International Standard

ISO 15708-2

Third edition
2025-01

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 15708-2:2025(en)

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Published in Switzerland

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Foreword

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This document was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 5, *Radiographic testing.*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 138, *Non-destructive testing,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This third edition cancels and replaces the second edition (ISO 15708-2:2017), which has been technically revised.

The main changes are as follows:

— addition of normative references;

— correction of the vacuum level for activating the turbo pump in A.1.1;

— addition of photon counting as an example under semiconductors in A.2.3;

— editorial changes.

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

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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.

This document is applicable only to industrial imaging (i.e. non-medical applications) and provides a consistent set of definitions of CT performance parameters, including the relationship between these performance parameters and CT system specifications.

This document is applicable to industrial computed tomography.

This document does not apply to other techniques 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, *Non-destructive testing — Radiation methods for computed tomography — Part 1: Terminology*

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

ISO 15708-4, *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 terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

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 linear X-ray attenuation coefficients are displayed 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 volumes 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

Among the radiographic techniques, CT can be an excellent examination technique whenever the primary goal is to locate and quantify volumetric details in three dimensions. In addition, since CT 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, in which 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 separated from each other, preserving the full spatial information.

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

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 therefore 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. For known materials, the additional information can be used for improved discrimination or improved characterization.

4.3 Limitations of CT

CT is an indirect test procedure and absolute CT measurements (e.g. of the size of material inhomogeneities or of wall thicknesses) shall be based on a comparison with other absolute measurement procedures in accordance with 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 shall 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 in 4.4.1. See ISO 15708-3 for a more detailed description.

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 can correspond to a broad range of materials.

Furthermore, there shall be sufficient X-ray transmission (≥ 10 %, see 8.2) through the sample at all projection angles without saturating any part of the detector.

4.4 Main CT process steps

4.4.1 Acquisition

Multiple projections are systematically recorded during a CT scan: 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 acquired. The CT image quality can be improved by increasing the number of projections in a scan.

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. These corrections are applied to each subsequently acquired image of the CT data set. Some systems can be configured to enhance either the X-ray settings or 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 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 note 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 certain regions of larger objects, it introduces artefacts (due to incomplete data) which can sometimes be reduced by special processing.

Radiographic imaging, as used for CT examination, is always affected by noise. In radiography this noise arises from two sources:

a) intrinsic variation corresponding to photon statistics in the emission and detection of photons;

b) variations specific to instruments and processing used.

Noise in CT projections is often amplified by the reconstruction algorithm. In CT images, statistical noise appears as random variation superimposed on the CT grey value of each voxel, limiting the 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 techniques.

The reconstruction software can 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 specified 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 can 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 depend 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 data can be misinterpreted in this process step.

To highlight features of interest during visualisation, different digital filter operations can be performed. It is characteristic of all these operations 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 its 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 shall 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 technique (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 can be detrimental for specific measurement or analysis tasks, but can also 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 document.

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 (including any mechanical structures that influence 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. For example, in scanners designed for *in vivo* animal studies or for imaging large structures, the source and detector can orbit around the sample.

In most micro-/nano- or sub-micro-tomography systems, the resolution is determined primarily by the X-ray focal spot size. Due to geometric magnification, the detector element spacing can be much larger than the computed voxel size, and a thicker and therefore more efficient scintillator can be used. A disadvantage of this approach is that the sample should be located very close to the source in order to achieve high magnification ratios. This is particularly problematic 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 can be optimised for resolution, energy, speed of acquisition or simply cost. Although a particular system can operate in a wide range of conditions, it will operate optimally in a much smaller range and the user should consider the main application when choosing one model over another and not simply over-specify.

For example, a high-resolution CT system (small X-ray focal spot size) can have a considerably lower flux output at more modest resolution settings than one designed to operate at modest resolution only. 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.

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. The resolution and scan times depend on the X-ray exposure, i.e. the faster the scan, the worse the SNR, as well as 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 when the X-ray accelerating voltage is set so that approximately 10 % to 20 % transmission through the sample is achieved. If the transmission is too low, the low number of detected photons leads to excessive noise. Conversely, if the transmission is too high, the contrast) is too low. However, the SNR does not vary sharply with voltage, 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 to 35 % or 40 % transmission. For a given sample size, the X-ray exposure required to maintain a fixed SNR is proportional to the fourth power of resolution (for a given detector). For example, doubling the resolution requires a 16-fold increase in exposure, while a 10-fold increase in resolution requires a 10,000-fold increase in exposure. Therefore, it is crucial to use the same or similar samples when comparing the image quality of one system to another.

5.2 Radiation sources

Most industrial CT systems use a high-voltage generator driving the X-ray source, which 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. The selection of a suitable X-ray source depends on the range of samples (size, composition and material density) to 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 varies depending upon the settings for voltage (kV) and current (µA/mA); the higher the power the larger the focal spot will become.

The 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 overall system to display an image of an object, or feature within an object, of a certain size. For example, it is 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 rather 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 scattering and beam hardening effects.

Further 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. These considerations mean that modern scanners tend to use large detector arrays that often contain several hundred to over thousands or millions of sensors.

Filtration at the detector using material inserted into the ray path in front of the detector (behind the test object) is helpfully. The filter absorbs (and scatters) radiation depending on its material characteristics, as specified in 5.1. In addition, each detector performs a certain amount of filtration when the rays pass through the detector housing. Additional filtration can be used to reduce the intensity of detected scatter.

Typically, three types of detectors are in use:

a) gas ionization detectors;

b) scintillation detectors;

c) semiconductor detectors.

Further details are given in Annex A.

5.4 Manipulation

Mechanical scanning devices ensure the relative movement between the test object, the source and the detector. In principle, it makes no difference whether the test object is moved systematically relative to the source and detector or whether the source and detector are moved relative to the test object. Physical considerations such as the weight or size of the test object shall be the decisive factors for the most suitable movement.

Further details are given in Annex A.

5.5 Acquisition, reconstruction, visualization and storage system

All CT systems are equipped with a data acquisition system that captures the sequence of projections (digital radiography images), controls the sample manipulation and, in most cases, the X-ray source.

The projections are forwarded either during or after recording to a reconstruction system which is either integrated into the acquisition unit or is a separate stand-alone device.

Once the projections are received by the reconstruction system, they are processed into a CT volume either simultaneously or after the scan is completed. The CT volume is then forwarded to a visualisation system for analysis.

Offline storage and archiving of CT volumes shall be considered.

For more details, see Annex A.

6 CT system stability

6.1 General

Because capturing CT projections can take some time, there is ample possibility for external factors to influence the results. It is therefore important to set up a CT system in a suitable location where the likelihood of external influence is minimised. The ultimate resolution of the CT system determines the extent to which the device needs to be isolated. For example, devices that work at the sub-micron level are rather affected than that 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 housed in a temperature- and humidity-controlled facility mounted on a vibration isolation rig, as with co-ordinate measurement machines (CMMs), however this is not always practicable. 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),

— 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

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

Ideally, for the optimum CT results, the X-ray source should generate an X-ray beam with constant intensity, focal spot size and focal spot position.

The recommendations of the X-ray source supplier for generating a stable X-ray beam shall be followed.

With some CT systems, it is possible to adjust the intensity of the captured image during image acquisition and processing to compensate small changes in X-rays intensity during the scan.

6.3 Manipulator stability

Precision, repeatability and stability are crucial factors that shall be considered when specifying sample manipulation devices for CT systems. It is therefore essential that the positioning 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 with an accuracy of at least 1/5th of the ultimate resolution of the CT system. A system capable of generating a 3D CT volume with a voxel size of 5 µm from 3 000 projections should therefore be able to position the sample to within 1 µm and 1/15 000th of a full rotation of the rotational stage.

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

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

7 Geometric alignment

For an 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, it is possible to compensate for known misalignments; 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 taken into account 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 can 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 mathematical compensation or feedback for mechanical adjustment, a test procedure in accordance with ISO 15708-4 shall be carried out to quantify the alignment. This should include measurements of tilt and position of the rotation axis and detector with respect to the source. Such a procedure can 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 can 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 to 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 has a circular cross section such as a hollow or solid 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 shall be possible.

In some instances, object geometry or attenuation limits 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 captured from all angles.

8.2 Materials (including a table of X-ray voltage versus 10 % transmission)

Nominal thicknesses in mm for various materials where 10 % transmission can be achieved at a range 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. For accelerating voltages up to 225 kV, a Caesium Iodide (CsI) scintillator was used; above this, Gadolinium Oxysulphide (GADOX) was used as the scintillator material. It is worth noting that when a 10 mm thick cadmium tungstenate ($CdWO_4$) scintillator is used instead of GADOX, there is hardly any appreciable difference in attenuation, although more photons are detected.

According to 5.1, a minimum transmission of 10 % is recommended to achieve an optimal SNR in the CT image. However, useful data can be generated with a lower transmission allowing the inspection of greater layer thicknesses. Lower transmission can often be compensated for by extending the acquisition time, although the resulting images may be more susceptible to artefacts due to beam-hardening and scattering.

The following table serves only as an approximate guide to indicate total material thickness of a sample for optimum imaging in different X-ray systems. The cord length on curved geometries should be considered, too.

Table 1 — Material thicknesses for 10 % transmission for various materials and X-ray voltages

Materials	material thicknesses for 10 % transmission mm				
	Accelerating X-ray 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
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 particularly 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), but higher energy devices are also available generating X-rays up to 450 kV.

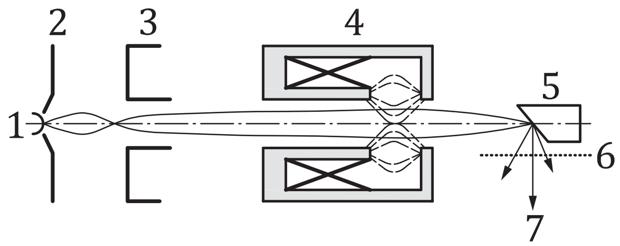
Most open tube designs are used for X-ray sets with a nominal focal spot size smaller than 100 µm in diameter. This type of source is often referred to as a microfocus X-ray set or, if the nominal focal spot size is less than 1 µm, a nanofocus X-ray device.

An open tube, similar to a sealed unit, consists of a high voltage generator coupled to an evacuated chamber housing a filament, a cathode assembly, an anode, a magnetic or electrostatic lens (or lenses) and a target. The open tube differs from a sealed unit by having a vacuum chamber that can be opened to allow filament replacements.

As the vacuum chamber can be opened to atmosphere, an external vacuum system is required to pull the chamber down to a vacuum. Usually, the system consists of a turbo-molecular pump (turbo-pump) mounted directly to the vacuum chamber and a roughing pump (backing pump) connected to the chamber via a vacuum gauge and pipe system. The roughing pump is used to pull the initial vacuum down at start-up, once a pre-determined vacuum level is detected by the gauge (about 1 mbar), the turbopump is activated to further lower the vacuum and maintain it at around 10^{-4} mbar, while the system is powered up; during this time, the roughing pump becomes a backing pump to evacuate the exhaust from the turbo pump.

As already mentioned, the vacuum chamber can be opened to allow filament replacements. 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 shall therefore be replaced, which 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, but their lifetime depends entirely on the operating conditions. The filament is located exactly in the centre of a “focus cup” which is in fact the cathode assembly.

To generate the X-rays, a current (µA/mA) is applied to the filament causing the emission of a stream of electrons, while at the same time a voltage difference (kV) is applied between the cathode and anode accelerating the electrons. The electrons are accelerated between the cathode and anode and enter a beam tube surrounded by a magnetic lens through a hole in the centre of the anode. This lens focuses the electron beam to the required size onto a metallic target material; the resulting interactions at atomic level between the incident incoming electron beam and the electrons in the target material generate X-rays. See Figure A.1 for a simplified schematic of an open tube X-ray set.



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 sets, except that the vacuum chamber is, as the name suggests, a sealed vessel. This means that it is not possible to change a filament or the target material if these fail at some point and require a replacement tube or 'insert'. In most cases, the tube housing can be retained and a replacement tube inserted.

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

Sealed tubes are often used for imaging larger or denser samples where penetration is more important than ultimate resolution. Typically, sealed tubes are available in the energy ranges from 0 kV to 600 kV and 0 mA to 40 mA (non-continuous with voltage).

There are also "microfocus" sealed tube X-ray sources, but to achieve their small focal spot size and a reasonable tube life, these are operated 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 when very high energies are required, usually on dense materials.

Commercial linear accelerators are usually available in energy ranges from 1 MeV to 16 MeV with a nominal focal spot size less than 2 mm. The beam is not adjusted incremental as with conventional X-ray systems, but a linear accelerator has some pre-set energy values (for example, 3 MeV and 6 MeV) with a known dose from which the desired exposure time can be calculated.

To generate the high energy X-ray beam, a linear accelerator uses a radio frequency wave guide instead of a potential difference to accelerate electrons that are fired from an electron gun at a target (tungsten is also the most common target material here). The target is heavily shielded and has 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

In a transmission target, the electron beam is focused onto a thin target material that is tightly coupled or bonded to the output window of the tube. Interactions are limited to a small area on the target, and with thin materials for both the target and the output window, inherent filtering is also minimised.

Transmission targets provide 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 shall be kept down due to limited cooling available to the target material. Cooling is normally achieved 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 resulting X-ray beam is emitted from the same side as the electron beam and then out through an output window.

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

Although the focal spot of a reflection target is larger than of a transmission target and the stand-off between the position of the focal spot and sample is greater (which reduces the geometric magnification), the intensity of the X-ray beam is much greater and in a more defined cone.

Reflection targets also suffer from less inherent filtration than transmission targets, as the X-ray beam only needs to pass through the output window and not the target material as well. Therefore, sources using reflection targets are more suitable for low energy inspection of less dense materials.

A.1.4.4 Other target types

Besides reflection and transmission targets, other interchangeable target designs are available for open tubes, 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, a ‘pit’ will eventually form in the area on the target material where the electron beam is focused, in which is vaporized as plasma. When a pit forms, the focal spot increases in size. 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

Almost all industrial sealed and open tube X-ray devices use tungsten for their target material as standard, other metals are uncommon for sealed tubes. However, on the more specialised open tube-based systems targets made from other metals are quite often found.

Alternative metals to tungsten can be used to provide different characteristic X-rays to improve the inspection of samples with low energy attenuation.

All X-ray devices have some inherent filtering by the target material and the output window. However, by adding additional external metal filters in the form of thin sheets of known thickness, it can 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, but users should be aware of the possibility of using them.

A.2 Detectors

A.2.1 Ionization detectors

In ionization detectors, the incoming X-rays ionise a noble element that can be in either a gaseous state or, if the pressure is high enough, in a liquid state. The ionised electrons are accelerated to an anode by applying an electric potential, where they produce a charge proportional to the incident signal. The ionisation detectors used in CT systems are typically operated in a current integration mode rather than pulse counting mode. In some implementations of the technology, charge amplification can also be engineered. Ionisation detectors are robust and can be used in various designs. A single detector housing can be subdivided into segments to form 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

Scintillation detectors 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 in relation to the incident flux and coupling them with a device that converts optical input into an electrical signal, sensors suitable for CT can be developed. 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.). Like 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 for two reasons. Firstly, the use of the detector’s wide 2D field is not compatible with narrow collimation of the beam. In addition, the detector’s structure leads to a certain amount of backscattering. This can be a problem when high energy X-rays are used.

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

A.2.3 Semiconductor detectors

Semiconductor detectors are 2D detectors (panels) that directly convert incident radiation into electrical charge (e.g. by photon counting), using semiconductors like selenium or cadmium telluride.

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

A.3 Manipulation

Creating 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 both. In most cases, the movement will be rotational around an axis that is perpendicular to the primary X-ray beam. There are other techniques, but these are customised solutions to unique problems not suitable that cannot be addressed in this document.

A sample will either be placed on 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