideal representation of the object with a smooth, two-dimensional Gaussian-like function called the point-spread-function (PSF). The specification of the PSF of a system is an important characterization of a CT system and can be derived fairly accurately from the parameters of the CT system. The effect of the PSF is to blur the features in the CT image. This has two effects: (*1*) small objects appear larger and (*2*) sharp boundaries appear diffuse. Blurring the image of small objects reduces resolution since the images of two small point-like objects that are close together will overlap and may be indistinguishable from a single feature. Blurring sharp edges reduces the perceptibility of boundaries of different materials for the same reason. This effect is especially important at interfaces between materials, where the possibility of separations of one type or another are of the greatest concern. Thus, knowledge of the PSF of a CT system is crucial to the quantitative specification of the maximum resolution and contrast achievable with that system.~~

~~5.3.1.3 It should be noted, since it is a common source of misunderstanding, that the smallest feature that can be detected in a CT image is not the same as the smallest that can be resolved. A feature considerably smaller than a single pixel can affect the pixel to which it corresponds to such an extent that it will appear with a visible contrast relative to adjacent pixels. This~~

~~phenomenon, the "partial-volume effect," is discussed in 7.6. The difference between the resolution of a small feature and the resolution of its substructure is of fundamental importance for CT.~~

~~5.3.2 *Statistical Noise*—All images made from physical interactions of some kind will exhibit intrinsic statistical noise. In radiography, this noise arises from two sources: (*1*) intrinsic statistical variations due to the finite number of photons measured; and (*2*) the particular form of instrumentation and processing used. A good example in conventional radiography is film that has been underexposed. Even on a very uniform region of exposure, close examination of the film will reveal that only a small number of grains per unit area have been exposed. An example of instrumentation induced noise is the selection of coarse- or fine-grain film. If the films are exposed to produce an image with a given density, the fine-grain film will have lower statistical noise than the coarse-grain film. In CT, statistical noise in the image appears as a random variation superimposed on the CT level of the object. If a feature is small, it may be difficult to determine its median gray level and distinguish it from surrounding material. Thus, statistical noise limits contrast discrimination in a CT image.~~

~~5.3.2.1 Although statistical noise is unavoidable, its magnitude with respect to the desired signal can be reduced to some extent by attempting to increase the desired signal. This can be accomplished by increasing the scan time, the output of the X-ray source, or the size of the X-ray source and detectors. Increasing the detector and source size, however, will generally reduce spatial resolution. This tradeoff between spatial resolution and statistical noise is a fundamental characteristic of CT.~~

~~5.3.3 *Artifacts*—An artifact is something in an image that does not correspond to a physical feature in the test object. All imaging systems, whether CT or conventional radiography, exhibit artifacts. Examples of artifacts common to conventional radiography are blotches of underdevelopment on a film or scattering produced by high-density objects in the X-ray field. In both cases, familiarity with these artifacts allows the experienced radiographer to discount their presence qualitatively.~~

~~5.3.3.1 CT artifacts manifest themselves in somewhat different ways, since the CT image is calculated from a series of measurements. A common artifact is caused by beam hardening and manifests itself as cupping, that is, a false radial gradient in the density that causes abnormally low values at the interior center of a uniform object and high values at the periphery. Artifacts occurring at the interfaces between different density materials are more subtle. There is often an overshoot or undershoot in the density profile at such a density boundary. The interface density profile must be well characterized so that delaminations or separations are not obscured. If the interface profile is not well characterized, false positive indications of defects or, more importantly, situations in which defects go undetected will result. Thus it is important to understand the class of artifacts pertinent to the inspection and to put quantitative limits on particular types of artifacts. Some of the artifacts are inherent in the physics and the mathematics of CT and cannot be eliminated (see 7.6). Others are due to hardware or software deficiencies in the design and can be eliminated by improved engineering.~~

~~5.3.3.2 The type and severity of artifacts are two of the factors that distinguish one CT system from another with otherwise identical specifications. The user must understand the differences in these artifacts and how they will affect the determination of the variables to be measured. For instance, absolute density measurements will be affected severely by uncompensated cupping, but radial cracks can be visible with no change in detectability.~~

~~6. Apparatus~~

~~6.1 Modern CT systems, both industrial and medical, are composed of a number of subsystems, typically those shown in Fig. 3. The choice of components for these subsystems depends on the specific application for which the system was designed; however, the function served by each subsystem is common in almost all CT scanners. These subsystems are:~~

~~6.1.1 An operator interface,~~
~~6.1.2 A source of penetrating radiation,~~
~~6.1.3 A radiation detector or an array of detectors,~~
~~6.1.4 A mechanical scanning assembly,~~
~~6.1.5 A computer system,~~
~~6.1.6 A graphical display system, and~~
~~6.1.7 A data storage medium.~~

~~6.2 *Operator Interface*—The operator interface defines what control the operator has over the system. From the perspective of the user, the operator interface is the single most important subsystem. The operator interface ultimately determines everything from the ease of use to whether the system can perform repetitive scan sequences. In short, the operator interface determines how the system is used.~~

~~6.3 *Radiation Sources*—There are three rather broad types of radiation sources used in industrial CT scanners: (*1*) X-ray tubes, (*2*) linear accelerators, and (*3*) isotopes. The first two broad energy spectra are (polychromatic or bremsstrahlung) electrical sources; the third is approximately monoenergetic radioactive sources. The choice of radiation source is dictated by precisely the same rules that govern the choice of radiation source for conventional radiographic imaging applications. A majority of existing CT scanners use electrical bremsstrahlung X-ray sources: X-ray tubes or linear accelerators. One of the primary advantages of using an electrical X-ray source over a radioisotope source is the much higher photon flux possible with electrical radiation generators, which in turn allows shorter scan times. The greatest disadvantage of using an X-ray source is the beam hardening effect associated with polychromatic fluxes. Beam hardening results from the object preferentially absorbing low-energy photons contained in the continuous X-ray spectrum. Most medical scanners use for a source an X-ray tube operating with a potential of~~

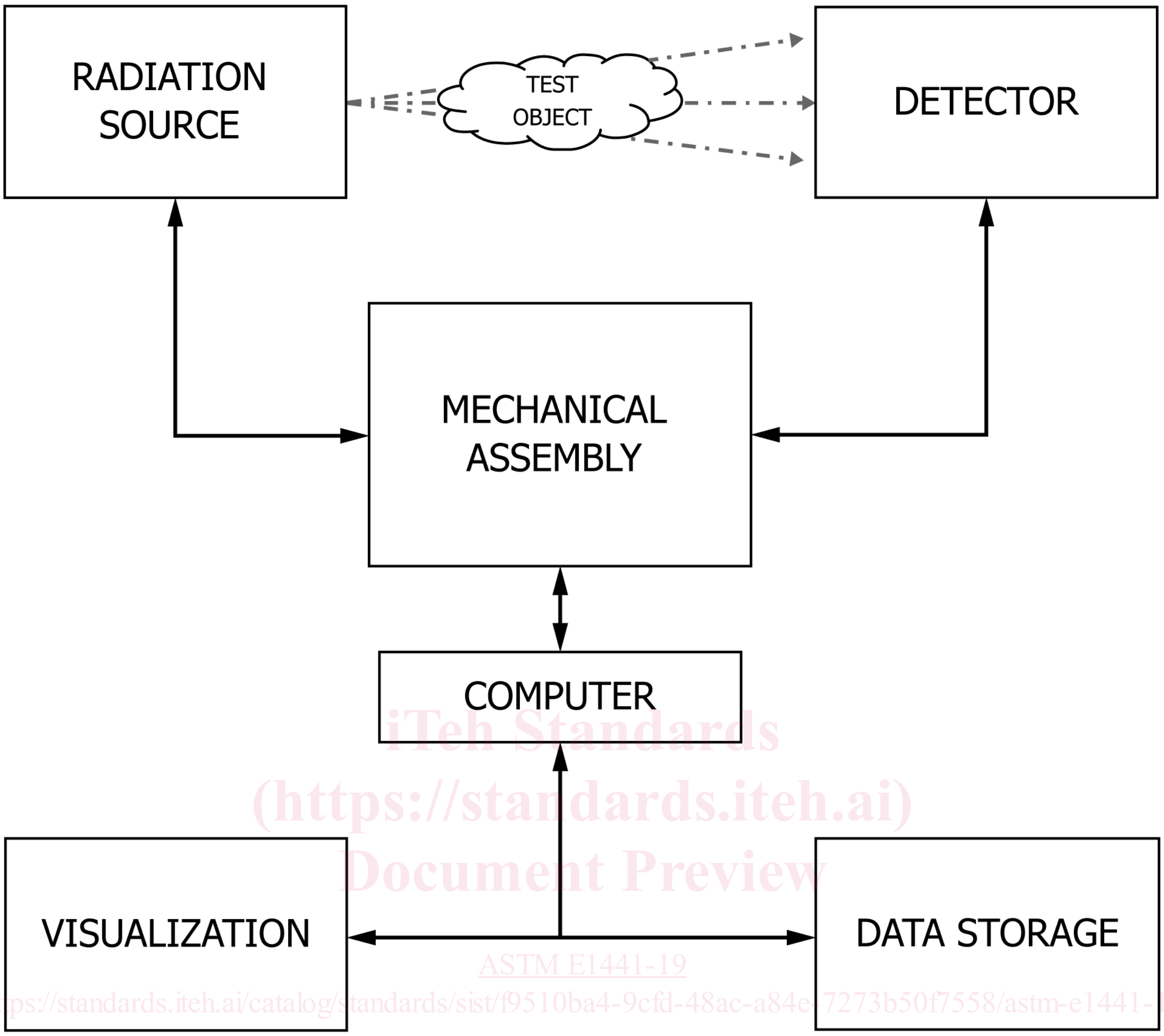


FIG. 3 Typical Components of a Computed Tomography (CT) System

~~120 to 140 kV. Industrial scanners designed for moderate penetrating ability also use X-ray tubes, but they usually operate at higher potentials, typically 200 to 400 kV. Systems designed to scan very massive objects, such as large rocket motors, use high-energy bremsstrahlung radiation produced by linear accelerators. These sources have both high flux and good penetration, but they also have a broad continuous spectrum and the associated beam-hardening effect. Isotope sources are attractive for some applications. They offer an advantage over X-ray sources in that problems associated with beam hardening are nonexistent for the monoenergetic isotopes such as Cesium-137 and Cobalt-60. They have the additional advantages, which are important in some applications, that they do not require bulky and energy-consuming power supplies, and they have an inherently more stable output intensity. The intensity of available isotopic sources, however, is limited by specific activity (photons/second/gram of material). The intensity affects signal-to-noise ratio, and, even more importantly, the specific activity determines source spot size and thus spatial resolution. Both of these factors tend to limit the industrial application of isotopic scanners. Nevertheless, they can be used in some applications in which scanning time or resolution is not critical.~~

~~6.4 *Radiation Detectors*—A radiation detector is used to measure the transmission of the X-rays through the object along the different ray paths. The purpose of the detector is to convert the incident X-ray flux into an electrical signal, which can then be handled by conventional electronic processing techniques. The number of ray sums in a projection should be comparable to the number of elements on the side of the image matrix. Such considerations result in a tendency for modern scanners to use large detector arrays that often contain several hundred to over a thousand sensors.~~

~~6.4.1 *Scintillation Detectors*—This type of transducer takes advantage of the fact that certain materials possess the useful property of emitting visible radiation when exposed to X-rays. By selecting fluorescent materials that scintillate in proportion to the incident flux and coupling them to some type of device that converts optical input to an electrical signal, sensors suitable for CT can be engineered. The light-to-electrical converter is usually a photodiode or photomultiplier tube, but video-based approaches~~

~~are also widely employed. Like ionization detectors, scintillation detectors afford considerable design flexibility and are quite robust. Scintillation detectors are often used when very high stopping power, very fast pulse counting, or areal sensors are needed. Recently, for high-resolution CT applications, scintillation detectors with discrete sensors have been reported with array spacings on the order of 25 μm. Both ionization and scintillation detectors require considerable technical expertise to achieve performance levels acceptable for CT.~~

~~6.5 *Mechanical Scanning Equipment*—The mechanical equipment provides the relative motion between the test article, the source, and the detectors. It makes no difference, at least in principle, whether the test object is moved systematically relative to the source and detectors, or if the source and detectors are moved relative to the test object. Physical considerations such as the weight or size of the test article should be the determining factors for the most appropriate motion to use.~~

~~6.5.1 The majority of scan geometries that have been employed can be classified as one of the following four generations. This classification is a legacy of the early, rapid development of CT in the medical arena and is reviewed here because these terms are still widely used. The distinctions between these early scan geometries are illustrated in Fig. 4.~~

~~6.5.1.1 First-generation CT systems are characterized by a single X-ray source and single detector that undergo both linear translation and rotational motions. The source and detector assembly is translated in a direction perpendicular to the X-ray beam. Each translation yields a single view, as shown in Fig. 2. Successive views are obtained by rotating the test article and translating again. The advantages of this design are simplicity, good view-to-view detector matching, flexibility in the choice of scan parameters (such as resolution and contrast), and ability to accommodate a wide range of different object sizes. The disadvantage is a longer scanning time.~~

~~6.5.1.2 Second-generation CT systems use the same translate/rotate scan geometry as the first generation. The primary difference is that second-generation systems use a fan beam of radiation and multiple detectors so that a series of views can be acquired during each translation, which leads to correspondingly shorter scan times. Like first-generation systems, second-generation scanners have the inherent flexibility to accommodate a wide range of different object sizes, which is an important consideration for some industrial CT applications.~~

~~6.5.1.3 Third-generation CT systems normally use a rotate-only scan geometry, with a complete view being collected by the detector array during each sampling interval. To accommodate objects larger than the field of view subtended by the X-ray fan, it is possible to include part translations in the scan sequence, but data are not acquired during these translations as during first- or second-generation scans. Typically, third-generation systems are faster than their second-generation counterparts; however, because the spatial resolution in a third-generation system depends on the size and number of sensors in the detector array, this improvement in speed is achieved at the expense of having to implement more sensors than with earlier generations. Since all elements of a third-generation detector array contribute to each view, rotate-only scanners impose much more stringent requirements on detector performance than do second-generation units, where each view is generated by a single detector.~~

~~6.5.1.4 Fourth-generation CT systems also employ a rotate-only scan motion. The difference between third-generation and fourth-generation systems is that a fourth-generation CT system uses a stationary circular array of detectors and only the source moves. The test specimen is placed within the circle of detectors and is irradiated with a wide fan beam which rotates around the test article. A view is made by obtaining successive absorption measurements of a single detector at successive positions of the X-ray source. The number of views is equal to the number of detectors. These scanners combine the artifact resistance of second-generation systems with the speed of third-generation units, but they can be more complex and costly than first-, second-, or third-generation machines, they require that the object fit within the fan of X-rays, and they are more susceptible to scattered radiation.~~

~~6.5.1.5 Several other CT scanner geometries that have been developed and marketed do not precisely fit the above categories. However, there is no agreed-upon generation designation for them.~~[4]

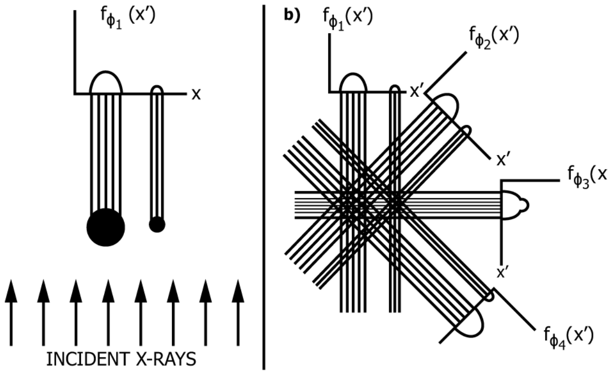


FIG. 4 ~~Four Sketches Illustrating the Evolution of Medical CT Scan Geometries. Each Embodiment is Representative of a Distinct Generation of Instrumentation~~Schematic Illustrations of How CT Works

~~*(1)* The cine CT system has no mechanical scanning motion. In this system both the X-ray detector and the X-ray tube anode are stationary. The anode, however, is a very large semicircular ring that forms an arc around the Object scan circle, and is part of a very large, non-conventional X-ray tube. The source of X-rays is moved around the same path as a fourth generation CT scanner by steering an electron beam around the X-ray anode. The detectors are positioned opposite the source circle and full rotational scans are created without the need for object or system motion. Because the electron beam can be moved very rapidly, this scanner can attain very rapid image acquisition rates. This system has been referred to variably as fifth generation and sixth generation. It has also been described as a stationary-stationary scanner. The terms millisecond CT, ultrafast CT and electron beam CT have also been used, although the latter can be confusing since the term suggests that the object is exposed to an electron beam.~~

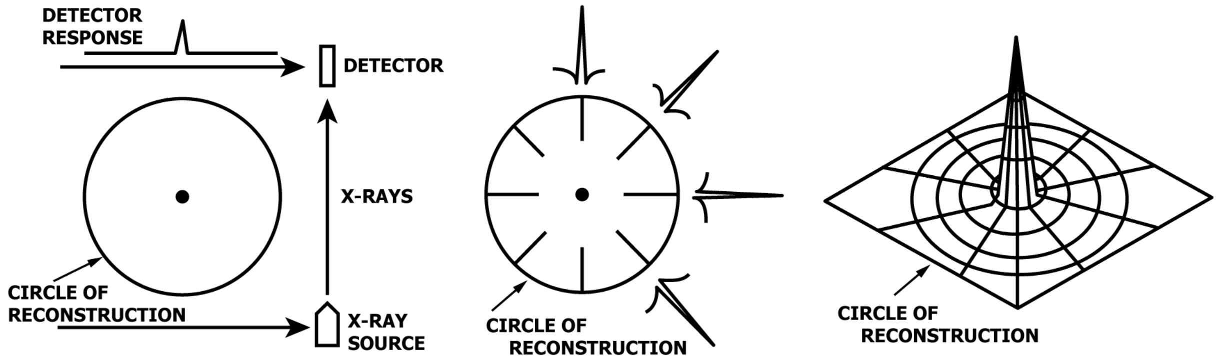
~~*(2)* In volume CT, a cone beam or highly-collimated, thick, parallel beam is used rather than a fan beam, and a planar grid replaces the linear series of detectors. This allows for much faster data acquisition, as the data required for multiple slices can be acquired in one rotation. It is computationally more intensive (although high speed computers are now making this approach practical) and corrections for scatter and hardening effects may be required for sufficient image quality. Large cone beam angles may lead to unsharpness at the outer volume elements.~~

~~6.5.2 A significant factor in driving medical CT systems to use rotate-only scan geometries was the requirement that scanning times be short compared to the length of time that a patient can remain motionless or that involuntary internal motion can be ignored (that is, seconds). These considerations are not as important for industrial applications in which scan times for specific production-related items can typically be much longer (that is, minutes) and the dose to the object is often not an important factor. A second-generation scan geometry is attractive for industrial applications in which a wide range of part sizes must be accommodated, since the object does not have to fit within the fan of radiation as it generally does with third- or fourth-generation systems. A third-generation scan geometry is attractive for industrial applications in which the part to be examined is well defined and scan speed is important. To date, first- and fourth-generation scan geometries have seen little commercial application, but there may be special situations for which they would be well suited. The ability of CT to image and quantify internal features makes it the nondestructive examination method of choice for inspecting parts containing complex internal structures or having various internal layers. When 100 %, or a large area, of a part needs to be inspected using CT, the most economical approach would be to use a volumetric CT system employing an area detector, assuming the desired image quality and uniformity can be obtained.~~

~~6.6 *Computer Systems*—The computer system(s) performs two major tasks: (*1*) controlling the scan motion, source operation, and data acquisition functions; and (*2*) handling the reconstruction, image display and analysis, and data archival and retrieval functions.~~

~~6.7 *Image Display and Processings*—Image display and processing are subfunctions of the computer system that provide a degree of image interaction not available with conventional radiography. The mapping between the pixel linear attenuation coefficient and the displayed intensity of the pixel can be changed to accommodate the best viewing conditions for a particular feature. Image processing functions such as statistical and densitometric analyses can be performed on an image or group of images. The digital nature of the image allows major advances in the way data are processed, analyzed, and stored. This process of mapping reconstructed pixel values to displayed pixel values is shown in Fig. 5.~~

~~6.8 *Archival Data Storage*—Information such as image data, operating parameters, part identification, operator comments, slice orientation, and other data is usually saved (archived) in a computer-readable, digital format on some type of storage medium. The advantage of saving this material in computer-readable format rather than in simple hardcopy form is that it would take dozens of pictures of each slice at different display conditions to approximate the information contained in a single CT image. Also, images~~



A. PROJECTION OF POINT OBJECT B. FILTERED BACK PROJECTION TECHNIQUE C. RECONSTRUCTION IMAGE OF A POINT

FIG. 5 ~~Conceptual Illustration of the Process of Mapping a Large Range of Image Values Onto a Much Smaller Range of Displayable Values. Two Important Cases are Shown: the One on the Left Illustrates the Case of Maximum Image Latitude; the One on the Right Illustrates the Case of Maximum Contrast Over a Narrow Range of Contrast~~Filtered Convolution Backprojection

~~of samples made with old and new data sets can be compared directly, and subsequent changes in reconstruction or analysis procedures can be reapplied to saved data or images.~~

~~6.9 These elements are the basic building blocks of any CT system. Each CT system will have its own particular set of features. It is the responsibility of the user to understand these differences and to select the system most appropriate for the intended application.~~

6. Computed Tomography (CT) Overview

6.1 CT is a radiographic examination method that uses a computer to reconstruct an image of one or more cross-sectional plane (slice(s)) through an object. The result is a quantitative map of the linear X-ray attenuation coefficient, μ, at each point in the plane. The linear attenuation coefficient characterizes the local instantaneous rate at which X-ray photons are attenuated during the scan, by scatter or absorption, from the incident radiation as it propagates through the object.

6.2 One particularly important property of the total linear attenuation coefficient is that it is dependent upon atomic number and is proportional to material density, which is a fundamental physical property of all matter. The fact that CT images are proportional to density is perhaps the principal virtue of the technology and the reason that image data are often thought of as representing the distribution of material density within the object being examined; however, the linear attenuation coefficient also carries an energy dependence that is a function of material composition (atomic number). This feature of the attenuation coefficient may or may not (depending on the materials and the energies of the X-rays involved) be more important than the basic density dependence. In some instances, this effect can be detrimental, masking the density differences in a CT image; in other instances, it can be used to advantage, enhancing the contrast between different materials of similar density.

6.3 The fundamental difference between CT and conventional radiography is shown in Fig. 1. In conventional radiography, information on the slice plane "P" projects into a single line, "A-A;" whereas with the associated CT image, the full spatial resolution of the plane is preserved. CT information is derived from a large number of systematic observations at different viewing angles, and an image of the slice plane is then reconstructed with the aid of a computer. The image is generated in a matrix of voxels. The resultant map is an image of the object under examination. Thus, by using CT, one can, in effect, slice open the object under examination, examine its internal features, record the different attenuations, perform dimensional measurements, and identify any material or structural anomalies that may exist.

6.4 From Fig. 1, it can be appreciated readily that if an internal feature is detected in conventional projection radiography, its position along the line-of-sight between the source and the film is unknown. Somewhat better positional information can be determined by making additional radiographs from several viewing angles and triangulating. This triangulation is a rudimentary, manual form of tomographic reconstruction. In essence, a CT image is the result of triangulating every point in the plane from many different directions.

6.5 As with any modality, CT has its limitations. Candidate objects for examination must be small enough to be accommodated by the handling system of the CT equipment available to the user and radiometrically translucent at the X-ray energies employed by that particular system. In addition, the detector cannot be saturated in any view. This requirement can limit CT as compared to 2D radiography where one may saturate parts of the detected image in order to obtain proper signal through an area of interest where for CT, for a given view/projection image, the detector can only be saturated in an area outside the part.

6.6 *Types of CT:*

6.6.1 *Fan Beam CT (2D-CT)*—In a system which is able to perform a 2D-CT (or fan beam CT), a linear detector array (LDA) is being used. The projections needed for a reconstruction are typically collected by rotating the sample (or source and detector around the sample) at least 180° plus opening angle of the fan beam. With this kind of geometry, a single slice of object can be reconstructed. The object may be translated along the rotation axis to collect other slices.

6.6.1.1 Slice thickness is set by the X-ray optics of the system. It is a function of the object position (the magnification of the scan geometry) and the effective sizes (normal to the scan plane) of the focal spot of the source and the acceptance aperture of the detector. The effective size of the focal spot is determined by its physical size and any source-side collimation. The maximum thickness is achieved with the maximum effective focal spot size and the maximum effective acceptance aperture. The minimum thickness is achieved with the minimum focal spot size permitted and the minimum effective acceptance angle permitted. Due to the collimation (tube and detector) often used in this geometry, the influence of scattered radiation, which disturbs the reconstruction process significantly (artifacts), is minimal. Multiple slices along the axis of rotation may be stacked into a 3-D data set and rendered as a 3-D image. Two types of scan motion geometries are most common: translate-rotate motion and rotate-only motion.

6.6.1.2 *Translate-rotate Motion*—The object is translated in a direction perpendicular to the direction and in the plane of the X-ray beam. Full data sets are obtained by rotating the test object between translations by the fan angle of the beam and again translating the object until a minimum of 180° of data have been acquired. The main advantage of this design is ability to accommodate a wide range of different object sizes including objects too big to be subtended by the X-ray fan. The disadvantage is longer scan time. If the test object is larger than the prescribed field of view (FOV), either by necessity or by accident, unexpected and unpredictable artifacts or a measurable degradation of image quality can result.

6.6.1.3 *Rotate-only Motion*—A complete view is collected by the detector array during each sampling interval. A rotate-only scan has lower motion penalty than a translate-rotate scan and is attractive for industrial applications where the part to be examined fits within the fan beam and scan speed is important. If the test object is larger than the prescribed field of view (FOV), either by necessity or by accident, unexpected and unpredictable artifacts or a measurable degradation of image quality can result.

6.6.2 *Cone Beam CT (3D CT)*—In a system which is able to perform a 3D-CT (or cone beam CT), an area scan detector, typically a digital detector array (DDA), is used, where each row of the area array "acts" like a linear array. The projections needed for a reconstruction are typically collected by rotating the sample (or source and detector around the sample) at least 180° plus opening angle of the cone beam. With this kind of geometry, a volume with multiple slices of object can be reconstructed, Feldkamp reconstruction (a reconstruction process that reconstructs 3D data directly to a 3D image), with a single rotation of the object. Compared to the fan beam geometry, scattered radiation within the used cone cannot be reduced by collimation. Usually the image quality of the slices produced is worse in quality compared to the fan beam geometry. Additionally, the cone beam geometry produces another artifact, which depends on the opening angle of the cone parallel to the rotation axis. This artifact is widely known as Feldkamp artifact (see 9.7.6). The influence of the Feldkamp artifact can be reduced by minimizing the opening angle of the cone, which should be no larger than 11° in total if Feldkamp's reconstruction algorithm is used. The scanning and acquisition process for larger volumes is typically less time consuming than fan beam CT.

6.6.2.1 Mathematically only 180° plus the fan angle is required for CT reconstruction of the described method. It is, however, best practice to acquire a full 360° of data as this provides redundant information which fills in for detector defects (for example, bad pixels) and reduces artifacts. This also allows for checking the first versus the last image as a check for object motion during the scan.

6.6.2.2 *Extended Field of View/Offset Scanning*—Another method for increasing the width of the FOV while using a smaller area detector is to offset the position of the detector (or shift rotation axis, or a combination of both), collimate the beam asymmetrically, and scan the object. Each projection will be viewing a little more than half the total diameter of the field of view. For offset scanning, the center of rotation must always be within each projection (Fig. 2). This method requires 360° of data for mathematical sufficiency.

6.6.3 *Helical CT*—In a system which is able to perform Helical CT (or Spiral CT), a multi-row LDA or an area scan detector is being used. The projections needed for a reconstruction are typically collected by rotating the sample (or source and detector around the sample) combined with a linear movement along the rotation axis. With this kind of geometry, a volume with multiple slices of object can be reconstructed with multiple rotations of the object. Compared to the fan beam geometry, scattered radiation within the cone cannot be reduced by collimation. Usually the quality of the slices produced is worse in quality compared to the fan beam geometry but improved compared to the cone beam geometry. Contrary to cone beam CT, Helical CT avoids the Feldkamp cone artifact since all measured object details will pass the central plane. The acquisition process for larger volumes is less time consuming than fan beam CT. Helical CT can theoretically be used to measure infinitely long objects, like those produced in extrusion processes.

6.6.4 *Computed Laminography (Planar CT, Tomosynthesis, Coplanar Translational, Coplanar Rotational Laminography)*—Laminography is a radiographic technique in which the relative motion of the source, detector, and object show a specific plane more clearly. Some systems will utilize a reconstruction algorithm to assist in the image development. This method is especially suitable for large or flat objects that are either difficult to rotate or have geometries that make penetration from some angles impossible.

6.6.5 *Irregular (Optimized) Geometries for CT*—The quality of a CT volume is highly influenced by the geometry of the part. Due to the circular trajectories being used in most CT geometries unfavorable transmission directions are produced during the scan. Lack of penetration in these positions can lead to unwanted artifacts in the reconstruction. Collecting the projections on an arbitrary path (for example, optimized based on the object geometry) can avoid the unfavorable positions and therefore reduce artifacts. To make use of the arbitrary geometries, special reconstruction methods are necessary. In most cases, algebraic reconstruction is used, which can deal with any kind of geometry.

7. Basic Hardware Configuration

7.1 CT systems are composed of a number of subsystems, typically those shown in Fig. 3. The choice of components for these subsystems depends on the specific application for which the system was designed; however, the function served by each subsystem is common in almost all CT scanners. These subsystems are:

7.2 *Source of Penetrating Radiation*—There are three rather broad types of radiation sources used in industrial CT scanners: (1) X-ray tubes, (2) accelerators, and (3) isotopes. The first two broad energy spectra are polychromatic (or Bremsstrahlung) electrical sources; the third is approximately monoenergetic radioactive sources. The choice of radiation source is dictated by the same rules that govern the choice of radiation source for conventional radiographic imaging applications.

7.2.1 *X-ray Sources*—While the CT systems may utilize either gamma-ray or X-ray generators, the latter is used for most applications. For a given focal spot size, X-ray generators (that is, X-ray tubes and linear accelerators) are several orders of magnitude more intense than isotope sources. Most X-ray generators are adjustable in peak energy and intensity and have the added safety feature of discontinued radiation production when switched off; however, the polychromaticity of the energy spectrum from an X-ray source causes artifacts such as beam hardening (the anomalous decreasing attenuation toward the center of a homogeneous object) in the image if uncorrected.

7.2.2 *Isotope Sources*—Isotope sources are attractive for some applications. They offer an advantage over X-ray sources in that problems associated with beam hardening are reduced or nonexistent for these monoenergetic/discrete energies type sources. They have the additional advantages, which are important in some applications, that they do not require bulky and energy-consuming power supplies, and they have an inherently more stable output intensity. The intensity of available isotopic sources, however, is limited by specific activity (decays per second per mass of 1 gram). The intensity affects signal-to-noise ratio, and, even more importantly, the specific activity determines source spot size and thus spatial resolution. Both of these factors tend to limit the industrial application of isotopic scanners. Nevertheless, they can be used in some applications in which scanning time or resolution is not critical.

7.2.3 *Source Setup*—Caution is advised against applying practices developed for projection radiography. Except at very high energies, mass attenuation differences between materials (signal contrasts) tend to decrease as the mean X-ray energy is increased; whereas, X-ray production and penetrability (signal levels) tend to increase under the same condition. Therefore, the optimum source energy for a given part is not determined by the lowest possible X-ray energy that provides adequate penetration but rather by the X-ray energy that produces the maximum signal-to-noise ratio (SNR). When a part consists of a single material or several materials with distinct physical density differences or different atomic numbers, or both, the best SNR may be obtained at a high source energy. In such cases, the decreased image noise at higher energies is more important than the increased contrast at lower energies. When chemically different components have the same or similar physical densities, the best discrimination of materials may be obtained at a low source energy. In such cases, the increased contrast at lower energies may be more important than the decreased image noise at higher energies. Use of beam filters near the source is a common way of optimizing the beam, similar to 2D radiography

7.3 *Radiation Detection Systems*—The detection system is a transducer that converts the transmitted radiation containing information about the test object into an electronic signal suitable for processing. Most systems convert X-rays to visible light in a scintillator and then detect the light with photo diodes. The detection system may consist of a single sensing element (single pixel detector), a linear detector array (LDA) of sensing elements, or a digital detector array (DDA) of sensing elements. The more detector pixels used at the same time, the faster the required scan data can be collected; but there are important tradeoffs to be considered. Single pixel detectors are used for parallel and fan-beam geometry. LDAs are used with fan-beam CT systems where the beam is collimated to a small slit to reduce scatter radiation. DDAs are used with cone-beam CT systems which can get a 3D volume image much faster than parallel and fan-beam geometry systems but are prone to scatter radiation which can be corrected by software.

7.3.1 A single pixel detector provides the least efficient method of collecting data but entails minimal complexity, eliminates detector cross talk and detector matching, and allows for collimation in two directions just to the active area. A very efficient scintillator for very high energy can be used as there is only a single pixel. This type of detector needs a mechanical movement and an exposure for each pixel of a projection, whereas an LDA needs only one exposure per projection. The CT result is a one slice image of the object.

7.3.2 Linear Detector Arrays (LDAs) have reasonable scan times at moderate complexity, acceptable cross talk and detector matching, and a flexible architecture (length of the detector and width of the collimator slit) that typically accommodates a collimation in one direction. A highly efficient scintillator with a large thickness compared to the pixel size can be used. Also, for high energies sufficient X-ray quanta are converted to light. An LDA generates one scanline per exposure. Rotating the object creates the sinogram. The CT result is a one slice image of the object. A 3D image could be created by generating multiple slices.

7.3.3 DDAs as area imaging devices can capture much more information in a single exposure than an LDA using the cone beam of the X-ray source. Collimation smaller than the active area of the DDA can be used to reduce scattered radiation and good practice is to collimate to the FOV needed for a given object. For uniform scintillator screens (Gd_2O_2S plastics, for example), the thickness of the scintillator screen will reduce the resolution when it exceeds the pixel size as the unsharpness from internal light scatter becomes bigger than the pixel size. However, a thinner scintillator converts less X-ray quanta—especially for higher energies—which results in a much lower SNR so use of a thicker scintillator or conversion screen, or both, may be desirable even though it reduces resolution. It should also be noted that in some instances a collimated 2D scintillator like CsI may mitigate this issue, particularly at lower energies. LDAs bypass this constraint by using single collimated pixels which allows for much thicker scintillators without resolution reduction. A DDA creates an area view; after rotating of the object by 360° a 3D volume image is the result. For more information about the properties of DDAs, and their constraints, refer to Guide E2736.

7.3.4 The application ranges of the three different technologies differ due to the pros and cons. For very high energies (>>MeV) where a very high collimation is required for scatter prevention, many high energy CT systems are equipped with LDA detectors. Due to the higher scintillator efficiency and physical reduction of scatter by the fan beam and collimation slit, LDA CT systems usually offer a better image quality compared to CT systems with DDAs; LDAs are commonly used in the energy range from 0.4 to 20 MeV. When possible, DDAs are preferred because they deliver 3D scans within a much shorter time. It is also becoming increasingly common to build a system with both an LDA and DDA to allow for either option.

7.4 *Mechanical Scanning Equipment*—The mechanical equipment provides the relative motion between the test object, the source, and the detectors. It makes no difference, at least in principle, whether the test object is moved systematically relative to the source and detectors, or if the source and detectors are moved relative to the test object. Physical considerations such as the weight or size of the test object should be the determining factors for the most appropriate motion to use.

7.5 *Computer Systems*—The computer system performs the tasks of Operator Interface, acquisition, reconstruction, visualization, and storage.

7.5.1 The Operator Interface is the primary control of the system and the test examination, including controls for acquisition, reconstruction, visualization, and storage.

7.5.1.1 Acquisition refers to the control of the mechanical handling system and electronic controls for the data collection for the specific examination. This includes controlling the scan motion, source operation, and data acquisition functions.

7.5.1.2 Reconstruction refers to the parameters and mathematical operations for creation of the resultant slice or volume.

7.5.1.3 Visualization includes the image display and processing of the reconstructed data. Image display and processing are subfunctions of the computer system that provide a degree of image interaction not available with conventional radiography. The mapping between the pixel linear attenuation coefficient and the displayed intensity of the pixel can be changed to accommodate the best viewing conditions for a particular feature. Image processing functions such as statistical and densitometric analyses can be performed on an image or group of images. The digital nature of the image allows major advances in the way data are processed, analyzed, and stored.

7.5.1.4 *Storage*—Storage includes the archiving requirements for the CT examination. Information such as image data, operating parameters, part identification, operator comments, slice orientation, and other data is usually archived in a computer-readable, digital format on some type of storage medium. An advantage of saving this material in computer-readable format (rather than in simple hardcopy) is that old and new data sets can be compared directly, and subsequent changes in reconstruction or analysis procedures can be reapplied to saved data or images.

8. ~~Theoretical Background~~ General Principles of CT/Main CT Process Steps

~~7.1 *Background*—This section will cover the theoretical background associated with CT. First, the means of penetrating radiation interaction will be discussed. Second, the specifics of CT will be delineated.~~

~~7.2 *X-Ray Interactions*—Penetrating radiation is classified according to its mode of origin. Gamma rays are produced by nuclear transitions and emanate from the atomic nucleus. Characteristic X-rays are produced by atomic transitions of bound electrons and emanate from the electronic cloud. Continuous X-rays, or bremsstrahlung, are produced by the acceleration or deceleration of charged particles, such as free electrons or ions. Annihilation radiation is produced by the combination of electron-positron pairs and their subsequent decomposition into pairs of photons. All evidence suggests that the interaction of these photons with matter is independent of their means of production and is dependent only on their energy. For this reason, this document refers to penetrating radiation in the energy range from a few keV to many MeV as X-rays, regardless of how they are produced.~~

~~7.2.1 X-rays can in theory interact with matter in only four ways: they can interact with atomic electrons; they can interact with nucleons (bound nuclear particles); they can interact with electric fields associated with atomic electrons, or atomic nuclei, or both; or they can interact with meson fields surrounding nuclei. In theory, an interaction can result in only one of three possible outcomes: the incident X-ray can be completely absorbed and cease to exist; the incident X-ray can scatter elastically; or the incident X-ray can scatter inelastically. Thus, in principle, there are twelve distinct ways in which photons can interact with matter (see Fig. 6). In practice, all but a number of minor phenomena can be explained in terms of just a few principal interactions; these are highlighted in Fig. 6. Some of the possible interactions have yet to be physically observed.~~

~~7.2.2 The photon-matter interactions of primary importance to radiography are the ones which dominate observable phenomenon: photoelectric effect, Compton scattering, and pair production. Their domains of relative importance as a function of photon energy and material atomic number are shown in Fig. 7. At energies below about 1 MeV, pair production is not allowed energetically; and X-ray interactions with matter are dominated by processes involving the atomic electrons. Of the other possible interactions (see Fig. 6), Rayleigh scattering is typically small but non-negligible; the rest are either energetically forbidden or insignificant. At energies above 1 MeV, pair production is energetically allowed and competes with Compton scattering. Of the other possible interactions, photo-disintegration is typically negligible in terms of measurable attenuation effects, but at energies above about 8 MeV can lead to the production of copious amounts of neutrons. The rest of the interactions are either energetically forbidden or insignificant.~~

~~7.2.3 The three principle interactions are schematically illustrated in Fig. 8. With the photoelectric effect (see Fig. 8), an incident X-ray interacts with the entire atom as an entity and is completely absorbed. To conserve energy and momentum, the atom recoils and a bound electron is ejected. Although the subsequent decay processes lead to the generation of characteristic X-rays and secondary electrons, these are not considered part of the photoelectric effect. As can be seen in Fig. 7, the photoelectric effect predominates at low energies. Photoelectric absorption depends strongly upon atomic number, varying approximately as *z* raised to the 4th or 5th power.~~

~~7.2.4 With Compton scattering (see Fig. 8), an incident X-ray interacts with a single electron (which, practically speaking, is almost always bound) and scatters inelastically, meaning the X-ray loses energy in the process. This type of scattering is often referred to as incoherent scattering, and the terms are used interchangeably. To conserve energy and momentum, the electron recoils and the X-ray is scattered in a different direction at a lower energy. Although the X-ray is not absorbed, it is removed from the incident beam by virtue of having been diverted from its initial direction. The vast majority of background radiation in and~~