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Radiography: theory

Andrew Middleton and Janet Lang

Introduction; types of radiation, safety; generation and properties of X-rays; objects and X-rays

INTRODUCTION

The cartoon reproduced as Figure 1.1 was published in the magazine *Life*, within a few months of Röntgen's discovery of X-rays. It is a typical manifestation of the excitement and public interest which his work provoked. However imperfectly, the public grasped that Röntgen had discovered a new way of 'looking' not just at objects but also through them. Of course, everyone knew that light passed through transparent and semi-transparent materials such as glass and paper; even a human hand gave a blood red

The new Roentgen photography
'Look pleasant, please.'

Figure 1.1. *Contemporary cartoon from* Life *magazine, February 1896.*

glow when held up to a strong light, but no details could be seen. Röntgen's first published pictures showed a hand, with the bones, flesh and a ring on one of the fingers, all clearly visible (Röntgen 1896). This was a totally new phenomenon. Within months, a beam of X-rays had been used to show up lead pellets accidentally shot into a New York lawyer's hand. The medical use of X-rays was launched. Archaeological applications also followed swiftly on Röntgen's discovery: a paper published by Culin in 1898 describes work carried out by Dr Charles Leonard to produce radiographs of a Peruvian mummy and other artefacts from the University of Pennsylvania Museum (see Chapter 7).

Nowadays we are quite familiar with the medical uses of X-rays; for instance, to image bones or to produce dental or chest X-rays (or, more correctly, chest radiographs). These illustrate several of the key characteristics of radiography – the images are life-size, denser regions, such as bone, stand out from softer tissues as lighter areas on a conventional film radiograph, and they contain information from the whole depth of the subject, from the ribs through to the spine on a chest radiograph. This means that all the internal features of the patient (or any other object) are superimposed on top of one another. This can sometimes result in radiographic images that are difficult to interpret. However, these difficulties arising from the projection of a three-dimensional subject onto a two-dimensional radiograph can usually be overcome, for instance, by recording radiographs from different angles or by the use of more sophisticated techniques such as stereo-viewing, real-time radiography or computed tomography (CT scanning) (see also Chapters 2 and 7).

Thus, radiography offers the possibility of obtaining a fascinating insight into the internal structure of objects as disparate as the human body and complex pieces of machinery. Given that this can be done without inflicting any damage to an inanimate object (the exposure of living tissues must always be carefully controlled, see Box 1.2), it is easy to appreciate why radiography is being used increasingly in the study of archaeological and cultural objects. It is capable of answering many questions about manufacture, function and state of preservation, sometimes providing information that is unobtainable by any other technique. The purpose of this chapter is to provide some technical background in order to indicate the scientific framework on which radiographic practice rests. It is hoped that this will also help to indicate the general potential and limitations of radiography in the study of cultural material, but these aspects will be discussed more fully in relation to particular materials and classes of artefact in the chapters which follow.

RADIATION USED IN RADIOGRAPHY

In addition to X-rays, several other types of radiation are used in radiography to produce images, including electrons, neutrons and γ-rays. Sources of all four types of radiation are discussed briefly in the following sections, although the main concern of this book is with the use of X-rays and also electrons for certain specialist applications.

Electrons

Electrons useful to the radiographer may be derived in two, rather different ways: from the decay of radioactive substances, and from the impact of high-energy X-rays on a heavy metal such as lead. Electrons produced through radioactive decay are known as β-rays or β-particles. Electrons are strongly absorbed by all materials, including air, and have very limited penetration: even the more energetic, such as those emitted by strontium-90 (2.25 MeV), are absorbed by 2–3 mm of aluminium foil. However, this lack of penetration can be used to good effect to radiograph thin, low-density materials. ^{14}C (carbon-14 or radiocarbon) sources have commonly been used. The radioactive ^{14}C may be incorporated in a sheet of Perspex or aluminium foil, and in this form it is convenient and safe to handle provided rubber gloves are worn. Sources are usually supplied with their own shielded containers, but a ^{14}C source can be stored in a secure lockable metal box (e.g. a suitably sized cashbox) as it does not require lead shielding. β-radiography is ideal for imaging thin, flat materials such as paper, where a good contact can be maintained between the sheet or foil source and the subject (see Chapter 5).

Electrons are emitted when some heavy metals, like lead, gold or cadmium, are irradiated with a high-energy X-ray beam and, when generated in this way, are utilized for two different radiographic methods. The electrons emitted during the irradiation of a thin lead foil can be used to make electron radiographs of paper and similar materials, providing an alternative to the use of β-rays. This technique, electron (transmission) radiography, is described in

Chapter 5; an early account of the method was given by Tasker and Towers in 1945. The second application, electron emission radiography (sometimes referred to as autoradiography), can be used where an artist has employed paints or pigments containing heavy metals: a high-energy X-ray beam causes electron emission from the areas covered with the heavy metal paints or pigment. The image of their distribution can be recorded on an X-ray film (see Chapter 5). This technique has also been used to image other flat subjects such as the designs on corroded medieval glass (Knight 1989) and a painting on copper (Bridgman *et al.* 1965). A third use of electrons occurs when lead screens are employed as intensifiers, increasing the contrast range of radiographs.

Neutrons

The possibility of using a neutron beam in radiography was realized only 3 years after Chadwick discovered the neutron in 1932, by Kalman and Kuhn, using a small accelerator source in Berlin (Matfield 1971). From the viewpoint of the radiographer of cultural material, the key property of thermal neutrons (those most-commonly used for radiography) is that they are more strongly absorbed by organic materials than by many heavier materials. This is the converse of X-rays and γ-rays (see below) and offers the possibility of revealing such details as the organic materials in scabbards or the fittings of iron blades (Masuzawa 1986; Tuğrul 1990; Rant *et al.* 1995). An example illustrating the usefulness of this property of neutrons is presented in Box 1.1 (see also Figure 3.3).

Box 1.1. Examination of a lead-wrapped bottle using neutron radiography

This item had been found in the Canadian west, in an area near Frog Creek. An incident of historical significance had occurred in the 1880s and an officer had recorded the details in two copies. He returned to Montréal with one copy, but placed the other in a bottle, which he wrapped with lead and buried.

Before unwrapping or opening the bottle, it was desired to verify the condition of the bottle inside the wrapping, as well as the seal and contents. X-rays are not, of course, very well suited to such an examination.

Neutron radiography was employed, in order to obtain contrast from the paper even behind the lead wrap. Figure 1 very clearly shows folded paper inside a glass bottle with the cork and wax seal askew. Based upon this evidence, the conservators decided not to open the bottle.

Rankin MacGillivray
Nray Services Inc., Canada

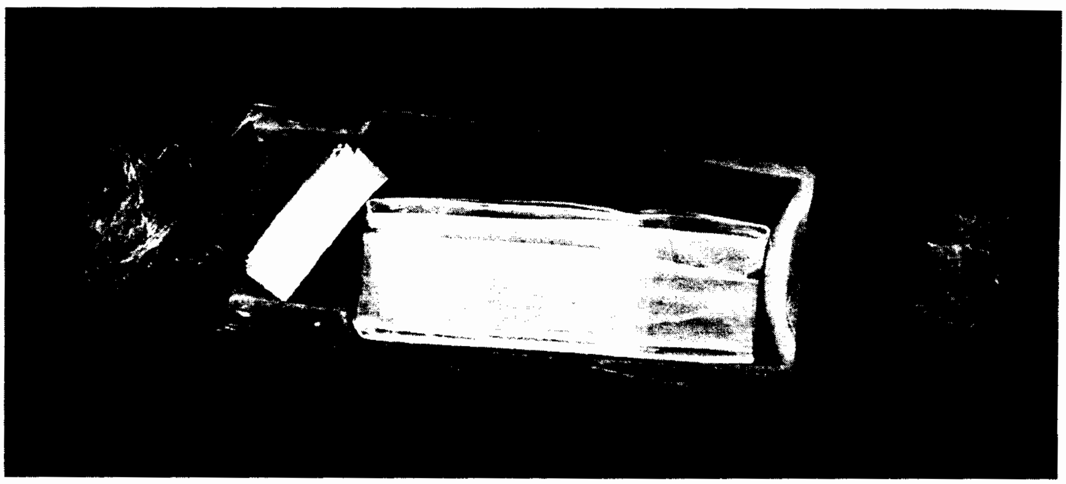

Figure 1. *Neutron radiograph of the lead-wrapped bottle, revealing the folded paper inside.*

However, the practical use of neutrons for radiography is inconvenient and is usually carried out at a specialist facility. A disadvantage is that short-lived radioactivity may be induced in the object which has been irradiated, necessitating safe storage after exposure.

γ-rays

γ-rays are a form of high-energy electromagnetic radiation (Table 1.1) emitted by radioactive materials during decay. Radium, first isolated by Marie and Pierre Curie in 1898, is probably the best-known naturally occurring radioisotope. However, most of the sources commonly used for radiography, such as ^{192}Ir (iridium-192) and ^{60}Co (cobalt-60), are made artificially. The γ-rays are emitted as line spectra of discrete energies and different relative intensities (Figure 1.2), which are characteristic of the particular source. The energies of γ-rays are very high and are usually quoted in million electron volts (MeV), for example the γ-radiation from a cobalt-60 source has energies of 1.17 and 1.33 (MeV). Radiation of this energy has considerable penetrative capabilities: it takes 13 mm of lead to halve the intensity of the γ-radiation produced by a cobalt-60 source. Halmshaw (1995, pp. 29–30) notes that the radiographic qualities of cobalt-60 radiation are equivalent to those of X-rays generated by a potential of 2300 kV: this may be compared with the maximum potential used in a typical industrial X-ray generator of 250 or 320 kV. The volt (V) is the SI unit of electrical potential difference, whereas the electron volt (eV) is a unit of energy. However, it is often convenient to refer to the 'energy' of the X-ray beam in terms of the potential (i.e. the kV) applied to the tube.

Table 1.1. The electromagnetic spectrum

Type of radiation	*Wavelength, λ (m)*	*Quantum energy*
Gamma rays	10^{-16}	12400 MeV
	10^{-15}	1240 MeV
	10^{-14}	124 MeV
	10^{-13}	12.4 MeV
	10^{-12}	1.24 MeV
	10^{-11}	124 keV
	10^{-10}	12.4 keV
	10^{-9}	1.24 keV
X-rays	10^{-11}	124 keV
	10^{-10}	12.4 keV
	10^{-9}	1.24 keV
Ultraviolet	10^{-8}	124 eV
	10^{-7}	12.4 eV
Visible spectrum	*c.* 5×10^{-7}	
Infra-red	*c.* 7×10^{-5}	

After Tennent (1971).

Three practical considerations distinguish γ- from X-radiation. Firstly, γ-sources are portable (subject to Health and Safety regulations), they can be operated without the electricity or cooling water required to run an X-ray generator, and are considerably cheaper to buy than an X-ray set. Secondly, γ-radiation is emitted continuously and cannot be switched off, which means that for reasons of safety γ-sources must be kept in special containers shielded with lead, tungsten alloy or depleted uranium in steel. When required for radiography, the source has to be removed from its container by a remote control mechanism. Thirdly, γ-sources gradually lose their activity with time, the rate of loss depending on the half-life of the radioisotope being used: for example, the intensity of a cobalt-60 source decreases to half its original value in 5.3 years, so that the source has a finite useful lifespan. Halmshaw (1995, pp. 52–74) provides a useful discussion on the use of γ-sources. However, the γ-ray sources most-commonly used (^{192}Ir and ^{60}Co) produce high-energy radiation which, unlike the output from an X-ray generator, cannot be controlled and, in general, yields radiographs with rather low contrast.

In view of these disadvantages, it is not surprising that γ-rays have rarely been used for archaeological or art-historical material. However, they have been employed for several high-profile projects where the use of γ-radiography offered particular advantages. In the late 1950s, a ^{24}Na (sodium-24) source was used to survey a fallen lintel stone at Stonehenge, to ensure that it was sound enough to be lifted back

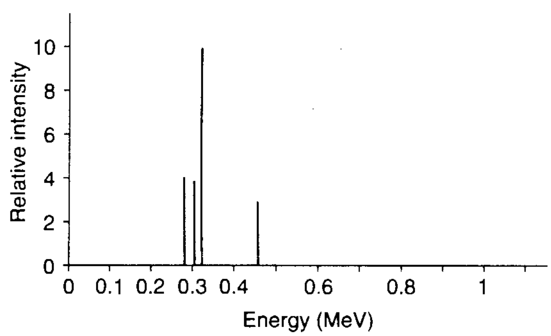

Figure 1.2. *Spectrum of an iridium-192 source.*

on top of two upright stones (Hinsley 1959). More recent examples include a study of a bronze statue of Napoleon in the Brera Gallery in Milan, using an ^{192}Ir (iridium-192) source (Canova 1990), and part of an extensive study of the Chimera of Arrezzo (Massimi *et al.* 1991), using cobalt-60. An iridium-192 source was used also in the study of large Classical bronzes carried out in connection with the Fire of Hephaistos exhibition (Mattusch 1996) when a 300 kV X-ray set did not provide adequate radiographs.

X-rays

X-rays, like γ-rays, are a form of electromagnetic radiation (Table 1.1); they are produced when fast-moving electrons interact with matter. The spectrum of X-rays obtained is, in fact, composed of two superimposed spectra: the characteristic or line spectrum of discrete energies and a general spectrum with a continuous range of energies (Figure 1.3). The characteristic spectrum is unique to the material being bombarded and therefore can be used in elemental analysis, but it does not play a major part in X-radiography. The continuous or 'white' spectrum, also known as Bremsstrahlung ('braking' radiation), arises from the energy released when fast-moving electrons are slowed down rapidly by passing through the electron field around an atomic nucleus. It is the continuous X-ray spectrum which is useful for radiography.

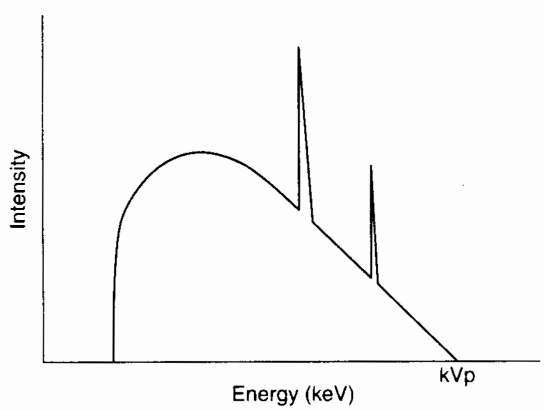

Figure 1.3. *Graph of X-ray intensity and energy showing the characteristic X-ray peaks of the target material superimposed on the general spectrum. kVp is the maximum (peak) kilovoltage. The effective energy of the spectrum will be one-third to one-half of the peak kilovoltage.*

X-rays are commonly characterized by their energy (E) or by their wavelength (λ). These properties are inter-related. In particular, energy and wavelength can be related by the expression:

$$E = hc/\lambda \qquad (1.1)$$

where h is the Planck's constant and c is the velocity of light. By substitution of the known values for h and c, the expression becomes:

$$E\ (\text{keV}) = 1.24/\lambda\ (\text{nm}) \qquad (1.2)$$

From this equation it can be seen that X-rays of higher energies will have shorter wavelengths. The X-rays with the shortest wavelength (λ_{min}) will be produced by the maximum kilovoltage applied to the X-ray tube (described below). This peak kilovoltage is sometimes referred to as kVp but more generally it is stated simply as kV. There is a sharp cut-off in the X-ray spectrum at λ_{min}: no X-rays of shorter wavelength are produced (see Figure 1.7).

Summary of the Properties of X-rays and γ-rays

X-rays and γ-rays have a number of characteristics:

- they are unaffected by electrical or magnetic fields;
- they travel in straight lines, at the speed of light;
- they penetrate matter and are more or less attenuated in the process, depending upon the material, its density and its thickness;
- they affect photographic films and cause some materials to fluoresce;
- they cannot be detected by human senses;
- they damage living tissues.

Safety

The use of ionizing radiation, as in radiography, is subject to stringent safety regulations (see Box 1.2). Health and Safety issues are also involved in working in workshops with electrical equipment and chemicals, and need to be addressed.

GENERATION OF X-RAYS

The basic equipment and arrangements needed to carry out radiographic examinations of cultural

Box 1.2. Health and safety

X-rays and γ-rays, along with other forms of radiation including β-rays and neutrons, are hazardous to health and each country has its own regulations for the use of ionizing radiation. Readers are strongly advised to familiarize themselves with the current directives and regulations in the country where they are working, always remembering to keep up to date with any changes which may be introduced. The UK regulations are subject to European Union (EU) Directives and therefore similar to those of other EU countries, but it is essential to check in case there are local differences. In the USA, the OSHA (Occupational Safety and Health Administration), part of the Department of Labor, is the relevant organization. Standards for equipment in the USA are set up by the US Food and Drug Administration Centre for Devices and Radiology Health (21 CFR-1020.40). The Internet is a useful source of information.

Radiographic work in the UK is currently governed by the ***Ionizing Radiation Regulations 1999 SI 1999 3232*** which are based on a revision of the EU Basic Safety Statute. The ***Radioactive Substances Act 1993*** may also apply. The Regulations are *Statutory Instruments* and therefore have legal status. The Regulations lay down the rules under which radiography can be carried out and cover the responsibilities of employers and employees. The provisions must be obeyed by all those who are involved in radiography, even as visitors. They are administered by the *Health and Safety Executive* (HSE) which is part of the Department of the Environment, Transport and the Regions (1999). http://www.legislation.hmso.gov.uk/

The Regulations are set out and their implementation is explained in the *Approved Code of Practice*. This document also has legal status and gives practical advice on how to comply with the law.

The *Regulations* and *Code* cover all aspects of the use of ionizing radiation. This includes the initiation, arrangement and monitoring of equipment and facilities, the appointment of Radiation Protection Advisors (RPAs), the provision of Local Rules, dose rates, the monitoring of staff exposure to radiation, the responsibilities and duties of management and operating staff, training and record keeping. It is important to remember that the appointed RPA should be informed and consulted about changes in working practice or equipment or the undertaking of any new work.

The disposal of waste (e.g. radiographic/photographic chemicals and lead, as well as radioactive sources) is also a health and safety matter and must be dealt with according to the current safety regulations, which will also include directives on all matters relating to health and safety, including, for example, working in reduced lighting (i.e. under safelights or in complete darkness).

material are shown schematically in Figure 1.4. Essentially, these comprise a source of X-rays, some means of supporting and perhaps manipulating the object, and a means of observing and recording the radiographic image that results from directing the beam of X-rays through the object.

A modern X-ray set comprises several essential parts which enable it to produce an X-ray beam reliably and on demand. At its heart is the X-ray tube; also required are a control unit and a suitable cooling unit, the nature of which is dictated by the power of the X-ray set.

X-ray Tubes

The X-ray tube shown diagrammatically in Figure 1.5 has a number of necessary features:

1. The source of electrons is usually a wire filament in the cathode, heated to incandescence by a low-voltage electric current (measured in milliamps, mA), causing it to emit a steady stream of electrons.
2. The potential applied between the cathode and the anode accelerates the electrons towards the target; the magnitude of the potential (or accelerating voltage) is usually expressed as kilovolts (kV).
3. The X-rays are produced at the target, which is embedded in the anode. The target is usually made of tungsten because it is an efficient source of high-energy X-rays. It is also a refractory element with a high melting point (3410°C). This is an important consideration because most (typically about 99%) of the energy applied to the tube is converted into heat, mainly at the target. Molybdenum is used as the target in some medical X-ray tubes as it produces a greater X-ray intensity at the lower energy end

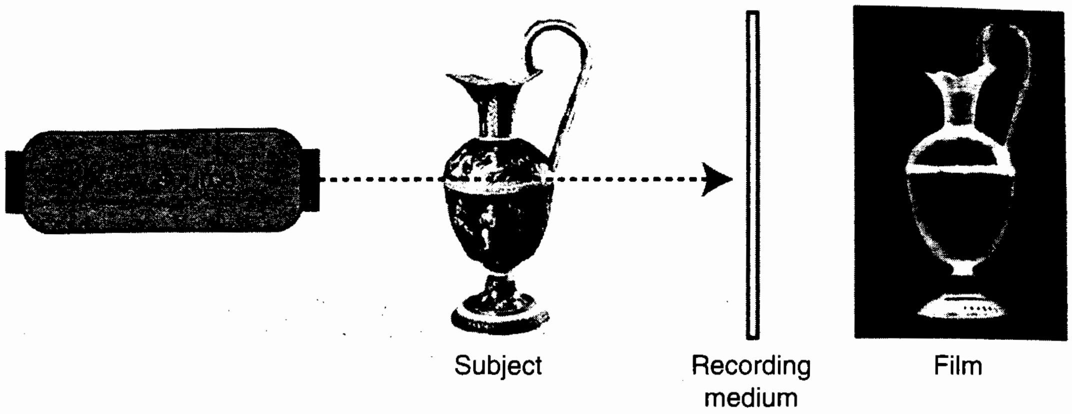

Figure 1.4. *Schematic representation of the radiographic process, with a radiation source, a subject and a means of recording the image (e.g. film).*

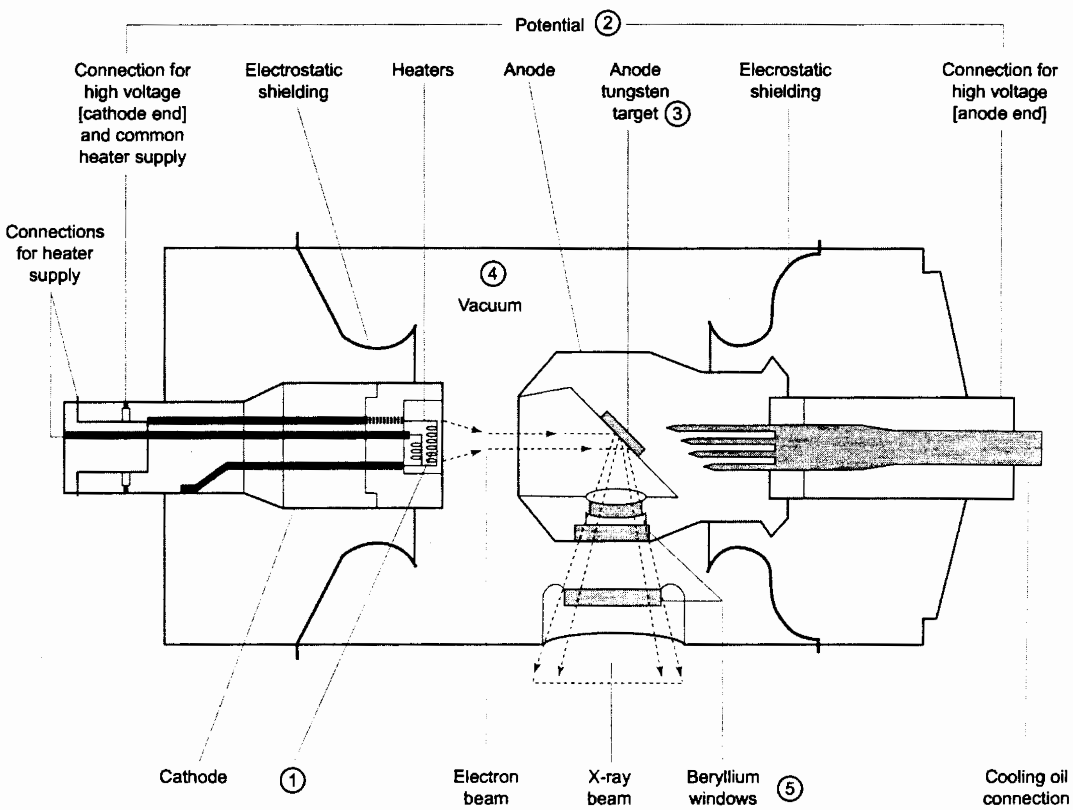

Figure 1.5. *Cut-away diagram of a typical constant potential X-ray tube.*

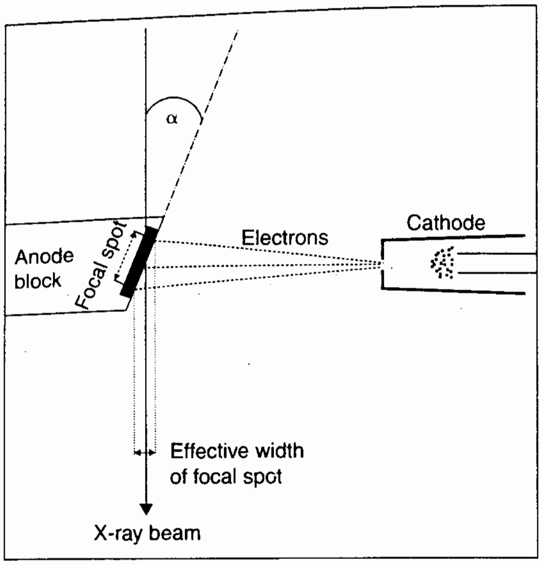

Figure 1.6. *Diagram showing how the effective focal spot size is reduced by 'viewing' the focal spot at an angle α.*

of the spectrum. The target is usually embedded in a good conductor of heat (copper), which is cooled by oil circulating through it.

4. A vacuum surrounds the filament and target, which allows the stream of electrons to be sustained.
5. The exit window for the X-ray beam is often made of beryllium which is a light element; this minimizes absorption of the X-ray beam as it passes through the window, which is particularly important when using low-energy X-rays.

For most applications the line focus type of X-ray tube is most suitable as it has a small effective focal spot (Figure 1.6). The influence of focal spot size on image quality is discussed below under geometrical considerations. Tubes with panoramic rod anodes are used in some medical and industrial applications where an all-round view of a vessel or a tube is required (Halmshaw 1995, p. 40). This type of anode can be put inside the vessel and film is attached around the outside, an arrangement which is very convenient for weld inspection on pipes. The quality of the image is not as good as a line X-ray set although it has the advantage of presenting a single wall thickness of the object on the radiograph, instead of both sides being superimposed.

An X-ray set is designed to operate within set limits of potential (kV) and current (mA). It is not normally possible to use a machine outside those limits, so care must be taken to select a generator with capabilities appropriate to the applications envisaged (see Box 2.2). Typically, an X-ray cabinet may have a range of 10–130 kV, while an industrial set may have a range of 50–150 kV or 50–320 kV; specialized sets may operate at lower potentials or up to 420 kV. More powerful sets (betatrons and linear accelerators or linacs) exist and are used industrially for special applications. X-ray sets in purpose-built shielded cabinets normally have a maximum potential of 150 kV. Medical diagnostic X-ray sets are usually designed to operate with a very short exposure time, high current and low kilovoltage (typically 70 kV, several hundred milliamperes and an exposure time of less than a second for a typical chest radiograph). Minimization of the dose to the patient is of course important, but very short exposure times also serve to reduce the effects of patient movement. These machines usually have a minimum of *c.* 40 kV, although X-ray tubes designed for mammography may operate down to 30 kV. A hospital X-ray set was successfully used to radiograph Byzantine icons painted on wood (Politis *et al.* 1993). As the maximum possible exposure time was very short (between 3 and 4 seconds), multiple exposures of the same icon were made in the same position, giving a total exposure of between 9 and 16 seconds, using a tube voltage between 32 and 40 kV (mammography-type tube). It is important that care is taken not to overload this type of set by running it for longer times than those for which it was designed.

Microfocus X-ray Sets

Although the X-ray beam itself cannot be focused through a lens like light, the electron beam used within the X-ray tube to generate the X-rays can be focused by electrostatic means, so that it is possible to reduce the diameter of the electron beam before it reaches the anode of the X-ray tube. Thus, an X-ray source with a focal spot size of only a few micrometres can be produced. Microfocus tubes with a range of voltages are available, but the current tends to be low (a typical current of e.g. 0.1 mA for a 10 μm focal spot at 200 kV is quoted by Halmshaw 1995, p. 41). Initial problems of the target overheating have been avoided either by deflecting the electron beam electromagnetically to different positions on the target anode or by using a rotating anode. Cabinet X-ray sets with microfocus tubes offering a focal spot size of 70 μm and energy range of 10–110 kVp are available (e.g. Faxitron). The principal advantage of microfocus tubes is that enlarged images can be formed with negligible loss of sharpness; they also offer the possibility of reducing the effect of internally generated scatter (see below) by leaving a small gap (say 20 mm) between the object and film, again without significant loss of sharpness. The use of the microfocus tube is mentioned again in Chapter 2 (in the section on Geometric considerations).

Characteristics of the X-ray Beam

The characteristics of the X-ray beam, such as its intensity and penetrative power, can be controlled by varying the cathode current and the tube voltage (potential). These characteristics, along with the focal spot size and other factors, affect image quality; this is discussed more fully later in the chapter. The current (mA) controls the intensity of the radiation; intensity is defined as the energy per unit area per unit time. The potential (kV) applied to the X-ray tube controls the maximum energy and the energy distribution of the X-rays and therefore determines the penetrative power of the beam.

Changing the Current

The effect of increasing the current (mA) is shown in Figure 1.7. As the current is increased, more electrons are produced, which in turn produce more X-rays. The energy of the X-rays is not increased, so that the wavelength distribution remains the same. The practical effect is to decrease the time required to radiograph an object, but if the object is very dense and difficult to penetrate, increasing the current will not improve matters very much because the penetrating power of the beam is not increased.

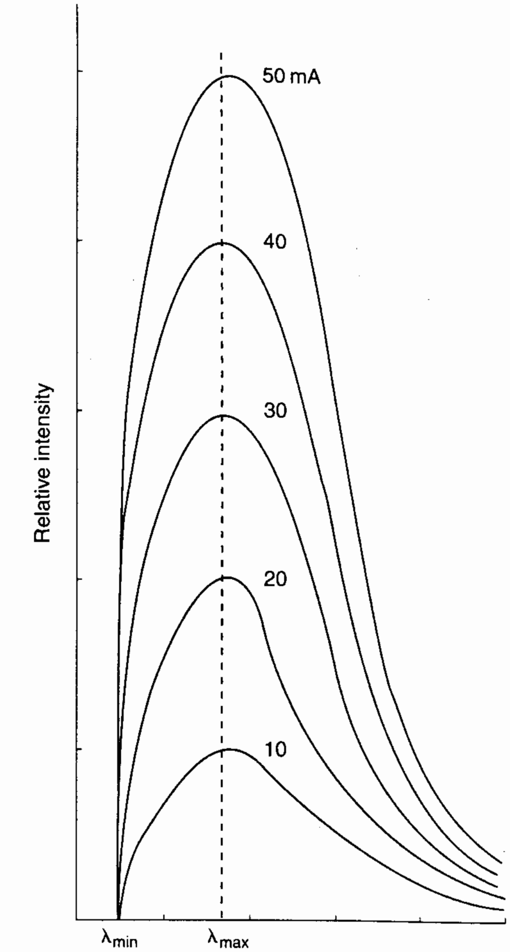

Figure 1.7. *Diagram showing the variation of intensity and wavelength as the current (mA) is varied.* λ_{min} *and* λ_{max} *remain unchanged (after Bertin 1975).*

Changing the Potential (kV)

Figure 1.8 illustrates the effect of increasing the tube voltage (kV). The graph shows that at a higher kilovoltage both the proportion of shorter wavelength (higher-energy) X-rays and the overall intensity increases. At the same time λ_{min} decreases, so that the beam becomes more penetrating. Thus, by controlling the kV the penetrative characteristics of the X-ray beam can be altered: for example, a 100 kV X-ray beam would penetrate 10 mm of steel but by increasing the voltage to 300 kV a steel section up to 40 mm thick could be radiographed. For convenience, X-rays are sometimes classified by their penetrative power: those produced by high-energy sources are more penetrative and are termed hard X-rays, whilst those of lower energy are less penetrating and termed soft X-rays. Particularly soft X-rays with energies less than about 20 kV are sometimes called *Grenz rays* (Graham and Thompson 1980). They can be especially useful for the radiographic examination of low-density materials such as paper, textiles and fish bones (e.g. cartilage), as described in Box 1.3.

Box 1.3. Textiles and organic artefacts

When exploring paint layers on canvas (Chapter 6) or X-raying mummies (Chapter 7), the textiles incorporated in them are often considered as an incidental component or even as a hindrance to gaining a clear image of the intended subject. However, suitably filtered, low-energy X-rays can be used to produce remarkably detailed images of organic objects including textile artefacts (Brooks and O'Connor 2005). The Turin shroud has been recorded and explored using radiography (Mottern *et al.* 1980) and components of upholstery have also been investigated (Gill and Doyal 2001). Nevertheless, textiles have generally not been the primary subjects of radiographic studies. Radiographs can identify hidden aspects such as seaming, fillings, repairs, areas of degradation and structural supports or more subtle details such as internal stitching threads and variations in weave structure. Technological features such as differential metal weightings in woven silk textiles may also been mapped (Brooks *et al.* 1996).

For example, this early 18th century stomacher, the detachable upper front section of a woman's gown, in Figure 1, is constructed from layers of silk, linen canvas and paper stiffened by baleen (whalebone) inserted into closely sewn channels (Figure 2) (Barbieri 2003). It had undergone many modifications and repairs before being concealed in a building (Eastop and Dew 2003). Radiography provided a means of assessing and recording the condition of the internal components of this multi-layered object,

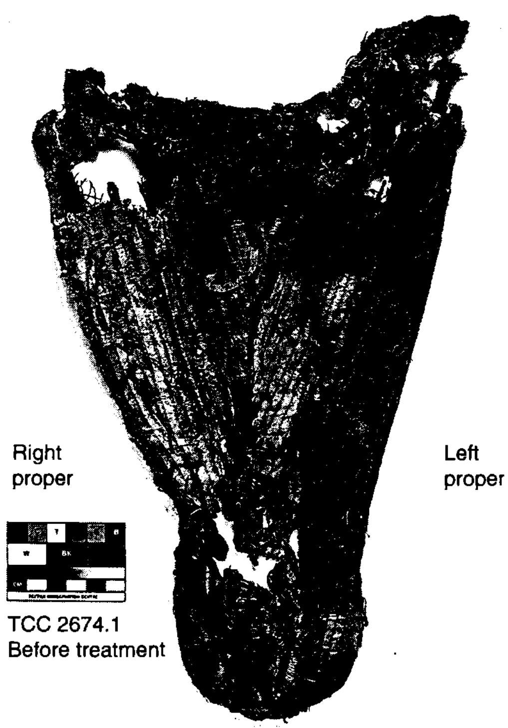

Figure 1. *Early 18th century stomacher in textile, paper and baleen (copyright of the Textile Conservation Centre).*

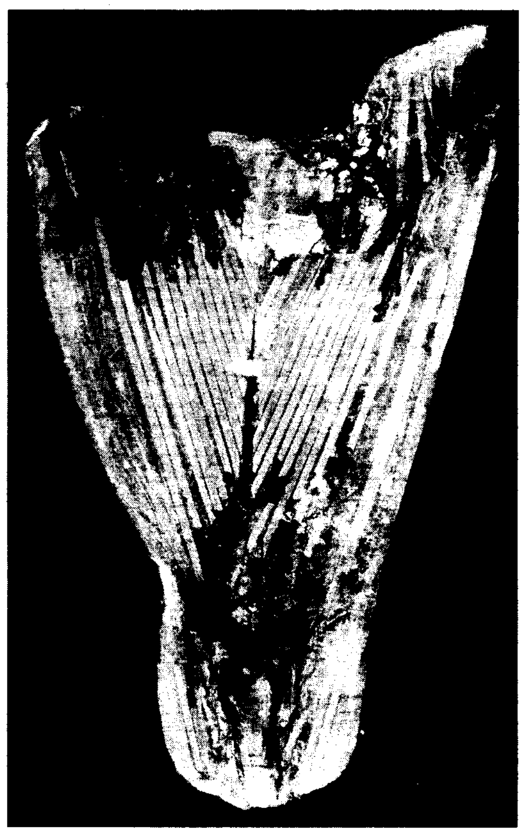

Figure 2. *Radiograph, 15 kV, aluminium foil filter, showing the construction and areas of decay (copyright, Sonia O'Connor).*

revealing details of its construction and contributing insights into its complex 'object biography' (Figure 3) (Kopytoff 1986). This object was radiographed as part of a study funded by the Arts and Humanities Research Board (AHRB) Research Centre for Textile Conservation and Textile Studies. The aim of this interdisciplinary research is to explore the potential of radiography as a tool for the study and conservation decision-making of ancient, historic and contemporary textiles. Specialist equipment and techniques are also being explored, including microfocus radiography, computer tomography and real-time radiography. A book based on this work is planned for this series (O'Connor and Brooks forthcoming).

Sonia O'Connor
University of Bradford
(The stomacher is published by
kind permission of the owner.)

Figure 3. *Detail of radiograph showing the canvas, paper, silk and insect nibbled ends of the baleen strips, stitching and stitch holes (copyright, Sonia O'Connor).*

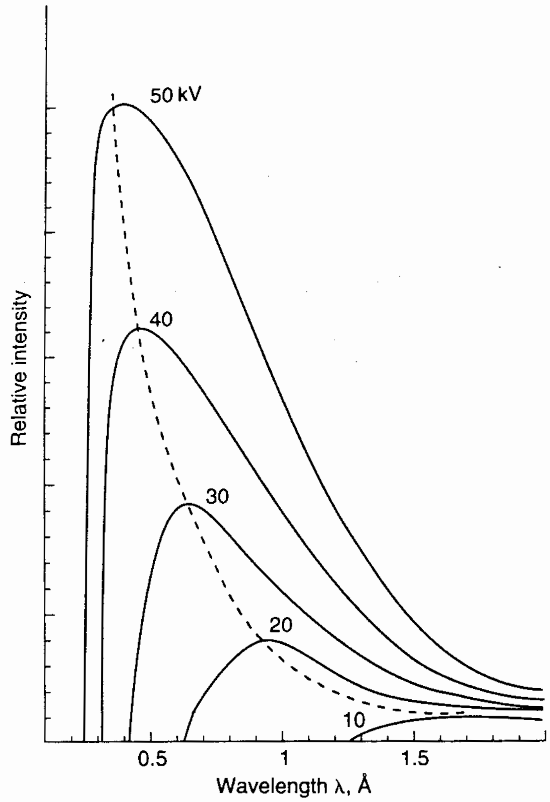

Figure 1.8. *Diagram showing the variation of intensity and wavelength as the potential (kV) applied to the X-ray tube is varied. As the potential is increased, λ_{min} and λ_{max} decrease and the beam becomes more penetrating (after Bertin 1975).*

OBJECTS AND X-RAYS

Attenuation

X-rays (and γ-rays) may be transmitted through matter without suffering any loss of energy or change of direction. However, if all X-rays were transmitted unchanged, there would of course be no useful radiograph but simply a blackened film. It is fundamental to the success of radiography that the X-ray beam is more or less attenuated as it passes through matter. The degree of attenuation depends upon the composition, density and thickness of the object and also upon the energy of the X-rays. The term attenuation encompasses the losses in intensity arising from a number of processes involving absorption (i.e. partial or total loss of energy) and scattering (i.e. the direction of the X-ray beam is changed and it may also suffer a loss of energy). The term absorption is sometimes used interchangeably with attenuation to include all losses, including those from scatter.

The progressive attenuation of the beam as it travels through matter is an exponential process:

$$I_x = I_o e^{-\mu x} \qquad (1.3)$$

where:

I_x = intensity at depth, x;
I_o = intensity of the incident beam;
e = natural logarithm base;
μ = linear attenuation coefficient.

which is to say that a given thickness of a particular material will absorb a fixed proportion of the incident beam. This leads to the concept of half-value thickness; that is, the thickness of a material required to reduce the incident radiation to one-half of its original intensity ($I_x/I_o = 0.5$). The degree of attenuation varies from one material to another: lead absorbs X-rays very strongly because of its high density and atomic number, lighter materials absorb less strongly. The level of attenuation also varies with the energy of the incident X-rays: lower-energy (softer) X-rays are absorbed more strongly and are scattered more readily than higher-energy (harder) X-rays. For these reasons it has been useful to produce tables of comparative data on the absorption of X-rays of different energies by a variety of materials. One such table, after Bertin (1975), is reproduced here as Table 1.2.

Another commonly used aid for estimating suitable exposure conditions for different materials is a table of approximate equivalent thickness factors, shown in Table 1.3 (after Quinn and Sigl 1980). In each column of this table (i.e. at a particular kV) equivalent thickness factors are given for several different metals, relative to a standard metal. Between 50 and 100 kV aluminium is taken as the standard metal, but at higher X-ray energies (150 kV and above) steel is taken as the standard. The exposure required can be calculated by multiplying the exposure needed for the same thickness of the standard metal at the same kilovoltage by the appropriate factor. For example, at 100 kV, 10 mm of copper would require 18 times the exposure of 10 mm of aluminium.

Table 1.2. Approximate half-value thicknesses (mm) for materials of different density (l), at two different X-ray energies

Applied (kV)	*Effective (kV)**	*Water (l = 1)*	*Aluminium (l = 2.7)*	*Copper (l = 8.9)*	*Lead (l = 11.2)*
300	154	1160	20	3.9	0.4
200	102	530	16	1.7	0.1

After Bertin (1975).
* This takes account of the fact that the X-ray beam includes a spectrum of energies, with only the highest corresponding to the maximum applied kilovoltage (kVp).

Table 1.3. Approximate equivalent thickness factors

Material	*50kV*	*100kV*	*150kV*	*220kV*	*400kV*
Aluminium	1.0	1.0	0.12	0.18	
Steel		12.0	1.0	1.0	1.0
Copper		18	1.6	1.4	1.4
Brass*			1.4	1.3	1.3
Lead			14.0	12	

After Quinn and Sigl (1980).
* Brass containing lead will have a higher equivalence value.

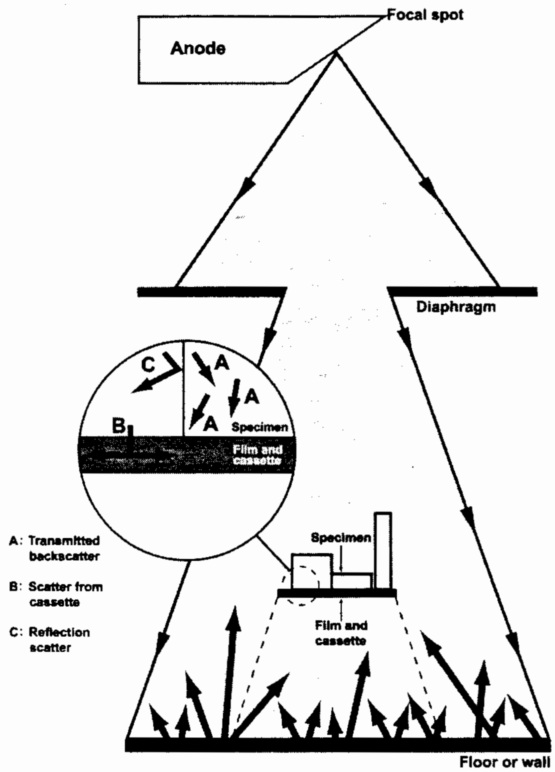

Figure 1.9. *Diagram showing how scattering occurs in radiography.*

Scatter

Several different processes may give rise to scattered radiation but a discussion of these is beyond the scope of this book (discussion of the various mechanisms is included in texts such as Farr and Allisy-Roberts 1997 and Halmshaw 1995). Some consideration of scatter is important, however, because if scattered radiation reaches the film it does not provide useful information but tends to 'fog' the image with the visual equivalent of noise.

The thicker and more irregular in shape the object is, the more scatter tends to occur. Additional scattered radiation may be generated when the primary and scattered X-rays strike the floor, or any other objects in the immediate vicinity (Figure 1.9). To improve image clarity it is important to reduce scatter to a minimum, and there are a number of steps which may be taken to do this. As discussed, using a sheet of copper (between 0.6 and 2 mm thick) to filter the X-ray beam as it emerges from the exit window of the tube will remove the softer, more easily scattered components: this is useful when radiographing thicker and denser objects (cast statues, for instance). The spread of the beam can be reduced by a heavy metal diaphragm at the X-ray set and a localizer (a metal cone) which acts as a diaphragm between the X-ray tube and the object, preventing the sideways spread of the radiation. Lead sheet laid under the cassette will help to prevent scatter from the floor or table. Scatter can also be reduced by masking around the object with lead sheet, lead shot (in bags) or barium putty (wrapped in plastic). Above about 120 kV, it is usual to put thin card backed lead sheet on either side of the film in the cassette. As well as cutting out scatter this also intensifies the image by the emission of electrons which contribute to the

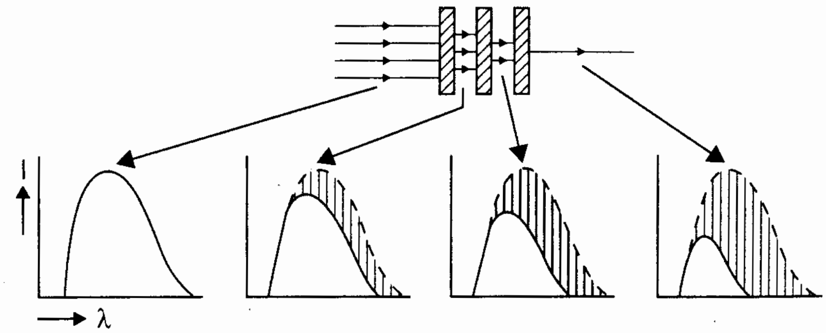

Figure 1.10. *Schematic representation of the effect on the X-ray beam as it passes through successive filters. Intensity and* λ_{max} *are reduced (after Gilardoni 1994).*

development of the image; and the exposure latitude range is increased (see also Chapter 2).

In the medical field, various grids are used; these are made of lead slats arranged and shaped so that the scattered radiation is absorbed by the lead, while the undeviated X-rays from the primary beam pass between the slats when the tube is correctly positioned in relation to the film. To avoid an image of the lead slats appearing on the film, the grid may be motorized (e.g. the Potter-Bucky grid), so that it moves across the film while the exposure is taking place (see Farr and Allisy-Roberts 1997). Such grids are not normally used for cultural material as they are relatively expensive and require longer exposure times.

Filters

The fact that X-ray attenuation varies with the energy of the incident X-rays can be put to good effect. The diagram reproduced as Figure 1.10 shows how the overall intensity of the continuous spectrum X-ray beam is reduced as it passes through several sheets of metal. The less energetic, longer wavelengths are less penetrating and are absorbed more readily, so that the proportion of shorter wavelength X-rays in the emerging beam increases and effectively the beam is harder and more penetrating. However, a longer exposure or higher current is required to compensate for the loss of intensity.

To utilize this effect in practice, metal filters are attached just in front of the window of the X-ray tube. An aluminium filter (about 1 mm thick) will remove the longest wavelength X-rays but, to harden the beam appreciably, copper sheet (usually from 0.6 mm to several millimetres in thickness) or lead (0.25 mm at 150 kV, 0.5 mm at 200–250 kV) are used. The resulting hard and homogeneous radiation is employed in electron radiography (see Chapter 5).

Inverse Square Law

When X-rays leave the target, they travel in divergent straight lines so that a cone-shaped beam is generated by a point source. The intensity of the beam decreases as it moves away from the source, spreading out and covering an increasingly wide area (Figure 1.11). The relationship between the intensity and distance from the source can be expressed by the equation:

$$I_2 = I_1 \cdot D_1^2/D_2^2 \qquad (1.4)$$

if the intensity at a distance D_1 is I_1 and the intensity at D_2 is I_2.

This relationship is known as the *inverse square law*: if the distance of the object from the X-ray source is doubled from say, 50–100 cm, then the intensity at the object will be reduced to a quarter of its original value. If the object is placed too far away from the X-ray tube there will be insufficient intensity to make a radiograph in a reasonable time. Source-to-film distances of between 60 cm and 1 m are commonly used with conventional X-ray sets. Using a shorter distance has the disadvantage that the image quality deteriorates, although the intensity is greater.

Geometric Considerations

Geometric factors influencing the quality of the image, apart from the size and shape of the object

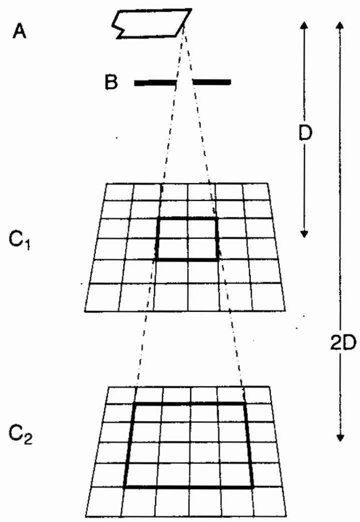

Figure 1.11. *Diagram showing the effect of the inverse square law.*

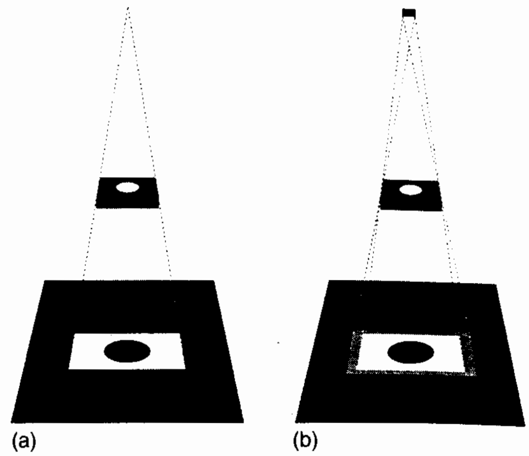

Figure 1.12. *Effect of geometry on the shadow image. (a) Point source with a large distance between the source and the subject: the shadow is sharp edged. (b) Larger source with the same distance between the source and the subject; the shadow has a penumbra or unsharp edge (after Quinn and Sigl 1980).*

itself, include the size of the source (or focal spot), and the spatial relationships between the film, object and source. A good quality image is required to be sharp and the geometric unsharpness, U_g, can be expressed by the formula:

$$U_g = S\, b/a \tag{1.5}$$

where S is the size of the source, a, the object-to-source distance and b, the object-to-film distance. If S is large, or the object-to-film distance, b, is large, U_g increases; in other words, the quality deteriorates. These effects are summarized in Figures 1.12 and 1.13. If the unsharpness increases, the detection of changes in contrast becomes more difficult. If a feature is small (an engraved line, for instance), the difference in contrast between the feature and its background may not be visible (Figure 1.14).

From the figures it can be seen that it should be possible to magnify the image by increasing the object-to-film distance, b. But it is also apparent that because industrial X-ray sets have relatively large focal spots (typically about 1 mm by 1 mm or more), any attempt to deliberately magnify the image on the film by moving the object away from the surface of the cassette will be frustrated: because the unsharpness, U_g, will usually increase to an unacceptable level. Stegemann *et al.* (1992) have expressed the relationship between the magnification (M), the unsharpness (U_g) and the size of the source (S) by the equation:

$$U_g = S(M - 1) \tag{1.6}$$

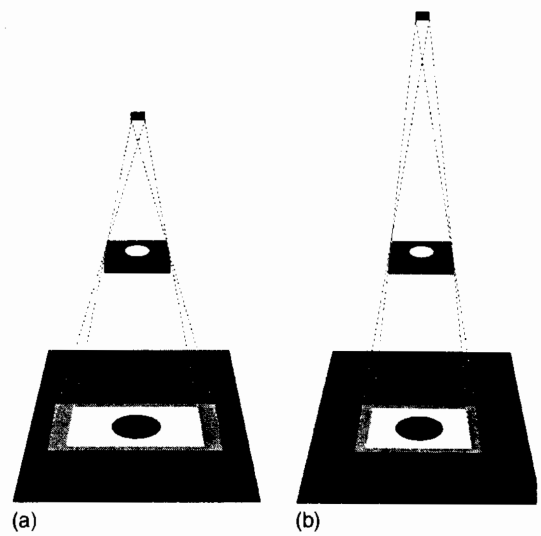

Figure 1.13. *Effect of geometry on the shadow image. As the distance between the source and the subject is increased between (a) and (b), the size of the penumbra in (b) is reduced (after Quinn and Sigl 1980).*

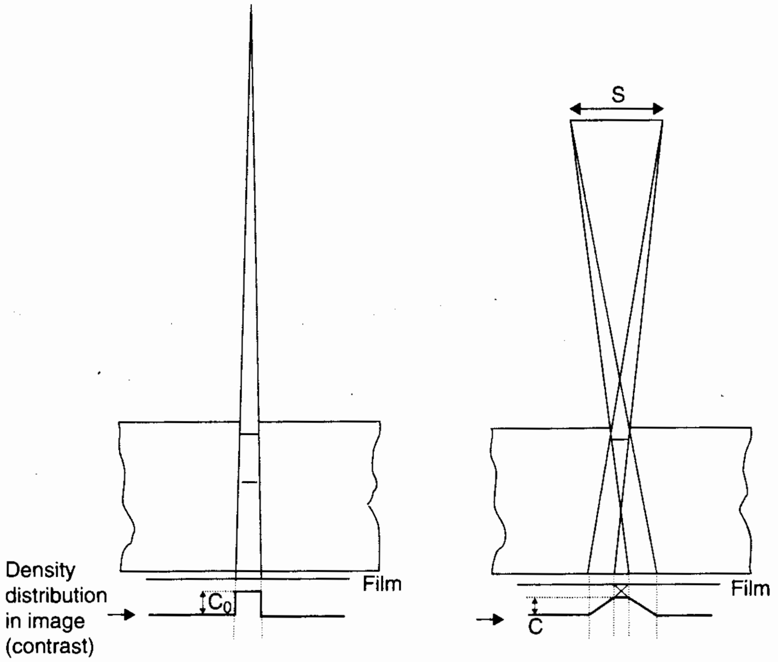

Figure 1.14. *The effect of geometric unsharpness on the image of a small feature, resulting from a large source, S and a reduction in the distance between the source and object: the edges are less defined and the contrast is reduced (from C_0 to C) (after Halmshaw 1995).*

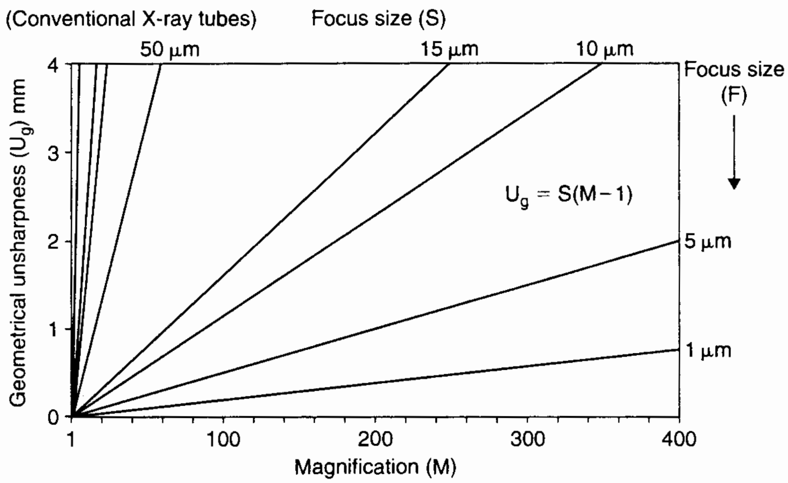

Figure 1.15. *Relationship between focal spot sizes 2 mm to 1 μm, the magnification (M) and the unsharpness, U_g (after Stegemann* et al. *1992).*

If small features or discontinuities, say less than about 1 mm, are being examined, the geometric unsharpness obviously must not exceed 1 mm and, ideally, should be significantly less than this. If the source size is 1 mm, the equation shows that the unsharpness will be unacceptable when the magnification exceeds a factor of 2. With a microfocus tube, however, source size (S) is extremely small (say 0.01 mm), so that high magnifications may be possible without significant loss of quality (Figure 1.15). This is illustrated by the magnified image of part of a Brazilian banknote (Figure 1.16) in which fine details are clearly visible. The potential of microfocus X-ray tubes has not been extensively exploited in the archaeological field as yet, but work on the methods used to join the links of mail from the Anglian helmet from York (Tweddle

Figure 1.16. *Enlarged image of scanned radiograph of part of a Brazilian banknote. The original radiograph was produced using a microfocus X-ray tube. See also Figure 9.6(b).*

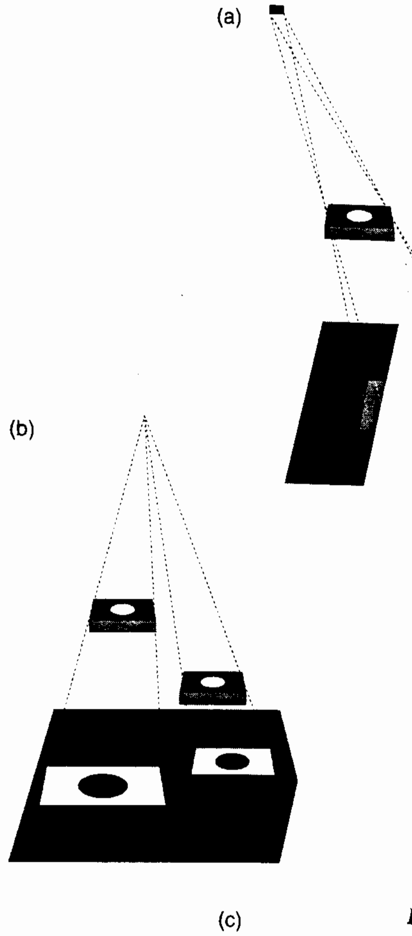

Figure 1.17. *D occurs if the subje X-ray beam (afte distorted if the s distances appea distances and a of a single obje*

1992), using a microfocus tube, shows that it can be a valuable non-destructive tool for the examination of small areas.

Distortion of the image and other misleading results due to geometric effects are also possible, as illustrated in Figures 1.17 and 1.18. The handles of the 14th century AD inlaid lacquer sutra box (Figure 1.18) are the same size, but the one which was further away from the film has been enlarged. The orientation of any fault or feature of interest relative to the X-ray beam is an important consideration when positioning an object. Ideally, the centre of the X-ray beam should be perpendicular to the film and pass through the middle of the feature. Unfortunately, as shown schematically in Figure 1.19, it is not possible to arrange this in all situations: the

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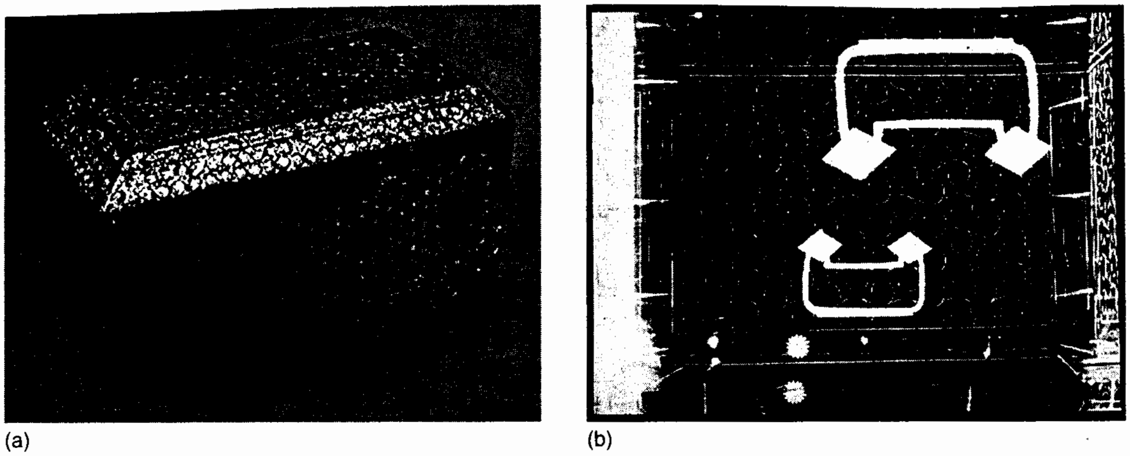

Figure 1.18. *(a) 14th century AD Korean lacquer sutra box with brass handles and inlaid with metal wire and mother of pearl. (b) The handle and wire on the end furthest from the film are enlarged on the radiograph, the nails holding the box together can be seen but the mother-of-pearl inlaid is not dense enough to show.*

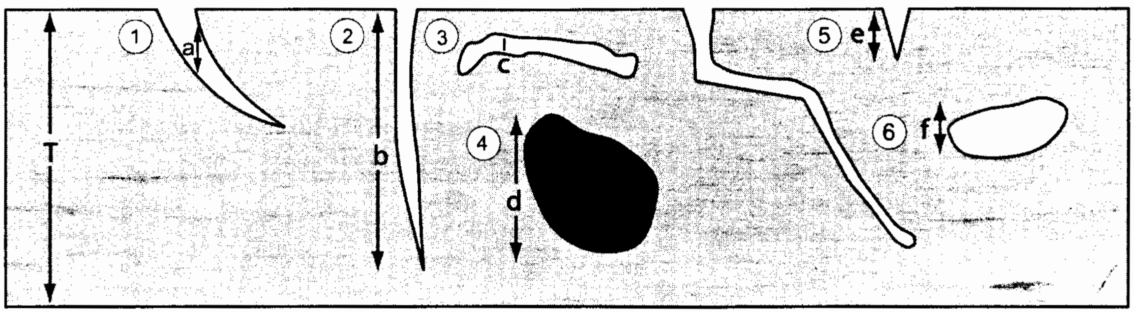

Figure 1.19. *Effects of orientation, geometry and material on the imaging of features. (1) Oblique crack. Distance X-rays travel through the material of the bar (path difference) T – a, but the value of 'a' varies in this case, depending on the orientation and thickness of the crack. (2) Near-vertical crack, depth 'b'. Path difference T – b. (3) Thin horizontal crack, depth 'c'. Path difference T – c. (4) Inclusion of denser material provides a lighter area on the radiograph; the difference depends on the absorption of the material and the thickness, 'd', of the inclusion. (5) Shallow engraved line, depth 'e'. Path difference T – e. (6) Void, depth 'f'. Path difference T – f.*

orientation of the features or their very existence may not even be known, there may be a multiplicity of features with different orientations, or the overall shape of the object may be awkward.

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