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Standard Guide for X-Ray Compton Scatter Tomography[1]

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 reapproval. A superscript epsilon (ε) 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 test object;

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

1.2.3 The ability to image test 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 test 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 test 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 test 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 Kv constant potential X-ray source:

Material	Practical Thickness Range
Steel	Up to about 3 mm (⅛ 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 Test Method for Controlling Quality of Radiographic Testing Using Wire Penetrameters[2]

E 1025 Practice for Hole-Type Image Quality Indicators Used for Radiography[2]

E 1255 Practice for Radioscopy[2]

E 1316 Standard Terminology for Nondestructive Examinations[2]

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

E 1453 Guide for the Storage of Media that Contains Radioscopic Data[2]

E 1475 Guide for Data Fields for Computerized Transfer of Digital Radiological Test Data[2]

E 1647 Practice for Determining Contrast Sensitivity in Radioscopy[2]

[1] This guide is under the jurisdiction of ASTM Committee E-07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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

2.2 *ANSI/ASNT Standards:*

ASNT Recommended Practice No. SNT-TC-1A Personnel Qualification and Certification in Nondestructive Testing[3]

ANSI/ASNT CP-1 89 Standard for Qualification and Certification in Nondestructive Testing Personnel[3]

2.3 *Military Standard:*

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

3. Terminology

3.1 *Definitions*:

3.1.1 CST, being a radiologic examination method, used much that 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 radioscopic 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 test 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 test object. Each slice image contains test object information which lies predominantly within the desired slice. To make an analogy as to how CST works, consider a book. The test object may be larger or smaller (in length, width and depth) then the analogous book. The CST slice images are the pages in the book. Paging through the slice images provides information about test object features lying at different depths within the test 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 test 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 test 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 test 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 test object features outside the plane of examination. The result is a radioscopic image that contains information primarily from the slice plane. Scattered radiation limits image quality in normal radiographic and radioscopic 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 test object scatters, the better the CST result. Low subject contrast materials that cannot be imaged well by conventional radiographic and radioscopic 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 1 in. (25 mm) depth in aluminum or 2 in. (50 mm) in plastic is achievable, the examination depth is decreased dramatically as the material density increases. Proper image interpretation requires the use of standards and test 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 inspecting 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.

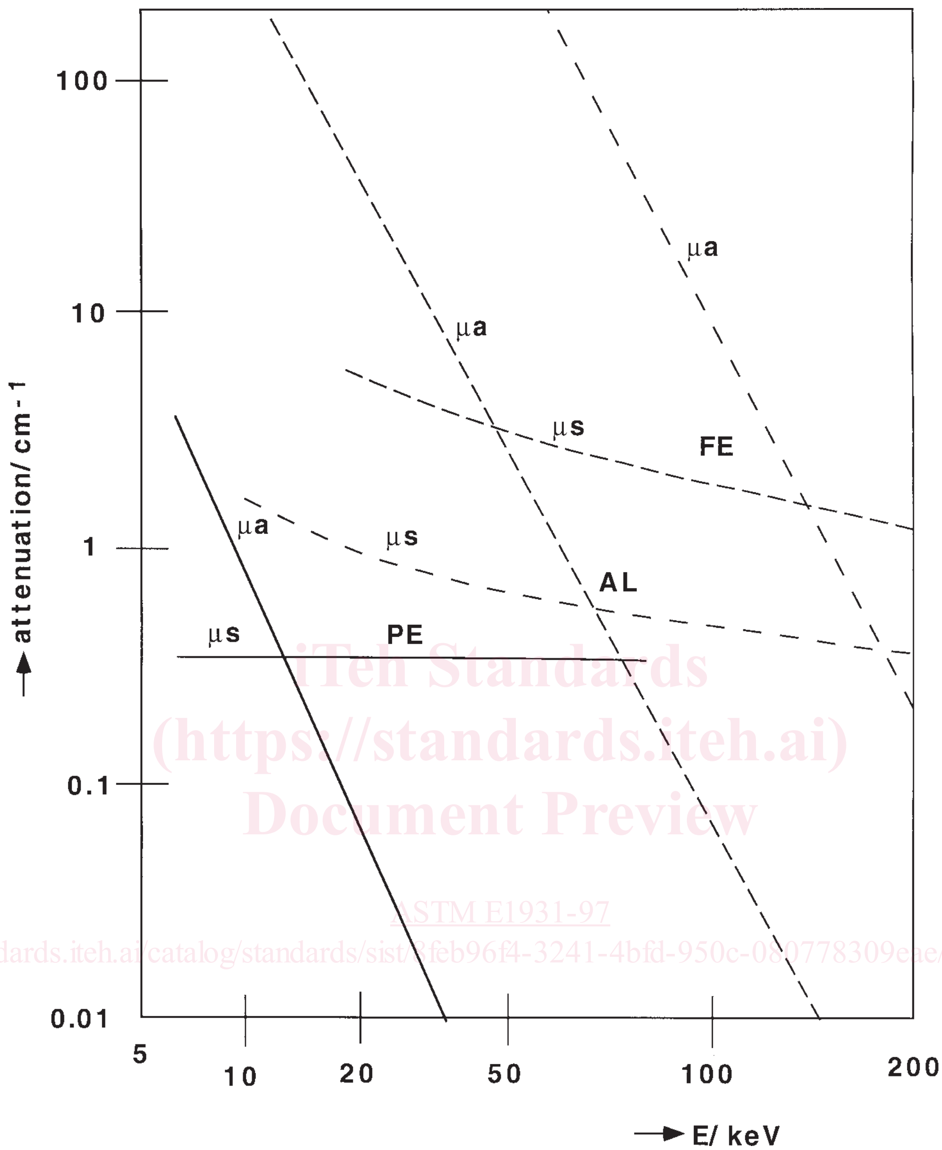
6. Technical Description

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 absorption is strongly dependent upon the atomic number and also the electron density of the absorbing material. Compton

[3] Available from American National Standards Institute, 11 W. 42nd St., 13th Floor, New York, NY 10036.

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

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 Kv 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 Kv. 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 inspected 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 test 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 useable image. The test 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 test 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 test 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 test 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 of 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 θ 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 μ_a for all three materials falls sharply with increasing energy, while the scatter coefficient μ_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
θ = scattering angle.

It can be seen from Eq 1 that the energy of the scatter radiation E' decreases with increasing scattering angle θ. 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:

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

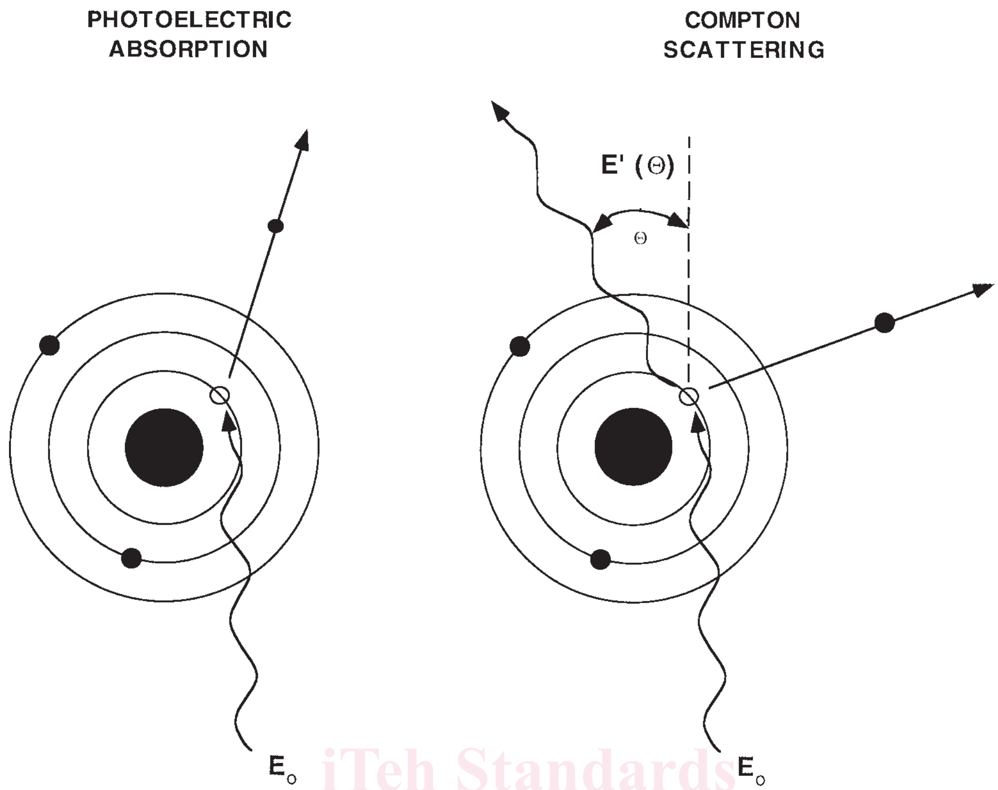


FIG. 2 Principals of Photoelectric Absorption and Compton Scattering

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 test object in this energy range.

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

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

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. μ is the total linear attenuation coefficient,

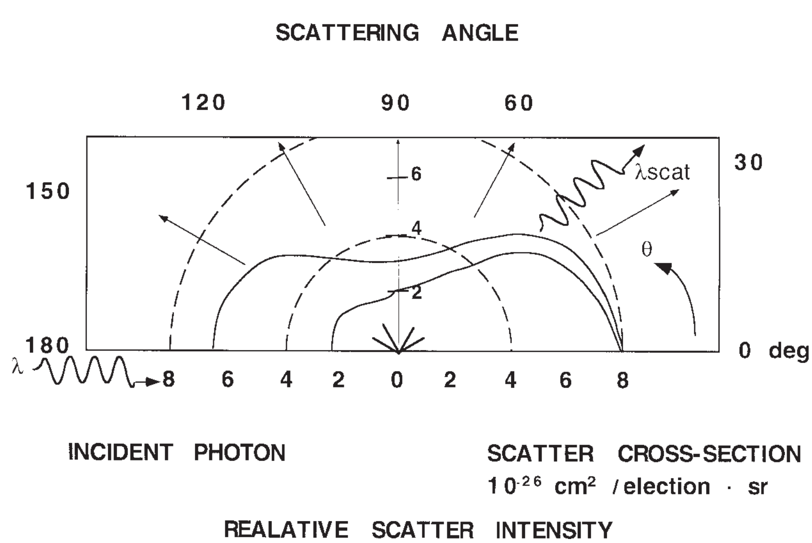


FIG. 3 Polar Plot of Scattering Angle Calculated at Primary Radiation Energies of 30 and 300 keV

$1-e^{-\mu_C W}$ = the fraction of photons scattered from the primary beam in a voxel of length W. μ_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'. μ' 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, μ' is not equal to μ. 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 μ except for a small discontinuity region of length W and whose attenuation coefficient is μ_D.

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

$$I_T = I_0 e_{-\mu L} \quad (4)$$

$$I_{T'} = I_0 e^{-(\mu L + \mu_D W)} \quad (5)$$

From these equations the subject contrast is as follows:

$$C = \frac{(I_{T'} - I_T)}{I_T} \times 100\ \% \quad (6)$$

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

$$= e^{\mu_D W} - 1 \quad (8)$$

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

$$C = (1 + (\mu_D W) - 1) \times 100\ \% = \mu_D W \times 100\ \% \quad (9)$$

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 test object of thickness L contains a small discontinuity of length W and having a linear attenuation coefficient of μ_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:

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

$$I_{SC'} = (F_p)\,(W)\,(\mu_D)\,(F_S)\,(K) \quad (11)$$

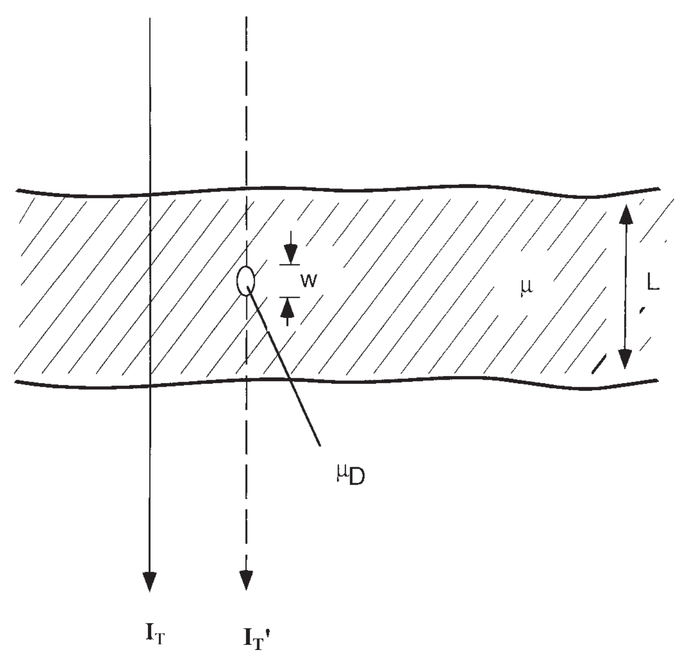


FIG. 4 Schematic Representation of the Transmitted Beam Imaging System Technique