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Non-destructive testing — Radiation methods — Computed tomography —

Part 1:
Principles

Essais non destructifs — Moyens utilisant les rayonnements — Tomographie informatisée —

Partie 1: Principes

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this part of ISO 15708 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15708-1 was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 5, *Radiation methods*.

ISO 15708 consists of the following parts, under the general title *Non-destructive testing — Radiation methods — Computed tomography*:

— *Part 1: Principles*

— *Part 2: Examination practices*

Annex A forms a normative part of this part of ISO 15708.

Introduction

This part of ISO 15708 provides a tutorial introduction to the theory and use of computed tomography. It begins with an overview intended for the interested reader possessing a general technical background. Subsequent, more technical clauses describe the physical and mathematical basis of CT technology, the hardware and software requirements of CT equipment, and the fundamental measures of CT performance.

This part of ISO 15708 includes an extensive glossary (with discussions) of CT terminology and an extensive list of references to more technical publications on the subject. Most importantly, this part of ISO 15708 establishes consensus definitions for basic measures of CT performance, enabling purchasers and suppliers of CT systems and services to communicate unambiguously with reference to a recognized standard. It also provides a few carefully selected equations relating measures of CT performance to key system parameters.

Non-destructive testing — Radiation methods — Computed tomography —

Part 1:
Principles

1 Scope

This part of ISO 15708 gives guidelines for, and defines terms for addressing the general principles of X-ray CT as they apply to industrial imaging. It also gives guidelines for a consistent set of CT performance parameter definitions, including how these performance parameters relate to CT system specifications.

2 Pre-amble

CT, being a radiographic modality, uses much the same vocabulary as other X-ray techniques. Because a number of terms have meanings or carry implications unique to CT, they appear with explanations in annex A. Throughout this part of ISO 15708, the term "X-ray" is used to denote penetrating electromagnetic radiation, however, electromagnetic radiation may be either X-rays or gamma rays.

3 Abbreviations

—	BW	beam width
—	CDD	contrast-detail-dose
—	CT	computed tomography
—	CAT	computerized axial tomography
—	DR	digital radiography
—	ERF	edge response function
—	LSF	line spread function
—	MTF	modulation transfer function
—	NDE	non-destructive evaluation
—	PDF	probability distribution function
—	PSF	point spread function

4 Requirements

4.1 Summary of computed tomography

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

This part of ISO 15708 is intended to satisfy two general needs for users of industrial CT equipment:

a) the need for a tutorial document addressing the general principles of X-ray CT as they apply to industrial imaging;

b) the need for a consistent set of CT performance parameter definitions, including how these performance parameters relate to CT system specifications.

Potential users and buyers, as well as experienced CT inspectors, will find this part of ISO 15708 a useful source of information for determining the suitability of CT for particular examination problems, for predicting CT system performance in new situations and for developing and prescribing new scan procedures.

This part of ISO 15708 does not specify test objects and test procedures for comparing the relative performance of different CT systems; nor does it treat CT inspection techniques, such as the best selection of scan parameters, the preferred implementation of scan procedures, the analysis of image data to extract densitometric information or the establishment of accept/reject criteria for a new object.

Standard practices and methods are not within the purview of this part of ISO 15708. The reader is advised, however, that examination practices are generally part- and application-specific, and industrial CT usage is new enough that in many instances a consensus has not yet emerged. The situation is complicated further by the fact that CT system hardware and performance capabilities are still undergoing significant evolution and improvement. Consequently, an attempt to address generic examination procedures is eschewed in favour of providing a thorough treatment of the principles by which examination methods can be developed or existing ones revised.

The principal advantage of CT is that it non-destructively provides quantitative densitometric (i.e., density and geometry) images of thin cross sections through an object. Because of the absence of structural noise from detail outside the thin plane of inspection, images are much easier to interpret than with conventional radiographic data. The new user can learn quickly (often upon first exposure to the technology) to read CT data because the images correspond more closely to the way the human mind visualizes three-dimensional structures than conventional projection radiography. Further, because CT images are digital, they may be enhanced, analysed, compressed, archived, input as data into performance calculations, compared with digital data from other NDE modalities, or transmitted to other locations for remote viewing. Additionally, CT images exhibit enhanced contrast discrimination over compact areas. This capability has no classical analogue. Contrast discrimination of better than 0,1 % at three-sigma confidence levels over areas as small as one-fifth of one percent the size of the object of interest are common.

With proper calibration, dimensional inspections and absolute density determinations can also be made very accurately. Dimensionally, virtually all CT systems provide a pixel resolution of roughly 1 part in 1 000, and metrological algorithms, using *a priori* knowledge, can often measure dimensions to one-tenth of one pixel or so with three-sigma accuracies. Attenuation values can also be related accurately to material densities. If details in the image are known to be pure homogeneous elements, the density values may still be sufficient to identify materials in some cases. For the case in which no *a priori* information is available, CT densities cannot be used to identify unknown materials unambiguously, since an infinite spectrum of compounds can be envisioned that will yield any given observed attenuation. In this instance, the exceptional density sensitivity of CT can still be used to determine part morphology and highlight structural irregularities.

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

CT, as a digital technique with data convertible to other formats, has proven valuable in the industrial application areas of rapid prototyping, reverse engineering and metrology. Rapid prototyping can be accomplished utilizing a class of manufacturing techniques where parts are built from computer models in a variety of materials. Stereolithography is one such technique that can utilize the thin slice information of CT to produce accurate polymer parts. Taking multiple CT slices, the two-dimensional images can be assembled to produce complete three-dimensional representations of scanned components. The data are presented to the stereolithography system as full volume information or simply contour plots, allowing the generation of either filled or hollow polymer parts. The choice of data would be based on the rapid tooling techniques that are applied in the specific application area.

CT-assisted reverse engineering methods are successful in enabling older designs without computer-aided design (CAD) files to access the many available rapid tooling techniques currently available. In reverse engineering applications, as in rapid prototyping, the two-dimensional images can be assembled to produce complete three-dimensional representations of scanned components. There are many computational methods that allow the CT-derived digital data to be transformed to a point cloud – a collection of points in 3-dimensional space that represent the surface of the part – or CAD contours, which can be used to reverse engineer the part. The CAD contours produced from CT data have been determined to be accurate to within a few thousandths of an inch. Thus, CT data are similar to dimensional data from coordinate measuring machines except they provide the following advantages:

a) CT data are acquired without contacting the part;

b) CT data not only provide surface information but also accurate measurements of all internal structures;

c) CT images can be formed of any object without special programming, regardless of its structural complexity.

Metrology of the CT data – evaluating dimensional measurements – can be accomplished using a number of techniques. Some examples of common techniques are direct measurement from the CT image data, measurement of the point cloud or registering the point cloud with the CAD model to produce a 3-D variance map. The deviations between the inspection data and the design data are evaluated based on the necessary tolerances for the application.

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

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

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

4.2 General description of computed tomography

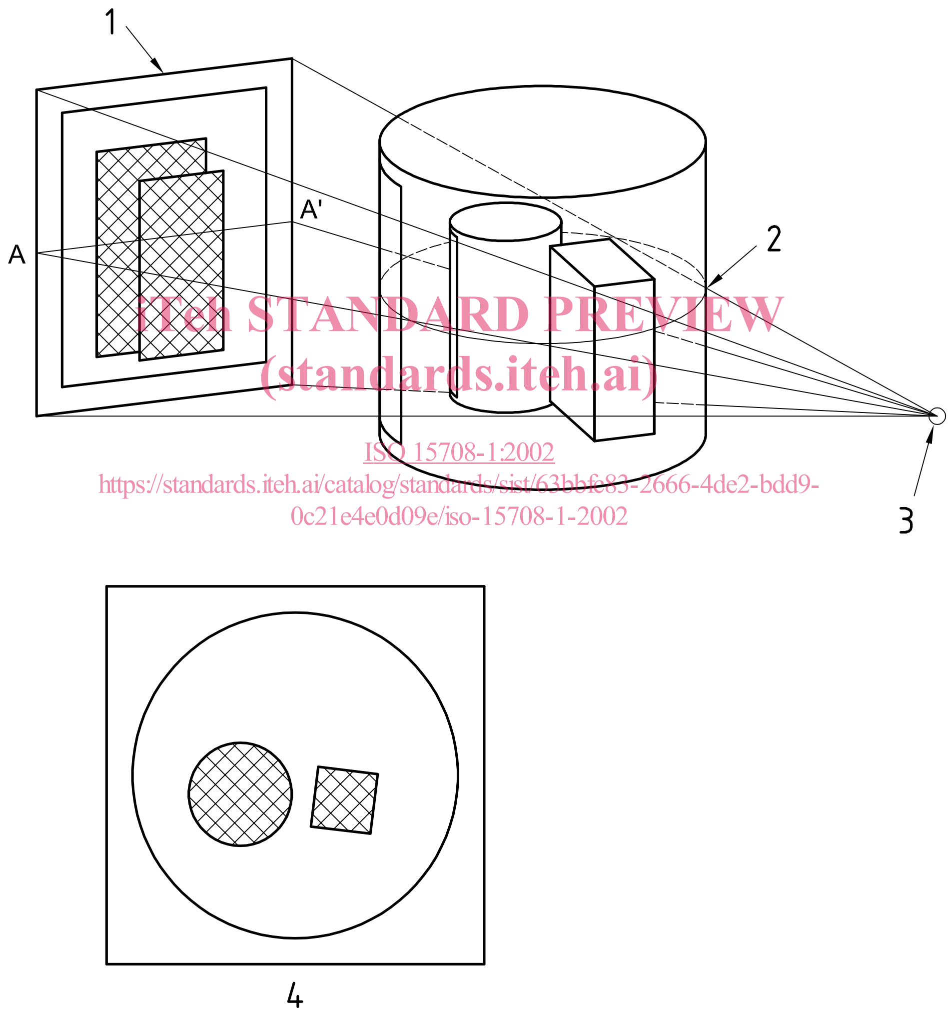
CT is a radiographic inspection method that uses a computer to reconstruct an image of a cross-sectional plane (slice) through an object. The resulting cross-sectional image is a quantitative map of the linear X-ray attenuation coefficient, μ, at each point in the plane. The linear attenuation coefficient characterizes the local instantaneous rate at which X-rays are removed during the scan, by scatter or absorption, from the incident radiation as it propagates through the object (see clause 6). The attenuation of the X-rays as they interact with matter is a well-studied problem [20] and is the result of several different interaction mechanisms. For industrial CT systems with peak X-ray energy below a few MeV, all but a few minor effects can be accounted for in terms of the sum of just two interactions: photoelectric absorption and Compton scattering [20]. The photoelectric interaction is strongly dependent on the atomic number and density of the absorbing medium; the Compton scattering is predominantly a function of the electron density of the material. Photoelectric attenuation dominates at lower energies and becomes more important with higher atomic number, while Compton scattering dominates at higher energies and becomes more important at lower atomic number. In special situations, these dependencies can be used to advantage.

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

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

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

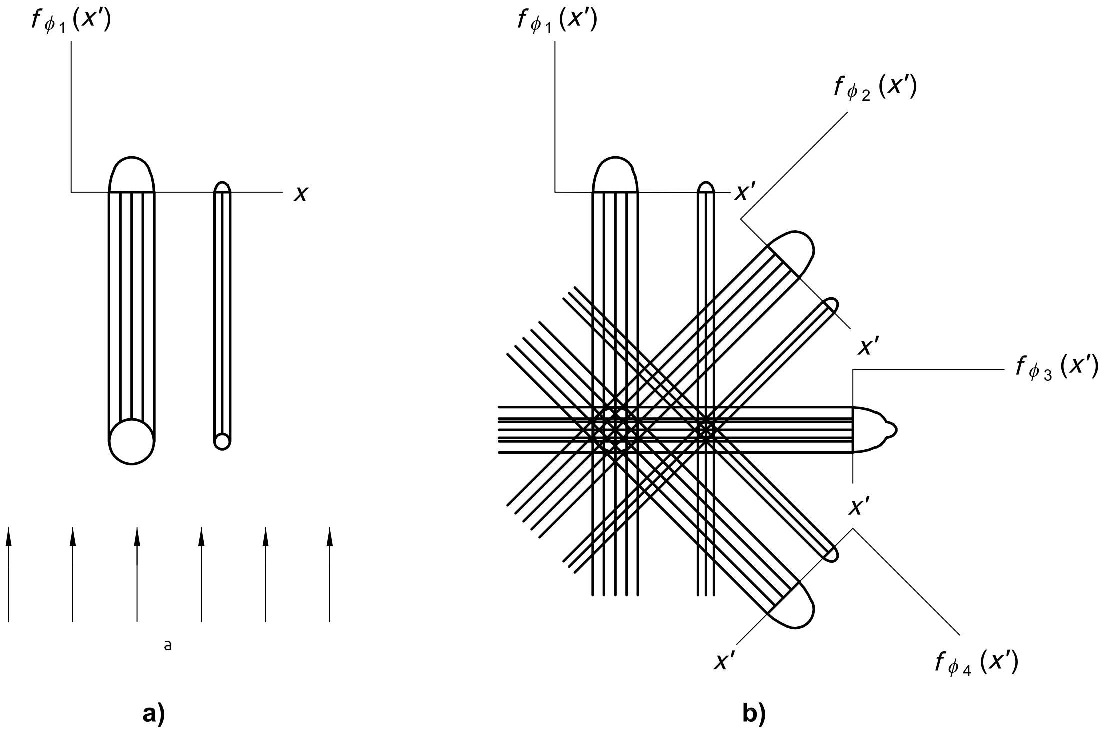
Because of the volume of data that shall be collected and processed with CT, scans are usually made one slice at a time. A set of X-ray attenuation measurements is made along a set of paths projected at different locations around the periphery of the test article. The first part of Figure 2 illustrates a set of measurements made on a test object containing two attenuating discs of different diameters. The X-ray attenuation measurement made at a particular angle, ϕ_1, is referred to as a single view. It is shown as $f(x')$, where x' denotes the linear position of the measurement. The second part of Figure 2 shows measurements taken at several other angles $f(x')$. Each of the attenuation measurements within these views is digitalized and stored in a computer, where it is subsequently conditioned (e.g., normalized and corrected) and filtered (convolved), as discussed in more detail in clause 6. The next step in image processing is to back-project the views, which is also shown in the second part of Figure 2. Back-projection consists of projecting each view back along a line corresponding to the direction in which the projection data were collected. The back-projections, when enough views are used, form a faithful reconstruction of the object. Even in this simple example, with only four projections, the concentration of back-projected rays already begins to show the relative size and position of features in the original object.



Key

1	Radiograph
2	Slice (plane P)
3	X-ray source
4	CT slice view (plane P)

Figure 1 — A CT image versus a conventional radiograph



[a] Incident X-rays.

Figure 2 — Schematic illustrations of how CT works

4.3 System capability

4.3.1 General

The ability of a CT system to image thin cross-sectional areas of interest through an object makes it a powerful complement to conventional radiographic inspections. Like any imaging system, a CT system can never duplicate exactly the object that is scanned. The extent to which a CT image does reproduce the object is dictated largely by the competing influences of the spatial resolution, the statistical noise and the artifacts of the imaging system. Each of these aspects is discussed briefly here. A more complete discussion will be found in clauses 7 and 8.

4.3.2 Spatial resolution

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

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

Other techniques to improve spatial resolution in specific regions of larger objects is known as region-of-interest (ROI) tomography[59], [68]. ROI tomography reconstructs a convex region within an object, utilizing a projection subset, on a specified sampling grid, providing higher resolution in this reduced area.

It can also be shown that a given CT image is equivalent to the blurring (convolution) of the ideal representation of the object with a smooth, two-dimensional Gaussian-like function called the point spread function (PSF). The specification of a system's PSF is an important characterization of a CT system and can be derived fairly accurately from the parameters of the CT system. The effect of the PSF is to blur the features in the CT image. This has two effects:

a) small objects appear larger;

b) sharp boundaries appear diffuse.

Blurring the image of small objects reduces resolution since the images of two small point-like objects that are close together will overlap and may be indistinguishable from a single feature. Blurring sharp edges reduces the perceptibility of boundaries of different materials for the same reason. This effect is especially important at interfaces between materials, where the possibility of separations of one type or another are of the greatest concern. Thus, knowledge of a CT system's PSF is crucial to the quantitative specification of the maximum resolution and contrast achievable with that system.

NOTE Since it is a common source of misunderstanding, that the smallest feature that can be detected in a CT image is not the same as the smallest that can be resolved. A feature considerably smaller than a single pixel can affect the pixel to which it corresponds to such an extent that it will appear with a visible contrast relative to adjacent pixels. This phenomenon, the “partial-volume effect,” is discussed in clause 6. The difference between the resolution of a small feature and the resolution of its substructure is of fundamental importance for CT.

4.3.3 Statistical noise

All images made from physical interactions of some kind will exhibit intrinsic statistical noise. In radiography, this noise arises from two sources:

a) intrinsic statistical variations due to the finite number of photons measured;

b) the particular form of instrumentation and processing used.

A good example in conventional radiography is film that has been underexposed. Even on a very uniform region of exposure, close examination of the film will reveal that only a small number of grains per unit area have been exposed. An example of instrumentation induced noise is the selection of coarser fine-grain film. If the films are exposed to produce an image with a given density, the fine-grain film will have lower statistical noise than the coarse-grain film. In CT, statistical noise in the image appears as a random variation superimposed on the CT number of the object. If a feature is small, it may be difficult to determine its median grey level and distinguish it from surrounding material. Thus, statistical noise limits contrast discrimination in a CT image.

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

4.3.4 Artifacts

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

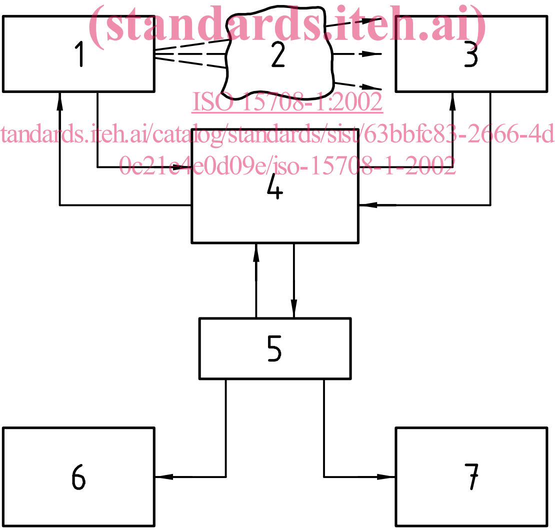
CT artifacts manifest themselves in diverse ways, since the CT image is calculated from a series of measurements. A common artifact is caused by beam hardening and manifests itself as cupping, i.e., a false radial gradient in the density that causes abnormally low values at the interior centre of a uniform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

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

5 Apparatus

5.1 Subsystems

Modern CT systems, both industrial and medical, are composed of a number of subsystems, typically those shown in Figure 3.



Key

1 Radiation source
2 Test object
3 Detectors
4 Mechanical assembly
5 Computer
6 Graphical display system
7 Data storage

Figure 3 — Typical components of a CT system

The choice of components for these subsystems depends on the specific application for which the system was designed; however, the function served by each subsystem is common in almost all CT scanners. These subsystems are:

a) an operator interface;

b) a source of penetrating radiation;

c) a radiation detector or an array of detectors;

d) a mechanical scanning assembly;

e) a computer system;

f) a graphical display system;

g) a data storage medium.

5.2 Operator interface

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

5.3 Radiation sources

There are three rather broad types of radiation sources used in industrial CT scanners:

a) X-ray tubes;

b) linear accelerators;

c) isotopes.

The first two broad energy spectra are polychromatic or Bremsstrahlung electrical sources and the third is approximately monoenergetic radioactive sources. The choice of radiation source is dictated by precisely the same rules that govern the choice of radiation source for conventional radiographic imaging applications. A majority of existing CT scanners use electrical Bremsstrahlung X-ray sources either X-ray tubes or linear accelerators. One of the primary advantages of using an electrical X-ray source over a radioisotope source is the much higher photon flux possible with electrical radiation generators, which in turn allows shorter scan times. The greatest disadvantage of using an X-ray source is the beam hardening effect associated with polychromatic fluxes. Beam hardening results from the object preferentially absorbing low-energy photons contained in the continuous X-ray spectrum. Most medical scanners use as a source an X-ray tube operating with a potential of 120 kV to 140 kV. Industrial scanners designed for moderate penetrating ability also use X-ray tubes, but they usually operate at higher potentials, typically 200 kV to 400 kV. Systems designed to scan very massive objects, such as large rocket motors, use high-energy Bremsstrahlung radiation produced by linear accelerators. These sources have both high flux and good penetration, but they also have a broad continuous spectrum and the associated beam-hardening effect. Isotope sources are attractive for some applications. They offer an advantage over X-ray sources in that problems associated with beam hardening are nonexistent for the monoenergetic isotopes such as caesium^{137} and cobalt^{60}. They have the additional advantages, which are important in some applications, that they do not require bulky and energy-consuming power supplies, and they have an inherently more stable output intensity. The intensity of available isotopic sources, however, is limited by specific activity (photons/second/gram of material). The intensity affects signal-to-noise ratio and, even more importantly, the specific activity determines source spot size and thus spatial resolution. Both of these factors tend to limit the industrial application of isotopic scanners. Nevertheless, they can be used in some applications in which scanning time or resolution is not critical.