



# Standard Guide for X-Ray Compton Scatter Tomography<sup>1</sup>

This standard is issued under the fixed designation E 1931; 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 approval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 *Purpose*—This guide covers a tutorial introduction to familiarize the reader with the operational capabilities and limitations inherent in X-ray Compton Scatter Tomography (CST). Also included is a brief description of the physics and typical hardware configuration for CST.

1.2 *Advantages*—X-ray Compton Scatter Tomography (CST) is a radiologic nondestructive examination method with several advantages that include:

1.2.1 The ability to perform X-ray examination without access to the opposite side of the examination object;

1.2.2 The X-ray beam need not completely penetrate the examination object allowing thick objects to be partially examined. Thick examination objects become part of the radiation shielding thereby reducing the radiation hazard;

1.2.3 The ability to image examination object subsurface features with minimal influence from surface features;

1.2.4 The ability to obtain high-contrast images from low subject contrast materials that normally produce low-contrast images when using traditional transmitted beam X-ray imaging methods; and

1.2.5 The ability to obtain depth information for examination object features thereby providing three-dimensional examination. The ability to obtain depth information presupposes the use of a highly collimated detector system having a narrow angle of acceptance.

1.3 *Applications*—This guide does not specify which examination objects are suitable, or unsuitable, for CST. As with most nondestructive examination techniques, CST is highly application specific thereby requiring the suitability of the method to be first demonstrated in the application laboratory. This guide does not provide guidance in the standardized practice or application of CST techniques. No guidance is provided concerning the acceptance or rejection of examination objects examined with CST.

1.4 *Limitations*—As with all nondestructive examination methods, CST has limitations and is complementary to other NDE methods. Chief among the limitations is the difficulty in

performing CST on thick sections of high-Z materials. CST is best applied to thinner sections of lower Z materials. The following provides a general idea of the range of CST applicability when using a 160 keV constant potential X-ray source:

Material	Practical Thickness Range
Steel	Up to about 3 mm [ $\frac{1}{8}$ in.]
Aluminum	Up to about 25 mm [1 in.]
Aerospace composites	Up to about 50 mm [2 in.]

The limitations of the technique must also consider the required X, Y, and Z axis resolutions, the speed of image formation, image quality and the difference in the X-ray scattering characteristics of the parent material and the internal features that are to be imaged.

1.5 The values stated in both inch-pound and SI units are to be regarded separately as the standard. The values given in parentheses are for information only.

1.6 *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 to determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

### 2.1 ASTM Standards:

E 747 Practice for Design, Manufacture, and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology<sup>2</sup>

E 1025 Practice for Hole-Type Image Quality Indicators Used for Radiography<sup>2</sup>

E 1255 Practice for Radioscopy<sup>2</sup>

E 1316 Standard Terminology for Nondestructive Examinations<sup>2</sup>

E 1441 Guide for Computed Tomography (CT) Imaging<sup>2</sup>

E 1453 Guide for the Storage of Media that Contains Radioscopic Data<sup>2</sup>

E 1475 Guide for Data Fields for Computerized Transfer of Digital Radiological Examination Data<sup>2</sup>

E 1647 Practice for Determining Contrast Sensitivity in Radioscopy<sup>2</sup>

### 2.2 ANSI/ASNT Standards:

<sup>1</sup> This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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<sup>2</sup> Annual Book of ASTM Standards, Vol 03.03.

ASNT Recommended Practice No. SNT-TC-1A Personnel Qualification and Certification in Nondestructive Testing<sup>3</sup>

ANSI/ASNT CP-1 89 Standard for Qualification and Certification in Nondestructive Testing Personnel<sup>3</sup>

2.3 *Military Standard:*

MIL-STD-410 Nondestructive Testing Personnel Qualification and Certification<sup>4</sup>

### 3. Terminology

#### 3.1 Definitions:

3.1.1 CST, being a radiologic examination method, uses much the same vocabulary as other X-ray examination methods. A number of terms used in this standard are defined in Terminology E 1316. It may also be helpful to read Guide E 1441.

### 4. Summary of Guide

4.1 *Description*—Compton Scatter Tomography is a uniquely different nondestructive test method utilizing penetrating X-ray or gamma-ray radiation. Unlike computed tomography (CT), CST produces radiosopic images which are not computed images. Multiple slice images can be simultaneously produced so that the time per slice image is in the range of a few seconds. CST produces images that are thin with respect to the examination object thickness (slice images) and which are at right angles to the X-ray beam. Each two-dimensional slice image (*X–Y* axes) is produced at an incremental distance along and orthogonal to the X-ray beam (*Z*-axis). A stack of CST images therefore represents a solid volume within the examination object. Each slice image contains examination object information which lies predominantly within the desired slice. To make an analogy as to how CST works, consider a book. The examination object may be larger or smaller (in length, width and depth) than the analogous book. The CST slice images are the pages in the book. Paging through the slice images provides information about examination object features lying at different depths within the examination object.

4.2 *Image Formation*—CST produces one or more digital slice plane images per scan. Multiple slice images can be produced in times ranging from a few seconds to a few minutes depending upon the examined area, desired spatial resolution and signal-to-noise ratio. The image is digital and is typically assembled by microcomputer. CST images are free from reconstruction artifacts as the CST image is produced directly and is not a calculated image. Because CST images are digital, they may be enhanced, analyzed, archived and in general handled as any other digital information.

4.3 *Calibration Standards*—As with all nondestructive examinations, known standards are required for the calibration and performance monitoring of the CST method. Practice E 1255 calibration block standards that are representative of the

actual examination object are the best means for CST performance monitoring. Conventional radiologic performance measuring devices, such as Test Method E 747 and Practice E 1025 image quality indicators or Practice E 1647 contrast sensitivity gages are designed for transmitted X-ray beam imaging and are of little use for CST. With appropriate calibration, CST can be utilized to make three-dimensional measurements of internal examination object features.

### 5. Significance and Use

#### 5.1 *Principal Advantage of Compton Scatter Tomography*—

The principal advantage of CST is the ability to perform three-dimensional X-ray examination without the requirement for access to the back side of the examination object. CST offers the possibility to perform X-ray examination that is not possible by any other method. The CST sub-surface slice image is minimally affected by examination object features outside the plane of examination. The result is a radiosopic image that contains information primarily from the slice plane. Scattered radiation limits image quality in normal radiographic and radiosopic imaging. Scatter radiation does not have the same detrimental effect upon CST because scatter radiation is used to form the image. In fact, the more radiation the examination object scatters, the better the CST result. Low subject contrast materials that cannot be imaged well by conventional radiographic and radiosopic means are often excellent candidates for CST. Very high contrast sensitivities and excellent spatial resolution are possible with CST tomography.

5.2 *Limitations*—As with any nondestructive testing method, CST has its limitations. The technique is useful on reasonably thick sections of low-density materials. While a 25 mm [1 in.] depth in aluminum or 50 mm [2 in.] in plastic is achievable, the examination depth is decreased dramatically as the material density increases. Proper image interpretation requires the use of standards and examination objects with known internal conditions or representative quality indicators (RQIs). The examination volume is typically small, on the order of a few cubic inches and may require a few minutes to image. Therefore, completely examining large structures with CST requires intensive re-positioning of the examination volume that can be time-consuming. As with other penetrating radiation methods, the radiation hazard must be properly addressed.

### 6. Technical Description

#### 6.1 *General Description of Compton Scatter Tomography*—

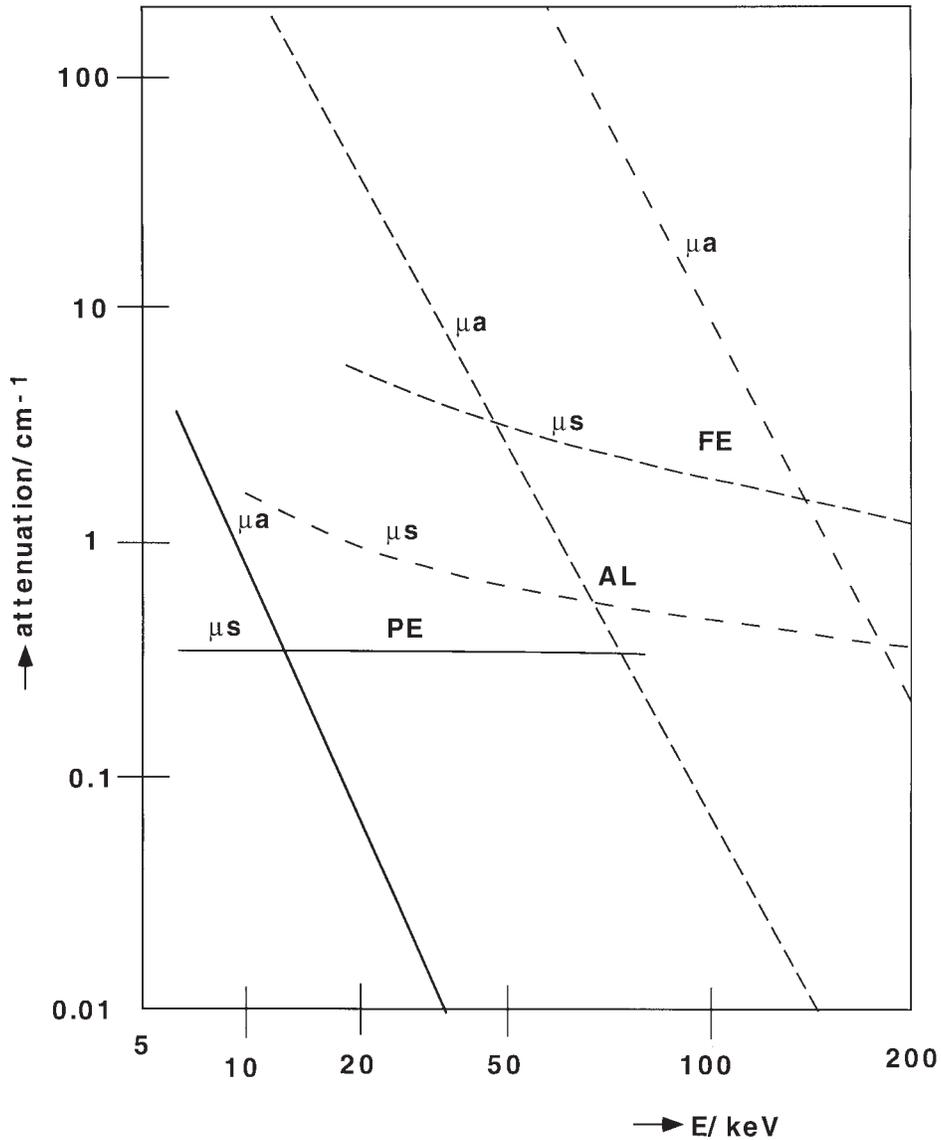
Transmitted beam radiologic techniques used in radiography, radioscopy and computed tomography have dominated the use of penetrating radiation for industrial nondestructive examination. The transmitted beam technique depends upon the penetrating radiation attenuation mechanisms of photoelectric absorption and Compton scattering. For low-*Z* materials at energies up to about 50 keV, the photoelectric effect is the dominant attenuation mechanism. As X-ray energy increases, Compton scattering becomes the dominant attenuation mechanism for large scattering angles in low-*Z* materials. Pair production comes into play above 1.02 MeV and can become the dominant effect for higher X-ray energies. Photoelectric

<sup>3</sup> Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

<sup>4</sup> Available from Standardization Document Order Desk, Bldg. 4 Section D, 700 Robbins Ave. Philadelphia, PA 19111-5094, Ans:NPODS.

absorption is strongly dependent upon the atomic number and also the electron density of the absorbing material. Compton scattering also depends upon the  $Z$  of the scattering material,

but to a lesser degree than is the photoelectric effect. These relationships may be seen in Fig. 1. The following relationships show the approximate dependence of the photoelectric effect



NOTE 1—Hubbell, J.H. and Seltzer, S.M., Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients, 1 keV to 20 MeV for Elements  $Z = 1$  to 92 and 48 Additional Substances of Dosimetric Interest, NISTIR 5632, 1996. Available from National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899.

FIG. 1 Linear Absorption and Scatter Coefficients for Polyethylene, Aluminum and Iron

and Compton scattering upon target material  $Z$  and incident X-ray energy  $E$ :

Photoelectric Effect	$Z^5 / E^{-7/2}$
Compton Scattering	$Z / E$
Pair Production:	$Z^2 (\ln E - \text{constant})$

6.1.1 CST is best suited for lower  $Z$  materials such as aluminum ( $Z=13$ ) using a commercially available 160 keV X-ray generating system. Somewhat higher  $Z$  materials may be examined by utilizing a higher energy X-ray generator rated at 225, 320, or 450 keV. It is useful to envision the CST process as one where the X-rays that produce the CST image originate from many discrete points within the examined volume. Each Compton scatter event generates a lower energy X-ray that emanates from the scattering site. Singly scattered X rays that reach the detector carry information about the examination object material characteristics at the site where it was generated. The scatter radiation is also affected by the material through which it passes on the way to the detector. The external source of primary penetrating radiation, that may be either X rays or gamma rays, interact by the Compton scattering process. The primary radiation must have adequate energy and intensity to generate sufficient scattered radiation at the examination site to allow detection. The examination depth is limited to that depth from which sufficient scattered radiation can reach the detector to form a usable image. The examination object is therefore effectively imaged from the inside out. The CST image is formed voxel (volume element) by voxel in raster fashion where the detector's field-of-view intersects with the central X-ray beam at the examination site. The primary radiation beam source and scattered radiation detector are highly collimated to assure collection of singly-scattered radiation from a known small volume of the examination object. Multiple scattered radiation causes a loss of spatial resolution. Moving the intersection of the radiation source and detector lines of sight in a systematic fashion allows a tomogram, or slice image to be produced. Changing the distance at which the radiation source and detector lines of sight intersect allows the tomogram to be produced at a selected depth below the examination object surface.

6.2 *Significant Differences in the Transmitted Beam and Compton Scattered X-Ray Imaging Techniques*—The differences between conventional transmitted beam and Compton Scatter Imaging are so significant that CST must be considered a separate examination technique. For transmitted beam techniques, the radiation source characteristics must be carefully controlled. The energy and intensity must be selected carefully to fully penetrate the ation object and provide the required contrast sensitivity. Thick sections of high-density materials require a high-energy radiation source while thin sections of low-density materials require a low-energy radiation source. For CST applications, the energy and intensity of the primary radiation beam is relatively less important. The primary radiation beam energy and intensity are not critical as long as they remain stable and are sufficient to generate adequate scatter radiation at the CST examination depth. Small focal spot size is critical to transmitted beam image sharpness. The primary radiation beam focal spot size is of much less significance for CST techniques. What is important is high specific activity, or the number of X rays or gamma rays generated per unit area (or

volume) of the primary radiation source resulting in a lower noise CST image and faster examination speed. For this reason an X-ray source is often a better choice than a radioisotope for CST. Radiation detection and other image forming considerations may also differ substantially from other radiologic imaging methods.

6.3 *Theory of Compton Scatter Tomography*—In the energy range appropriate for CST (roughly 50 keV to 1 MeV), the primary interaction mechanisms between electromagnetic radiation and matter are photoelectric absorption and inelastic (Compton) scatter. Fig. 2 illustrates the principles of photoelectric absorption and Compton scattering. As an X-ray having an energy  $E_0$  collides with an electron, the electron absorbs energy from the incoming X-ray photon and is ejected from its shell. In the case of photoelectric absorption, the incoming photon's energy is totally absorbed. As the energy  $E_0$  of the incoming photon increases, the probability of photoelectric absorption decreases while the probability of Compton scattering increases. The Compton scattering creates a new X-ray having and energy  $E'$ , and travelling at an angle  $\theta$  with respect to the direction of the original primary X-ray.

6.3.1 Fig. 1 shows how material linear attenuation coefficients due to photoelectric absorption and Compton scattering vary with energy for polyethylene, aluminum and iron. The linear absorption coefficient  $\mu_a$  for all three materials falls sharply with increasing energy, while the scatter coefficient  $\mu_s$  remains nearly constant. For low- $Z$  materials, scatter begins to dominate photoelectric absorption at primary radiation energies above 50 keV allowing the use of scatter radiation instead of the attenuated primary beam radiation for imaging purposes. It should also be noted that unlike the linear attenuation coefficient, the scatter coefficient is relatively independent of the primary penetrating radiation energy  $E_0$ . Many of the restrictions on energy selection associated with transmitted beam techniques are not a consideration with CST. For example, low-density aerospace composite materials can be imaged at higher energies of 100 keV or more producing high contrast using CST techniques.

6.3.2 The energy of the scattered X-ray is given by:

$$E' = \frac{E_0}{1 + \left(\frac{E_0}{m_e c^2}\right) (1 - \cos\theta)} \quad (1)$$

where:

$E_0$  = energy of the primary radiation photon,

$E$  = energy of the scattered X-ray,

$m_e c^2$  = rest energy of the electron, and

$\theta$  = scattering angle.

It can be seen from Eq 1 that the energy of the scatter radiation  $E'$  decreases with increasing scattering angle  $\theta$ . The amount of Compton scattering in any material is proportional to its electron density.

6.3.3 Disregarding the effects of pair production that come into play above 1.02 MeV, the total attenuation is the sum of attenuation due to photoelectric absorption and Compton scattering:

$$\mu_T = \mu_a + \mu_s \quad (2)$$

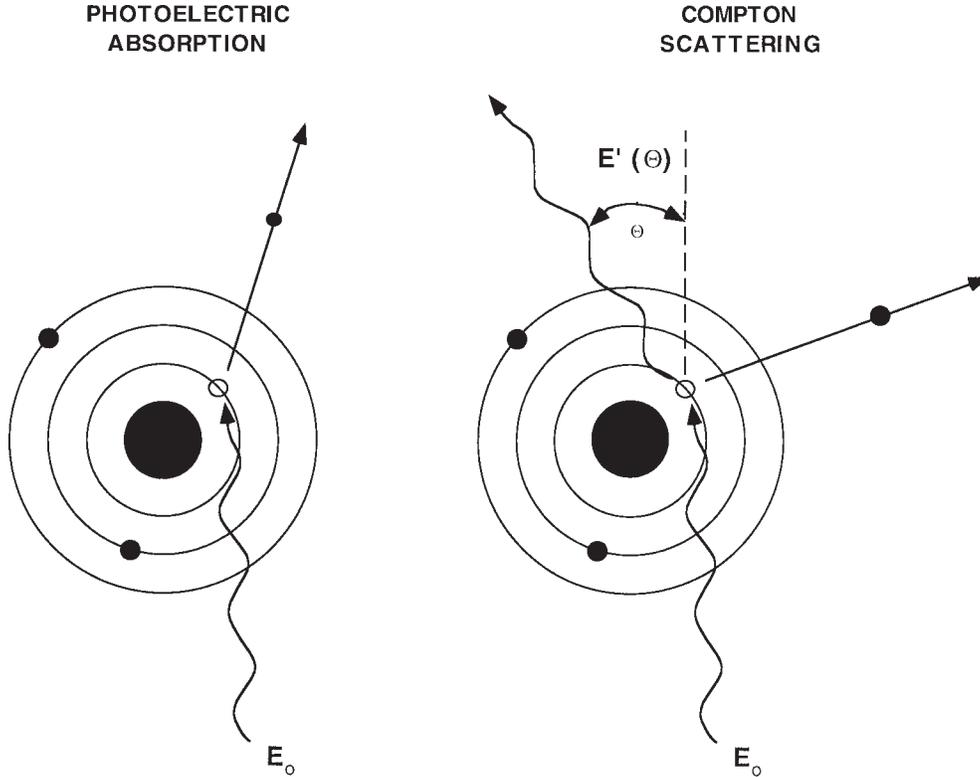


FIG. 2 Principals of Photoelectric Absorption and Compton Scattering

Fig. 3 is a polar plot of Compton scatter angular intensity at 30 and 300 keV. Although the scatter radiation angular distribution becomes more intense in the forward direction as energy increases, there is sufficient intensity at all angles to permit the technique. The detector and the primary radiation source can therefore be positioned on the same side of the examination object in this energy range.

6.3.4 The intensity of radiation  $I_{SC}$  scattered from a volume element (voxel)  $dV$  inside the examination object can be approximated as follows:

$$I_{SC} = (K) (n_e) (dV) (I_0) (e^{-\mu t}) (1 - e^{-\mu_s W}) (e^{-\mu_s t'}) + M \quad (3)$$

where:

- $K$  = constant of proportionality representing the differential scatter cross-section, detector efficiencies and all other object-dependent effects,
- $n_e$  = number of electrons acting as scatter centers,
- $I_0$  = incident flux,
- $e^{-\mu t}$  = the attenuation along the primary beam path  $t$ .  $\mu$  is the total linear attenuation coefficient,

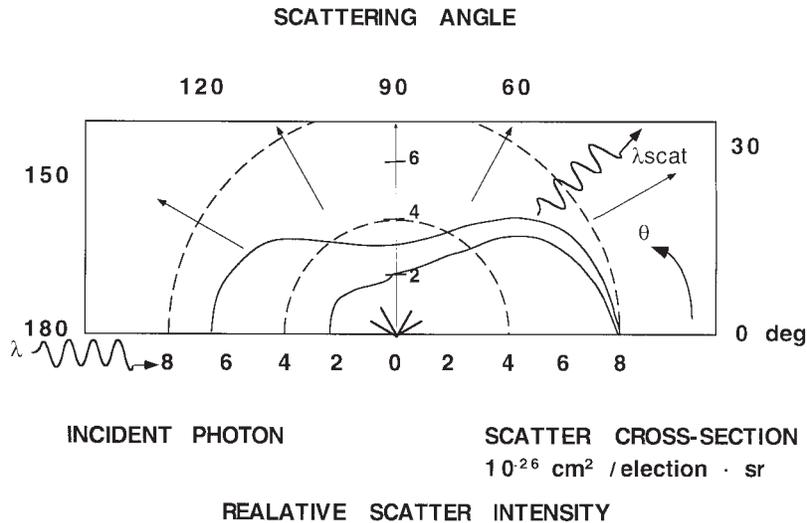


FIG. 3 Polar Plot of Scattering Angle Calculated at Primary Radiation Energies of 30 and 300 keV

$I - e^{-\mu_C W}$  = the fraction of photons scattered from the primary beam in a voxel of length  $W$ .  $\mu_C$  is the Compton linear attenuation coefficient. The scattering voxel is the intersection of the incident pencil beam with the solid angle subtended by the detector,

$e^{-\mu' t'}$  = the attenuation along the scattered beam path  $t'$ .  $\mu'$  is the total linear attenuation coefficient of the lower energy scattered beam, and

$M$  = multiple scatter component originating from quanta scattered more than once outside the voxel.

The two exponential terms describe the radiation attenuation along the primary radiation beam path  $t$  as well as the scattered beam path  $t'$ . Due to the lower X-ray energy along the scatter path,  $\mu'$  is not equal to  $\mu$ . The last term represents attenuation due to multiple scatter of the original Compton scatter photon. The influence of multiple scatter radiation had to be minimized in order to provide information about only the voxel of interest where the scattered radiation originated. This may be accomplished by tightly collimating the detector to limit its field-of-view to the desired examination voxel and by software.

6.4 Contrast Sensitivity—One significant benefit of CST as compared with conventional transmission imaging is increased contrast sensitivity. Fig. 4 is a generalized representation of transmission beam imaging to determine the relationship between discontinuity size and subject contrast.

6.4.1 To find an expression for the sensitivity of the transmitted beam technique, consider a homogeneous material of thickness  $L$  whose attenuation coefficient is  $\mu$  except for a small discontinuity region of length  $W$  and whose attenuation coefficient is  $\mu_D$ .

6.4.1.1 The intensities of the radiation beams passing through the homogeneous examination object with and without the small discontinuity are given by:

$$I_T = I_0 e^{-\mu L} \tag{4}$$

$$I_T = I_0 e^{-(\mu L + \mu_D W)} \tag{5}$$

From these equations the subject contrast is as follows:

$$C = \frac{(I_T - I_T)}{I_T} \times 100 \% \tag{6}$$

$$= \frac{e^{(-\mu L + \mu_D W)} - e^{-\mu L}}{e^{-\mu L}} \tag{7}$$

$$= e^{\mu_D W} - 1 \tag{8}$$

Assuming a small discontinuity allows the exponent to be replaced by its power expansion to the first order providing the following expression:

$$C = (1 + (\mu_D W) - 1) \times 100 \% = \mu_D W \times 100 \% \tag{9}$$

Thus, in a transmission imaging system, contrast is directly proportional to the discontinuity size.

6.4.2 Fig. 5 is a generalized representation of a CST system. The examination object of thickness  $L$  contains a small discontinuity of length  $W$  and having a linear attenuation coefficient of  $\mu_D$ .

6.4.2.1 The CST system contrast may be determined by comparing the scatter signals,  $I_{SC}$  and  $I_{SC'}$ , from two similarly located voxels. The first voxel lies entirely within the homogeneous materials while the second voxel lies entirely within the discontinuity. The mean scatter signals from the parent material voxel and discontinuity voxel at a certain depth as shown in Fig. 5 are given as:

$$I_{SC} = (F_p)(W)(\mu)(F_s)(K) \tag{10}$$

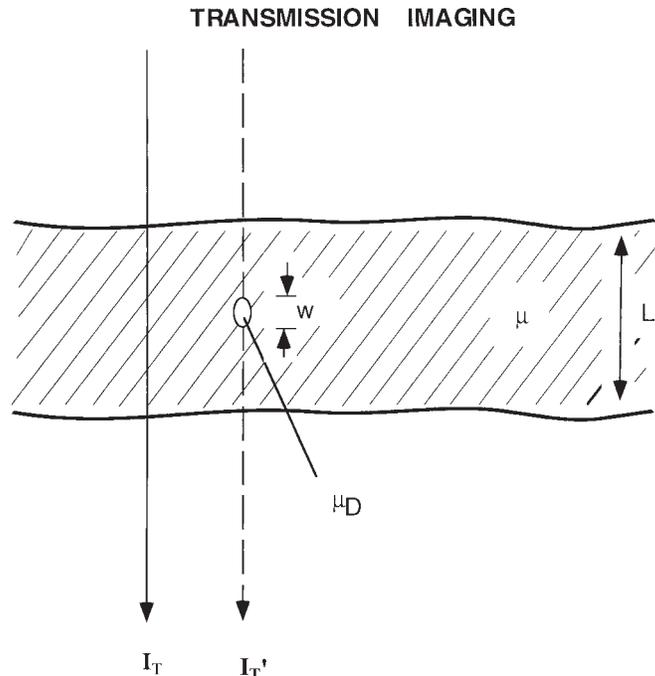


FIG. 4 Schematic Representation of the Transmitted Beam Imaging System Technique

COMPTON SCATTER TOMOGRAPHY

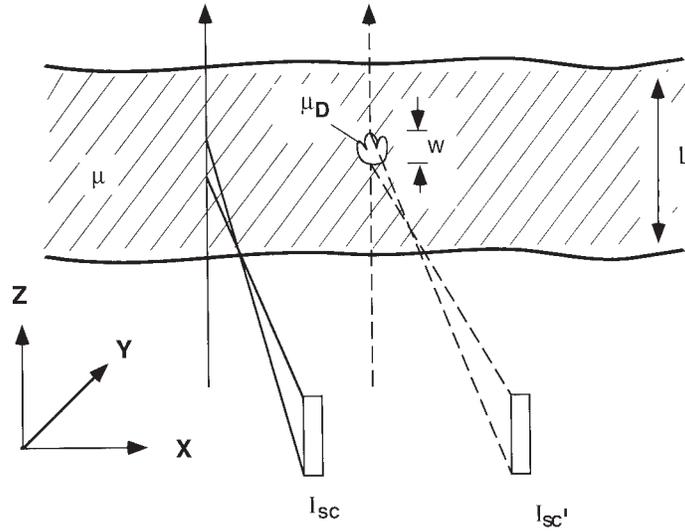


FIG. 5 Schematic Representation of the Compton Scatter Tomography Technique

$$I_{sc'} = (F_p) (W) (\mu_D) (F_s) (K) \quad (11)$$

where:

- $F_p$  = attenuation of primary radiation beam,
- $F_s$  = attenuation of scattered radiation beam,
- $\mu$  = total linear attenuation in the parent material voxel,
- $\mu_D$  = total linear attenuation in the scattering voxel, and
- $K$  = constant of proportionality.

The contrast may therefore be estimated according to the following expression:

$$C = \frac{(I_{sc} - I_{sc'})}{I_s} \times 100 \% = \frac{(\mu - \mu_D)}{\mu} \times 100 \% \quad (12)$$

$$C = \frac{\Delta\mu}{\mu} \times 100 \% \quad (13)$$

where:

$$\Delta\mu = \mu - \mu_D$$

6.4.3 CST contrast depends upon the ratio of the scattering coefficients of the parent material ( $\mu$ ) and the discontinuity ( $\mu_D$ ) and is independent of the object thickness. Assuming an air-filled discontinuity (no scatter) in aluminum with an examination voxel lying wholly within the discontinuity, scatter imaging contrast approaches 100 % for a small void. However, even a high-contrast CST image can be lost to noise if the technique is improperly applied.

6.4.4 An important consideration for CST is that the material between the scattering voxels in the region of interest and the detector must not unduly attenuate the scattered radiation or the CST signal can become so weak it is lost in the noise. Therefore, the most successful implementations of CST are those involving relatively thin sections of low-density materials where the region of interest lies relatively close to the surface.

6.5 Sensitivity Compared to Transmission Imaging—Transmission imaging contrast sensitivity depends upon the

often very small difference between the radiation intensities of the parent material path and the parent material with discontinuity path. On the other hand, scatter imaging contrast depends upon the often large difference between the scattering coefficients of the parent material and the discontinuity. If the discontinuity is a void, it may scatter little, if any, radiation while the parent material scatters considerably thus yielding useful contrast.

6.5.1 The contrast sensitivity offered by CST can be much higher than for transmission imaging as long as the difference in the parent material and discontinuity signal is greater than the statistical fluctuations due to system and radiation noise. The higher contrast of the CST method is of practical value only if the noise levels are the same in both methods. Therefore, the contrast/noise ratio is of greater value for a comparison of CST and transmission imaging systems. Noise factors for transmission and CST systems may be represented as follows:

$$\sqrt{\frac{1}{N_{trans}}} \quad (14)$$

and:

$$\sqrt{\frac{1}{N_{scat}}} \quad (15)$$

6.5.2 Defining the sensitivity of both CST and transmission imaging as the difference in signals in a examination object having a thickness equal to  $L$  with and without a small discontinuity at a depth  $L$  divided by the noise it follows:

$$S_{trans} = L (\mu - \mu_D) \sqrt{N_{trans}} \quad (16)$$

$$S_{scat} = (\mu / \mu_D - 1) \sqrt{N_{scat}} \quad (17)$$

6.5.3 For comparable noise levels, the relative sensitivity for both methods is given by:

$$S_{scat}/S_{trans} = \sqrt{1/\mu L} \quad (18)$$

The sensitivity of the CST technique competes successfully with the transmission technique as the examination object becomes radiologically thin where the product of  $\mu L$  is not more than 1.

**6.6 In-Plane Spatial Resolution**—Spatial resolution for CST can compare favorably with the radioscopic transmission imaging technique. However, it must be remembered that spatial resolution for the CST technique is a three-dimensional ( $X, Y, Z$ ) figure of merit while only two-dimensional ( $X, Y$ ) for the transmission imaging system. It is nevertheless useful to compare the sensitivity of small in-plane features for the CST technique with conventional transmission imaging system performance. It can be seen from Fig. 5 that the CST image voxel is formed by the intersection of the primary radiation beam and the detector fields-of-view. This volume determines the smallest geometric feature which can be imaged. Spatial resolution for the CST technique is therefore determined by the dimensions of the primary radiation beam and the detector fields-of-view at the voxel and is a function of the angle between the primary central radiation beam and the detector's line-of-sight. Collimation of both the primary radiation beam and detector and the angle between the central primary radiation beam and the detector's line-of-sight may be selected to determine the required in-plane  $X$ - $Y$  spatial resolution. However, the smaller the X-ray beam and the detector field-of-view become, the slower the examination speed. This is due to fewer Compton scattered X rays being produced per unit time and fewer singly-scattered Compton X rays being detected per unit time. Therefore, there is a trade-off between spatial resolution and examination speed. In-plane  $X$ - $Y$  spatial resolution may be well within the submillimetre range.

**6.7 Tomographic Slice Thickness**—Tomographic slice thickness, or  $Z$ -axis resolution, is also a function of the primary radiation beam and detector collimation and the angle between the central primary radiation beam and the detector's line-of-sight. Tomographic slice thickness can be well within the submillimetre range.

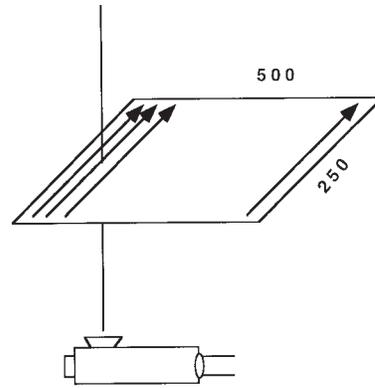
**6.8 Selection of the Tomographic Plane**—It may also be seen from Fig. 5 that the plane of examination is determined by where the central primary radiation beam and the detector's line-of-sight intersect along the  $Z$ -axis. The plane of examination may be selected by changing the primary radiation source and detector distance to the examination object or by adjusting the angle between the central radiation beam and the detector's line-of-sight.

**6.9 Examination Speed**—Examination speed is highly dependent upon a number of factors including the radiation source and collimation, the detector and collimation, the selected spatial resolution, allowable noise, material density, tomographic slice depth in the material and scan plan parameters. Fig. 6 shows a typical scan plan where the radiation source and detector (not shown) are moved with respect to the examination object in the  $X$ - $Y$  plane. In the example shown, 250 data points are collected along the direction of travel with 500 scan line index steps. For example, this scan plan might cover a 25 by 50 mm [1 by 2 in.] area and require from 1 to 6 min to collect the data depending upon the material density,

tomographic slice depth and the acceptable image noise level. Larger areas are examined by re-positioning the radiation source and detector with respect to the examination object and repeating the raster scan. It is possible to perform simultaneous examination of multiple tomographic slices at increasing depths to speed the examination process. This may be accomplished by the use of multiple detectors arranged at slightly different angles with respect to the central radiation beam. Scattering is produced from a range of depths as the primary radiation beam passes the examination object. Tomographic-plane examination depth is set by the intersection of the central primary radiation beam with the detector's line-of-sight. In the example shown in Fig. 6, tomographic data is simultaneously collected from twenty-two imaging planes. The examination object material thickness represented by the twenty-two planes is a function of slice image plane thickness and plane-to-plane spacing.

**6.10 Examination Object Size Limitations**—One of the real advantages of CST is that there is no examination object size limitation. This is due to the fact that the radiation source and detector are on the same side and may be positioned anywhere there is physical access to the region of examination object interest. Since there is not a requirement for the primary radiation beam to completely penetrate the examination object, the examination object can be thick with respect to the beam's penetrating power. The examination depth is limited primarily by the ability of sufficient numbers of low-energy Compton X rays to reach the detector with sufficient energy to be detected. There is no requirement for direct access to the examination part surface since the CST technique is non-contact. Stand-off distances in the range of several centimetres are practical. It should be remembered that while there are no examination object size limitations, there are limitations as to the examination depth. The examination depth must be radioscopically thin where  $\mu L < 1$ . With a 160 keV X-ray source, examination depths of several centimetres are possible in aluminum. With less dense materials, such as aerospace composites, the examination depth may increase to tens of centimetres. In steel the examination depth may be in the range of millimetres. Increasing the primary radiation beam energy will increase the examination depth.

**6.11 CST Image Formation**—The CST image is formed in computer memory as a three-dimensional representation of voxel  $X$ - $Y$  position versus detected scattered X-ray intensity. As the scanning process shown in Fig. 6 progresses, the encoded  $X$ - $Y$  positions are fed to a computer. Simultaneously, the detected radiation intensity is fed to the computer and a three-dimensional map of  $X$  position,  $Y$  position and brightness (radiation intensity) is formed. The image display is similar to a normal radioscopic image display. However, only information contained within a defined plane is presented. Image data from several tomographic planes may be simultaneously processed by multiplexing the input data. Fig. 7 is a simulated CST image display of a homogeneous examination object containing a spherical void. The void extends from a depth beginning at Plane 2 to a depth represented by Plane 6. The void produces no scatter radiation with respect to the parent material which produces scatter.



Original data set

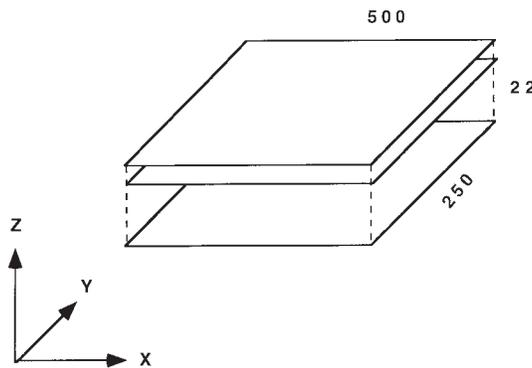


FIG. 6 Typical CST Imaging Scan Plan

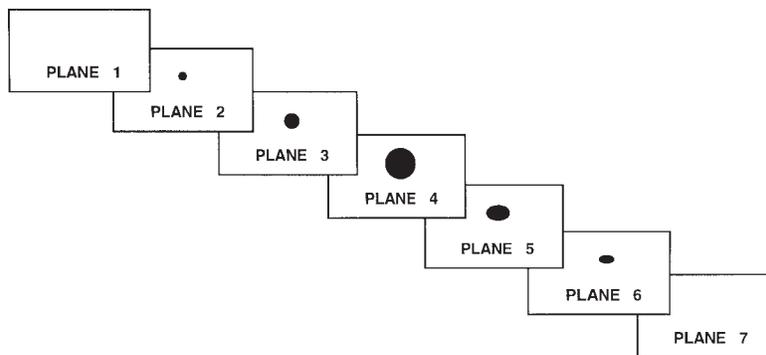


FIG. 7 Simulated CST Image Display of a Homogenous Examination Object Containing a Void

6.12 *Artifacts*—CST has no computational artifacts as the CST image is produced directly from raw scattered X-ray data. However, CST, like any imaging process has artifacts which are unique to CST.

6.12.1 Features lying outside the slice thickness can affect the scattered X-ray photon on its way to the detector thereby altering the scattered radiation signal (see Fig. 8). This can give the appearance of a lower density feature than actually lies in

the image slice. Additional (multiple) scatter of the original scattered X-ray caused by either the homogeneous bulk material or an anomaly (high- or low-density inclusion) in the detector's line of sight can cause artifacts in the CST image. Very tight detector collimation as well as software corrections can minimize the effect of multiple scatter. A high- or low-density inclusion in the detector's line of sight can also change the effective total absorption along the scattered photon's

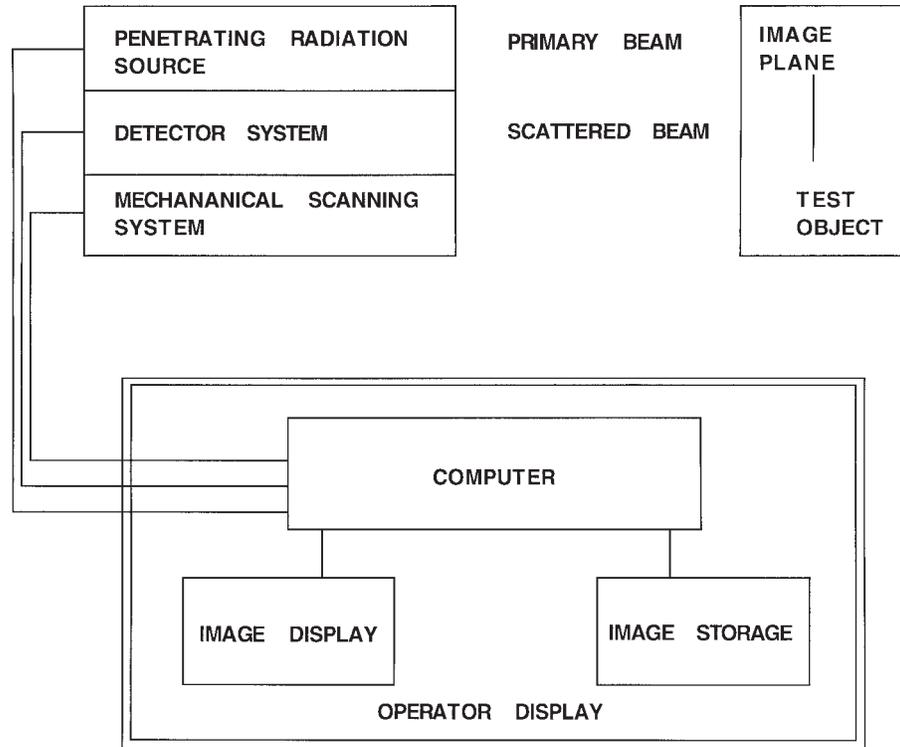


FIG. 8 Typical CST System Block Diagram

thereby causing an image artifact. Slightly re-positioning the CST setup with respect to the examination object can often determine whether an indicated feature lies in the desired slice plane or is an anomaly. If the suspected low-density feature remains stationary with respect to other slice features, it is a valid indication. If the suspected low-density feature moves with respect to other slice features, it does not lie in the desired slice.

## 7. Apparatus

7.1 Like modern radiosopic systems, CST systems comprise a number of subsystems that generally include:

- 7.1.1 A source of penetrating radiation,
- 7.1.2 A radiation detector, or array of detectors,
- 7.1.3 A mechanical scanning system,
- 7.1.4 A computer system,
- 7.1.5 An image display system,
- 7.1.6 An image data storage system, and
- 7.1.7 An operator interface.

7.2 *Radiation Sources*—X-ray as well as gamma-ray sources have been successfully used for CST. Since the primary radiation source serves only to excite the Compton scattering process, the radiation source should be optimized for this process. From an energy standpoint, the radiation source must be sufficiently energetic to penetrate the examination object material to at least the required depth and excite the Compton scattering process. The resulting Compton scattered X rays must be sufficiently energetic to exit the examination object and reach the detector. However, the radiation source should not be excessively energetic for two reasons: the probability of an interaction with an electron decreases with

increasing energy; and the difficulty of completely shielding the nearby detector from radiation source crosstalk increases. Therefore, the primary radiation energy must be appropriately selected. Another important consideration is radiation intensity, or the number of photons per unit time delivered to the examination voxel. In terms of energy selection, radiation beam intensity, and safety, the X-ray source is preferred over the radioisotope.

7.3 *Detectors*—The selection of a detector for Compton scattered X rays is very important to the success of the CST system. Because the scattered radiation intensity is very low, the detector will most likely be operated in a counting mode. The detector must exhibit excellent conversion efficiency and a fast recovery time. The scattered radiation energy is often very low so that the detector must exhibit low inherent filtration, high sensitivity and low noise. If the CST imaging system is to involve multiple detectors in a compact design, the detectors must also be small. Three classes of detectors which can be successfully used for CST are scintillation, ionization and solid state detectors.

7.4 *General CST Arrangement*—There are many possible arrangements for the radiation source and detector for CST. One such general arrangement is shown in Fig. 9 and uses nine detectors, for example. In this arrangement, the conical X-ray beam is collimated to form a small-diameter pencil beam. By action of a small aperture that is common to all detectors, each of the nine detectors receives scattered radiation originating from selected depths in the examination object. Each detector therefore receives scatter radiation from incremental depths along the primary X-ray beam to provide simultaneous image

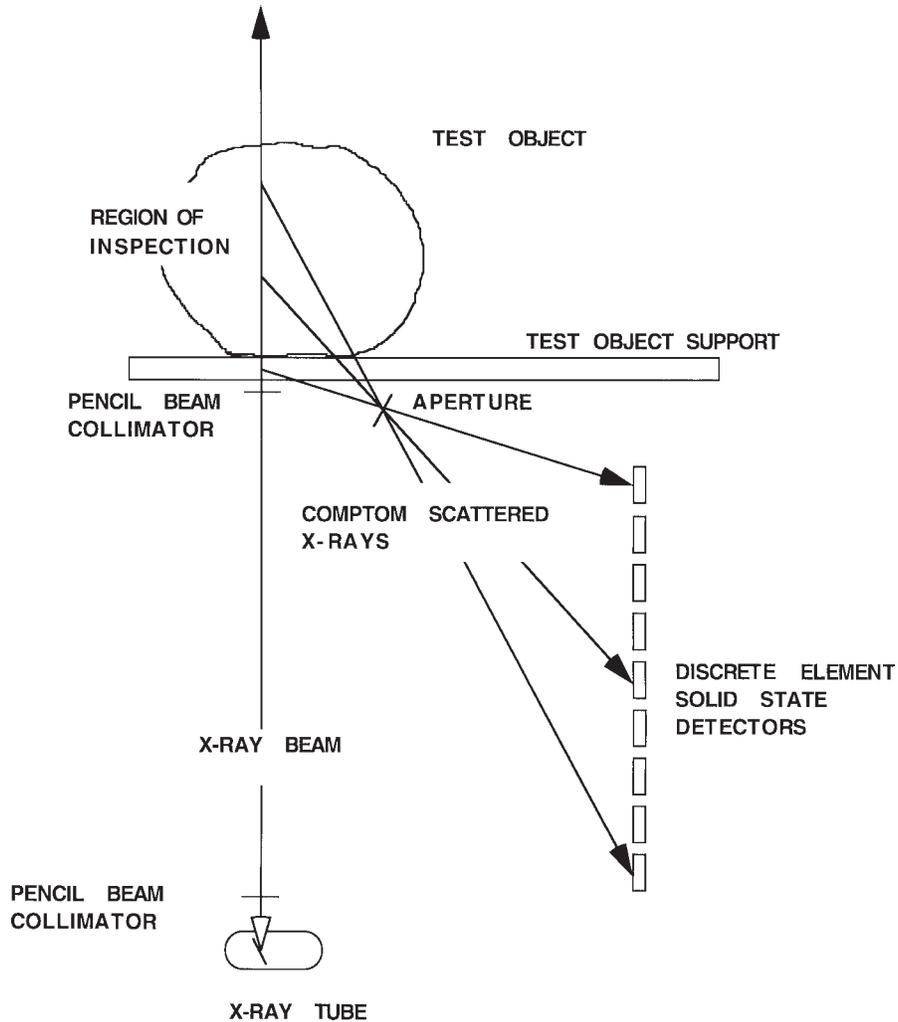


FIG. 9 General Arrangement of X-Ray Source, Detector Array and Examination Object for a Simultaneous Multi-Plane Compton Tomographic Imaging System

information lying in nine tomographic slice thicknesses. Moving the examination object or radiation source and detector in an  $X - Y$  raster scan allows all nine slice plane images to be formed simultaneously from individual data points. One technique is to use a flying spot X-ray, or scanning pencil beam, in conjunction with a linear array detector to generate complete lines of image data, rather than points.

7.5 Data Processing—Data processing may be utilized to enhance the CST image quality. Because the CST image is a digital image formed in a computer environment, many forms of data processing are possible. One form of raw data processing that is very desirable corrects for decreasing image brightness as the path lengths for the scattered X rays increase as illustrated in Fig. 10. In a homogenous material, it is

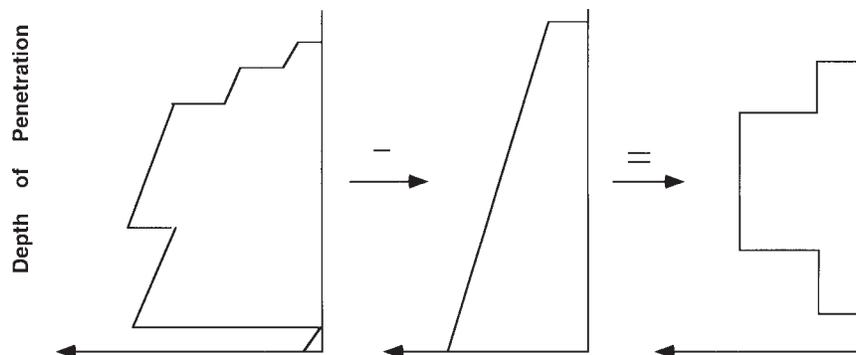


FIG. 10 CST Brightness Data Bias Caused by Differing Tomographic Plane-to-Detector Path Lengths

desirable that the CST image for all tomographic planes have uniform brightness. This brightness non-uniformity may be compensated automatically by subtracting a compensating brightness mask during the initialization of the CST system. Pulse amplitude discrimination, pulse shaping and other techniques commonly employed in photon counting instrumentation may also be utilized with good success. Once the tomographic images are generated, they may be processed by conventional image processing techniques to enhance certain features. For example, a high-pass filter may be utilized to enhance edges. Contrast manipulation may be used to increase image contrast or shift brightness values as may be desired.

7.5.1 Fig. 11 illustrates how a set of slice images may be converted to another set of slice images at a different angle with respect to the original images. This may be desirable when the feature of interest is not accommodated by the initial slice plane orientation. Re-generating the slice images also allows the examination object to be examined from any angle - even tumbled in space to provide an enhanced 3-D effect.

7.6 *Image Data Storage System*—CST images are digital and may therefore be archived on magnetic or optical media without loss of fidelity. Refer to Guide E 1453 for information on storage of magnetic media. Guide E 1475 contains information on the standardization of data fields containing radiologic examination data.

7.7 *Operator Interface*—The CST system operator interface is similar to other radiologic imaging system interfaces. Typically, the collection and processing of CST data is automated with the operator required only to set up the scan parameters and initiate the process. Tomographic images are presented on a video screen for manual interpretation or may be interpreted automatically by computer for some applications.

**8. Procedure**

8.1 *Examination Object Requirements*—CST examination has been successfully employed on a wide range of parent materials. These include electronics, plastics, aerospace composite materials, rubber, rocket propellant, aluminum and steel. The best candidates will be lower density materials having a propensity to produce scatter radiation. The technique works well on composites and assemblies where scatter characteristics change abruptly. The detection of corrosion in aluminum aircraft assemblies has been successfully demonstrated. As with all nondestructive testing techniques, a trial on examina-

tion objects containing known internal conditions is the best way to determine the suitability of the technique.

8.2 *Equipment Capabilities*—CST equipment tends to be specialized with some systems custom designed for specialized applications. For example, standard CST equipment is available which is powered by 160 keV constant potential industrial X-ray generator. Such equipment can offer the capability of simultaneously producing twenty-two slice plane images. Typical scan depths of up to 50 mm with maximum resolution of 0.4 by 0.4 by 0.4 mm is available. Scan area is 50 by 100 mm. Scan times range from approximately 1 to 6 min depending upon the examination object material and desired image quality.

8.3 *Set-Up*—A proper set-up is critical to the success of CST tomographic imaging. The mechanical set-up must be stable with no relative motion between the radiation source, detector and examination object. The examination volume must be carefully aligned with the examination object as to X-Y position and depth. The examination result can be no better than the quality of the mechanical set-up. One of the great advantages of CST is that the set-up is non-contacting and made entirely on one side of the examination object. If an area larger than the scan area is to be examined, it will be necessary to re-position the CST scanner. Re-positioning will require an accurate scan plan lay-out to ensure that no important examination object areas are missed.

8.4 *Radiation Safety*—Radiation shielding is a very important consideration. The radiation energies and intensities associated with the primary radiation beam pose a serious health hazard. The examination object and CST scanner must be suitably radiation shielded in accordance with good radiation safety practices and in accordance with local, state and federal radiation safety requirements. In general, the CST technique is much less difficult to shield than a transmission beam imaging system of similar primary radiation beam energy and intensity. This is due to the fact that the primary radiation beam is highly collimated and closely coupled to the examination object. In some applications involving thick examination objects, the examination object itself may provide a substantial amount of radiation shielding.

8.5 *Image Quality*—As with all radiologic imaging techniques, image quality is a prime consideration. Unfortunately, most transmission X-ray image quality indicators, such as Test Method E 747 or Practice E 1025 IQIs, are not useful for CST.

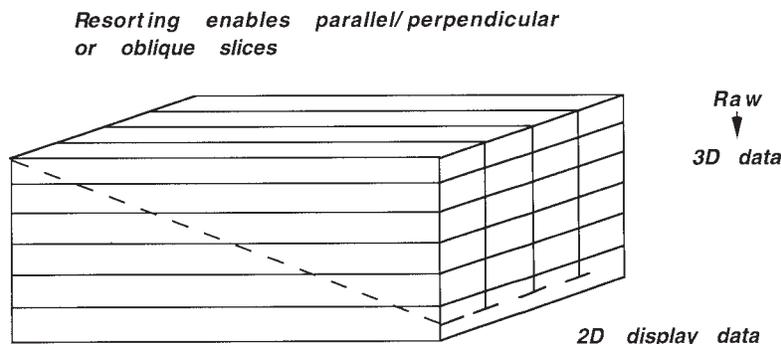


FIG. 11 Tomographic Slice Images May be Generated at Any Angle With Respect to the Original Slice Images

Therefore, the user will have to be resourceful in developing phantoms or calibration blocks which accurately represent the examination object's internal conditions. The best calibration block is often an actual examination object whose internal condition has been physically documented by sectioning and re-assembling or by other means. Such a device(s) should be the basis for determining initial image quality and periodically monitoring image quality. This device is known as a Representative Quality Indicator (RQI).

8.6 *Recording of CST Examination Results*—Traditional radiologic imaging recording means also work well for CST. These would include the video printer, the video cassette recorder and preferably image data storage in a digital format on either magnetic or optical media. Optical media should be considered for archival quality storage. Guide E 1475 contains valuable information on standardized recording data fields for digital radiologic examination data.

## 9. Interpretation of Results

9.1 This guide does not provide guidance on the interpretation of examination results, that is a matter of agreement between the provider and user of radiologic examination results. This guide attempts to familiarize the reader with the basic theory and practice of CST. As with all radiologic examination techniques, the obtained results depend upon many interrelated factors. Prospective users will be well advised to spend time in an applications laboratory setting before attempting the application of CST in a production

setting. The results may be expected to be a function of the specific application. Proper interpretation of CST results depend upon a good understanding of the advantages and disadvantages of CST, the details of the examination object's material and internal structure and the applicable accept/reject criteria.

## 10. Precision and Bias

10.1 CST is capable of providing both qualitative and quantitative information about an examination object. Qualitative information includes examination object internal features and shapes lying within a known thin slice. Quantitative information includes three-dimensional information about the location and dimension of internal features. As with all indirect measurement systems, the precision and bias of CST is directly related to the accuracy with which the equipment is calibrated and how closely the measurement technique replicates the calibration technique. Faulty interpretation of the examination results can lead to incorrect qualitative and quantitative measurements even though the equipment is properly calibrated.

10.2 Because of the sources of error listed in the previous section and other potential errors, this guide makes no statement as to the precision and bias of CST.

## 11. Keywords

11.1 back-scatter; compton scatter tomography; computed tomography; CST; radiologic; radiosopic; slice image; tomography

## APPENDIX

### (Nonmandatory Information)

#### X1. ADDITIONAL PUBLICATIONS

Gray, R. R., et al., "The Measurement of Local Void Fraction With Side-Scatter Gamma Technique," *Proceedings 26th Int. Instr. Symp.*, 1980.

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Harding, G. et al., "X-ray Imaging with Compton Scatter Radiation" *Philips Tech. Rev.* 41, 1983-1984.

Holt, R.S., "Compton Imaging," *Endeavour*, New Series 9, 1985.

Harding, G. and Tischler, R., "Dual Energy Compton Scatter Tomography," *Phys. Med. Biol.* 31, 1986.

The subject is described in standard texts on nuclear physics, such as, Glen Knoll: *Radiation Detection and Measurement*, 2nd Edition, Wiley.

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