Standard Guide for Computed Tomography (CT) System Selection[1]

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

1. Scope*

1.1 This guide covers guidelines for translating application requirements into computed tomography (CT) system requirements/specifications and establishes a common terminology to guide both purchaser and supplier in the CT system selection process. This guide is applicable to the purchaser of both CT systems and scan services. Computed tomography systems are complex instruments, consisting of many components that must correctly interact in order to yield images that repeatedly reproduce satisfactory examination results. Computed tomography system purchasers are generally concerned with application requirements. Computed tomography system suppliers are generally concerned with the system component selection to meet the purchaser's performance requirements. This guide is not intended to be limiting or restrictive, but rather to address the relationships between application requirements and performance specifications that must be understood and considered for proper CT system selection.

1.2 Computed tomography (CT) may be used for new applications or in place of radiography or radioscopy, provided that the capability to disclose physical features or indications that form the acceptance/rejection criteria is fully documented and available for review. In general, CT has lower spatial resolution than film radiography and is of comparable spatial resolution with digital radiography or radioscopy unless magnification is used. Magnification can be used in CT or radiography/radioscopy to increase spatial resolution but concurrently with loss of field of view.

1.3 Computed tomography (CT) systems use a set of transmission measurements made along a set of paths projected through the object from many different directions. Each of the transmission measurements within these views is digitized and stored in a computer, where they are subsequently conditioned (for example, normalized and corrected) and reconstructed, typically into slices of the object normal to the set of projection paths by one of a variety of techniques. If many slices are reconstructed, a three dimensional representation of the object is obtained. An in-depth treatment of CT principles is given in Guide E1441.

1.4 Computed tomography (CT), as with conventional radiography and radioscopic examinations, is broadly applicable to any material or object through which a beam of penetrating radiation may be passed and detected, including metals, plastics, ceramics, metallic/nonmetallic composite material and assemblies. The principal advantage of CT is that it has the potential to provide densitometric (that is, radiological density and geometry) images of thin cross sections through an object. In many newer systems the cross-sections are now combined into 3D data volumes for additional interpretation. Because of the absence of structural superposition, images may be much easier to interpret than conventional radiological images. The new purchaser can quickly learn to read CT data because images correspond more closely to the way the human mind visualizes 3D structures than conventional projection radiology. Further, because CT images are digital, the images may be enhanced, analyzed, compressed, archived, input as data into performance calculations, compared with digital data from other nondestructive evaluation modalities, or transmitted to other locations for remote viewing. 3D data sets can be rendered by computer graphics into solid models. The solid models can be sliced or segmented to reveal 3D internal information or output as CAD files. While many of the details are generic in nature, this guide implicitly assumes the use of penetrating radiation, specifically X rays and gamma rays.

1.5 *Units*—The values stated in SI units 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.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

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***A Summary of Changes section appears at the end of this standard**

responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1316 Terminology for Nondestructive Examinations
E1441 Guide for Computed Tomography (CT) Imaging
E1570 Practice for Computed Tomographic (CT) Examination
E2339 Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)
E2767 Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for X-ray Computed Tomography (CT) Test Methods

3. Terminology

3.1 *Definitions*—For definitions of terms used in this guide, refer to Terminology E1316 and Guide E1441, Appendix X1.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *purchaser*—purchaser or customer of CT system or scan service.

3.2.2 *scan service*—use of a CT system, on a contract basis, for a specific examination application. A scan service acquisition requires the matching of a specific examination application to an existing CT machine, resulting in the procurement of CT system time to perform the examination. Results of scan service are contractually determined but typically include some, all, or more than the following: meetings, reports, images, pictures, and data.

3.2.3 *subsystem*—one or more system components integrated together that make up a functional entity.

3.2.4 *supplier*—suppliers/owners/builders of CT systems.

3.2.5 *system component*—generic term for a unit of equipment or hardware on the system.

3.2.6 *throughput*—number of CT scans performed in a given time frame.

4. Summary of Guide

4.1 This guide provides guidelines for the translation of examination requirements to system components and specifications. Understanding the CT purchaser's perspective as well as the CT equipment supplier's perspective is critical to the successful acquisition of new CT hardware or implementation, or both, of a specific application on existing equipment. An understanding of the performance capabilities of the system components making up the CT system is needed in order for a CT system purchaser to prepare a CT system specification. A specification is required for acquisition of either CT system hardware or scan services for a specific examination application.

4.2 Section 7 identifies typical purchaser's examination requirements that must be met. These purchaser requirements factor into the system design, since the system components that are selected for the CT system will have to meet the purchaser's requirements. Some of the purchaser's requirements are: the ability to support the object under examination, that is, size and weight; detection capability for size of defects and flaws, or both, (spatial resolution and contrast discrimination); dimensioning precision; artifact level; throughput; ease of use; archival procedures. Section 7 also describes the trade-offs between the CT performance as required by the purchaser and the choice of system components and subsystems.

4.3 Section 8 covers some management cost considerations in CT system procurements.

4.4 Section 9 provides some recommendations for the procurement of CT systems.

5. Significance and Use

5.1 This guide will aid the purchaser in generating a CT system specification. This guide covers the conversion of purchaser's requirements to system components that must occur for a useful CT system specification to be prepared.

5.2 Additional information can be gained in discussions with potential suppliers or with independent consultants.

5.3 This guide is applicable to purchasers seeking scan services.

5.4 This guide is applicable to purchasers needing to procure a CT system for a specific examination application.

6. Basis of Application

6.1 The following items should be agreed upon by the purchaser and supplier.

6.1.1 *Requirements*—General system requirements are covered in Section 7.

7. Subsystems Capabilities and Limitations

7.1 This section describes how various examination requirements affect the CT system components and subsystems. Trade-offs between requirements and hardware are cited. Table 1 is a summary of these issues. Many different CT system configurations are possible due to the wide range of system components available for integration into a single system. It is important to understand the capability and limitations of utilizing one system component over another as well as its role in the overall subsystem. Fig. 1 is a functional block diagram for a generic CT system.

7.1.1 *Pencil-Beam, Fan-Beam and Cone-Beam Type Systems:*

7.1.1.1 *Pencil Beam Systems*—The x-ray beam is collimated to a pencil and the effective pixel size becomes the size of the beam on the detector area. The beam is translated over the object and the object rotated after each pass of the beam over the object or the beam and detector are translated and rotated around the object to build up linear slice profiles. If a three dimensional data set is desired the object or beam/detector

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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.

TABLE 1 Computed Tomography (CT) System Examination Requirements and Their Major Ramifications

Requirement	Components/Subsystems Affected	Reference
Object, size and weight	Mechanical handling equipment	7.2
Object radiation penetrability	Dynamic range	7.3
	Radiation source	7.3.1
Detectability		7.4
Spatial resolution	Detector size/aperture	7.4.1.1
	Source size/source spot size	7.4.1.2
	Mechanical handling equipment	7.4.1.5
Contrast discrimination	Strength/energy of radiation source	7.4.2
	Detector size/source spot size	7.4.2.1
Artifact level	Mechanical handling equipment	7.4.3
Throughput/speed of CT process		7.5
Scan time	(Spatial resolution) (Contrast discrimination)	7.5.1
Image matrix size (number of pixels in image)	Number/configuration of detectors	7.5.2
	Amount of data acquired	
	Computer/hardware resources	
Slice thickness range	Detector configuration/collimators	7.5.3
	System dynamic range	
Operator interface		7.6
	Operator console	7.6.1
	Computer resources	7.6.2
Ease of use		7.6.3
Trade-offs		7.6.4

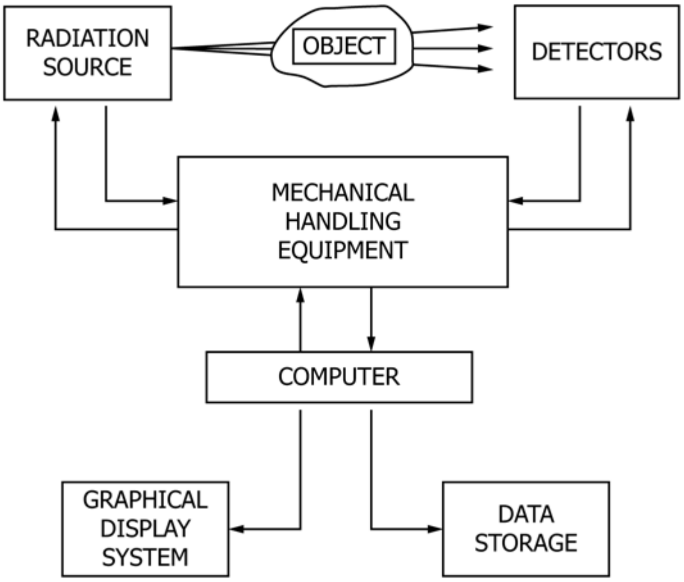

FIG. 1 Functional Block Diagram for a Generic CT System

must elevate so that multiple slices are generated. The advantage of this method is detector simplicity and scatter rejection with the primary disadvantage being long scan times.

7.1.1.2 *Fan-Beam Systems*—The x-ray beam is collimated to a fan and detected by a linear detector array that usually has a collimator aperture. The pixel size is defined by the width of the fan-beam on the detector height (vertically) and by the detector element pitch (horizontally). Linear profiles are captured as the object or beam/detector rotates. If three dimensional data is desired the object or beam/detector must elevate to capture multiple slices. The advantage of this method is faster scan times than pencil-beam systems and some scatter rejection with the primary disadvantage being long scan times for 3D data.

7.1.1.3 *Cone-Beam Systems*—The x-ray beam is usually collimated to the entire or a selected portion of the active area of a two dimensional detector array and full 2D images are captured as the object or beam/detector rotates. In this manner multiple slices are generated without needing to elevate. The primary advantage of this technique is speed or acquiring 3D data, with the primary disadvantage being increased scatter due to larger field of view.

7.2 *Object, Size and Weight*—The most basic consideration for selecting a CT system is the examination object's physical dimensions and characteristics, such as size, weight, and material. The physical dimensions, weight, and attenuation of the object dictate the size of the mechanical subsystem that handles the examination object and the type of radiation source and detectors, or both, needed. To select a system for scan services, the issues of CT system size, object size and weight, and radiation energy must be addressed first. Considerations like detectability and throughput cannot be addressed until these have been satisfactorily resolved. Price-performance tradeoffs must be examined to guard against needless costs.

7.2.1 The maximum height and diameter of an object that can be examined on a CT system defines the equipment examination envelope. Data must be captured over the entire width of the object for each view. If the projected x-ray beam through the object does not provide complete coverage, the object or beam/detector must translate. Some specialized algorithms may allow the reduction of this requirement but detectability and scan time may be affected. The weight of the object and any associated fixturing must be within the manipulation system capability. For example, a very different mechanical sub-system will be required to support and accurately move a large, heavy object than to move a small, light object. Similarly, the logistics and fixturing for handling a large number of similar items will be a much different problem than for handling a one-of-a-kind item.

7.2.2 *Two Most Common Types of Scan Motion Geometries*—Both geometries are applicable to 2D fan beam or 3D cone beam systems.

7.2.2.1 *Translate-Rotate Motion*—The object or detector is translated in a direction perpendicular to the direction and parallel to the plane of the X-ray beam. Full data sets are obtained by rotating the article 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 advantage of this design is simplicity, good view-to-view detector matching, 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. Reconstruction software must correctly account for fan/cone beam effects which can be complicated by translation of the object.

7.2.2.2 *Rotate-Only Motion*—The object remains stationary and the source and detector system is rotated around it or the object rotates and the source and detector remain stationary. A complete view is generally collected by the detector array during each sampling interval. A rotate-only scan has lower motion overhead than a translate-rotate scan, and is attractive for industrial applications where the object to be examined fits within the fan beam, and scan speed is important. Irrespective of whether the sample translates and rotates, or both, or the source/detector system rotates, the principles of CT are the same. In 2D fan beam type systems, the sample/object may also be elevated through the fan beam in order to build up a three dimensional stack of cross-sectional views. In a cone beam type system, the rows of the detector array provide the third dimension. The sample/object may need to be elevated or translated in order to provide complete coverage if the sample/object is larger than the cone beam (the projected area of the sample/object on the detector array area.) For some applications a rotate/translate combination, or helical, scan may be appropriate.

7.2.3 The purchaser of CT equipment should be aware that important cost trade-offs may exist. For instance, the cost of a mechanical subsystem with translate, rotate, and elevate functions incorporated in one integrally constructed piece of hardware is relatively cost invariant for vertical motions up to some limit, but increases drastically above that point. The casual specification of an elevation could have severe cost implications; whereas the simple expediency of turning the object over could effectively extend the examination envelope with no cost impact. Similarly, the specification of a large field of view could drive system size and cost soaring; whereas the application of prior information or limited angle reconstruction techniques, or both, could enable the examination with a much smaller scanner.

7.2.4 Automatic material handling equipment is an option that can be acquired with a CT system for mounting and removing objects. The advantages are lower overhead and greater throughput. The main disadvantages are added costs and complexity to the system design.

7.3 *Object Radiation Penetrability*—Next to examination envelope and weight, the most basic consideration is radiation penetrability. Object penetrability determines the minimum effective energy and intensity for the radiation source. As in any radiological situation, penetrability is a function of object material, density and morphology (shape and features/geometry). The rules for selecting CT source energy are approximately the same as those for conventional radiography, with the understanding that for CT, the incident radiation must be able to penetrate the maximum absorption path length through the object in the plane of the scan. The lowest signal value should be larger than the root-mean-square (RMS) of the electronic noise. The required flux is determined by how many photons are needed for statistical considerations. The spot size is determined by the spatial resolution and specimen geometry requirements.

7.3.1 *X-ray Sources*—Electrical X-ray generators offer a wider selection in peak energy and intensity and have the added safety feature of discontinued radiation production when switched off. The disadvantage is that the polychromaticity of the *Bremsstrahlung* energy spectrum causes artifacts such as cupping (the anomalous decreasing attenuation toward the center of a homogeneous object) in the image if uncorrected. Filtering of the x-ray beam can "Harden" the x-ray spectrum by reducing the amount of lower energies which can help reduce artifacts. Harder beam spectrum results in lower image contrast and may need for higher primary beam exposure dose, therefore, selection of the correct filtering is very important. X-ray tubes and linear accelerators (linacs) are typically several orders of magnitude more intense than isotope sources. However, X-ray generators have the disadvantage that they are inherently less stable than isotope sources. X rays produced from electrical radiation generators have source spot sizes ranging from a few millimetres down to a few micrometres. Reducing the source spot size reduces geometric unsharpness, thereby enhancing detail sensitivity. However, the basic spatial resolution (SRb) of the detector must also be able to support this increased spatial resolution. Smaller source spots permit higher spatial resolution but at the expense of reduced X-ray beam intensity. Reduced X-ray beam intensity implies longer scan times or inspection of smaller or less dense objects. Also to keep in mind, unlike radiography, CT can require extended, continuous usage of the X-ray generator. Therefore, an increased cooling capacity of the X-ray generator should be considered in the design and purchase, in anticipation of the extended usage requirements.

7.3.2 *Radioisotope Sources*—A radioisotope source can have the advantages of small physical size, portability, low-power requirements, simplicity, discrete spectral lines, and stability of output. The disadvantages are limited intensity per unit area, limited peak energy, and increased regulatory concerns.

7.3.3 *Synchrotron Radiation (SR) Sources*— Synchrotron radiation (SR) sources with special equipment (like monochromaters) 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 about 20 to 30 keV. Since any CT system is limited to the examination of samples with radio-opacities consistent with the penetrating power of the X rays or gamma rays employed, monochromatic SR systems can, in general, image only small (1- to 5-mm) low density objects. Some synchrotron sources also have a polychromatic, or white, beam line available allowing CT of higher density materials. It should also be noted that synchrotrons produce a wide flat beam, typically several centimeters wide by a few hundred microns tall. This means an object is typically translated to obtain a full 3D. In addition to the above consideration a synchrotron beams are virtually parallel which means resolution depends primarily on the detector's effective pixel size. For this reason high end cameras and scintillators are typically employed.

7.3.4 *Filters*—Oftentimes, filters and compensators are used to tune the source to the desired output. The use of filters and compensators will reduce the full capability of the source, causing additional limitations to source output.

7.4 *Detectability*—Once the basic considerations of object size, weight, and radiation penetrability have been addressed, the specific examination requirements are handled. The most important is the capability of the CT system to image the characteristics of concern in the object. This is a detectability issue. Detectability is an all-encompassing term that includes elements of spatial resolution, contrast discrimination, and artifacts. Spatial resolution characterizes how faithfully the CT system reproduces the features of the examination specimen in an image. Contrast discrimination characterizes the amount of random noise in the CT image and the ability to detect features within noise, that is, the signal to noise ratio for a given feature of interest. The former quantifies our knowledge of an object, the latter our uncertainty. Together, they form a complementary pair of variables that fully characterize any imaging system. Artifacts are reproducible features in an image that are not related to actual features in the object. The purchaser is normally interested in detecting geometrical (dimensional) and material (density, porosity, inclusions, etc.) anomalies. From experience, allowable variations are generally known and codified. They usually take the form of simple declarative statements: For example: Critical dimensions must be accurate to ±25 µm (0.001 in.); Void diameters must be less than 1 mm (0.040 in.); Porosity must represent less than 1 % missing volume; Density variations over 1 cm^2 (0.40 $in.^2$) must be less than 1 %; etc. These so-called application requirements are often explicitly known. The system component engineer must determine the spatial resolution and contrast discrimination needed to obtain the specified dimensional accuracy and defect sensitivity. This in turn sets upper limits on the amount or type, or both, of artifacts that can be tolerated. Making this connection between specifications and performance requirements is generally a difficult task that is best solved collaboratively between purchaser and supplier.

7.4.1 *Spatial Resolution*—All imaging systems, CT included, are limited in their ability to reproduce object morphology. Sometimes features can be detected but not accurately measured. That is, an infinitely small, infinitely dense point in the object will be imaged not as a point, but as a spot—possibly a very small spot, but a spot of finite size nonetheless. Hence, the image of a real object will exhibit a certain amount of unsharpness (blurred edges). CT spatial resolution is a measure of this unsharpness and obeys much the same rules as any radiological imaging modality: it is limited by the effective size of the detectors (pixels), the size of the source spot, and the relative position of the specimen with respect to the source and detector. Other factors, such as sampling, motion uncertainty, reconstruction matrix size, image display matrix, and reconstruction algorithms, can degrade the inherent spatial resolution.

7.4.1.1 *Radiation Detection*—The detection system converts the transmitted radiation into an electronic signal. The detector element is typically a scintillation detector that is optically coupled to a photo-conversion device such as a photodiode or photomultiplier tube. Alternatively, some systems use other types of detectors. For fan-beam type systems, the in-plane detector width is determined in part by the spatial resolution requirement. This detector width is either designed in the system or, for variable aperture systems, can be set by some kind of shielding aperture plates that define the detector's field of view. The detection system may consist of a single sensing element, an area array of sensing elements, or a linear array of sensing elements. The more detectors used, the faster the required scan data can be collected; but there are important trade-offs to be considered.

(1) A single detector provides the least efficient method of collecting data but entails minimal complexity, eliminates concerns of scatter between elements, differences in detector response, and allows an arbitrary degree of collimation and shielding. Translation motion is required for two dimensional reconstructions and elevate motion is required to create three dimensional reconstructions.

(2) An area detector provides the most efficient method of collecting data but entails the transfer and storage of large amounts of information, forces trade-offs between scatter, elements, and detector efficiency, and creates serious collimation and shielding challenges. However, using cone beam reconstruction algorithms three dimensional renderings of the object can be made. Guide E2736 contains information about area digital detector arrays.

(3) Linear arrays have performance characteristics intermediate between these two extremes, for example, reasonable scan times at moderate complexity, acceptable scatter between elements, and differences in detector response. Linear arrays have a flexible architecture that typically accommodates good collimation and shielding but require elevate motion for three dimensional reconstructions. In some cases several linear areas are combined to allow faster scans while keeping some of the collimation benefits.

(4) An important aspect of the detection system is the electronics system used to convert the analog signal received to a digital stream for processing. The front-end analog electronics amplify the detector signal to a magnitude that can be digitized. Fast systems demand good fidelity of the amplified signal. What makes the task especially demanding is that many signals, differing by several orders of magnitude, are frequently multiplexed on the same line in rapid succession; intersignal amplification rates are measured in microseconds. The analog-to-digital (A/D) conversion is performed as close to the analog amplification chain as possible. The accuracy requirement of the A/D must be consistent with the statistical limitations of the largest and the smallest detectable signals.

7.4.1.2 *Source Spot Size*—The source spot is the source region from which X rays or gamma rays emanate. In an electrical radiation generator, like an X-ray tube or linear accelerator, it is the area where the electrons strike the target. In an isotopic source, it is the area from which the radiation effectively emerges. The size and shape of the source spot is an important determinant of the aperture function (see ASTM source focal spot standards). For instance, source spots in linear accelerators are typically shaped as Gaussian distributions; whereas source spots in X-ray tubes are often double-peaked. Source spots associated with isotopic sources can be either more or less complex. Since source spots do not generally have sharp edges—or even symmetric shapes, it is common practice to define an effective size for convenience. The actual intensity distribution is important information, but is too complex to be readily useful. Consequently, reported source spot sizes are a function of the definition and method used to measure them. For example, the average radius of the region from which 99 % of the emissions emerge will be much larger than the standard deviation of the intensity distribution. In other words, source spot characteristics can be quantified in different ways. For this reason, comparisons between sources, especially those provided by different suppliers, are difficult to make. Another source selection factor to consider is stability. In selecting an electrical source, appreciate that spot position can wander over time, and changes in accelerating potential can occur.

7.4.1.3 Often, the in-plane source spot size and the in-plane detector width can be adjusted over a limited range of options, allowing spatial resolution to be engineered somewhat. Spatial resolution is a combination of geometrical and detector factors with the geometrical contribution dependent on focal spot size. In general, the smaller the source spot or detector size, or both, the better the spatial resolution. Since spatial resolution limits dimensional accuracy and resolving power (that is, the ability to distinguish two nearby point objects as separate entities), it is desired to select the smallest possible source spot and detector sizes. On the other hand, the accuracy of dimensional measurements also depends on the contrast discrimination of the system, which, in turn, depends on the number of detected photons. The smaller the selected source spot or detector size, or both, the fewer the number of photons detected per unit scan time, and the poorer the contrast discrimination. However, desire to maximize throughput or scanner limitations often precludes arbitrarily long scan times. An evaluation of the trade-offs among spatial resolution, contrast discrimination, and scan time usually comes after it is first determined that adequate spatial resolution can be achieved irrespective of any other considerations. The ultimate selection of the optimum combination of performance parameters is a value judgment best made by the purchaser in conjunction with the supplier.

7.4.1.4 The prospective purchaser can make a preliminary determination as to whether a given CT system has the necessary spatial resolution for a given application using the following guidelines. First, if dimensioning is important, sharp high-contrast edges free of artifacts typically can be located to about one tenth of the effective beam width associated with a given system. Effective beam width is the x-ray beam size at the detector and could be defined by a fan-beam collimator, detector aperture, or by the pixel height. As long as the estimated accuracy is within a factor of close to two of the dimensional accuracy requirement set by the application, the particular system being considered should be deemed a potential candidate for use. If the application requires dimensional measurements of low-contrast features, the accuracy will be worse, but precisely how much worse is difficult to quantify. Second, if resolving fine features is important, two high-contrast features in an image typically can be distinguished as separate entities provided they are physically separated in the object by at least the effective beam width. For example, if the effective beam width is 1 mm (0.040 in.), it should be possible to distinguish features like passageways or embedded wires, as long as they are separated from each other by more than 1 mm (0.040 in.) center-to-center. As long as the effective beam width is within 25 % or so of the resolving power requirement set by the application, the particular system being considered should be deemed a potential candidate for use. The lower the contrast, the harder it will be to distinguish features. If the application requires resolving low-contrast features, the accuracy will be worse, but precisely how much worse is difficult to quantify. The purchaser should also appreciate that if the object is highly attenuating, the image may exhibit artifacts that could limit or preclude measurements in the affected regions.

7.4.1.5 *Accuracy of Mechanical Handling Equipment/ Motion Control/Manipulation Systems*—The object manipulation system has the function of holding the object and providing the necessary range of motion to position the object area of interest between the radiation source and detector. Since spatial resolution is limited by many things, including the relative position of the object with respect to the source and detector, any problems with alignment or accuracy of the mechanical system will show up as degraded resolution. It is typically more difficult to align hardware for translate-rotate motion machines, but the sampling rate is adjustable up to some limit. In contrast, rotate-only motion machines typically are not as difficult to align, but they do not give the option of adjusting linear sampling to satisfy the required sampling rates. In either case, artifacts occur and the resolution is degraded if alignment is compromised.

(1) Because the inherent resolution of a system can be degraded by the mechanical handling equipment, fine spatial resolution requirements can drive mechanical designs and tolerances to extremely high costs. Typically, system designs can accommodate spatial resolutions up to some limit. Beyond that limit, redesign with different, more accurate system components and different assembly procedures is required.

7.4.1.6 *Spatial Resolution Trade-offs*— Spatial resolution requirements can affect an entire range of system components and subsystems. Spatial resolution requirements place limits on the accuracy and repeatability of the mechanical handling equipment. Spatial resolution requirements also limit the source spot size and detector aperture width and element (pixel) size, and define the geometry between source and detector. The system configuration defines the effective beam width at the object.[3,4] Thus, a requirement for high spatial resolution at a certain frequency may require a microfocus source or small detector apertures. It might require sampling at smaller spatial intervals. It also might affect the speed of the data acquisition process. Use of reconstruction filters can also affect spatial resolution capability.

7.4.2 *Contrast Discrimination*—All imaging systems, CT included, are limited in their ability to reproduce object composition. That is, two regions of identical material will be imaged, not as smooth areas of equal CT value, but as grainy areas of statistically variable CT values. Hence, upon repeated examination, the mean value of two regions will vary randomly in relative magnitude. Contrast discrimination is a measure of

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[3] Bracewell, R. N., "Correction for Collimator Width in X-Ray Reconstructive Tomography," *Journal of Computer Assisted Tomography,* Vol 1, No. 2, 1977, p. 251.

[4] Yester, M. W. and Barnes, G. T., "Geometrical Limitations of Computed Tomography Scanner Resolution," *SPIE Proceedings, Applications of Optical Instrumentation in Medicine*, Vol 1, 27, 1977, pp. 296–303.

this variability and obeys much the same rules as any radiological imaging modality: it depends on the number of detected photons, which in turn, depends on all scan parameters affecting the data collection process, such as sampling interval, source spot size and flux, detector size and stopping power, linear and angular sample rates, etc.

7.4.2.1 Often, many of these parameters can be adjusted over a limited range of options, allowing contrast sensitivity to be engineered somewhat. In general, the greater the number of photons detected, the better the contrast sensitivity. Since contrast sensitivity limits the low-contrast discrimination of different materials and influences the accuracy of dimensional measurements, it is desired to select scan parameters that maximize the number of detected photons. However, contrast sensitivity improves as the square root of the detected flux, and significant improvements are difficult to achieve by simply scanning longer, because scan times rapidly become impractical. The one option for improving image quality at no expense in scan time is to increase source spot and detector sizes; but desire to maximize or maintain spatial resolution often precludes arbitrary adjustment of source spot and detector sizes. An evaluation of the trade-offs among contrast discrimination, spatial resolution, and scan time usually comes after it is first determined that adequate contrast discrimination can be achieved irrespective of any other considerations. The ultimate selection of the optimum combination of performance parameters is a value judgment best made by the purchaser in conjunction with the supplier.

7.4.2.2 Rules of thumb can be given to help the prospective purchaser make a preliminary determination as to whether a given CT system has the necessary contrast discrimination for a given application. First, if small-area high-contrast (that is, inclusions) discrimination is important, small (approximately 4 pixels) regions typically can be discriminated against a uniform background when the relative contrast between feature and host is greater than 5 to 6 times the single-pixel image noise in the vicinity. For example, if the image noise in the region of interest is about 2 %, a small feature will need to have a contrast of at least 10 % to be visible. As long as the expected or estimated image noise associated with a given system is within a factor of two or so of the noise requirement set by the application, the particular system being considered should be deemed a potential candidate for use. As a point of reference, 1 % image noise is considered excellent, a few percent is considered good, 5 % is considered mediocre, greater than 10 % is considered poor. The purchaser should also appreciate that if the object is highly attenuating, the image may exhibit artifacts that could mimic or mask small high-contrast features in affected regions.

7.4.2.3 Second, if density (that is, large-area low-contrast) discrimination is important, large (greater than 400 pixels) regions typically can be discriminated against a uniform background when the relative contrast between feature and host is greater than about three times the single-pixel image noise in the vicinity divided by the square root of the number of pixels, i.e., larger features with smaller contrast can be detected. For example, if the image noise in the region of interest is about 2 %, a compact feature 20 by 20 pixels in size will need to have a contrast of at least 0.3 % (that is, 3 by 2 %/20) to be visible. As long as the expected or estimated image noise associated with a given system is within a factor of two or so of the noise requirement set by the application, the particular system being considered should be deemed a potential candidate for use. As above, if the object is highly attenuating, the image may exhibit artifacts that could mimic or mask large low-contrast features in the affected regions.

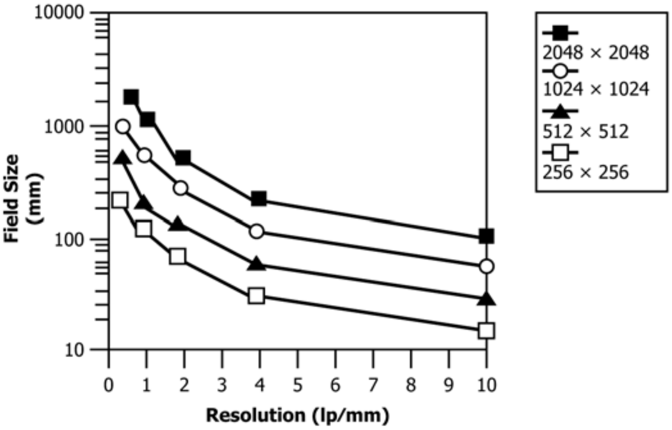
7.4.3 *Artifact Content*—Artifacts are reproducible features in an image that are not related to actual features in the object. Artifacts can be considered correlated noise because they form fixed patterns under given conditions yet carry no object information. Some artifacts are due to physical and mathematical limitations of CT, for example beam hardening, radiation scatter, and partial volume effects. Some artifacts are due to system deficiencies such as mechanical misalignment, insufficient linear or angular sampling, or both, crosstalk between detectors, etc. Artifacts are always present at some level. Often, they are the limiting factor in image quality. In general, artifacts become important when a CT system is used beyond its design envelope. A common instance is when object attenuations cause minimum signals to be comparable to, or less than, sensor offsets due to electronic noise and unwanted scatter. Mitigating the effect of artifacts in the image is best done by addressing the underlying problems at their origin. If artifacts cannot be reduced or eliminated at their origin, the next option is to attempt a software fix. As a rule, most artifacts are best corrected before image formation by applying transformations to the data. In the end, if artifacts preclude the use of a given system for a particular application, the purchaser must consider the use of another more capable system if one is available, or the modification of the object specifications. That failing, the purchaser must work with suppliers to determine if the technology exists to satisfy the application at hand, or conclude that CT is not presently a viable examination technique for the object.

7.5 *Throughput*—The next step in specifying a CT system is the consideration of throughput. Throughput generally refers to how many scans can be generated per unit time; it is usually implied or taken for granted that any detailed analyses will be performed off-line in a noninterfering manner. The importance of throughput varies depending on the circumstance. For an application study, spatial resolution and contrast discrimination are usually of primary concern and throughput is an issue only insofar as it affects the amount of scan time that must be budgeted. On the other hand, for routine examination use, throughput is usually a major concern, since it is intimately tied to financial considerations.

7.5.1 *Scan Time*—The purchaser should recognize that scan time is intimately related to spatial resolution and contrast discrimination. For a given system, the specification of any two fixes the third. For a new system, the specification of all three may or may not be technically possible, and if a design solution does exist, it may not be economically practical. Ideally, these issues are addressed jointly by purchaser and supplier.

7.5.1.1 For an existing system, the purchaser can normally influence scan time by judicious selection of available scan parameters. Though it must be recognized that it may not be possible to satisfy simultaneously the throughput, spatial resolution, and contrast discrimination requirements of an application for which the system was not designed. Typically, the purchaser selects source and detector parameters yielding the minimum spatial resolution (that is, the largest effective beam width that the application can tolerate). If spatial resolution is unimportant, then the purchaser should select the largest possible effective beam width that the scanner can accommodate. Next, the purchaser should select scan parameters yielding the minimum contrast discrimination that the application can tolerate. If contrast discrimination is unimportant, then the purchaser should select the fastest possible scan time that the scanner can accommodate. Key parameters affecting scan time are: image matrix size, slice thickness, field of view, and sampling interval. The first two warrant further discussion and are covered in 7.5.2 and 7.5.3. Field of view is dictated by the object size. The complete object must be scanned whether by fitting it within the x-ray beam and detector or by translation/elevation of the object or source/detector. Sampling interval refers to the time associated with individual sensor measurements. It is often specified in terms of milliseconds for tube-based systems and in terms of pulses for linear-accelerator-based systems. Optimum selection may also depend on secondary factors such as beam current or pulse rate. Particular systems may offer other purchaser-adjustable parameters as well. The inexperienced purchaser should consult the supplier to finalize the selection of scan parameters.

7.5.1.2 For a new system, the specification of scan time will govern more subsystem choices, and by implication cost, than perhaps any other variable. Since spatial resolution sets limits on the size of the source spot, and contrast discrimination sets limits on the number of detected photons, scan time determines the minimum brightness of the radiation source. Such a source may or may not be available. Since those X rays or gamma rays have to be detected within prescribed time constraints, scan time also determines the scan geometry, the size of the detector array, and the speed of the mechanical equipment. Such scan speeds may or may not be practical. Since spatial resolution limits the size of the detectors, scan time also indirectly influences the number of detectors. This suggests the number of detectors may or may not be economically viable. If the basic design requirements are determined to be feasible, they in turn place requirements on other less obvious design elements. The mechanical subsystem must be able to move the specified loads at the indicated speed to a well-determined accuracy; thus, hardware rigidity and choice of motors, brakes, sensors and controllers are all influenced by scan time. The detector subsystem must be able to collect data at a well-defined sampling rate set by the specified speed; thus, analog-to-digital conversion, on-the-fly processing, data transfer rates, and computer architecture are all influenced by scan time. The supplier may have little or no choice in the selection of subsystem components that can satisfy these demands. Since high-performance radiation sources, mechanical equipment, and computer hardware can be expensive, the specified CT system may be technically feasible but economically impractical.



NOTE 1—These are the maximum fields of view that can be imaged at full resolution with number of pixels available.

FIG. 2 Effect of Resolution on Field Size for Several Pixel Matrix Sizes

7.5.2 *Image Matrix Size*—Image matrix size governs the number of views and the number of samples per view that must be acquired to satisfy reconstruction demands. The amount of data needed increases as the square of the matrix size increases. To minimize scan time, the smallest matrix size that is compatible with the application requirements should be selected. The minimum size of the image matrix is dictated by the required spatial resolution; contrast discrimination is usually not a factor in matrix selection. As a rule of thumb, in a fan-beam type system the maximum pixel size should be one half the effective beam width. In a cone-beam/area array detector type system the effective beam width is the pixel height. From a knowledge of the effective beam width, the minimum matrix size can be readily determined given the required field of view. Fig. 2[5] shows the effect of resolution on the field size for several common matrix sizes.

7.5.3 *Slice Thickness*—To minimize scan time with an existing system, the user should specify the largest slice thickness consistent with the application requirements. Since slice thickness affects the spatial resolution of the data in the axial direction perpendicular to the scan plane, the maximum acceptable slice thickness is dictated by the object. If the slice thickness is too large, important features could be obscured or artifacts induced. The higher the rate of change of object morphology in the axial direction, the thinner the required slice thickness. In specifying a new system, the purchaser should realize that the specification of a large slice thickness intended to minimize scan time carries hidden cost implications. The maximum slice thickness defines the height of the detectors, a design parameter that can have a cost impact. Also, the greater the slice thickness adjustment, the greater the operating range that the detectors and associated data acquisition electronics must accommodate. A high-dynamic-range data acquisition system can be a significant cost element. In addition area type

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[5] Source Document: WRDC-TR-90-4026 “A Guide to Computed Tomography System Selection,” Burstein, P., and Bossi, R., August 1990. Available from Air Force Research Laboratory, AFRL/MLLP Building 655, 2230 Tenth Street, Suite 1, Wright-Patterson AFB, OH 45433-7814.

systems typically allow a user to bin pixels, providing multiple settings with different speed/resolution combinations.

7.6 *Operator Interface*—The operator interface controls the function of the CT system and determines its ease of use. The control software, hardware mechanisms, and interface to a remote data workstation, if applicable, are among those items controlled by this interface. Override logic, emergency shutdown and safety interlocks are also controlled at this point.

7.6.1 There are three generic types of operator interfaces:

7.6.1.1 A programming operator interface, where the operator types in commands on a keyboard. Although less user-friendly, this type offers the greatest examination range of flexibility and versatility.

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

7.6.1.3 A graphical user interface employing a software display of the menu or windowing type and providing a 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.

7.6.2 *Computer Resources*—Computed tomography (CT) requires substantial computational resources. This applies both to a large capacity for image storage and archival, and to the ability to perform mathematical computations on the image efficiently, especially for the back-projection operation. Historically, these mathematical operations (on the order of 1 by 10^9 per image) were done by specialized hardware controlled by a minicomputer system. This hardware can be either generalized array processors or specialized back-projection hardware, or both. 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, and perhaps archival production, is often appropriate. An efficient CT system will also have substantial random access memory (RAM), as well as both substantial on-line disk storage capacity and off-line archival storage capacity. Commercial systems can generate from hundreds to tens of thousands of megabytes of images per day. Computer clusters and graphical processing units (GPUs) can be used to considerably decrease the time of the reconstruction process.

7.6.2.1 *Software*—Computed tomography (CT) system suppliers know that during the implementation phase of a new system, there can be wide-ranging variations from the baseline. The changes from one CT application to the next, even with the same instrument, can involve major effort. The design imperative dictates minimal change in hardware because hardware changes are very expensive. For this reason, control, measurement, and other logic functions are assigned as often as possible to computer-based systems, where changes can be accommodated in software.

7.6.2.2 Software can be segregated into three categories: logic and control; algorithms and computation; and data transfer.

(1) Logic and Control—The logic and control functions reside in several places: the operating system; microprocessor-based subsystems that define the functionality of the subsystems in the radiation bay; and the operator's console. There is often a shell program, based in the console, that lets everything else run. Sometimes the operating system itself provides the shell.

(2) Algorithms and Computation—Algorithms typically reside in the central processing unit (CPU) and in any specialized hardware processors that may be used. The aim of CT is to obtain information regarding the nature of material occupying exact positions inside an object. In current CT scanners this information is obtained by reconstructing individual cross sections of the object from the measured intensity of radiation beams transmitted through that cross section. There is an exact mathematical theory of image reconstruction 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. Over time, a large 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. An in-depth treatment of reconstruction algorithms is covered in Guide E1441.

(3) Data Transfer—Data manipulation software is included as a separate software category because the problems associated with the prodigious data transfer rates often require specialized approaches, sometimes including a dedicated data bus.

7.6.2.3 The physical hardware for CT systems is always computer-based, which can be programmed and reprogrammed for various changing CT system requirements. Generally, software-based functions minimize problems for the CT system supplier. However, software development is the most expensive and time-consuming activity associated with the development of CT systems; its value lies in accommodating change.

7.6.3 *Ease of Use*—Computed tomography (CT) systems vary in the extent to which purchasers can create, modify or elaborate image enhancement or automated evaluation processes. The presence (and the level of sophistication and versatility) of a user command language, or a learning mode, is an important consideration if a variety of objects are to be scanned or if the examination process is to be improved as experience is gained.

7.6.4 *Operator Interface Trade-offs*— Requirements for the operator's interface can often be a significant cost driver. Thus, for instance, readouts of position of various moving assemblies or control of collimators situated on either side of a specimen may be desirable, but could require extensive programming effort. Every new automatic feature involves additional software development. Unless that feature has already been developed, specifying its inclusion may be expensive.

7.6.4.1 The trade-off involved in selecting the operator interface is basically one of cost versus performance. High performance is usually equated with user-friendly interface, automatic sequencing, parallel tasking, high-speed data handling, high-resolution/high-quality display, image processing options, and good system diagnostics for operations and troubleshooting. Generally, a higher cost operator console and interface will provide easier operation and overall time savings. Because CT is primarily an image-based examination technology, the highest quality image display and data handling capability consistent with the data quality should be maintained.

7.7 *Data Storage Medium*—Many CT examination applications require an archival-quality record of the CT examination to be kept. This could include the raw data as well as the reconstructed image. Export formats and headers of digital data therefore need to be specified so information can be retrieved at a later date. The DICONDE standards (E2339, E2767) are one way to store reconstructed images. However, there is no standard method for storage of raw CT data. Each archiving system has its own specifics as to image quality, archival storage properties, equipment, and media cost. Computer systems are designed to interface with a wide variety of peripherals. As technology advances or needs change, or both, equipment can be upgraded easily and affordably. The examination record archiving system should be chosen on the basis of these and other pertinent parameters. 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.

8. Management Cost Considerations for CT System Procurement

8.1 For procurement of CT system hardware, the specification should be realistic in terms of cost. One technique for controlling the overall system cost is to request options. Options to a basic CT system allow the selection of enhanced features that fall within budget.

8.2 For procurement of CT scan services, it is best to conduct application studies on multiple CT systems, before selecting a system for a production run examination. In this way, scan service requirements first can be optimized for resolution, contrast discrimination, measurement capability, documentation, and cost.

8.3 Documentation requirements also must be considered as costly, and labor intensive to generate. The more documentation stipulated, the higher the costs involved.

8.4 *Some Hidden Cost Elements*—If a system procurement is contemplated, the hidden life-cycle costs should be considered. Some factors to consider are as follows:

8.4.1 *Reliability and Maintainability Requirements:*

8.4.1.1 Prototype CT systems versus production units.

8.4.1.2 Commercial off the shelf (COTS) equipment.

8.4.2 *Maintenance Personnel Requirements:*

8.4.2.1 Power requirements.

8.4.2.2 Facility requirements.

8.4.3 *Operator Requirements:*

8.4.3.1 Certification and training requirements.

8.5 There are severe cost consequences if over- or under-specifying a CT system occurs. An example of the system changes resulting from seemingly innocuous user changes is useful.

8.5.1 Assuming that computer system and peripheral costs are generally comparable across all systems, the primary cost differences caused by a design change will occur in the source-detector-gantry equipment. Suppose that a system is designed to examine multilayer objects that are 300 mm (11.41 in.) in diameter with a spatial resolution consistent with the pixel size. Suppose the baseline uses 512 resolution elements across a 375 mm (14.76 in.) field of view. If the application requirement dictates that flaws between 1 mm (0.04 in.) layers be identifiable, then the system defined will perform the job nicely and be able to identify which layer is affected. If now the requirement is changed to require the examination of an object with a thinner layer, such as 0.38 mm (0.014 in.), the 512-resolution element system will no longer be able to discriminate on which side of the interface a flaw has occurred. Meeting this one requirement would necessitate the following system changes:

8.5.1.1 A mechanical system more accurate by a factor of two than the previous one.

8.5.1.2 A slowdown in scan time by a factor of four if the detector package can be adjusted to compensate, or eight owing to the necessity for more views at increased flux.

8.5.1.3 Image storage requirements are up by a factor of four.

8.5.1.4 Increased reconstruction times of up to a factor of eight.

8.5.2 The change in costs for these additional requirements could be as high as for the baseline system itself. The biggest cost over the long run is likely to be the operational slowdown caused by the reduction in scan time. The point of this illustration is to understand the ramification of each of the requirements. The costs of overspecification, or underspecification, can be significant.

9. Recommendations for Procurement

9.1 The preparation of a CT system specification is a critical part in the process of system procurement. System procurement can refer to either the acquisition of a CT hardware system as a nondestructive evaluation tool, or the purchase of scan service for a specific examination requirement. This section provides some useful advice in assembling the specification.

9.2 For either type of procurement, prior to preparing the specification, it is critical to define the purposes of the system, for example, research or production system, versatile or dedicated examination system. If possible, quantify specimen size range, anticipated quantities, required sensitivity, and throughput. Hold early discussions with suppliers to avoid the potential problem of putting unrealistic or overly expensive requirements into the specification. By addressing the various trade-off factors, a realistic specification may be developed (see Section 7).

9.3 The specification should focus heavily on the application requirements for the specific examination. Important factors to consider include object size and composition, critical flaw sizes, feature sizes, density differences between constituents, human factors, throughput, and reporting requirements. The specification should not define in detail the actual hardware configuration, nor should it attempt to be too specific about spatial resolution, contrast discrimination, matrix size, and similar technical details. These will be determined based on the performance and cost trade-offs. The required performance should detail any compatibility requirements, which in turn might define specific hardware or software constraints.

9.4 Provisions should be made to train the necessary individuals in CT. Whether the procurement is to be for the acquisition of CT hardware or scan services, a knowledge of this nondestructive evaluation method is necessary. This training can be obtained by reading Guide E1441, Practice E1570, and current literature, talking to suppliers, and talking to other users of CT.

9.5 *CT Hardware Procurements*—For a system acquisition, provisions should be made to establish and train a team of people to oversee the procurement and evaluation process. Once procured, this team can integrate the CT system into its intended role in the business.

9.5.1 During the preparation and evaluation of the specification, a level of expertise in the CT area is required to ensure a competent procurement. The oversight team must establish an evaluation and scoring system. One useful suggestion is to include individuals with varying backgrounds on the evaluation team such as nondestructive examination engineers, systems engineers, computer scientists, process/product engineers, facility engineers, Quality Assurance/Quality Control (QA/QC) personnel and management. Areas that should be considered in the evaluation of a CT system are as follows:

9.5.1.1 Radiation source,
9.5.1.2 Detector system,
9.5.1.3 Data processing system,
9.5.1.4 Software,
9.5.1.5 System resolution/contrast sensitivity,
9.5.1.6 Artifacts,
9.5.1.7 Graphics display,
9.5.1.8 Hardcopy,
9.5.1.9 Mechanical systems,
9.5.1.10 Scan time/reconstruction time,
9.5.1.11 Data archiving,
9.5.1.12 Conformance to other delivered systems,
9.5.1.13 Options/upgrades,
9.5.1.14 Documentation,
9.5.1.15 Facility requirements,
9.5.1.16 Spare parts/accessories,
9.5.1.17 Maintenance and repair,
9.5.1.18 Training,
9.5.1.19 Warranty,
9.5.1.20 Previous experience,
9.5.1.21 Cost, and
9.5.1.22 Supplier site visits and acceptance testing.

9.5.2 Once the procurement is under contract, the team should work closely with the supplier, from design to installation of the system. As the equipment is being provided, the team can be establishing an experience base to bring the equipment on-line quickly once delivered.

9.5.3 Ideally, the CT system to be acquired should be a mature design, should have undergone an evolutionary process, and should incorporate no radically new technology. New subsystems in and of themselves are not the problem; but frequently their integration into an older system can take significant time and effort. Efforts that involve significant software development are always expensive. Wherever possible, standard designs, existing software, and commercial off the shelf (COTS) components should be used, even if slight compromises in CT system performance is the price.

9.5.4 This is not to say that new technology should not be procured. If the need is there, and it cannot be met by current design, it is imperative that a prototype system that includes that new key element be procured. But from a reliability and maintainability aspect, an attempt at a production unit is the lower risk alternative. If the application dictates significant departures from prior designs, a cost and risk reduction method for the procurement is to treat the performance specifications as targets rather than requirements.

9.5.5 As a minimum, documentation should include sufficient hardware and software information so that a technical expert in the area who is unfamiliar with this particular system can troubleshoot, isolate, or repair the equipment. Complete documentation does not necessarily require military specification class drawings, but rather supplier-formatted informational documents. Required levels of detail in the documentation should be specified in the procurement package.

9.6 *CT Scan Services Procurement*—During the procurement of scan services, it is necessary to have a level of general expertise in nondestructive evaluation techniques and a specific knowledge of CT to ensure a satisfactory procurement. Though it may not be necessary to convene a large, diverse team, CT is a costly nondestructive evaluation medium, and some experience or prior training is needed to achieve an optimum scan service procurement.

9.6.1 One method for defining the optimum CT system for scan services is to conduct an application study on multiple machines. From an analysis of the results from the various systems, the optimum examination approach can be determined. Once the optimum CT system is identified, the scan service procurement can be let for the long-term examination needs.

9.6.2 The deliverables associated with scan service are contractually determined; but at a minimum, the deliverables should include a report detailing the system configuration, scan parameters used, and an analysis of the results. Additionally, deliverables may include reproductions of the images and copies of the data.

10. Precision and Bias

10.1 No statement is made about either the precision or bias of this guide for CT system selection since the result merely states whether there is conformance to the criteria for success specified in the guide.

11. Keywords

11.1 artifacts; computed tomography (CT); contrast discrimination; detectability; dynamic range imaging; nondestructive evaluation; spatial resolution; scan services; throughput

SUMMARY OF CHANGES

Committee E07 has identified the location of selected changes to this standard since the last issue E1672-06 that may impact the use of this standard (June 15, 2012).

(1) Substantial changes are offered to update the document to include the more recent technologies, which had not been addressed: Section 1 and Section 7.

(2) Minor changes have been incorporated into paragraphs 8.4.3 and 9.5.1.22.

(3) Units statement is added and all units are represented appropriately.

(4) Addition of 2 references.

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