
**Non-destructive testing — Radiation
methods for computed tomography —
Part 2:
Principles, equipment and samples**

*Essais non destructifs — Méthodes par rayonnements pour la
tomographie informatisée*

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by the European Committee for Standardization (CEN) (as EN 16016-2) and was adopted, under a special "fast-track procedure", by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 5, *Radiographic testing*, in parallel with its approval by the ISO member bodies.

This second edition of ISO 15708-2 cancels and replaces ISO 15708-1:2002, of which it forms the subject of a technical revision. It takes into consideration developments in computed tomography (CT) and computational power over the preceding decade.

A list of all parts in the ISO 15708 series can be found on the ISO website.

Non-destructive testing — Radiation methods for computed tomography —

Part 2: Principles, equipment and samples

1 Scope

This document specifies the general principles of X-ray computed tomography (CT), the equipment used and basic considerations of sample, materials and geometry.

It is applicable to *industrial* imaging (i.e. non-medical applications) and gives a consistent set of CT performance parameter definitions, including how those performance parameters relate to CT system specifications.

This document deals with computed axial tomography and excludes other types of tomography such as translational tomography and tomosynthesis.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15708-1:2017, *Non-destructive testing — Radiation methods for computed tomography — Part 1: Terminology*

ISO 15708-3:2017, *Non-destructive testing — Radiation methods for computed tomography — Part 3: Operation and interpretation*

ISO 15708-4:2017, *Non-destructive testing — Radiation methods for computed tomography — Part 4: Qualification*

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15708-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

4 General principles

4.1 Basic principles

Computed tomography (CT) is a radiographic inspection method which delivers three-dimensional information on an object from a number of radiographic projections either over cross-sectional planes (CT slices) or over the complete volume. Radiographic imaging is possible because different materials

have different X-ray attenuation coefficients. In CT images, the X-ray linear attenuation coefficients are represented as different CT grey values (or in false colour). For conventional radiography the three-dimensional object is X-rayed from one direction and an X-ray projection is produced with the corresponding information aggregated over the ray path. In contrast, multiple X-ray-projections of an object are acquired at different projection angles during a CT scan. From these projection images the actual slices or volume are reconstructed. The fundamental advantage compared to radiography is the preservation of full volumetric information. The resulting CT image (2D-CT slice or 3D-CT volume), is a quantitative representation of the X-ray linear attenuation coefficient averaged over the finite volume of the corresponding volume element (voxel) at each position in the sample.

The linear attenuation coefficient characterizes the local instantaneous rate at which X-rays are attenuated as they propagate through the object during the scan. The attenuation of the X-rays as they interact with matter is the result of several different interaction mechanisms: Compton scattering and photoelectric absorption being the predominant ones for X-ray CT. The linear attenuation coefficient depends on the atomic numbers of the corresponding materials and is proportional to the material density. It also depends on the energy of the X-ray beam.

4.2 Advantages of CT

This radiographic method can be an excellent examination technique whenever the primary goal is to locate and quantify volumetric details in three dimensions. In addition, since the method is X-ray based it can be used on metallic and non-metallic samples, solid and fibrous materials and smooth and irregularly surfaced objects.

In contrast to conventional radiography, where the internal features of a sample are projected onto a single image plane and thus are superposed on each other, in CT images the individual features of the sample appear separate from each other, preserving the full spatial information.

With proper calibration, dimensional inspections and material density determinations can also be made.

Complete three-dimensional representations of examined objects can be obtained either by reconstructing and assembling successive CT slices (2D-CT) or by direct 3D CT image (3D-CT) reconstruction. Computed tomography is thus valuable in the industrial application areas of non-destructive testing, 2D and 3D metrology and reverse engineering.

CT has several advantages over conventional metrology methods:

- acquisition without contact;
- access to internal and external dimensional information;
- a direct input to 3D modelling especially of internal structures.

In some cases, dual energy (DE) CT acquisitions can help to obtain information on the material density and the average atomic number of certain materials. In the case of known materials the additional information can be traded for improved discrimination or improved characterization.

4.3 Limitations of CT

CT is an indirect test procedure and measurements (e.g. of the size of material faults; of wall thicknesses must be compared with another absolute measurement procedure, see ISO 15708-3). Another potential drawback of CT imaging is the possible occurrence of artefacts (see 4.5) in the data. Artefacts limit the ability to quantitatively extract information from an image. Therefore, as with any examination technique, the user must be able to recognize and discount common artefacts subjectively.

Like any imaging system, a CT system can never reproduce an exact image of the scanned object. The accuracy of the CT image is dictated largely by the competing influences of the imaging system, namely spatial resolution, statistical noise and artefacts. Each of these aspects is discussed briefly in 4.4.1. A more complete description will be found in ISO 15708-3.

CT grey values cannot be used to identify unknown materials unambiguously unless a priori information is available, since a given experimental value measured at a given position may correspond to a broad range of materials.

Another important consideration is to have sufficient X-ray transmission through the sample at all projection angles (see 8.2) without saturating any part of the detector.

4.4 Main CT process steps

4.4.1 Acquisition

During a CT scan, multiple projections are taken in a systematic way: the images are acquired from a number of different viewing angles. Feature recognition depends, among other factors, on the number of angles from which the individual projections are taken. The CT image quality can be improved if the number of projections of a scan is increased.

As all image capture systems contain inherent artefacts, CT scans usually begin with the capture of offset and gain reference images to allow flat field correction; using black (X-rays off) and white (X-rays on with the sample out of the field of view) images to correct for detector anomalies. The capture of reference images for distortion correction (pin cushion distortion in the case of camera-based detector systems with optical distortion), and centre of rotation correction can also take place at this stage. Each subsequent captured image for the CT data set has these corrections applied to it. Some systems can be configured to either the X-ray settings or enhance the image to ensure that the background intensity level of the captured images remains constant throughout the duration of the CT scan.

The quality of a CT image depends on a number of system-level performance factors, with one of the most important being spatial resolution.

Spatial resolution is generally quantified in terms of the smallest separation at which two features can be distinguished as separate entities. The limits of spatial resolution are determined by the design and construction of the system and by the resolution of and number of CT projections. The resolution of the CT projection is limited by the maximum magnification that can be used while still imaging all parts of the sample at all rotation angles.

It is important to notice that the smallest feature that can be detected in a CT image is not the same as the smallest that can be resolved spatially. A feature considerably smaller than a single voxel can affect the voxel to which it corresponds to such an extent that it appears with a visible contrast so that it can be easily detected with respect to adjacent voxels. This phenomenon is due to the “partial-volume effect”.

Although region-of-interest CT (local tomography) can improve spatial resolution in specified regions of larger objects, it introduces artefacts (due to incomplete data) which can sometimes be reduced with special processing.

Radiographic imaging as used for CT examination is always affected by noise. In radiography this noise arises from two sources: (1) intrinsic variation corresponding to photon statistics related to the emission and detection of photons and (2) variations specific to instruments and processing used. Noise in CT projections is often amplified by the reconstruction algorithm. In the CT images statistical noise appears as a random variation superimposed on the CT grey value of each voxel and limits density resolution.

Although statistical noise is unavoidable, the signal-to-noise ratio can be improved by increasing the number of projections and/or time of exposure for each of them, the intensity of the X-ray source or the voxel size. However, some of these measures will decrease spatial resolution. This trade-off between spatial resolution and statistical noise is inherent in computed tomography.

4.4.2 Reconstruction

A CT scan initially produces a number of projections of an object. The subsequent reconstruction of the CT image from these individual projections is the main step in computed tomography, which distinguishes this examination technique from other radiographic methods.

The reconstruction software may apply additional corrections to the CT projections during reconstruction, e.g. reduction of noise, correction of beam hardening and/or scattered radiation.

Depending on the CT system, either individual CT slices or 3D CT images are reconstructed.

4.4.3 Visualization and analysis

This step includes all operations and data manipulations, for extracting the desired information from the reconstructed CT image.

Visualisation can either be performed in 2D (slice views) or in 3D (volume). 2D visualisation allows the user to examine the data slice-wise along a defined axis (generally it can be an arbitrary path).

For 3D imaging, the CT volume or selected surfaces derived from it, are used for generating the desired image according to the optical model underlying the algorithm. The main advantage of this type of visualisation is that the visual perception of the image corresponds well with the natural appearance of the object for the human eye, although features may appear superimposed in the 2D-representation on a screen.

During visualisation, additional artefacts of different origin can occur, especially in the 3D imaging of the CT volume. Such artefacts due to sampling, filtering, classification and blending within the visualisation software are dependent on the hardware and software used, as well as the visualisation task at hand. Therefore such artefacts are not included in the definition of artefacts as found in 4.5. Nevertheless, the user should be aware that misinterpretation of the data might also occur in this process step.

To highlight features of interest during visualisation different digital filter operations can be performed. A characteristic of all these operations is that although they enhance one or more properties of the data, they simultaneously deteriorate other properties (for example: highlighting the edges deteriorates recognition of inner structures of an object). Therefore digital filters should always be used cautiously for specific tasks, being aware which benefits and which detriments they are associated with.

A computer used for 3D visualisation should be able to process the complete volume of interest in the main memory. The corresponding monitor should have a resolution, a dynamic range and settings sufficient for the given visualisation task. Adequate vision of the personnel is to be ensured in accordance with ISO 9712.

4.5 Artefacts in CT images

An artefact is an artificial feature which appears on the CT image but does not correspond to a physical feature of the sample. Artefacts result from different origins; they can be classified into artefacts arising from the measurement itself and the equipment (artefacts due to a finite beam width, scattered radiation, instabilities and detector peculiarities) and artefacts inherent to the method (e.g. beam hardening). Artefacts can also be divided into acquisition artefacts (e.g. scattered radiation, ring artefacts) and reconstruction artefacts (e.g. cone beam artefacts). Some artefacts can be eliminated by using an appropriate measurement technique with suitable parameters, while others can only be reduced in their extent. Artefacts may be detrimental for specific measurement or analysis tasks, but may have no impact on certain other analyses. With this fact in mind, the type and extent of artefacts in a data set has to be evaluated in the context of the corresponding analysis task.

Noise and the partial volume effect are not considered as artefacts in this standard.

More details are given in ISO 15708-3:2017, 5.5.

5 Equipment and apparatus

5.1 General

In relation to performance, a CT system can be considered as comprising four main components: the X-ray source, detector, sample manipulation stages (the latter including any mechanical structure that influences image stability) and reconstruction/visualisation system.

Generally the source and detector will be fixed while the sample rotates in the beam to acquire the necessary set of projections. In scanners for example designed for *in vivo* animal studies or for imaging large structures, the source and detector may orbit around the sample, as in medical scanners.

In the majority of micro-/nano- or sub-micro-tomography systems, the resolution is determined primarily by the X-ray focal spot size. Geometric magnification allows the detector element spacing to be much larger than the computed voxel size and a thicker and therefore more efficient scintillator to be used. A disadvantage of this approach is that to obtain high magnification ratios, the sample should be located very close to the source. This is a particular problem if the sample is to be mounted in some form of environmental chamber or, for example, an *in situ* loading stage. This imposes a lower limit on the source to sample distance, thus reducing X-ray fluence (resulting in a lower signal-to-noise ratio and/or increased acquisition time) and requiring the detector to be mounted proportionately further away in order to achieve the same magnification factor. Alternatively, if the sample to detector distance is low compared with the source to sample distance, the detector resolution becomes the limiting factor, rather than the spot size. In this case, the increased source to detector distance again means reduced X-ray fluence and high-resolution detectors tend to require thinner and hence less efficient scintillators.

CT systems may be optimised for resolution, energy, speed of acquisition or simply cost. Although a particular system may operate over a wide range of conditions, it will operate optimally over a much smaller range and the user should consider the prime application when selecting one model over another and not simply over-specify.

For example, a high-resolution CT system (small X-ray focal spot size) may have a considerably lower flux output at more modest resolution settings than one designed to operate at such resolution. Furthermore, a high performance rotation stage for a high-resolution scanner will have a much smaller load limit. Similarly, a system designed for high energy imaging will require a thicker phosphor screen, giving poorer resolution compared with a thinner screen, which is adequate at lower energies.

Some CT systems can provide interchangeable X-ray target heads (transmission or reflection, see [Annex A](#)) and/or interchangeable detectors, but these will come at a higher price.

When comparing resolution and scan times on different CT systems, it is important to consider the signal-to-noise ratio (SNR), see ISO 15708-3:2017, 5.1.3. This is dependent on the X-ray exposure and thus the faster the scan, the worse the SNR. It is also dependent on the sample type and geometry. A sample with a high void volume fraction (or with a high proportion of relatively low absorbing regions), such as a foam or cancellous bone sample, will exhibit a better SNR than a more homogeneous sample.

For a given exposure, the best SNR is obtained with the X-ray accelerating voltage set to give approximately 10 %–20 % transmission through the sample. If the transmission is too low, the low number of photons detected will give rise to excessive noise. Conversely, if it is too high, the contrast (signal in SNR) will be too low. The SNR does not vary sharply with voltage however, and simulations of X-ray attenuation in aluminium indicate that the SNR only drops by 20 % of the peak value if the voltage is set for 35 % or 40 % transmission. For a given sample size, the required X-ray exposure to maintain a fixed SNR is proportional to the fourth power of resolution (for a given detector). Thus, for example, doubling the resolution will require a 16-fold increase in exposure while a 10-fold increase in resolution will demand a 10,000 fold increase in exposure. There is therefore a critical need to use the same or similar samples when comparing the image quality from one system with that of another.

5.2 Radiation sources

Most industrial CT systems will use an electrically generated X-ray source, and these can be subdivided into three main types:

- open tube (or vacuum demountable) x-ray sets;
- sealed tube constant potential x-ray sets;
- linear accelerators.

Each source type has a speciality; sometimes systems are supplied with more than one source so they can be used over a broader range of samples. Besides cost considerations, selection of a suitable X-ray source is dictated by the range of samples (size, composition and material density) that will be inspected and the resolution at which they are to be inspected.

X-ray set manufacturers will often quote a single focal spot size, this is a “nominal” measurement at a specific energy setting, the size of the focal spot will vary depending upon the voltage (kV) and current ($\mu\text{A}/\text{mA}$) settings used, the higher the power the larger the focal spot will become.

Focal spot size and the feature recognition (which is sometimes referred to by system manufacturers) are not the same as the spatial resolution of the CT system. The feature recognition is the ability of the complete system to display an image of an object, or feature within an object, of a certain size. For example, it is entirely possible for a system with an X-ray set being run at an energy that is producing a focal spot size of around $5\ \mu\text{m}$ to display an image of a dense wire cross-hair made from wire less than $1\ \mu\text{m}$ in diameter. This is more of an indication of the X-ray absorption characteristics of the material that the wire is made from than the actual resolution of the CT system, see [4.4.1](#).

The X-ray beam is often filtered to reduce lower energy X-rays and therefore to reduce scatter and beam hardening effects.

More details are given in [Annex A](#).
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5.3 Detectors

A radiation detector is used to measure the transmission of X-rays through the object along the different ray paths. The purpose of the detector is to convert the incident X-ray flux into an electrical signal that can be handled by conventional electronic processing techniques. The number of ray sums in a projection shall be comparable to the number of elements on the side of the image matrix. Such considerations result in a tendency for modern scanners to use large detector arrays that often contain several hundred to over thousands or millions of sensors.

Filtration at the detector by means of material inserted in the ray path before the detector (behind the test object) might be used. The filter absorbs (and scatters) radiation according to its material characteristics, as described in [5.1](#). In addition, each detector applies some amount of filtration as the rays pass through the detector housing. Additional filtration might be used to reduce the intensity of scatter detected.

Typically, three types of detectors are in use:

- a) gas ionization detectors;
- b) scintillation detectors;
- c) semiconductor detectors.

More details are given in [Annex A](#).

5.4 Manipulation

Mechanical scanning equipment provides the relative motion between the test article, the source and the detector. It makes no difference, at least in principle, whether the test object is systematically moved relative to the source and detector, or if the source and detector are moved relative to the test object. Physical considerations such as the weight or size of the test article shall be the determining factors for the most appropriate motion to use.

More details are given in [Annex A](#).

5.5 Acquisition, reconstruction, visualization and storage system

All CT systems will feature a data acquisition system to capture the sequence of projections (digital radiography images), control the sample manipulation and, in most cases, the X-ray source.

The projections will be passed on either during or after capture to a reconstruction system which is either integral with the acquisition unit or a separate standalone device.

Once the projections are received by the reconstruction system they are processed either simultaneously, or on completion of the scan, into a CT image. The CT image is then passed to a visualisation system for analysis.

Offline storage and archiving of CT images need to be considered.

For more details, see [Annex A](#).

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6 CT system stability (standards.iteh.ai)

6.1 General

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Because capturing CT projections can take some time, it is easy for external factors to influence the results. It is therefore important to site a CT system in a suitable location where the likelihood of encountering an external influence is minimised. The ultimate resolution of the CT system will dictate to what degree the equipment will need isolating, for example equipment working at the sub-micron level will be more easily affected than one working at the millimetre level.

These factors can take the form of natural environmental conditions, such as temperature and humidity, or man-made conditions, such as heat sources and vibration. Ideally, a high-resolution CT system should be located in a temperature and humidity controlled facility mounted on a vibration isolation rig, as with Co-ordinate Measurement Machines (CMMs), however this may not always be practical. Simpler solutions can include

- ensuring that the equipment is located on a solid floor which does not suffer vibration from foot or vehicle traffic or vibrations from machinery,
- locating the equipment in an area that does not experience large temperature fluctuations through the day while it is in use,
- mounting the equipment on vibration-damping feet,
- procuring equipment with temperature stabilisation systems or with a temperature compensated design (i.e. one that maintains positional accuracy over a small temperature range), and
- installing the equipment away from heat sources (boilers, radiators etc).

By carefully considering the location of where a CT system is installed it is possible to improve the quality of the results.