Designation: E 1570 – 00

Standard Practice for Computed Tomographic (CT) Examination[1]

This standard is issued under the fixed designation E 1570; 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 practice is for computed tomography (CT), which may be used to nondestructively disclose physical features or anomalies within an object under examination by providing radiological density and geometric measurements. This practice implicitly assumes the use of penetrating radiation, specifically x-ray and γ-ray.

1.2 CT systems utilize a set of transmission measurements made along paths through the examination object from many different directions. Each of the transmission measurements is digitized and stored in a computer, where they are subsequently reconstructed by one of a variety of techniques. A treatment of CT principles is given in Guide E 1441.

1.3 CT is broadly applicable to any material or examination object through which a beam of penetrating radiation passes. The principal advantage of CT is that it provides densitometric (that is, radiological density and geometry) images of thin cross sections through an object without the structural superposition in projection radiography.

1.4 This practice describes procedures for performing CT examinations. This practice is to address the general use of CT technology and thereby facilitate its use.

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 and health practices and determine the applicability of regulatory limitations prior to use.* For specific safety statements, see Section 8, NBS Handbook 114, and Federal Standards 21 CFR 1020.40 and 29 CFR 1910.96.

2. Referenced Documents

2.1 *ASTM Standards:*

E 1316 Terminology for Nondestructive Examinations[2]

E 1441 Guide for Computed Tomography (CT) Imaging[2]

E 1695 Test Method for Measurement of Computed Tomography (CT) System Performance[2]

2.2 *NIST Standard:*

NBS Handbook 114 General Safety Standard for Installations. Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies Up to 10 MeV[3]

2.3 *Federal Standards:*

21 CFR 1020.40 Safety Requirements of Cabinet X Ray Systems[4]

29 CFR 1910.96 Ionizing Radiation[4]

2.4 *ASNT Documents:*

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing[5]

ANSI/ASNT-CP-189 Qualification and Certification of Nondestructive Testing Personnel[5]

2.5 *Military Standard:*

MIL-STD-410 Nondestructive Testing Personnel Qualification and Certification[4]

2.6 *AIA Standard:*

NAS-410 Certification and Qualification of Nondestructive Testing Personnel[6]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this guide, refer to Terminology E 1316 and Annex A1 in Guide E 1441.

4. Summary of Practice

4.1 Requirements in this practice are intended to control the reliability and quality of the CT images.

4.2 CT systems are made up of a number of subsystems; the function served by each subsystem is common in almost all CT scanners. Section 7 describes the following subsystems:

4.2.1 Source of penetrating radiation,

4.2.2 Radiation detector or an array of detectors,

4.2.3 Mechanical scanning assembly, and

4.2.4 Computer system including:

4.2.4.1 Image reconstruction software/hardware,

4.2.4.2 Image display/analysis system,

4.2.4.3 Data storage system, and

4.2.4.4 Operator interface.

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[1] This practice is under the jurisdiction of ASTM Committee E-7 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

Current edition approved May 10, 2000. Published July 2000. Originally published as E 1570 – 93. Last previous edition E 1570 – 95a.

[2] *Annual Book of ASTM Standards*, Vol 03.03.

[3] Available from National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899.

[4] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

[5] Available from American Society for Nondestructive Testing, 1711 Arlingate Plaza, P.O. Box 28518, Columbus, OH 43228-0518.

[6] Available from the Aerospace Industries Association of America, Inc., 1250 Eye Street, N.W., Washington, DC 20005.

4.3 Section 8 describes and defines the procedures for establishing and maintaining quality control of CT examination services.

4.4 The extent to which a CT image reproduces an object or a feature within an object is influenced by spatial resolution, statistical noise, slice plane thickness, and artifacts of the imaging system. Operating parameters should strike an overall balance between image quality, inspection time, and cost. These parameters should be considered for CT system configurations, components, and procedures. The setting and optimization of CT system parameters is discussed in Section 9.

4.5 Methods for the measurement of CT system performance are provided in Section 10 of this practice.

5. Significance and Use

5.1 This practice is applicable for the systematic assessment of the internal structure of a material or assembly using CT technology. This practice may be used for review by system operators, or to prescribe operating procedures for new or routine test objects.

5.2 This practice provides the basis for the formation of a program for quality control and its continuation through calibration, standardization, reference samples, inspection plans, and procedures.

6. Basis of Application

6.1 This practice provides the approach for performing CT examinations. Supplemental information covering specific items where agreement between supplier[7] and purchaser[8] are necessary is required. Generally the items are application specific or performance related, or both. Examples include: system configuration, equipment qualification, performance measurement, and interpretation of results.

7. System Configuration

7.1 Many different CT examination system configurations are possible and it is important to understand the advantages and limitations of each. It is important that the optimum system parameters be selected for each examination requirement, through a careful analysis of the benefits and limitations of the available system components and the chosen system configuration.

7.2 *Radiation Sources*—While the CT examination 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.

7.2.1 X-rays produced from electrical radiation generators have focal spot sizes ranging from a few millimeters down to a few micrometers. Reducing the focal spot size reduces geometric unsharpness, thereby enhancing detail sensitivity. Smaller focal spots permit higher spatial resolution, but at the expense of reduced X-ray beam intensity.

7.2.2 A radioisotope source can have the advantages of small physical size, portability, low power requirements, simplicity, and stability of output. The disadvantages are limited intensity and limited peak energy.

7.2.3 Synchrotron Radiation (SR) sources produce very intense, naturally collimated, narrow bandwidth, tunable radiation. Thus, CT systems using SR sources can employ essentially monochromatic radiation. With present technology, however, practical SR energies are restricted to less than approximately 20 to 30 keV. Since any CT system is limited to the inspection of samples with radio-opacities consistent with the penetrating power of the X-ray employed, SR systems can in general image only small (about 1 mm) objects.

7.3 The detection system is a transducer that converts the transmitted radiation containing information about the examination object into an electronic signal suitable for processing. The detection system may consist of a single sensing element, a linear array of sensing elements, or an area array of sensing elements. The more detectors used, the faster the required scan data can be collected; but there are important tradeoffs to be considered.

7.3.1 A single detector provides the least efficient method of collecting data but entails minimal complexity, eliminates detector cross talk and detector matching, and allows an arbitrary degree of collimation and shielding to be implemented.

7.3.2 Linear arrays have reasonable scan times at moderate complexity, acceptable cross talk and detector matching, and a flexible architecture that typically accommodates good collimation and shielding. Most commercially available CT systems employ a linear array of detectors.

7.3.3 An area detector provides a fast method of collecting data but entails the transfer and storage of large amounts of information, forces tradeoffs between cross talk and detector efficiency, and creates serious collimation and shielding challenges.

7.4 *Manipulation System*—The manipulation system has the function of holding the object under examination and providing the necessary range of motions to position the examination object between the radiation source and detector. Two types of scan motion geometries are most common: translate-rotate motion and rotate-only motion.

7.4.1 With 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 examination object between translations by the fan angle of the beam and again translating the object until a minimum of 180 degrees of data have been acquired. The advantage of this design is simplicity, good view-to-view detector matching,

[7] As used within this document, the supplier of computed tomographic service refers to the entity that physically provides the computed tomographic services. The supplier may be a part of the same organization as the purchaser, or an outside organization.

[8] As used within this document, the purchaser of computed tomographic services refer to the entity that requires the computed tomographic services. The purchaser may be a part of the same organization as the supplier, or an outside organization.

flexibility in the choice of scan parameters, and 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.

7.4.2 With 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.

7.5 *Computer System*—CT requires substantial computational resources, such as a large capacity for image storage and archival and the ability to efficiently perform numerous mathematical computations, especially for the back-projection operation. Computational speed can be augmented by either generalized array processors or specialized back-projection hardware. The particular implementations will change as computer hardware evolves, but high computational power will remain a fundamental requirement for efficient CT examination. A separate workstation for image analysis and display often is appropriate.

7.6 *Image Reconstruction Software*— The aim of CT is to obtain information regarding the nature of material occupying exact positions inside an examination object. In current CT scanners, this information is obtained by "reconstructing" individual cross-sections of the examination object from the measured intensity of X-ray beams transmitted through that cross section. An exact mathematical theory of image reconstruction exists for idealized data. This theory is applied although the physical measurements do not fully meet the requirements of the theory. When applied to actual measurements, algorithms based on this theory produce images with blurring and noise, the extent of which depends on the quantity and quality of the measurements.

7.6.1 The simplifying assumptions made in setting up the theory of reconstruction algorithms are: (*1*) cross sections are infinitely thin (that is, they are planes), (*2*) both the source focal spot and the detector elements are infinitely small (that is, they are points), (*3*) the physical measurements correspond to total attenuation along the line between the source and detector, and (*4*) the radiation is, or can be treated as, effectively monoenergetic. A reconstruction algorithm is a collection of step-by-step instructions that define how to convert the measurements of total attenuation to a map of linear attenuation coefficients over the field of view.

7.6.2 A number of methods for recovering an estimate of the cross section of an object have evolved. They can be broadly grouped into three classes of algorithms: matrix inversion methods, finite series-expansion methods, and transform methods. See Guide E 1441 for treatment of reconstruction algorithms.

7.6.3 If the examination 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.

7.7 *Image Display*—The function of the image display is to convey derived information (that is, an image) of the examination object to the system operator. For manual evaluation systems, the displayed image is used as the basis for accepting or rejecting the examination object, subject to the operator's interpretation of the CT data.

7.7.1 Generally, CT image display requires a special graphics monitor; television image presentation is of lower quality but may be acceptable. Most industrial systems utilize color displays. These units can be switched between color and gray-scale presentation to suit the preference of the viewer, but it should be noted that gray-scale images presented on a color monitor are not as sharp as those on a gray-scale monitor. The use of color permits the viewer to distinguish a greater range of variations in an image than gray-scale does. Depending on the application, this may be an advantage or a disadvantage. Sharply contrasting colors may introduce false, distinct definition between boundaries. While at times advantageous, unwanted instances can be corrected through the choice of color (or monochrome) scale.

7.8 *Data Storage Medium*—Many CT examination applications require an archival-quality record of the CT examination. This could be in the form of raw data or reconstructed data. Therefore, formats and headers of digital data need to be specified so information can be retrieved at a later date. Each archiving system has its own specifics as to image quality, archival storage properties, equipment, and media cost. Computer systems are designed to interface to a wide variety of peripherals. As technology advances or needs change, or both, equipment can be easily and affordably upgraded. The examination record archiving system should be chosen on the basis of these and other pertinent parameters, as agreed upon by the supplier and purchaser of CT examination services. The reproduction quality of the archival method should be sufficient to demonstrate the same image quality as was used to qualify the CT examination system.

7.9 *Operator Interface*—The operator interface determines much of the function of the rest of the CT system. The control panel and image display system are the two significant subsystems affected. The control software, hardware mechanisms, and interface to a remote data workstation if applicable, are among those controlled by this interface. Override logic, emergency shutdown, and safety interlocks are also controlled at this point. There are three types of operator interfaces.

7.9.1 A simple programming console interface, where the operator types in commands on a keyboard. While being less "user friendly," this type can offer the greatest range of flexibility and versatility.

7.9.2 The dedicated console with specific function buttons and relatively rigid data and processing features. These systems are usually developed explicitly for standardized, nonvarying examination tasks. They are designed to be "functionally hardwired" for efficient throughput for that program. Medical CT equipment is often of this type.

7.9.3 A graphical user interface employing a software display of the menu or windowing type with means such as a pointing device for entering responses and interacting with the system. This approach has the advantage of being able to combine the best features of the other two types of operator interfaces.

7.10 *Automation*—A variation among CT systems is the extent to which users can create, modify or elaborate image enhancement or automated evaluation processes. The level of sophistication and versatility of a user command language or a "learning mode" is an important consideration for purchasers and suppliers who expect to scan a variety of objects or to improve their processes as they gain experience with CT.

8. Documentation

8.1 Documentation of the examination protocol shall cover the following:

8.1.1 *Equipment Qualifications*—The following system features shall be included:

8.1.2 *Examination Object Scan Plan*—A listing of examination object(s), scan parameters and performance measurements to be extracted from the image(s).

8.1.2.1 *Data Acquisition Parameters*—A listing of radiation source and detector-related variables include the following:

(1) Source energy,

(2) Intensity, current, Rad output or equivalent,

(3) Integration time, number of pulses or equivalent,

(4) Source spot size or isotope source size,

(5) Source filtration,

(6) Source collimation,

(7) Detector filtration,

(8) Detector collimation,

(9) Source-to-axis distances,

(10) Source-to-detector distance,

(11) Detector gain factor, gain range, or equivalent,

(12) Sampling parameters (linear increment, angular increment or equivalent),

(13) Number of detectors or channels,

(14) Scan mode, that is, translate-rotate or rotate only,

(15) Calibration of detector air counts (no examination object) and dark counts (no source) and frequency of calibration, and

(16) Position of slice plane and orientation of sample.

8.1.2.2 *Image Reconstruction Parameters*— A listing of expected image reconstruction variables including:

(1) Type of reconstruction (that is, normal, zoom, annular, limited-angle, and so forth),

(2) Conditioning of X-ray absorption measurements; reconstruction algorithm, view pre-processing, beam-hardening corrections, non-linearity corrections,

(3) Reconstruction diameter (field of view),

(4) Reconstruction pixel size, slice thickness or equivalent,

(5) Linear sampling intervals (if appropriate),

(6) Reconstruction matrix size,

(7) Pixel size and coordinates, and

(8) Position orientation/size (for zoom).

8.1.2.3 *Image Display Parameters*—A listing of the techniques and the intervals applied for standardizing the video image display as to brightness, contrast, focus, and linearity, which includes the following:

(1) Provisions for displaying a quantized color bar or gray scale to assist in this operation.

(2) Method used for adjusting the monitor and ensuring that the full range of colors or shades of gray are properly displayed.

(3) Transformation from CT number to color or gray scale look-up table (LUT).

(4) Upper and lower limits on the range of CT numbers displayed (or the equivalent description in terms of a range about an average value).

(5) If a nonlinear display technique, like histogram equalization or log transformation is used, describe the method.

8.1.2.4 *Image Analysis*—Digital image analysis techniques used to manipulate, alter, or quantify the image for the purpose of CT examination must be documented. The documentation shall include the following:

8.1.2.5 *Accept-Reject Criteria*—A listing of accept/reject criteria.

8.1.2.6 *Performance Evaluation*—A listing of the qualification tests and the intervals at which they are applied (see 10.2).

8.1.3 *Image Archiving Requirements*—A listing of the requirements for preserving a historical record of the examination results. The listing may include examination images along with written or electronically recorded alphanumeric or audio narrative information, or both, sufficient to allow subsequent reevaluation or repetition of the CT examination. The listing should specify data types (that is, raw data, image data, 16-bit, 8-bit, specially processed images, and so forth) along with the format or medium used. Data compression format also should be listed.

8.1.4 *Examination Record Data*—The examination record should contain sufficient information to allow the CT examination to be reevaluated or duplicated. Examination record data should be recorded simultaneously with the CT examination image and may be in writing or a voice narrative, providing the following minimum data:

8.1.4.1 The CT examination system designation, examination date, operator identification, operating turn or shift, and other pertinent examination and customer data,

8.1.4.2 Specific examination object data as to part number, batch, serial number, and so forth (as applicable),

8.1.4.3 Examination object orientation and examination site information (that is, scan height, slice thickness, and so forth) relative to system coordinates or by reference to unique examination object features. Slice planes can be annotated with respect to a preview radiogram, and

8.1.4.4 System performance monitoring by recording the results of the prescribed CT examination system performance monitoring tests, as set forth in Section 10, at the beginning and end of a series of CT examinations, not to exceed the interval set forth in 8.1.2.6 for system performance monitoring.

9. CT System Setup and Optimization

9.1 *CT Examination Setup*—In addition to the required flaw sensitivity, an examination setup should consider the expected distribution of anomalies, an acceptable rate of false negatives (that is, passed defects) and an acceptable rate of false positives (normal data mistaken for an anomaly). The following attributes should be considered when developing a CT examination setup for a group of examination objects:

9.1.1 Specimen (size, weight, and composition factors that determine the source accelerating potential and the mechanical handling equipment requirements),

9.1.2 Examination requirements (spatial resolution, contrast sensitivity, slice thickness, time), 9.1.3 System operation (system control, safety, calibration functions, scanning procedure),

9.1.4 Interaction with program flow (for example, concurrent data acquisition and review, automatic acquisition sequencing, archiving, automatic anomaly recognition, data output for statistical process control), and

9.1.5 Part handling (logistics for loading and unloading the examination object and the design and use of any associated fixturing.

9.2 *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, 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 is more important than the decreased image noise at higher energies.

9.2.1 Unless suitable measures are taken to reduce the effects of scattered radiation, it will reduce contrast over the whole image, or parts of it, and produce beam hardening artifacts. Scattered radiation is most serious for materials and thicknesses that have high X-ray absorption, because the scattering is more significant compared to the primary image-forming radiation that reaches the detector through the specimen.

9.2.2 Source collimation can limit the cross section of an X-ray beam to cover only the area of the examination object that is of interest in the examination. This reduces the radiation dose to the object and the amount of scattered radiation produced.

9.2.3 A radiation source often contains X-rays of differing energies. The use of source filtration will preferentially remove the low-energy content of the X-ray spectrum. However, filtration decreases the total number of photons, which reduces the amount of available signal and may increase the noise in the image. A tradeoff is clearly required, and some filtration generally is found to be useful. The amount of filtration depends on the source spectrum and the nature and size of the test object. Filtration can be mounted near the source or the detector. Filters are generally used to combat beam hardening artifacts (see 9.5.1). The influence of scattered radiation can be addressed with filtration by reducing the number of more readily scattered low-energy photons. Filtration used to reduce scattered radiation is typically more effective if placed in front of the dectector as opposed to placement at the source.

9.3 *Spatial Resolution*—The spatial resolution of a CT system is a function of the source focal spot size, the width of any detector apertures (linear detector arrays), and the source-to-detector and source-to-center of rotation distances. Many CT systems permit the spatial resolution to be adjusted by allowing the user some degree of control over some or all of these parameters. Refer to Guide E 1441 for a more thorough discussion of the interactions between these different variables. The mechanical accuracy of the positioning subsystem also can limit spatial resolution but the supplier of CT examination services typically has no control over this aspect of the system operation.

9.3.1 Examination object positioning can affect spatial resolution. Because of the extended sizes of the source spot and the active detection elements, the effective width of a measurement ray varies along its path from source to detector. This is reflected in a variation with object position of spatial resolution in images computed from measurements with such rays. The simplest approximation to the minimum effective ray width for a source spot size S and a detector active aperture size A separated by a distance L is approximately $AS/(A + S)$, and occurs at a location $LS/(A + S)$ from the source.

NOTE 1—If source and aperture differ substantially in size, this minimum is located close to the smaller; this is the case for a microfocus source and for high resolution detector systems. Optimal spatial resolution can usually be obtained by placing the object as near as possible to this position, but different tasks and object sizes should be checked experimentally.

NOTE 2—The best placement for spatial resolution may not be optimal for efficient use of detectors or for such other considerations as scatter sensitivity.

9.4 *Contrast Sensitivity*—Contrast sensitivity is affected by the noise in an image and is a strong function of the total number of photons detected. Most CT systems permit the contrast sensitivity to be adjusted by allowing some degree of control over parameters affecting the number of detected photons. At a given energy, the most important factors are: (*1*) source intensity, (*2*) the integration/counting time allowed for each individual measurement, (*3*) the size of the detector resolution aperture (single detector or linear detector array), (*4*) the size of the detector slice thickness aperture (linear detector array), (*5*) the source-to-detector distance, and (*6*) the amount of filtration employed. Refer to Guide E 1441 for a more thorough discussion of the interactions between these different variables.

9.4.1 Contrast sensitivity is also a function of the energy of the photons comprising the X-ray beam. For a fixed number of X-ray photons incident on a uniform composition object, the contrast sensitivity would generally be best if they have an energy which typically gives 13 % transmission (that is, where the typical product of thickness and linear attenuation coefficient equals two). This value is the result of the balance between less relative contrast at higher transmissions and more noise at lower transmissions. This exact result depends on the restrictions stated (fixed number of photons, uniform object composition, modest dynamic range), and should not be applied blindly to other situations.

9.4.1.1 The optimal acceleration voltage for CT contrast sensitivity, for CT images made with X-ray generators, is not a simple calculation. Because a given current in a X-ray generator at a voltage produces more photons at all energies (up to the end-point energy) than would the same current at a lower voltage, there is a potential for better results at the highest voltage possible. Whether this potential is realized in a particular case depends on whether the advantages of greater photon production efficiency will be overcome by the lower current typically required to meet wattage limits for a given spot size, or by saturation effects in the detection system. Different results have been reported for different systems and examination tasks; users should rely on tests if they wish to determine the optimal voltage for a particular examination. Because of substantial differences in detection characteristics, experience with X-ray film radiography should not be used to predict optimal settings for CT examinations.

9.5 *Image Artifacts*—Artifact content is one of the more difficult aspects of image quality to control or quantify. Artifacts can be viewed as correlated noise because they form fixed patterns under given conditions and are often the limiting factor in image quality. Mitigating their effects is best done by removing or reducing the cause that gave rise to them, a task that in many instances may not be feasible or practical. In some cases, it may be possible to reduce artifacts through the application of specialized software. Refer to Guide E 1441 for a more thorough discussion (also see 10.7). The use of special procedures or software, or both, to verify the existence (or absence) of artifacts or reduce the influence of artifacts on the CT examination task must be clearly specified.

9.5.1 Beam hardening artifacts (the anomalous decreasing attenuation toward the center of a homogeneous object) are most common to systems employing polychromatic X-ray sources. A mathematical correction at some stage in the reconstructive process can be very effective, and many systems allow the option of applying such a correction. Many different approaches have been developed, and some systems offer a choice of options. If a beam hardening correction is used, the specifics of the method employed must be well documented in order to permit duplication. Beam hardening can also be reduced by going to higher source energies or filtering the low-energy content of the incident radiation, or both.

9.5.1.1 A short laboratory procedure to verify the existence of a beam hardening artifact is as follows: If a high apparent density near the surface of an examination object is suspect, place a second object adjacent to the first and rescan. Part of the first object is now in the interior of the "paired object." If the apparent density of the suspect surface does not decrease, the measured high density is real. Instead, if it decreases, the first density measurement may have been affected by a beam hardening artifact.

9.5.2 Generally, an edge artifact manifests itself as a streak arising from a long straight edge. It is caused by the inability of the CT system to properly handle the sudden change in signal level that occurs at high-contrast boundaries. Such streaks may be reduced by any technique that can mitigate the rate of change at the offending boundary or can correct the raw data to compensate for measurement inaccuracies. Methods for lowering the contrast include imbedding the object being scanned in a second medium, water or sand for example, and increasing the source energy. Methods involving the use of special software typically incorporate the use of prior knowledge about the part and the application of a non-linear correction to the data. If edge artifact suppression techniques are used, the specifics of the method employed must be well documented in order to permit duplication.

9.6 *Speed of the Examination Process*— For a given spatial resolution and contrast sensitivity requirement, there must be a source capable of emitting the requisite number of photons per unit time. Since the number and configuration of detectors is usually fixed, it may not be possible to simultaneously accommodate resolution, contrast, and throughput demands with the available equipment.

9.6.1 Examples of linear array CT system adjustments to provide adequate signals at the detector for reconstruction, and optimize the speed of the examination process include: (*1*) allow more time for each individual measurement, increasing the overall examination time, (*2*) open the slice-thickness aperture plates which will provide better signal or contrast sensitivity while reducing defect sensitivity to anomalies that do not extend through the slice plane, (*3*) open the resolution aperture plates which will also provide better signal but will reduce the spatial resolution of the examination, or (*4*) a combination of these adjustments to meet the overall examination needs.

9.7 *Reconstruction Matrix Size*—The reconstruction matrix size governs the number of views and data samples in each view that must be acquired. The higher the resolution, the smaller the pixel size and the larger the pixel matrix for a given region of interest on the examination object. The reconstruction matrix size affects the number of scans and length of time necessary to examine an object.

9.8 *Slice Thickness*—Thicker slices provide better signal-to-noise ratio if the other scan parameters are unchanged. Alternatively, faster scans are possible without sacrificing SNR by acquiring thicker slices. Thicker slices, while increasing contrast sensitivity to features extending through the slice, decrease defect sensitivity to anomalies that do not extend through the slice.

9.8.1 For linear detection systems, 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.

9.8.2 For area detector systems, slice thickness is determined by software. The slice thickness can be defined before image reconstruction by averaging neighboring detector rows (in an arbitrary orientation), or after image reconstruction by averaging adjacent slice planes.

9.9 *System Operation*—All control functions as well as interface to a remote data workstation are controlled at the operator console. Override logic, calibration procedures, emergency shutdown, and other safety related operations are all controlled at this point. Written procedures intended to provide safe operating instructions for the CT system are to be located at the operator console and implemented by system operators, or used to train new operators. The following subjects should be addressed:

9.9.1 *Safety*—Identify all hazards and safe operating procedures that apply including:

9.9.1.1 Federal regulations,

9.9.1.2 State/local regulations,

9.9.1.3 Posting of area,

9.9.1.4 Personnel monitoring,

9.9.1.5 Positioning table lockout, and

9.9.1.6 Area evacuation.

9.9.2 Normal system power-up procedure (if applicable).

9.9.3 X-ray tube warm-up procedure.

9.9.4 Transport and loading of examination objects.

9.9.5 *Calibration Procedures*:

9.9.5.1 Electronic calibration,

9.9.5.2 Mechanical calibration, and

9.9.5.3 Others, as applicable.

9.9.6 *Scanning Procedure*—Digital radioscopy (preview radiogram) may be used before scanning to quantify examination object height and visually assess radioscopic image quality. When imaging an object for the first time, rescanning at several different system configurations is often typical. The machine operator is required to be proficient at the following:

9.9.6.1 Scan protocol editing,

9.9.6.2 Record keeping, and

9.9.6.3 Performance measurements.

9.9.7 Shutdown Procedure.

9.9.8 *System Maintenance*:

9.9.8.1 Coolants,

9.9.8.2 Lubricants,

9.9.8.3 X-ray system,

9.9.8.4 Positioning table,

9.9.8.5 Computer system, and

9.9.8.6 Others, as applicable.

9.10 *Interaction With Program Flow*— The complete examination procedure might include concurrent data acquisition and review, automatic acquisition sequencing, archiving, automatic anomaly recognition, or data output for statistical process control. These factors can affect the software designed to keep track of the images, the parameters recorded with the image, data compression algorithms, and so forth. Facility interface requirements to other operations should be established early.

10. Performance Measurement

10.1 Initially, CT examination system performance parameters must be determined and monitored regularly to ensure consistent results. The best measure of total CT system performance can be made with the system in operation, utilizing a test object under actual operating conditions. Performance measurements involve the use of a simulated test object (also known as a test phantom) containing actual or simulated features that must be reliably detected or measured. A test phantom can be designed to provide a reliable indication of the CT system's capabilities. Test phantom categories currently used in CT and simulated features to be imaged can be classified as noted in Table 1. Performance measurement methods are a matter of agreement between the purchaser and supplier of CT examination services.

TABLE 1 Test Phantom Categories

Phantom Type	Detectable Features
Resolution	Holes
	Squares
	Line pairs (or grids)
	Edges (for MTF calculation)
Contrast	Signal-to-noise ratio in a uniform material
	Small density variation
	Various solids
	Liquids with different contrast agents
Slice Thickness	Pyramids
	Cones
	Columnar row of beads
	Slanted sheets
	Spiral slits
Geometric Accuracy	Hollow cylinders
	Matrix of calibrated holes
	Simulated test object
Artifacts	Uniform density test object

10.2 Performance measurement intervals system performance measurement techniques should be standardized so that performance measurement tests may be readily duplicated at specified intervals. The CT examination system performance should be evaluated at sufficiently frequent intervals, as may be agreed upon by the supplier and user of CT examination services, to minimize the possibility of time dependent performance variations.

10.3 *Placement of a Simulated Test Object or Test Phantom*—The simulated test object or test phantom should be placed for examination in the same position used with the actual examination object to ensure that subtle effects such as object-related scatter and edge-induced artifacts are, as much as practical, realistically mimicked.

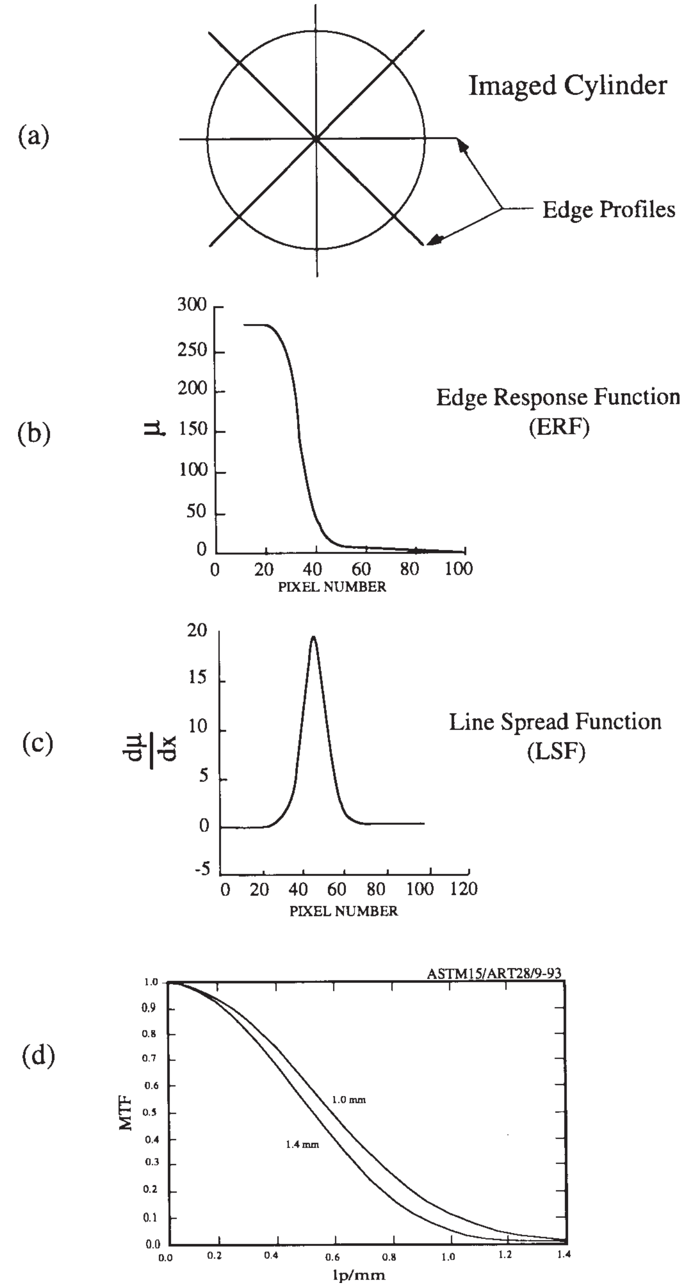
10.4 *CT Examination Techniques*—The CT scan parameters (radiation beam energy, intensity, source spot size (or isotope size), display parameters, image processing parameters, manipulation scan plan, scanning speed, and other system variables) utilized for the performance measurement shall be identical to those used for the examination object.

10.5 *Detection or Measurement with a Simulated Test Object or Test Phantom*—The test phantom may be an actual examination object with known features that are representative of the range of features to be detected, or may be fabricated to simulate a suitable range of representative features. Alternatively, the test phantom may be a one-of-a-kind or few-of-a-kind reference examination object containing known characteristics that have been verified independently. Test phantoms containing known, natural features (internal defects, density variations, or spatial irregularities) are useful on a single-task basis, but are not universally applicable. Where standardization among two or more CT examination systems is required, a duplicate manufactured test phantom can be used. Test phantoms shall approximate the examination object as closely as is practical, being made of the same material with similar dimensions and features in the CT examination region of interest. If the CT examination is to be for imperfections, manufactured test phantoms should include features, at least as small as those that must be reliably detected in the examination objects, in locations where they are expected to occur in the examination object. Where features are internal to the examination object, it is permissible to produce the test phantoms in sections. Ultimately, the ability of a given CT system to image structural details at the level dictated by the inspection application can be definitively and visually confirmed only by scanning a representative part known to contain features or flaws, or both, of the required size.

10.5.1 A test phantom manufactured as a simple cylinder of the same material as the examination object is recommended for the spatial resolution and signal-to-noise ratio measurements of 10.6. The size of the cylinder should be representative of the characteristic attenuation of the object to be examined. A cylinder made of denser material than the examination object can be made much smaller than the reconstruction diameter and has the advantage of providing a measure of the modulation transfer function (MTF) as a function of position. If, however, it is too small to support the SNR measurement, a separate test phantom may be required to obtain representative results. A cylinder of same or comparable density as the examination object can be made comparable in size to the reconstruction diameter and has the advantage of serving double duty for the MTF and SNR measurements. However, it also limits the amount of knowledge that can be obtained about MTF variations within the CT reconstruction. The cylinder diameter cannot exceed the reconstruction diameter.

10.6 *Quantitative Measurement of CT System Performance*—The extent to which a CT image reproduces the object is dictated largely by the competing influences of the spatial resolution, the statistical noise, and the artifacts (see 10.7) of the imaging system. Each of these aspects is discussed briefly in the following text. A more complete discussion can be found in Guide E 1441 or Test Method E 1695. Quantitative performance measurements should be performed using the system parameters and sample placement dictated in 10.3 and 10.4.

10.6.1 *Spatial Resolution*—The spatial resolution characterizes the ability of a CT system to image fine structural detail. It is best quantified by a measurement of the line-spread function (LSF) of the system or, equivalently, by the modulation transfer function (MTF), the frequency-space representation of the LSF. The recommended method is to determine the MTF by computing the amplitude of the Fourier transform of the LSF. The LSF is obtained by calculating the derivative of the profile of the edge of a cylindrical test phantom (see 10.5.1). The size of the cylinder to be used or the method of computation is a matter of agreement between the supplier and purchaser of CT examination services. If the spatial resolution varies significantly over the field of view, it is recommended that a small cylinder be used to make multiple measurements at a number of regularly spaced locations near the periphery and at one or more locations near the center. If the spatial resolution is fairly uniform, it is recommended that a cylinder large enough to provide a representative sampling of the periphery of the field of view be used to make a single measurement. Fig. 1 illustrates one acceptable method of obtaining the MTF from the image of a simple cylinder. The use of a cylinder (Fig. 1-a) is preferred because, once its “center of mass” is determined, profiles perpendicular to the cylinder edge may be readily extracted. Many non-overlapping profiles can be computed, aligned, concatenated, and smoothed to reduce system and quantization noise on the edge-response function (ERF) (Fig. 1-b). The LSF is estimated by taking the discrete derivative of the ERF (Fig. 1-c); and its discrete fourier transform (FT) is



(*a*) An Illustration of One-Dimensional Profiles Through the Center of the Imaged Cylinder.
(*b*) The Result of Aligning and Averaging Many Edge Profiles, the Edge-Response Function, ERF.
(*c*) The System Line-Spread Function, LSF, Obtained by Differentiation of the ERF.
(*d*) The System Modulation-Transfer Function, MTF, Obtained by Discrete Fourier Transformation of the LSF for Two Different Resolution Aperture Settings. The Smaller Aperture Setting Produces Slightly Better Modulation at Higher Frequencies.

FIG. 1 An Illustration of the Procedure for Obtaining the MTF From a CT Image of a Small Cylinder

taken to obtain the MTF (Fig. 1-d). Note that by convention, the height of the MTF is normalized to unity and plotted in spatial-frequency units of linepairs per millimeter (lp/mm). Linepair gages may be used to directly confirm the MTF at discrete points.

10.6.2 *Signal-to-Noise Ratio*—The SNR can be characterized by selecting a featureless region in the reconstructed image and determining the average and standard deviation for all CT numbers in the region. The test phantom or examination object to be imaged, object location within the reconstruction diameter, slice location, region location, and the region size is a matter of contractual agreement. The ratio of the average deviation to the standard deviation is used as a SNR measurement. If a test phantom rather than the examination object to be evaluated is used for the SNR measurement, it is recommended that a cylinder approximating the attenuation of the part be employed. The region of the reconstructed image selected for SNR measurement should be a homogenous area within the examination object or test phantom containing a reasonable number (>100) of pixels. The noise in a reconstructed image does have a positional dependence, especially near the edges of an object. Extremely large areas should not be used and care should be exercised in the selection of location so that positional variations in SNR do not mask variations reflective of real changes in sensitivity.

10.6.3 *Contrast Sensitivity*—Contrast sensitivity (often referred to as contrast discrimination) refers to the ability to detect the presence or absence of features in an image and is quantified as the minimum contrast required to detect a compact uniform feature of a given size against a uniform background. It is best characterized in a CT image by measuring the statistical noise in an image of a uniform cylinder and calculating, as a function of feature size, the threshold of detectability on the basis of a mathematical model. The size and material of the test cylinder to be used to measure the noise is a matter of agreement between the provider and user of the CT examination services, but the X-ray attenuation of the cylinder must approximate the attenuation of the article of inspection for the calculation to be relevant. Because contrast sensitivity entails making judgments about whether the presence or absence of a feature is statistically significant, false-positive and false-negative rates (see Guide E 1441) must be supplied. The rates to be used are also a matter of agreement. Density gages, consisting of low-contrast rods of different diameters, may be used to directly confirm contrast sensitivity as a function of size.

10.6.3.1 The image noise at the center of a uniform cylinder of material is characterized by measuring the standard error in the mean, σ_m, for different areas of interest. The process for determining σ_m begins by selecting a cursor, of known size, and measuring the mean value of the CT numbers within it. The cursor is then moved to an adjacent non-overlapping location and the measurement is repeated. This procedure is continued until enough independent data has been acquired to generate an accurate ensemble distribution, or histogram, of the sampling process. Experience has shown that if the radius of the region over which the data are taken is less than one-third the radius of the cylinder, other influences affecting the statistical nature of the noise will be negligible, providing more than sufficient area to make the required measurements. Once the histogram has been obtained, the standard deviation of the distribution is computed in the usual way. The result is called the *error in the mean* because it represents the uncertainty associated with a measurement of the average CT value over a particular area. Generally, the whole process is systematically implemented for different sized regions of interest, from an area of only one pixel to an area of 100 pixels, or more. Note that for the special case where the specified area is only a single pixel, the standard error in the mean equals the more familiar standard deviation used to compute the SNR. The subscript *m* is used to distinguish the error in the mean from the standard deviation, since the same symbol σ is used for both. The CT contrast sensitivity can be calculated as follows:

$$\Delta\mu(\%) = (p + q)\sigma_m(\%) \quad (1)$$

where:

$\Delta\mu(\%)$ = contrast between the feature and the background in percent,

$$\Delta\mu(\%) = |\mu_f - \mu_b|/\mu_b \times 100\ \% \quad (2)$$

$\sigma_m\ (\%)$ = standard error in the mean in percent,

$$\sigma_m(\%) = \sigma_m/\mu_b \times 100\ \% \quad (3)$$

p = contrast between the background and the decision threshold in units of σ_m,

$$p = |\mu_c - \mu_b|/\sigma_m \quad (4)$$

q = contrast between the feature and the decision threshold in units of σ_m,

$$q = |\mu_f - \mu_c|/\sigma_m \quad (5)$$

μ_b = measured mean value of the background,
μ_f = measured mean value of the feature, and
μ_c = the selected value of the decision threshold.

10.6.4 *Contrast-Detail-Dose Curves (CDD)*— A plot of the contrast required for probable discrimination of pairs of features as a function of their size (diameter) in pixels is called a contrast-detail-dose (CDD) curve. The CDD curve as an image quality indicator combines elements of both spatial resolution and contrast sensitivity. The CDD plot can be used to estimate the detection ability of a proposed CT system setup to detect a pair of features of a given size and composition. A detailed description of the CDD plot can be found in Guide E 1441 (see 10.5). It must be recognized that the minimum contrast at which a pair of features can be discriminated against a background of noise must be increased in direct proportion to the degree that loss of spatial resolution degrades the modulation between the features. A significant aspect of CT system performance is the resolving power with respect to larger, lower-contrast features in the presence of noise. The enhanced performance observed does not have a classical analogue and is unique to CT.

10.6.4.1 To determine the contrast-detail-dose curve, the error in the mean (σ_m) is divided by the MTF (determined at the same scanner configuration) and then plotted against the feature size (Fig. 2). If a uniform cylinder is used, the MTF can be obtained from an analysis of edge profiles as described in 10.6.1.

10.6.4.2 To predict from a CDD curve whether a pair of features of given diameter *D* and contrast (at the specified source energy) will be resolved, plot the point whose ordinate is the percent contrast:

$$\Delta\mu(\%)_{calc} = 100\,\% \times \frac{\left(\begin{array}{c}\text{Linear Attenuation}\\\text{Coefficient of Feature}\end{array} - \begin{array}{c}\text{Linear Attenuation}\\\text{Coefficient of Background}\end{array}\right)}{\begin{array}{c}\text{Linear Attenuation}\\\text{Coefficient of Background}\end{array}} \quad (6)$$

and whose abscissa is the size of the feature to be detected (diameter *D*) in pixels (Fig. 2). Many references list linear attenuation coefficients as functions of source energy.

NOTE 3—When referencing published data, be sure to use the "effective" energy of the radiation used. If this is not known, a reasonable rule of thumb would be ⅓ the accelerating potential if the examination object is weakly attenuating or ⅔ if the examination object is strongly attenuating.

If this point falls well to the right of the line it will probably be detected according to the user specified statistics. If it falls to the left, it will not. It must be emphasized that this method is meant to be a simple indicator of system capabilities and does not address complications such as the presence of CT artifacts.

10.7 *Artifacts*—An artifact is a reproducible feature in an image that does not correspond to a physical feature in the examination object. All imaging systems, whether CT or not, exhibit artifacts. In CT images, some artifacts are inherent in the physics and the mathematics of the technology and cannot be eliminated. Others are due to hardware or software deficiencies in the design and can be eliminated by system improvement. Examples of the latter type of artifact include scattered radiation and electronic noise. Examples of the former type of artifact include edge streaks and partial volume effects. Some artifacts, such as beam hardening artifacts, may be a combination of both types.

10.7.1 Artifacts that occur 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 worse, situations where defects go undetected will result.

10.7.2 The types and severity of artifacts are two of the factors that distinguish one CT system from another with otherwise identical specifications. The purchaser and supplier of CT examination services must understand the differences in these artifacts and how they will affect the integrity of the CT examination. For example, absolute density measurements will be severely affected by uncompensated beam hardening artifacts, but the same artifact will probably not affect the detectability of radial cracks.

10.8 *Importance of Proper Environmental Conditions*—Environmental conditions conducive to human comfort and concentration will promote examination efficiency and reliability, and must be considered in the performance of manual evaluation CT examination systems. A proper examination environment should take into account temperature, humidity, dust, lighting, access, and noise level factors. Proper reduced lighting intensity is extremely important to provide for high contrast, glare-free viewing of CT examination images.

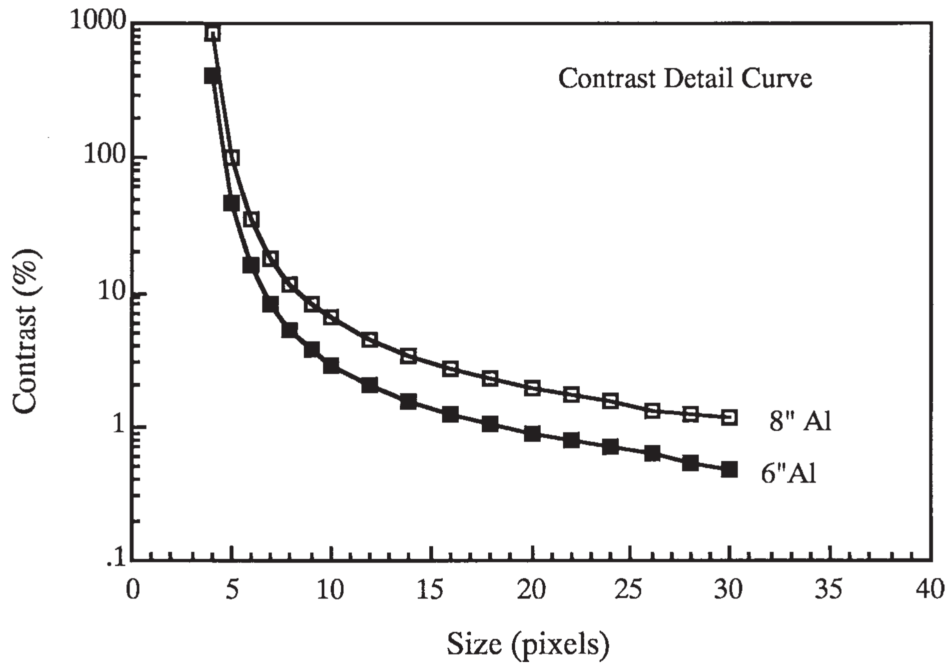


FIG. 2 A Contrast-Detail-Dose Curve (CDD) for a Six-Inch and Eight-Inch Disk of Aluminum

11. CT Examination Interpretation and Acceptance Criteria

11.1 *Interpretation*—Interpretation may be done either by an operator in a manual evaluation CT environment, or by means of a computer and appropriate software, in the case of an automated CT examination system. A hybrid environment may also be utilized whereby the computer and software presents to the operator a recommended interpretation, which is then subject to the operator's final disposition.

11.2 *Operator*—The supplier and purchaser should reach an agreement as to operator qualifications, including duty and rest periods. The supplier of CT examination services can use ASNT Recommended Practice SNT-TC-1A or MIL-STD-410, recommendations of formal classroom training with proficiency examinations, adequacy of the operator's vision, as well as on the job experience criteria as a model for any future certification programs.

11.3 *Accept/Reject Criteria*—Accept/Reject criteria shall be specified by contractual agreement between the purchaser and supplier of CT examination services.

12. Records, Reports, and Identification of Accepted Material

12.1 Records and reports shall be specified by agreement between purchaser and supplier. If an examination record archiving requirement exists, refer to 8.1.3 to outline the necessary information that should be a part of an archival examination record.

13. Safety Conditions

13.1 CT examination procedures shall be carried out under protective conditions so that personnel will not receive radiation dose levels exceeding that permitted by company, city, state, or national regulations.

14. Precision and Bias

14.1 CT images are suited for use in making quantitative measurements. The magnitude and nature of the error in CT-based measurements depends on the particulars of the scanner apparatus, the scan parameters, the object, and the features of interest. Among the parameters that can be estimated from CT images are feature size and shape, feature density contrast, wall thickness, coating thickness, absolute material density, and average atomic number.

14.2 The use of such quantitative measurements requires that the errors associated with them be established.

NOTE 4—This discussion addresses only the precision and bias of the measurements, not the noise or artifact in the images themselves.

14.3 *Precision*—The precision of the measurements can best be measured by seeing the distribution of measurements of the same feature under repeated scans, preferably with as much displacement of the object between scans as is expected in practice. This ensures that all effects which vary the results are allowed for; such as photon statistics, detector drift, alignment artifacts, spatial variation of the line-spread-function, object placement, and so forth.

14.4 One source of such variation in measurements is uncorrected systematic effects such as gain changes or offset displacements between different images. Such image differences can often be removed from the measurement computation by including calibration materials in the image, which is then transformed so that the calibration materials are at standard values. Since air is usually already present in the image, a single additional calibration material (preferably similar to the object material, and placed in a standard position in the image) is often sufficient.

14.5 *Bias*—In addition to random variation, measurements of any feature may also have a consistent bias. This may be due to artifacts in the image or to false assumptions used in the measurement algorithm. When determined by measurement of test objects, such biases can be removed by allowing for them in the algorithm.

14.6 Examination of the distribution of measurement results from repeated scans of test objects with known features similar to those which are the target of the NDE investigation, is the best method of determining precision and bias in CT measurements. Once such determinations have been made for a given system and set of objects and scanning conditions, they can be used to give well-based estimates of precision and bias for objects intermediate in size, composition, and form, as long as no unusual artifact patterns are introduced into the images.

15. Keywords

15.1 artifact; beam-hardening; computed tomography; contrast; contrast detail dose curves; contrast sensitivity; data storage; densitometric images; detection system; edge response function; field-of-view; gamma-ray; image analysis; image display; image reconstruction; line pairs/millimeter; line spread function; linear attenuation; manipulation system; modular transfer function; noise; pixel; reconstruction diameter; reconstruction matrix; signal-to-noise; slice plane thickness; spatial resolution; system configuration; test object; test phantom; voxel; X-ray