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abstract: This chapter aims to guide both specialists and nonspecialists in the use of radiography and its 3D corollary, tomography, for the technical investigation of the metal wall and interior of a bronze sculpture. Radiography is widely used among specialists studying bronze sculpture because it can reveal a great deal of information regarding production methods and previous restorations. In principle, bronzes can be radiographed regardless of their size or the nature of the alloy, but the amount that can be learned depends heavily on the experience of the operator of the radiographic instrumentation, and also on the experience of the researcher interpreting the results.

short\_title: Radiography and Tomography

Radiography is widely used among specialists studying %%bronze%% sculpture because it can reveal a great deal of information regarding production methods and previous restorations. **Figure 65** illustrates some of the many technical features of a bronze sculpture that can be observed using radiography. In principle, bronzes can be radiographed regardless of their size or the nature of the alloy, but the amount that can be learned depends heavily on the experience of the operator of the radiographic instrumentation, and also on the experience of the researcher interpreting the results.

This chapter aims to guide both specialists and nonspecialists in the use of radiography and its 3D corollary, tomography, for the technical investigation of the metal wall and interior of a bronze sculpture. Note that only radiography and tomography are dealt with in this chapter. Other techniques that may be applied to the study of the metal wall are dealt with elsewhere in the *Guidelines* (see [II.4§2.3.3](#II.4§2.3.3) for ultrasonic testing, [II.2§3.2](#II.2§3.2) for thermography, and [II.5§2.3.2](#II.5§2.3.2) for eddy currents).

The *interpretation* of radiographs is not the subject of this chapter, but some guidance in this respect may be found in relevant chapters of volume I. Here, the basic scientific principles of several radiographic techniques will be described, including X, gamma, and neutron radiography as well as X-ray and neutron tomography. Specific recommendations for working with bronze sculpture will be given with respect to both common examination methods as well as cutting-edge techniques. The advantages and drawbacks of available methods will be discussed, including costs and time requirements (see **table 13** for a summary). Given the large range of techniques available and their complexity, the descriptions of each technique are necessarily brief. For a synthesis, see **table 13**. For more detailed information, references to specialized literature are provided.[[1]](#endnote-1)

## 1 X-radiography

### 1.1 Scientific principles

Radiography is considered a nondestructive testing technique; normal application of radiographic techniques as practiced in the field of cultural heritage should pose no risk to objects.[[2]](#endnote-2) X-rays are, however, a form of ionizing radiation that can damage living tissues, and therefore the use of X-radiation is regulated in all countries, requiring appropriate safety training and controls. In addition, for bronze sculpture, an important consideration prior to radiography is that X-radiation exposure will interfere with subsequent trapped charge dating techniques—thermoluminescence (TL) and optically stimulated luminescence (OSL)—resulting in age estimates that are older than the actual age (see [II.8](#II.8)).

#### 1.1.1 Attenuation

A radiographic image is obtained by transmitting a beam of X-ray photons through an object. The transmitted X-rays are recorded by a detector placed at the rear of the object (**fig. 382**). Depending on the thickness of the object and the material from which it is made, the direct transmission of X-rays through the object is blocked, or attenuated, to a greater or lesser degree. Attenuation can be caused either by absorption or by scattering of the photons. Where X-rays pass through the object easily, the detector is strongly exposed, causing the image to appear dark. Where X-rays are more heavily attenuated, the image will appear light (only rarely is this convention inverted).

The actual attenuation of X-rays is dependent on two main parameters of the object being imaged. The type of atoms that compose the object (copper, lead, tin, iron, et cetera) greatly influences the attenuation. In general, the higher the average atomic number of the matter, the more attenuating it will be, so an object made of lead will be dramatically more attenuating that an object of the same dimensions made of aluminum.

The thickness of the object to be imaged also directly affects the attenuation of X-rays. Given two objects made of the same material, one twice as thick as the other, the thicker object will attenuate an X-ray beam twice as much as the thinner (**fig. 383**). Naturally, a porous object will attenuate X-rays less than a similar solid object, depending directly on the degree of %%porosity%%.

#### 1.1.2 X-ray energy

The attenuation of X-rays by an object is also dependent on the energy (or wavelength) of the X-rays used for imaging (**fig. 384**). Higher-energy X-rays are generally more penetrating than lower-energy X-rays. An X-ray tube may be set to produce X-rays at a range of energies. The tube is set to a certain energy level (expressed in kilovolts, or kV), which determines the maximum energy of X-rays produced (expressed in kiloelectron volts, or keV).

The nominal voltage setting may be somewhat misleading, since X-ray tubes produce a continuous spectrum of X-rays, with energies ranging from close to zero up to the nominal voltage setting. The dominant or average energy of the resulting X-ray beam will normally be between 25% and 50% of the nominal energy, with very little radiation actually being produced at the maximum level.

#### 1.1.3 X-ray sources

Most radiography for cultural heritage is conducted with X-ray tubes. Common industrial X-ray tubes have maximum nominal voltages of 100–450 kV (rarely up to 750kV). Conventional industrial X-ray tubes suitable for studying bronze sculpture are heavy and require large auxiliary transformers as well as circulating liquid cooling systems, making them difficult or impossible to transport for use in situ. Increasingly, portable X-ray tubes that are air cooled and can be plugged into an ordinary electrical wall socket are becoming available.

Also becoming available are pulsed X-ray systems that are compact and battery powered, and generate multiple short pulses of X-radiation (measured in nanoseconds), with maximum voltages approaching 400 kV. The short pulse length significantly reduces the health and safety hazard associated with their use, and their small size makes them suitable for in situ imaging. Unfortunately, the low total photon output of these generators means that they can only be used effectively with digital radiography (DR) detectors, and not with film or computed radiography (CR) systems (see below).

#### 1.1.4 Gamma and synchrotron radiography

In instances where conventional X-radiation is too limited in energy to penetrate high-density and/or thick artifacts (**figs. 385, 386**), gamma radiation may be used for imaging. Gamma rays are, like X-rays, photons of high-energy electromagnetic radiation, but are by definition produced by the decay of a radioactive source. For industrial gamma radiography, the two most common source materials are iridium-192 and cobalt-60. Radioactive sources have fixed, nearly monochromatic energy output. Iridium-192 has its primary gamma emission at around 380 keV, while cobalt-60 is at around 1,250 keV. Iridium-192 allows bronze statues with thickness of up to 5 cm to be examined,[[3]](#endnote-3) while Cobalt-60 will reach 10 cm. Contrast is rarely as good as for conventional X-ray radiography (**fig. 194**). For very thick objects, an alternative to gamma radiography is to use high-energy X-rays (6,000–30,000 keV) produced by linear accelerators or at larger particle accelerator facilities such as synchrotrons.

#### 1.1.5 Electron emission radiography

When exposed to high-energy X-rays (300–400 keV), secondary electrons are emitted by some of the atoms present in the upper surface layers of an artifact. The heavier the atoms present (that is, the higher their atomic number), the more intense the electron emission. These electrons may be collected on a film held in close contact with the surface; this is called electron emission radiography (**figs. 387, 388**). X-ray film is much more sensitive to electron exposure than to high-energy X-rays, so the dominant image produced on the film will reflect the distribution of heavy elements on the surface.

As opposed to transmission X-radiography, only the upper 50–100 µm of surface will contribute to an electron emission radiograph, and areas of higher density will appear darker rather than lighter. Electron emission may be used to great effect in imaging %%inlays%% of different metals (particularly silver or gold) in flat or very low relief objects such as bronze plaques (**fig. 389**).

Intimate contact between the film and the surface is required in order to limit the absorption of the emitted electrons by air. Since the film is pressed onto the surface, it cannot be used on fragile surfaces. Unfortunately, the preferred (single-sided) industrial films are not produced any more. CR plates are much less sensitive than film, and DR detectors are unsuitable for electron emission work.

#### 1.1.6 Detectors

Currently, three main types of X-radiographic detectors are in common use: silver halide film, CR plates or sheets, and DR detectors.

Film offers a wide range of sensitivity and very high resolution, and it is very easy to cut and bend in order to adapt to the different shapes and sizes of the objects. Exposure times are typically on the order of several minutes, though exposures measured in hours are not unheard of for large sculptures. Processing of film radiographs is relatively time and labor intensive, taking about ten minutes to develop a single sheet. Silver halide film is becoming somewhat more difficult to obtain, though a wide range of silver halide films are still produced for industrial radiography. The chemicals used to process film are becoming increasingly subject to regulation as pollutants.

CR uses photostimulable storage phosphor plates to record images. These plates may be housed in rigid cassettes or used as loose, flexible sheets similar to traditional film. First the plates are exposed, and the phosphor layer captures the energy of the incident X-rays. The plate is then inserted into a scanner that scans a focused laser across the surface, stimulating the release of the stored energy as light. The intensity of the luminescence at each point on the plate is recorded by an optical sensor, which generates a digital image. Scanning can take between one and ten minutes, depending on the resolution settings and the size of the plate. Plates can be erased and reused hundreds of times if well cared for. The range of sensitivity of CR systems is at least as good as film, while the resolution is not quite as good, with pixel dimensions of around 25–50µm. The plates are available in many sizes, including long strips around 35 cm wide and 150 cm (or more) long. They can, if necessary, be cut and bent like film. Exposure times are typically a quarter or half as long as film. Modern CR systems usually incorporate digital filters for edge enhancement and other image optimization tools. These tools can dramatically improve the visualization of subtle features in radiographs.

DR systems use fixed arrays of X-ray-sensitive pixels that send image data directly to a computer through a wired or wireless interface, where it can be captured, viewed, and saved in real time. DR detectors have a wide range of sensitivity, but overall sensitivity is much higher than with film or CR, resulting in much shorter exposures, often only one or several seconds. Averaging of multiple exposures is typically recommended to reduce noise. The short time needed to generate radiographs makes them easier for producing many different views of an object and facilitates the acquisition of short movies or image sequences that aid in the interpretation of complex three-dimensional forms (**figs. 121, 390**). With sufficient rotational precision, image sequences suitable for computed tomography (CT) can also be generated (see [II.3§2.1](#II.3§2.1) below). DR systems yield images with lower resolution than film or CR, with pixel dimensions on the order of 200 µm. The detector plates are manufactured in fixed sizes (typically from 2 × 2 cm up to a maximum of about 4 × 4 cm) and are housed in rigid cassettes that cannot be cut or bent. Most modern DR systems also include the same kind of digital image optimization filters that are found in CR systems.

Some DR systems utilize line-scan sensors that require an x, y displacement system to allow the complete scanning of the object. These detectors are often used for X-ray tomography. Their main advantage is a much lower cost than array detectors. Some systems also enable the scanning of much larger surfaces (100 × 100 cm versus around 40 × 40 cm) (see **table 15**).

#### 1.1.7 Controlling image quality: exposure time, current, and distance

Correct image exposure is normally obtained by adjusting the exposure time (usually expressed in seconds or S) and the tube current (expressed in milliamps or mA).[[4]](#endnote-4) The current determines the rate of X-ray production by an X-ray tube, or its brightness. The product of the current and the exposure time (mAS) determines the total quantity of photons emitted and is thus commonly used as a designation of overall exposure. The distance between the X-ray source and the detector has a strong influence on the time and current necessary for a proper exposure. Total exposure is inversely proportional to the square of the distance, so doubling the distance between source and detector requires that the exposure time (or current) be increased fourfold.

#### 1.1.8 Contrast

Contrast in a radiographic image can be controlled by adjusting the voltage setting of the X-ray tube. The higher the voltage, the lower the image contrast will be. As a general rule of thumb, select a voltage that is just above the minimum energy required to effectively penetrate the most attenuating region of the object.

#### 1.1.9 Sharpness: focal spot and distance

To guarantee maximum image sharpness, three main parameters may be adjusted: the distance from the detector to the object, the size of the X-ray tube’s focal spot (the area from which the X-rays are generated), and the distance from the focal spot to the object. The detector should be placed as close as possible to the area of interest of the examined object (**fig. 391** 3, 4), keeping the detector surface perpendicular to the beam (**fig. 391** 5, 6).

Very often the morphology of a three-dimensional subject does not allow close contact with all parts of it. Sharpness and depth of field can be increased by using a small focal spot. Depending on the model, the X-ray tubes may have different sizes of focal spots; the largest one allows the use of the entire power range of the tube, while with the smaller tube only the lower power range is accessible. The smaller the focal spot, the sharper the image (**fig. 391** 7, 8). Compensate for a consequent reduction in intensity by increasing exposure time.

To further increase sharpness, increase the distance between the X-ray source and the object (**fig. 391** 1, 2). This has the same effect on sharpness as shrinking the focal spot, and has the added benefit of reducing geometric distortion. The effective exposure will be reduced according to the inverse square principle, so exposure time will increase accordingly.

#### 1.1.10 Scattering

When making a radiograph, part of the X-ray beam is absorbed by the object and another part is transmitted to the detector to form the image. But at higher energies, a significant part of the beam is also scattered in all directions by the object itself and the room’s walls, floor, and ceiling. This generates fogging of the detector and a reduction in contrast (**fig. 392**). There are several strategies to reduce the effects of scatter. Lead shutters or a collimator may be placed in front of the X-ray source so that only the necessary area of the object is exposed by the beam, and X-rays that would fall outside the detector area are blocked. Lead sheeting several millimeters thick may also be placed immediately behind the detector and/or around the object to absorb the backscattered X-rays coming from the surroundings (walls, ceiling, floor).

#### 1.1.11 Filters and screens

The primary X-ray beam may be filtered at the source to selectively attenuate lower-energy X-rays, and thus increase the average energy of the output spectrum. This is usually accomplished using aluminum or copper filters from one to several millimeters thick. Such filtration reduces overall X-ray output (requiring longer exposures) but can increase the effective penetration of the beam and also reduce scattering to a certain degree by attenuating non-penetrating X-rays that still contribute to scatter.

At high-energy exposures, silver halide film may benefit from being inserted directly between two thin lead screens (around 50 µm thick). High-energy X-rays cause the lead to emit electrons, which exposes the film very efficiently, thus reinforcing or intensifying the image. These screens are frequently used with film and CR detectors for bronze objects (**figs. 37, 393**), but are not useful for DR detectors.

### 1.2 Application to bronze sculpture

#### 1.2.1 Configuration

Each sculpture is unique because of its shape, material, and facture. Thus, the geometric configuration of the X-ray source, the sculpture, and the detector must be optimized for each object, and unlike the case with medical or industrial applications, no preestablished protocol can or should be applied (compare for instance the operating conditions for three different bronzes as reported in **figs. 32, 37, 394**). The image obtained in an X-radiograph is the projection of a three-dimensional volume on a two-dimensional surface. The features present on many different planes are therefore merged, and determining the depth of any given feature can be very difficult.

To help locate features in three-dimensional space, it is therefore extremely helpful to make multiple images from different angles. A front view and a side view are the minimum for a radiographic study, while numerous views from different angles may be of great benefit. Complementary information will appear in the various images, leading to a clearer interpretation of the object. To aid in interpretation, it is very helpful to also have on hand high-resolution photographs taken from the same angle as the radiographs.

As a general rule, the larger the sculpture, the greater the optimal distance between the X-ray source and the object in order to minimize geometric distortion and enhance sharpness. For example, a distance of two meters is enough for a typical sculpture smaller than one meter. For a taller and broader sculpture, the X-ray tube might be positioned three meters from the object. If a complete radiograph of a medium-to-large sculpture is desired, limitations on detector size often make it necessary to make several successive exposures and stich them together to obtain a composite radiograph. Depending on the file size of each radiograph, stitched images can generate files of several hundred megabytes, requiring computers with adequate processing power.

When images are going to be stitched, the X-ray source and sculpture should stay in the same relative position for all exposures. The film or detector should then be moved for each exposure in an overlapping grid within a single plane perpendicular to the X-ray beam, and as close to the sculpture as possible.

#### 1.2.2 Optimizing image quality

In theory, one should use the lowest voltage possible as long as the X-ray can penetrate the object being studied. If the material is thin or if the metal is corroded, 250 kV or below may be sufficient (**fig. 394**). In practice, for most bronze sculptures, the variation in thickness will be significant and the contrast of the resulting radiographs will tend to be very high. As a result, voltages exceeding 250 kV are frequently required, often with significant beam filtration in order to reduce contrast and yield proper exposure in all areas of the image (**figs. 32, 395**). Steps to limit scatter should also be taken.

A trade-off when using very high voltages with beam filtering is that local contrast within relatively homogenous regions of the radiograph will be very low, making subtle details difficult to resolve. Advanced image filters used in CR and DR can compensate for this difficulty to some degree, but an alternative is to capture multiple images at lower voltage (higher contrast), exposing each to optimize exposure in different areas of the image. By using lower voltages on selected areas, small variations in thickness may be revealed. For objects with relatively thin walls, traces of hammering can be visualized by reducing the voltage (to less than 100 kV if possible), avoiding filtration, and working with long exposures and maximum tube current (**fig. 396**).

### 1.3 Cost and availability

The use of X-rays requires special infrastructure to contain the ionizing radiation. The walls of dedicated X-ray rooms are usually made of thick concrete sheathed with lead. Regulations for facilities and operator training vary depending on the relevant national and international agencies. X-radiography can also be carried out on-site with appropriate precautions. Here, too, detailed safety regulations will apply. For on-site work, the use of nanosecond-pulsed X-ray generators in conjunction with DR detectors offers significant advantages, since the total X-ray dose generated per image is reduced by many orders of magnitude.

A new installation of fully compliant X-ray facilities capable of imaging bronze sculpture will likely cost several hundreds of thousands of US dollars. If dedicated facilities are not available, private industrial radiography companies are often able to provide on-site mobile radiography services using tube radiation, pulsed generators, or isotope sources. The transportation, use, and control of isotope sources are all governed by specific rules defined by the International Atomic Energy Agency (IAEA).

Prior to using gamma radiography in the field, detailed compliance documents must be prepared in collaboration with the local authorities. The use of high-energy accelerator-based radiography is, of course, logistically and bureaucratically complex, involving transportation and security considerations as well as the preparation of a detailed research proposal to the relevant facility.

### 1.4 Possibilities for misinterpretation

The fact that all three distinct parameters contribute simultaneously to the attenuation of X-rays leads to possible misinterpretation of image density. For example, a 10 mm thick aluminum foil and a 3 mm thick bronze plate may yield similar gray levels. Conversely, two sheets of equal thickness, one of aluminum and the other of bronze, will appear with dramatically different gray levels on the picture (**fig. 388**). At the same time, two distinct materials may be difficult to distinguish if they have a similar atomic number. For example, pure copper and %%brass%% with 30% zinc will appear nearly the same if they have similar thicknesses (see also copper and steel in **fig. 388**).

The interpretation and identification of specific technological features in radiographs is also fraught with difficulties. Volume I contains numerous examples of clearly defined features, and the technical literature offers some additional guidance,[[5]](#endnote-5) but much still depends on the experience of the specialist in recognizing subtleties in the images and unraveling their meaning.

## 2 X-ray computed tomography (CT)

### 2.1 Scientific principles

X-ray tomography, also known as computed tomography (CT), is familiar to most from its medical application as so-called CAT scans. This technique generates a complete 3D model of an object, assigning a density value to each three-dimensional pixel, called a voxel. An X-ray tomograph is assembled by making a series of two-dimensional X-ray images as the object is rotated through 360 degrees (**figs. 121, 390, 397**). Each recorded image is called a projection. Traditionally, the number of projections needed to perform a workable tomography is calculated based on the size of the detector and the size of the object, with many hundreds of projections commonly required. The minimum number of projections is equal to the number of pixels occupied by the width of the object on the detector; the ideal number of projections equals the number of horizontal pixels in the image × Π / 2.[[6]](#endnote-6) Recently, a great deal of work has been done developing algorithms that can create reconstructions based on many fewer projections.[[7]](#endnote-7)

The set of projections is analyzed using sophisticated and computationally intensive computer algorithms in order to produce the final model. The results may be viewed as two-dimensional slices through the object at any desired angle, or voxels of similar density may be chosen for viewing, which allows a virtual three-dimensional view of selected components or features on the interior or exterior of the object. Tools for simple measurement (distance, angle, diameter; **fig. 398**) and for image processing with digital filters (noise reduction, sharpness, segmentation of different materials; **fig. 399**) are available. With advanced software, image analysis is possible (measurement of wall thicknesses, volume of porosity and inclusions, detection of %%defects%%, et cetera). The accuracy of these different tools obviously depends on the resolution of the initial set of projections.

### 2.2 Application to bronze sculpture

#### 2.2.1 Configuration

When making a tomographic reconstruction of a bronze sculpture, the subject should be positioned so as to present a minimum variation in thickness or density to the X-ray beam. It is often advantageous to angle the X-ray beam slightly upward or downward to avoid passing it directly through horizontal elements parallel to their long dimension. For example, outstretched arms or the tops of integrally %%cast%% bases can be very difficult to penetrate if the X-ray beam must pass through their length.

In tomography, the subject cannot come in contact with the sensor at any point in its rotation. This means that the bronze is often placed farther from the detector than in conventional radiography. Therefore, it is best to maintain a maximum distance from X-ray source to object as well as a small focal spot in order to maximize sharpness and minimize geometric distortions.

For conventional tomography, the bronze must appear entirely within the field of view of the detector on each projection to guarantee a satisfactory reconstruction. The size of the sensor (usually less than 50 × 50 cm for plane detectors) is thus a significant limiting factor for large works. It is possible to stitch together multiple radiographs into a series of larger projections, though this requires great precision and repeatability in the placement of the detector for each view.

#### 2.2.2 Optimizing image quality

In radiography, the parameters (voltage, intensity, exposure time) are adjusted for each shooting angle according to the thickness of the material to be X-rayed. In tomography, however, the shooting parameters cannot be changed during the scan. It is thus necessary to adjust the parameters to accommodate both the greatest and the least thickness encountered. To ensure penetration of thick parts and simultaneously avoid overexposure of thinner parts, very high voltage is often used and the beam is heavily filtered to further reduce contrast. Under these conditions, measures to reduce scatter are very important.

### 2.3 Cost and availability

Available CT equipment falls into two major categories: medical and industrial. Medical CT is generally limited in voltage to 160 kV or below, so industrial tomography equipment is typically used for most bronze sculpture. The size of the sculpture, the resolution needed, the thickness of the metallic wall, and the type of copper alloy are all considerations in determining the specific equipment required.[[8]](#endnote-8) Many of the same companies that provide on-site industrial radiography can also provide industrial CT services using tube or isotope sources.

Micro- and nanotomography, which use micro-focus X-ray sources to produce tomographic reconstructions of very high spatial resolution, are also available. These techniques are used mainly for the investigation of fine microstructures of small items (less than several centimeters in diameter).

It is also possible to configure an in-house CT system, particularly if a DR system is already present. Additional requirements would include a precision-controlled turntable with adequate weight capacity, a powerful computer, and tomography software.

The computer should be fast and have large capacity in order to view and analyze the tomographic reconstructions. The more pixels in the detector used, the larger the volume of data to be processed. The processing computer should have a minimum of 256 GB of RAM and be equipped with a powerful GPU (graphics processing unit) and CPU (central processing unit). An SSD (solid state drive) can also be advantageous to reduce the reconstruction time and also during the volume analysis process. A storage drive with capacity of several terabytes is needed for data backup. A number of commercial vendors supply software that can be used for tomographic reconstruction, and free open-source packages are also available.

In special instances, high-intensity and high-energy radiation generated at particle accelerator facilities may be used for creating tomographic reconstructions (**fig. 358**).

### 2.4 Possibilities for misinterpretation

The mathematical and physical complexity of tomographic reconstruction leads to many possibilities for the generation of “artifacts” in CT scans.[[9]](#endnote-9) Ring artifacts, beam hardening artifacts, and noise artifacts may appear to be features in the reconstruction, but are purely accidental products of the reconstruction algorithms. Working closely with an experienced CT interpreter is of great importance.

## 3 Neutron radiography and tomography

### 3.1 Scientific principles

Neutron radiography uses a beam of so-called thermal neutrons rather than photons to create radiographic images.[[10]](#endnote-10) A beam of thermal neutrons is typically produced at a nuclear reactor by slowing down, or moderating, the “fast” neutrons generated by nuclear fission, though radioisotopes may also be used as a neutron source. Whereas X and gamma photons interact with electrons, thermal neutrons are attenuated by either scattering or absorption by the nuclei of the atoms in the beam path.

Neutron radiography produces images that are fundamentally different than those of photon-based (X and gamma) methods (compare **fig. 400** with **fig. 401**). While X-ray attenuation is highly correlated with atomic number (larger and heavier elements such as lead block the transmission of X-rays more effectively than lighter elements such as aluminum), the attenuation of neutrons by matter is not dependent on atomic mass. Elements as diverse as hydrogen, cadmium, and mercury are very high attenuators, while sulfur, tin, and lead are nearly transparent (**fig. 402**).[[11]](#endnote-11) The extremely high attenuation of thermal neutrons by hydrogen means that organic materials or water are clearly visible in neutron radiographs while metal is relatively transparent. Neutron imaging is therefore complementary to traditional radiography.

Detectors for neutron radiography are usually made of two components: a conversion screen and a photon detector like that used for X-radiography. The conversion, or scintillation, screen (often made of a thin layer of gadolinium) converts the kinetic energy of the neutrons into visible or other radiation, which is then recorded on X-ray film or by a digital camera, CR plate, or DR detector.

Tomographic reconstructions from neutron radiographs are produced in the same manner as for X-ray tomography, with similar requirements for software and computational capability.

During neutron radiography, it is also possible to conduct neutron diffraction studies, which can characterize the structure of materials through their entire depth. This technique is described in [II.5](#II.5).

### 3.2 Application to bronze sculpture

Neutron radiography has two primary advantages for imaging bronze sculpture. First, very thick metal walls are easily imaged due to the low attenuation of neutrons by most metal elements. Second, neutron radiography can effectively image materials with lower density than the surrounding envelope. This is particularly true for organic materials inside of a bronze sculpture, as seen in the study of votive offerings in Tibetan Buddhist metal images.[[12]](#endnote-12) Metal objects such as silver, copper, and gold embedded in a denser material such as lead or tin may also be detected in this way (**figs. 403, 404**, see [Case Study 4](#CaseStudy4)). %%Core%% material may also be more effectively imaged with neutrons than with X-rays.[[13]](#endnote-13)

### 3.3 Cost and availability

The main drawback of neutron radiography is that so far, large-scale research facilities are required. Increasingly, certain facilities have promoted the use of neutron imaging and analysis for cultural heritage.[[14]](#endnote-14) In such cases there is often no fee per se for the imaging, but a lengthy application process may be necessary to secure the allocation of time and instrumentation at a reactor facility. Costs can, of course, be significant for transportation and security, and the administrative burden can be substantial.

Another serious consideration is that during imaging, atoms that absorb neutrons into their nuclei form radioactive isotopes that subsequently emit gamma radiation. These isotopes must be allowed to decay to safe levels before handling. Depending on the specific elements present and the length of exposure (tomography requiring significantly longer exposure than radiography), this period of quarantine may be several hours or days, or even longer, imposing additional cost and security considerations. Copper alloys are not usually subject to extended quarantine unless they contain substantial amounts of gold or arsenic. For example, no quarantine was needed for the Javanese statuettes discussed in [Case Study 4](#CaseStudy4).

### 3.4 Possibilities for misinterpretation

As with X-radiography, exposure to thermal neutrons will interfere with subsequent trapped-charge dating techniques (TL and OSL), resulting in age estimates that are greater than the actual age (see [II.8§1](#II.8§1)).

## Notes

1. For X-ray techniques, see in particular {Lang and Middleton 2005}. For neutron techniques see {Van Langh 2012}; {Chankow 2012}. [↑](#endnote-ref-1)
2. However, long-duration exposure to focused, high-intensity X-radiation has been shown to cause minor damage to organic materials such as wood ({Kozachuk et al. 2016}). [↑](#endnote-ref-2)
3. For example, the French sixteenth-century greater-than-life-size bronzes from Primatice at Fontainebleau, and Germain Pilon and Ponce Jacquio at Basilique de Saint Denis (Henri II and Catherine de Medici’s funerary monument), have been radiographed using an iridium source ({Castelle 2016}). [↑](#endnote-ref-3)
4. If rigorous optimization of image quality is desired, standardized image quality indicators (IQI), as are used in industrial foundries, may be used as a guide. See {Halmshaw 1995}, 146–60; {Ruault 1991}, 2:199–209. [↑](#endnote-ref-4)
5. {Mattusch 1996}; {Lang and Middleton 2005}; {Bassett 2008}. [↑](#endnote-ref-5)
6. {Buratti et al. 2016}. [↑](#endnote-ref-6)
7. {Sidky, Kao, and Pan 2006}; {Bian et al. 2010}. [↑](#endnote-ref-7)
8. {Plessis, le Roux, and Guelpa 2016}. [↑](#endnote-ref-8)
9. {Boas and Fleischmann 2012}. [↑](#endnote-ref-9)
10. For a thorough overview of neutron radiography see {Chankow 2012}. For general principles on neutron scattering and neutron reactors see {Bordenave and Mirebeau 2018}. [↑](#endnote-ref-10)
11. See {Halmshaw 1995}, 284–94. [↑](#endnote-ref-11)
12. {Mechling et al. 2018}; {Henss and Lehmann 2016}. For an overall view of the applications of cultural heritage see {Mannes et al. 2015}. [↑](#endnote-ref-12)
13. {Van Langh et al. 2009}. [↑](#endnote-ref-13)
14. For instance Paul Scherrer Institute in Villigen, Switzerland, and Budapest Neutron Centre. The Orphée reactor in Saclay, south of Paris, closed in 2019. The trend now is to produce neutron beams using high-voltage accelerators instead of nuclear plants. [↑](#endnote-ref-14)