BS ISO 15708-2:2017

BSI Standards Publication

Non-destructive testing — Radiation methods for computed tomography

Part 2: Principles, equipment and samples

National foreword

This British Standard is the UK implementation of ISO 15708-2:2017.

The UK participation in its preparation was entrusted to Technical Committee WEE/46, Non-destructive testing.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2017

ISBN 978 0 580 95775 8

ICS 19.100

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 March 2017.

Amendments/corrigenda issued since publication

Date	Text affected

INTERNATIONAL
STANDARD

ISO
15708-2

Second edition
2017-02

Non-destructive testing — Radiation methods for computed tomography —

Part 2:
Principles, equipment and samples

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

Partie 2: Principes, équipements et échantillons

Reference number
ISO 15708-2:2017(E)

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ISO copyright office
Ch. de Blandonnet 8 • CP 401
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
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Foreword

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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 (μA/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 μm to display an image of a dense wire cross-hair made from wire less than 1 μm 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.

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.

6 CT system stability

6.1 General

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.

6.2 X-Ray Stability

Computed tomography requires a very high degree of positional accuracy and consistent imaging results; there are many factors that can influence these essential requirements, not least of which is the stability of the X-ray source.

Ideally, for the best CT results the X-ray source needs to produce an X-ray beam of consistent: intensity, focal spot size and focal spot position.

The recommendations of the X-Ray source supplier to produce a stable X-ray beam shall be followed.

It is possible on some CT systems for the intensity of the captured image to be adjusted during image capture and processing to accommodate small changes in X-rays intensity during the scan.

6.3 Manipulator stability

Precision, repeatability and stability are critical elements that must be considered when specifying sample manipulation equipment for CT systems. It is therefore essential that the positional accuracy of the manipulator in all axes relevant to the CT data (i.e. magnification, horizontal, vertical and most importantly, rotational) can repeatedly position the sample to within at least 1/5th of the ultimate resolution of the CT system. So for example a system that is capable of producing a 3D CT volume with a 5 µm voxel size from 3 000 projections; the linear axes need to be capable of positioning the sample to within 1 µm and 1/15 000th of a full revolution of the rotational stage.

At high resolution, the relationship between the X-ray source, detector and manipulator throughout the duration of the CT scan must be considered. Any movement in the complete system can affect the quality of the results, and therefore its impact needs to be carefully considered.

For small samples, the accuracy and stability of the manipulation will often limit the ultimate resolution obtainable in the CT image.

7 Geometric alignment

For accurate reconstruction, it is important that the position and orientation of the rotation axis and detector with respect to the source are correctly represented in the reconstruction process. Usually the rotation axis is parallel with one of the detector axes and the central ray passes through the rotation axis to the centre of the detector perpendicular to the detector.

Depending on the complexity of the reconstruction algorithm, compensation for known misalignments may be possible; an offset in the centre of rotation can normally be accommodated (especially in nano-tomography due to the impracticality of alignment to the required precision).

Tilt of both the rotation axis and detector can be accommodated in the reconstruction, though this requires more computational power and is not typically implemented in commercially available systems. Partial compensation for a small amount of tilt may be implemented by adjustment of the rotation axis position in relation to the slice height, but this is only an approximation and accurate alignment is the preferred solution. The alignment precision for tilt depends on the dimensions of the projection image in terms of numbers of pixels.

For the purpose of mathematical compensation, or to provide feedback for mechanical adjustment, it is necessary to have a test procedure to quantify the alignment (see also ISO 15708-4:2017, 5.3). This should include measurements of tilt and position of the rotation axis and detector with respect to the source. Such a procedure may be implemented by the supplier, either during system commissioning only or as part of the regular service schedule for the system. Alternatively, alignment checks and adjustment could be carried out by the end user, however this would require the supply of an appropriate test piece, or pieces, together with adequate training and instruction.

8 Sample considerations

8.1 Size and shape of sample

The size and shape of the object that can be scanned depends on a number of factors. The object should not be so small that the focal spot size limits the resolution obtainable and should not be so large that the maximum energy of the radiation source will not penetrate it sufficiently at all angles.

For best results, the object should also have a small aspect ratio: an ideally shaped sample is a cylinder. Furthermore, complete CT reconstruction requires at least 180° plus the beam angle of the radiation source to be scanned. Therefore, sufficient rotational motion of the object must be possible.

In some instances, object geometry or attenuation limit the angular range in which data from all parts of the object can be acquired. CT images from such CT scans can contain artefacts due to the parts of the object which were not imaged at all angles.

8.2 Materials (including table voltage/thickness of penetration)

Nominal thicknesses in mm for various materials where 10 % transmission can be achieved at a number of different X-ray accelerating voltages are shown in Table 1. Typical X-ray spectra were derived from Monte-Carlo calculations ([1],[2] for voltages up to 300 kV). X-ray attenuation spectra were obtained from the XCOM database at the National Institute of Standards and Technology. A Caesium Iodide (CsI) scintillator has been used for accelerating voltages up to 225 kV, above that Gadolinium Oxysulphide (GADOX) has been used as the scintillator material. It is worth noting that while there is little appreciable difference in attenuation when using a 10 mm thick Cadmium Tungstenate ($CdWO_4$) scintillator, in place of GADOX, although more photons are detected.

As described in 5.1, 10 % transmission is recommended to give an optimal SNR in the CT image. However, useable data can be generated using less transmission, thus allowing greater thicknesses to be inspected. Increasing the acquisition time can often compensate for a reduced transmission, although the resultant images may be more prone to artefacts from beam-hardening and scatter.

The following table is intended only as an approximate guide to indicate total material thickness of a sample for optimal imaging in different X-ray systems, NB consideration should also be given to cord length on curved geometries.

Table 1 — 10 % transmission thicknesses for various materials and energies

Materials	**10 % transmission thicknesses** mm				
	Accelerating voltage				
	90 kV	160 kV	225 kV	300 kV	450 kV
	Scintillation screen				
	100 µm CsI	150 µm CsI	200 µm CsI	300 µm Gadolinium Oxysulphide	500 µm Gadolinium Oxysulphide
	Filtration				
	0,25 mm Cu	0,5 mm Cu	2 mm Cu	1 mm Pb	3 mm Pb
Al	25	35	50	60	80
Fe	2	4	9	16	26
Ti	5	10	20	30	50
Pb	0,3	0,5	0,7	2	5
W	0,2	0,3	0,4	1,3	3,5
Ni	1,4	3	7	13	20

Table 1 *(continued)*

Materials	**10 % transmission thicknesses** mm				
	Accelerating voltage				
	90 kV	160 kV	225 kV	300 kV	450 kV
	Scintillation screen				
	100 µm CsI	150 µm CsI	200 µm CsI	300 µm Gadolinium Oxysulphide	500 µm Gadolinium Oxysulphide
	Filtration				
	0,25 mm Cu	0,5 mm Cu	2 mm Cu	1 mm Pb	3 mm Pb
Zirconia	1,1	2,4	6	15	30
PMMA	95	105	120	140	170
Water	100	115	130	150	200

Annex A
(informative)

CT system components

A.1 Radiation sources

A.1.1 Open tube X-ray sets

Typically, open tube sources are high-resolution and relatively low energy units used for smaller samples, which are not especially dense, requiring high-resolution imaging. The energy range for open tube sources normally falls within 0 to 225 kV and 0 to 3 mA (non-continuous with the voltage), although higher energy sets are becoming available capable of producing X-rays up to 450 kV.

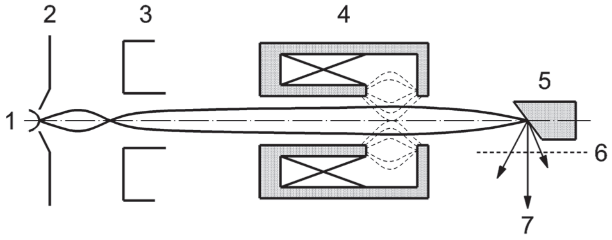
Most open tube designs are used for X-ray sets with a nominal focal spot size smaller than 100 µm in diameter. This type of source is often referred to as a microfocus X-ray set, or where the nominal focal spot size is less than 1 µm: a nanofocus X-ray set.

An open tube, like a sealed tube, X-ray set comprises of a high voltage generator coupled to an evacuated chamber housing a filament, a cathode assembly, an anode, magnetic or electrostatic lens (or lenses) and a target. The open tube differs from a sealed unit by featuring a vacuum chamber that can be opened to allow filament changes.

Because the vacuum chamber can be opened to atmosphere, an external vacuum system is required to pull the chamber down to a vacuum. Usually this system features a turbo-molecular pump (turbo-pump) mounted directly to the vacuum chamber and then a roughing pump (backing pump) connected through a vacuum gauge and pipe work to the chamber. The roughing pump is used to pull the initial vacuum down on start-up, once a pre-determined vacuum level is sensed by the gauge, around 102 mbar, the turbo pump is activated to pull the vacuum down further and maintain it, while the equipment is powered up, at around 10-4 mbar, meanwhile the roughing pump switches to becoming a backing pump to evacuate the exhaust from the turbo pump.

As already mentioned, the vacuum chamber can be opened to allow filament changes, to achieve the very small focal spot size a fine tungsten wire, or in some cases a lanthanum hexaboride (LaB_6) crystal, filament is used. These filaments are driven very hard and as a result fail requiring replacement, this is why an open tube is necessary. Typically a tungsten wire filament can last up to 250 h of X-ray “on” time, and a LaB_6 crystal 6 000 h or more, however their life span is entirely dependent on the operating conditions. The filament is precisely located in the centre of a “focus cup” which is in fact the cathode assembly.

To generate the X-rays, a current demand (µA/mA) is placed upon the filament causing the emission of a stream of electrons, at the same time a potential difference (kV) applied between the cathode and anode accelerating the electrons. The electrons are accelerated between the cathode and anode, passing through a hole in the centre of the anode and down a beam tube which is surrounded by a magnetic lens. This lens focuses the electron beam to the required size on a metallic target material; the resulting atomic level interactions between the incoming electron beam and the electrons within the target material generate X-rays.



Key

1	filament
2	cathode assembly
3	anode
4	magnetic lens
5	water or air cooled reflection target with choice of materials
6	vacuum envelope
7	X-rays

Figure A.1 — Simplified schematic of an open tube X-ray set

A.1.2 Sealed tube X-ray sets

Sealed tube X-ray sets operate in essentially the same way as an open tube with the exception that the vacuum chamber is, as the name suggests, a sealed vessel. This of course means that it is not possible to change a filament or the target material when they eventually fail, requiring a replacement tube or ‘insert’, in most cases the tube housing can be retained and a replacement tube fitted.

Since it is not possible to change the filament in a sealed unit, larger diameter wire is normally used, and the electron beam is not focused as tightly on the target material which also cannot be replaced. This results in the nominal focal spot sizes for sealed tubes being larger (typically greater than 250 µm) than for open tubes, however they can be run at considerably higher power settings.

Sealed tubes are often used for imaging larger or denser samples where penetration is of greater importance than ultimate resolution. Typically, sealed tubes are available in the energy ranges from 0 to 450 kV and 0 to 60 mA (non-continuous with voltage), however even higher energy sealed tubes are in development.

There are of course “microfocus” sealed tube X-ray sources, however to achieve their small focal spot size and a reasonable tube life they run at very low powers compared to the equivalent open tube source.

A.1.3 Linear accelerators

Although not used as commonly as open and sealed tube X-ray sources, a linear accelerator (or linac) is another X-ray source used for industrial CT where very high energies are required, usually on dense materials.

Commercial linear accelerators are typically available in energy ranges from 1 MeV to 16 MeV with a nominal focal spot size less than 2 mm. Beam adjustments are not incremental like conventional X-ray sets, instead a linear accelerator will have a few pre-set energy values (for example, 3 MeV and 6 MeV) which will have a known dose, from which the desired exposure time can be calculated.

To produce the high energy X-ray beam a linear accelerator uses a radio frequency wave guide, rather than potential difference, to accelerate electrons fired from an electron gun at a target (tungsten again being the most common target material). The target is heavily shielded and features a collimated aperture to ensure minimal secondary X-ray emissions from the set and a clean primary beam.

A.1.4 X-ray target assemblies

A.1.4.1 General

There are two main types of target assembly used on both open and sealed tube X-ray sources: transmission and reflection.

A.1.4.2 Transmission targets

With a transmission target the electron beam is focused on a thin target material closely coupled or bonded to the output window of the tube. Interactions are kept to a small area on the target and with thin materials for both the target and output window the inherent filtration is also minimised.

Transmission targets give the smallest focal spot sizes and, because the focal spot is so close to the output window, the highest geometric magnifications are possible. However the intensity of the x-ray beam is low as power has to be kept down due to limited cooling available to the target material, cooling is normally by convection using forced air or a heat exchanger.

A.1.4.3 Reflection targets

The electron beam is focused on an angled block or a rod of target material, the interactions take place on or very close to the target surface and the resultant X-ray beam is emitted from the same side as the electron beam and then out through an output window.

Because the target material is directly cooled, typically via forced air, re-circulating chilled water or oil, far greater energy can be put into the electron beam.

Although the focal spot from a reflection target is larger than a transmission target and the stand-off between the position of the focal spot and sample will be greater (reducing geometric magnification) the intensity of the X-ray beam is far greater and in a more defined cone.

Reflection targets also suffer from less inherent filtration that transmission targets because the X-ray beam need only pass through the output window, not the target material as well. This makes sources using reflection targets more suitable for low energy inspection of less dense materials.

A.1.4.4 Other target types

Besides reflection and transmission targets, open tubes have other interchangeable target designs available to them, some of which are of interest to the CT user. Target assemblies such as high speed rotating anodes allow an increase power capability of open tube while retaining a very small focal spot.

A.1.4.5 Target degradation

Regardless of target type or material, eventually the area on the target material where the electron beam is focused will develop a ‘pit’ where the material has been evaporated off as plasma. When a pit forms, the focal spot size will increase. In the case of sealed tubes, this can only be remedied by replacing the tube. An open tube has the advantage of allowing the target material to be replaced or, in some cases, indexed to a new position.

A.1.4.6 X-ray target materials and filtration

Nearly all industrial sealed and open tube X-ray sets use tungsten for their target material as standard, it is unusual for sealed tubes to use other metals. However, on the more specialised open tube based systems targets made from another metals are quite often found.

Alternative metals to tungsten can be used to provide different characteristic X-rays to improve low energy inspection on low attenuating samples.

All X-ray sets feature some inherent filtration from the target material and output window, however by adding additional external metal filters in the form of thin sheets of known thickness it may be possible for the user to improve image quality.

The use of characteristic X-rays and the effects of filtration are beyond the scope of this document, however users should be aware of the possibility of using them.

A.2 Detectors

A.2.1 Ionization detectors

In these, the incoming X-rays ionise a noble element that may be in either a gaseous or, if the pressure is high enough, liquid state. The ionised electrons are accelerated towards an anode by applying an electric potential, where they produce a charge proportional to the incident signal. Ionisation detectors used in CT systems are typically operated in a current integration rather than pulse counting mode. In some implementations of the technology, charge amplification can also be engineered. Ionisation detectors are rugged and amenable to different implementations. A single detector enclosure can be segmented to create linear arrays with many hundreds of discrete sensors. Such detectors have been used successfully with 2 MV X-ray sources and promise to be useful at higher energies as well.

A.2.2 Scintillation detectors

These take advantage of the fact that certain materials possess the useful property of emitting visible radiation when exposed to X-rays. By selecting fluorescent materials that scintillate in proportion to the incident flux and coupling them to some type of device that converts optical input to an electrical signal, sensors suitable for CT can be engineered. The light-to-electrical conversion can be accomplished in many ways. Methods include phosphor screens coupled to photodiodes or to photomultiplier tubes and image capture devices (i.e. charge coupled devices (CCDs), video systems, etc.). As with ionisation detectors, scintillation detectors offer considerable design flexibility and are quite robust. Scintillation detectors are often used when very high stopping power, very fast pulse counting, or 2D sensors are needed.

Digital detector arrays (DDAs), also known as “flat-panels”, using amorphous silicon plates (Si-A) and a scintillator (generally Gd_2O_2S or CsI) have become popular with active areas up to 400 mm× 400 mm. Their use in tomography requires the same precautions and calibrations (offset, gain and defective pixel correction) as with the other detectors.

There is a relatively large amount of scattered radiation when using flat panels; and this for two reasons. First, the use of the detector’s wide 2D field is incompatible with narrow collimation of the beam. Also, the detector’s structure creates a certain amount of back scattering. This can be a problem when high energy X-rays are used.

Compared with linear detectors, flat screens are used to rapidly acquire all the two-dimensional projections required for object volume tomography.

A.2.3 Semiconductor detectors

These are 2D detectors (panels) that directly convert incident radiation into electrical charge, using semiconductors like selenium or cadmium telluride.

Direct conversion has the advantage of avoiding light scattering in a scintillator, which therefore improves image resolution.

A.3 Manipulation

To produce a sequence of radiographic images for reconstruction into a 2D Slice or 3D CT Volume requires some form of movement; either of the sample, the X-ray/Imaging or a combination of the two. In most cases, the movement will be rotational about an axis that is perpendicular to the primary X-ray beam. Other techniques exist, however these are bespoke solutions to unique problems not suitable for coverage in this document.

A sample will either be placed upon a turntable stage and rotated while projections are captured at regular increments or, alternatively, the X-ray source and detector will be rotated about the sample under inspection capturing the projections. Depending upon the requirements of the CT reconstruction algorithm, the rotational movement will go through half, one or several revolutions during the projection acquisition sequence.

In addition to the rotational movement, some CT systems add a random linear motion across the X-ray beam during acquisition (a technique that is sometimes known as “jittering” or “shuttling”). The distance and direction of this movement is very precisely recorded so that the captured projections are re-aligned during their flat field and distortion correction sequence. This random movement is used to help reduce artefacts caused by regular defects in the X-ray detector. Another mechanical method used to reduce artefacts is to perform a ‘continuous rotation’ acquisition cycle, here the rotational movement is not in incremental steps but a continuous very slow rotation, with the read out time of the detector determining the incremental position for reconstruction.

Most industrial CT systems have a horizontal X-ray axis, however vertical axis machines are also in use. These either work like a medical CAT (computed axial tomography) scanner, with the X-ray source and detector rotating about a sample that is lying in a horizontal plain, or have a sample holding system on the vertically mounted rotational stage to secure the sample in place. Vertical axis CT systems with rotational sample stages tend to be limited to smaller samples that can easily be secured to the stage.

Where a CT system features a linear array X-ray detector an additional movement axis is required that allows the height of the sample to be adjusted about the rotational axis. This allows the slice position to be adjusted or moved incrementally when producing a data set for reconstruction in 3D.

A.4 Acquisition, reconstruction, visualization and storage system

A.4.1 Acquisition system

On a CT system data acquisition is usually handled by the main control unit for the entire system. This normally takes the form of a computer, on which a software package developed by the system manufacturer runs controlling all aspects of the CT system and providing an operator interface. From this interface, the user will have access to the various controls necessary to operate the machine; namely the X-ray controller, manipulator and imaging, as well as automated controls to carry out a CT scan and in some cases reconstruction. In addition to computer-based controls, some systems also feature manually operable ‘joystick’ controls for the individual manipulator axes, signals from these joysticks will be routed through the control software to ensure that it is aware of the manipulator position at all times.

Depending upon the control software, the operator will either set the X-ray, manipulator and imaging parameters themselves before engaging the CT scan, choose a pre-programmed CT scan sequence (for repeated inspection of identical components) or launch an automated sequence to find the ideal parameters and then start the scan.

The information necessary for reconstruction shall be recorded. This includes the position of the sample stage, X-ray settings, file names for the correction and CT projections, voxel sizes, number of projections, angular increment, etc.

A.4.2 Reconstruction system

The reconstruction software can be installed on the acquisition system computer or on a dedicated reconstruction computer (or cluster/network of computers). The computer(s) reconstructing the CT projection into a CT image will require large amounts of memory, processing power and storage space devoted to the reconstruction process.

A.4.3 Visualization system

While many CT system manufacturers include simple slice viewing capabilities in their reconstruction software, few offer their own volume rendering software to display complete 3D CT images for analysis. Proprietary standalone visualisation software packages are often supplied for CT image display and analysis.

These software packages provide the user with the ability to inspect, section, segment and measure their data in a 3D format on conventional displays or with advanced 3D display equipment.

A.4.4 Storage system

CT projections and their reconstructed CT images occupy large amounts of storage space on computer media. As these can very quickly fill a computer, hard drive data management is important. The user needs to consider what and how much data to keep; how quickly this data will need to be retrieved and whether a formal data archive is required.

When considering what data to keep, it is up to the user to decide whether they wish to retain the raw CT projections, CT images only, processed results from the CT images or combinations of all three.

By retaining the raw CT projections, it is possible to reprocess data to verify conclusions or, as reconstruction technology advances, reprocess the data more effectively, test new algorithms or new hardware.

If only the CT images are retained, then re-assessment is limited by the resolution and regions covered by the original reconstruction or reconstructions.

Retaining resultant images takes up the least storage space, however it requires confidence in the original conclusions, that re-analysis of the data will not be necessary and that sufficient information was obtained.

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ICS 19.100

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