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Advances in Ceramic Radiography and Analysis: Laboratory Methods

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The major variants of industrial and medical radiographic procedures are reviewed and evaluated for their usefulness in ceramic archaeological studies, with attention to documenting temper characteristics and paste-to-paste joins. Essential concepts and relationships between technique and image quality are summarized. Means for optimizing image sharpness, distortion, and contrast are outlined, including selection of focal spot size, focal spot to film distance, object to film distance, film type, object orientation, kilovoltage, milliamperage, tube source, window, filtration, film cassette material, and diaphragms, and the differing integration of these in medical versus industrial laboratory settings. Low radiographic contrast between temper and paste or paste-to-paste joins can be overcome by using industrial, slow, high-detail, high-contrast films or certain mammography films without intensifying screens, along with a low kilovoltage. The relative advantages of xeroradiography and X-radiography are evaluated. Charts for estimating proper X-radiographic exposure for sherds of differing thickness and temper density and other suggestions for operation and efficiency are given.

Keywords: X-RADIOGRAPHY, XERORADIOGRAPHY, CERAMIC TECHNOLOGY, CERAMIC TEMPER, OHIO WOODLAND PERIOD.

Introduction

Archaeological ceramics bear two broad classes of features that can be detected radiographically and that are useful for solving archaeological and anthropological problems. First are indicators of the primary and secondary techniques by which vessels were formed. The shape and orientation of radiographically detectable air pockets and temper inclusions within the walls of a vessel can indicate whether it was made by slab-building, coiling, throwing, and/or beating (Rye, 1977, 1981; Foster, 1983; Glanzman & Fleming, 1985, 1986). These broad distinctions, as well as the details of coil and slab size, morphology, and joining methods, constitute isochrestic or technological stylistic variation (Sackett, 1982; Lechtman & Merrill, 1977). They have been used to reconstruct learning pools and devise seriations (Glanzman & Fleming, 1985) and have potential for documenting vessel trade networks and marriage networks.

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Second, radiographs can be used to document a variety of tempering parameters. These include material types such as grasses, shell and rock; approximate mineralogical classes such as felsic, mafic, and opaque minerals; volumetric density; and size distribution (Titterington, 1935; Braun, 1982; Adler, 1983; Carr, 1985, 1989, 1990). Most basically, these attributes can be used along with surface-visible features to sort sherds from a deposit to their vessels of origin (Titterington, 1935; Carr, 1987). Vessel count data can have an advantage over sherd count data in reducing bias when estimating site occupation spans and population levels, frequencies of vessel trade, and stylistic-based measures of social interaction (Schiffer, 1975: 265–267; Plog, 1990). Also, the larger expanses of vessels that may be reconstructed with radiographically matched sherds can be useful for documenting the broadest levels of design organization and for estimating volume morphology, capacity, and function. Temper volumetric density and size distribution have been tracked through time in order to document changes in vessel technology, which were used to establish chronometric models for dating purposes (Braun, 1982; Carr, 1985). Temper density and size have also been used to monitor ecological trends in subsistence, diet, and residential mobility (Braun, 1987). The potential for using radiography to identify locally made and exotic vessels according to temper mineralogy, as in petrography, and to study vessel exchange, remains to be investigated (Carr, 1989).

To successfully use radiography for these applications requires methods that are capable of revealing ceramic diagnostic features with sufficient resolution and contrast. This article describes the key variants of radiographic methods that can be selected by the archaeologist to meet these requirements. Many of the specific techniques are not new and are known in industrial X-radiography and medical radiology. Rather, what is pertinent is how method can be tailored to the ceramic medium in order to create optimal radiographs. For example, previous pioneering work by Braun (1982) had the goal of documenting temper particles and quantifying temper volumetric density. The standard medical procedures that were used were not ideally suited to this task and resulted in radiographs where smaller temper particles were too indistinct and of too low a contrast to be counted. Alternative methods are proposed here for this and other tasks.

Some of the procedures discussed in this article are useful for documenting a wide range of ceramic characteristics whereas others are specific to one fundamental problem: describing the temper particles within vessels for their volumetric density, size distribution, shapes, and approximate mineralogy. The recommendations result from several years of experimentation with various radiographic methods and ceramics in industrial and medical laboratory settings.

Essentials of Radiography

Most archaeologists have seen medical radiographs, but the means by which these and other kinds of radiographs are made are probably unfamiliar. Even those who know photography will find some of the factors that govern radiographic quality new.

To appreciate how radiographic method can be adjusted to ceramic investigations, it is necessary to have a basic understanding of the X-ray machine and how X-rays are generated. Figure 1 shows the most important components from our perspective. The process of generating X-radiation is accomplished within a vacuum *X-ray tube*. It begins with an incandescent *filament*, which is heated by a current of a few amperes and low voltage so that electrons are driven from it. These are focused electromagnetically so as to produce a stream of electrons called the *tube current*, which is measured in milliamperes, commonly abbreviated to mA. The magnitude of the tube current can be controlled by increasing or decreasing the current that passes through the filament and the heat it generates.

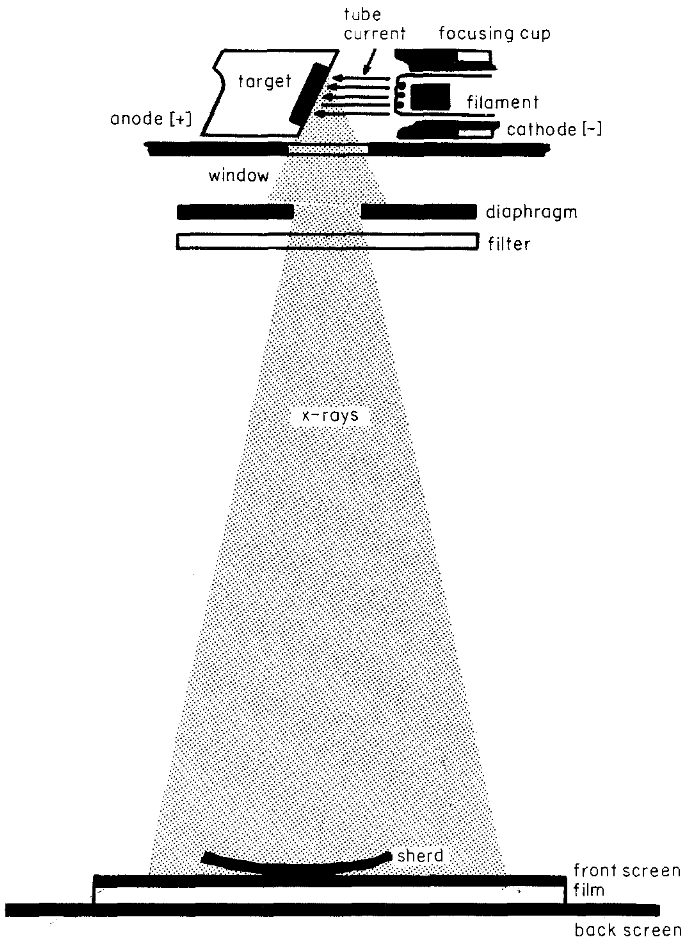


Figure 1. An X-ray machine and equipment.

The tube current is directed toward a *target* of metal. It is most commonly made of tungsten, which has a high melting point and increases the use-life of the X-ray tube. It can also be made of molybdenum. When the electrons hit the target and suddenly are stopped, they emit energy in the form of X-rays. These leave the X-ray tube through an opening in its lead housing called the *window*. Windows are made of many substances, including beryllium, glass, aluminium, and steel, which have various advantages in different applications.

The X-ray waves that are generated by an X-ray tube are characterized by two parameters: their *intensity* and their *wavelength*. The intensity of an X-ray wave is a measure of the number of photons per second that comprise it. The wavelength of an X-ray wave is the distance it travels in one vibration cycle. The shorter the wave length of a wave, the denser or thicker the materials it can penetrate and pass through. For this reason, shorter waves are sometimes called "hard radiation" whereas longer waves are called "soft radiation".

The X-rays that are generated by an X-ray tube using a given mA and a given voltage are not all of one wavelength and intensity. Rather, they vary in both dimensions, which

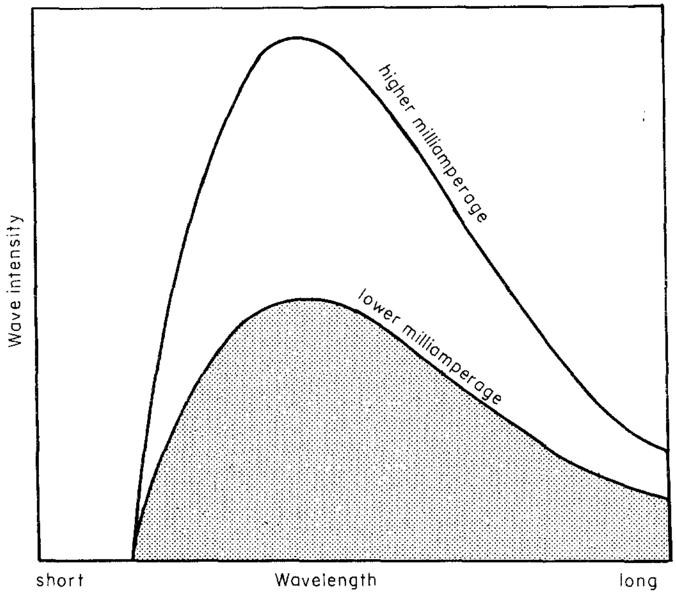


Figure 2. Two X-ray spectra, one at a lower mA and one at a higher. Increasing the mA of the tube current increases the intensity of waves of each wavelength in the spectrum.

can be described as an X-ray *spectrum* (Figure 2). The spectrum summarizes the different intensity of waves of different wavelengths that are emitted. Waves of medium wavelength have the greatest intensity, whereas those with shorter and longer wavelengths have lower intensity. Heuristically, one can think of a spectrum as a histogram of photons of varying wavelength.

The spectrum of emitted X-rays can be changed by varying either the mA of the tube current or the peak kilovoltage (kVp) applied to the tube. Increasing the mA of the tube current by definition increases the number of electrons in it that strike the target per second, the number of photons per second that are generated, and thus increases the intensity of waves of each wavelength in the spectrum. For example, in Figure 2, tube current mA has been doubled, and so has the intensity of waves of each wavelength. Increasing the kVp has a more complex effect (Figure 3). First, it increases the intensity of waves of each wavelength. Second, it changes the spectrum by adding new waves of shorter wavelength and greater penetrating effect to the old spectrum. The second effect results from the greater average speed with which electrons strike the target as kVp is increased.

Radiographic film darkens or becomes more *dense* as X-radiation impinges it. The degree of darkening depends on the total amount of radiation—number of photons—which reaches it and the nature of the film. Total irradiation, in turn, depends on the spectrum of the emitted X-rays and the duration of irradiation. Thus, operationally, radiographic density depends on several output parameters: the tube current mA, the kVp applied to the tube, and time. In addition, density depends on the distance of the X-ray source from the film. As X-rays leave the window of an X-ray machine, they spread outward in a cone such that their areal density, and thus intensity, decreases. In particular, intensity decreases with the square of distance from the focal spot.

The *exposure factor, E,* summarizes these relationships:

$$E = mt/d^2 \qquad (1)$$

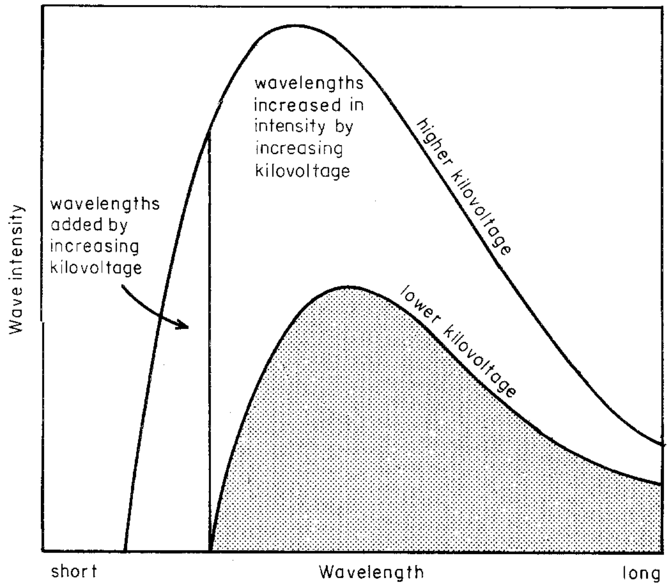


Figure 3. Increasing the kV applied to an X-ray tube increases the intensity of waves of each wavelength in the X-ray spectrum and adds waves of new, shorter wavelengths to it.

where m is mA, t is exposure time, and d is the focal spot to film distance. For a given machine operated at a given kVp, E is proportional to the number of photons emitted. In contrast, the term, *exposure*, refers simply to the mA and time of exposure:

$$e = mt \tag{2}$$

Of the X-rays that leave the window of an X-ray machine, some pass through the object being radiographed, some are absorption within the object, and some are scattered in all directions by the object and whatever surrounds it—the film cassette, table top, floor, etc. The radiation that is emitted from the X-ray machine is called *primary radiation*. That which passes through the object, directly or with internal scatter, is called *remnant radiation*, whereas that which is scattered externally is called *secondary radiation*. Remnant radiation and some secondary radiation then expose the film underneath the object.

If the object is heterogeneous in composition, such as a ceramic sherd with lighter clays and denser rock temper particles, its different phases will absorb the primary radiation to varying degrees and will allow varying amounts of radiation to pass through. This will expose the film underneath the object differentially and record the heterogeneity.

The intensity of remnant radiation that has passed through a phase depends in part on the phase's composition. Materials that are composed of proportionally more elements with higher atomic numbers and that consequently have higher specific gravities block more radiation. Temper minerals that differ in composition from each other and from their surrounding clay matrix are good examples (see below). In addition, the intensity of the remnant radiation depends on the intensity of the primary radiation, the thickness of the phase, and the applied kVp. For low to moderate kVp, including those at which ceramics are investigated, materials of different specific gravities become more similar in the degree to which they allow X-rays to pass and are less distinguishable radiographically as kVp increases. The potential that a material of a standard thickness has relative to another material for blocking X-rays generated with a given kVp is called its *adsorption coefficient*.

The quality of an *X*-ray image, or what is called its *detail*, depends on both the *sharpness* with which the boundaries of phases are recorded and the *contrast* between phases. Secondary, scattered radiation decreases contrast in an undesirable way by exposing the film at large and causing a *fog* over it. A variety of procedures can be used to minimize fogging and obtain optimal contrast (see below).

The grey-level distinctions that are obtained in a radiograph between two phases of a heterogenous material are termed *radiographic contrast*. This must be distinguished from *subject contrast*, which is the range of remnant radiation intensities that is transmitted through a specimen. Subject contrast depends upon the specimen's inherent density anomalies, the wavelengths of the primary radiation, and the distribution of scattered radiation, but is independent of radiation intensity (mA), time, distance from source, and film type. *Film contrast* refers to the range of grey levels that can be produced by a film with shifts in exposure.

Film contrast is often evaluated using a plot called the *characteristic* or *sensitometric curve* (e.g. Figure 7). It describes how the density (darkness-lightness) of a radiograph changes with exposure. Density is defined as:

$$D = \log(I_0/I_t) \tag{3}$$

where I_0 is the intensity of light that is incident on a radiograph and I_t is the intensity of light that is transmitted. Because density is defined as a logarithm, any given increase in density (e.g. 0·7) will always correspond to the *ratio* factor by which transmittance has been reduced (e.g. $5\times$). Exposure is expressed on a relative scale. A given exposure is measured in mA-seconds/distance^2 (mAs/distance^2) relative to some standard exposure factor. The characteristic curve is based on the logarithm of relative exposure. This is advantageous in that any given increase in log relative exposure (e.g. 0·3) will always correspond to the same ratio factor by which relative exposure is increased (e.g. $2\times$).

The slope of the characteristic curve for a given log relative exposure defines a change in radiographic density, i.e. radiographic contrast. Thus, one can compare the degree of contrast provided by different films by comparing the slopes of their characteristic curves. For example, Figure 13 shows the characteristic curves of several common industrial films at 200 kVp. The slope of each is quite similar, suggesting their similar film contrast at this kVp.

More detailed descriptions of radiographic technology, principles, and methods are given by Eastman Kodak (1980), Halmshaw (1983), Barrett & Swindell (1981), Christensen *et al.* (1978), and Cahoon (1956).

Laboratory Methods for Archaeological Ceramics

In recommending certain radiographic methods over others for studying archaeological ceramics, one must distinguish the two possible laboratory settings that an archaeologist might use: the medical and the industrial. These settings offer different ranges of alternative techniques. It is important to realize that it is not always possible to combine the most optimal alternatives from both settings. This arises from differences in goals and equipment limitations. For example, in the medical setting, patient radiation dosage is a critical variable and is responsible for limitations in the design of X-ray machines and supplies that are not present in an industrial setting. Also, the medical laboratory offers both molybdenum and tungsten target X-ray machines, whereas the industrial laboratory

Table 1. Technical parameters for radiographic experiments and work with Woodland ceramics from Southern Ohio

Focal spot size	0·7 mm^2 (actual size)
Focal spot-to-film distance (*ffd*)	31 in.
Object-to-film distance	Essentially 0
Peak kilovoltage	30 kVp in most cases 50 kVp in fewer cases
Milliamperage	4 mA for 30 kVp 3 mA for 50 kVp
Tube source	Tungsten
Window	Beryllium
Filters	None
Diaphram	None
Screens	Back lead only
Film type	Kodak Industrex M-2 (8 × 10 in. sheet film for small sherds; roll film for larger sections; each in ready-pack form)
Sherd thickness	2·5–16 mm, Most 3·5–8 mm

usually provides only the latter. Consequently, choosing optimal radiographic methods is a context-dependent problem.

When illustrating the recommendations to be made, reference is often made below to experiments and routine work that Carr has done with Woodland ceramics from southern Ohio. Unless otherwise stated, the technical parameters for this work are those shown in Table 1.

Factors affecting image sharpness

A radiograph is a shadow picture. Its appearance is determined in part by the principles of shadow formation as they pertain to light optics. Specifically, the sharpness of an image, such as that of a temper particle anomaly within clay, depends on (1) the size of the source of X-rays, (2) the distance from the source to the film—the *focus-film distance, ffd,* and (3) the distance of the object from the film. A crisp-bordered shadow is created only when the source is infinitely small compared to the focus-film distance. When this is not true, each point of the source creates its own shadow of the object and these are offset so as to create an image that is ill-defined in internal structure and boundary. The hazy boundary that surrounds the image is called its penumbra. Image sharpness decreases as the source becomes larger and/or the focus-film distance decreases. By the same logic, when the source is not a point source and the object is positioned away from the film, a hazy image is formed. Image sharpness decreases as the object-to-film distance increases.

Focal spot sized: For an X-ray machine, the focal spot size sets the size of the source. The focal spot is that portion of the target upon which the tube current is concentrated electromagnetically. The actual focal spot size may be fairly large, but because the target is set at an angle to the tube current, the effective focal spot is smaller (Figure 4).

Given the laws of shadow formation, it is preferable in all work to use as small a focal spot as possible. Most machines have one or two focal spot sizes. If there are two focal spots, the smaller is usually reserved for use at the lower kVp range of the machine with lower energy electrons, so as to not melt the target. The larger spot is used at higher energy levels. Machines with different kVp ranges and of different expense will vary in the spots they offer, smaller spots usually occurring in machines that offer lower kVp ranges or that

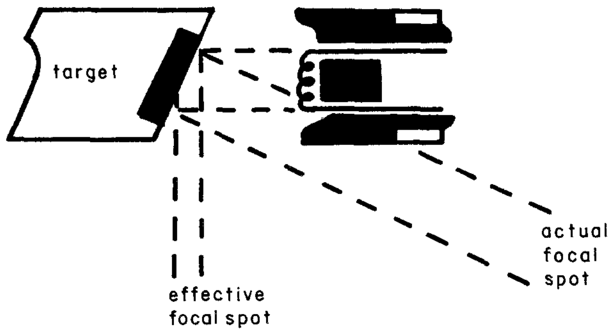


Figure 4. The effective focal spot of an X-ray machine is smaller than the actual focal spot because the target is set at an angle to the tube current.

are more expensive. Since ceramic radiography typically requires only very low kVp (less than 60 kVp), the researcher should attempt to use a machine that is designed for low kVp work and that is equipped with smaller focal spots. The smaller of the focal spots that are available should be used. Carr's work with Ohio ceramics, in the 30–50 kVp range, applied an actual focal spot of 0·7 mm.

Focal spot-to-film distance (ffd): In all radiographic work, the source should be positioned as far from the film as is practical, for two reasons. First, with a greater *ffd*, the source will more closely approximate a point and encourages image sharpness. Within limits, a larger *ffd* can help to compensate for a larger spot and improve image sharpness. Second, in ceramic work, sherds have curvature and may not entirely contact the film when laid upon it. This can cause a blurred image if a small *ffd* is used. To reduce blurring and help compensate for an object-to-film distance that cannot be overcome directly, the *ffd* can be increased (Rye, 1977: 210). Rye used a *ffd* of 165 cm. Carr used 79 cm and did not find blurring problems with sherd-film separations of a few cm.

Practical limits on the *ffd* include not only spatial constraints, but also the time one wishes to allocate to exposure. Exposure (mA × time) increases in direct proportion to the *square* of the *ffd*. Thus, for a given mA, if a 4 min exposure is required to obtain appropriate radiographic density at 20 in *ffd*, it will take an unwieldy 16 min at 40 *ffd*. To an extent, this problem can be overcome by increasing the tube current's mA instead of time. However, X-ray machines have maximal limits on the mA they use, in order to not melt the target. Thus, compensation can be only partial.

Object-to-film distance: To obtain a sharp image with 1:1 representation, the object should be positioned as close to the film as possible. For ceramic sherds or vessels which have a curved surface, this condition can be approximately met in three ways. (1) When sherds are small (*c.* < 7 mm in diameter) and of moderate curvature (*c.* > 25 cm diameter), they can be laid directly on sheet film, convex side down. This ensures that the maximum sherd area is the smallest distance from the film, whereas placing the sherds concave side down creates the opposite, undesirable condition. (2) For a larger or more curved specimen, roll film can be attached to it with masking tape so that the film surface abuts the sherd surface. The film can be cut to whatever length and width is desired to accommodate the morphology and size of the sherd. The film can be attached to either the convex or concave side of the specimen. However, when the source is above and the specimen is positioned on a table below, convex film attachment makes it easier to set the specimen perpendicular to the cone of X-rays (see below). (3) Whole vessels can be handled like large sherds, but interior, concave film attachment becomes necessary if the source is to remain outside the vessel.

Film type: As in photography, films vary in grain and the sharpness of the image that they are capable of producing. In a medical setting, general purpose films, such as Kodak XRP and equivalents, are too-coarse grained to give the resolution that is required to view, size, and count small temper particles (< 1 mm diameter) or microcracks. Braun (pers. comm.) discovered this limitation in his work on Illinois Woodland ceramics with Kodak XRP. Our own experiments on Ohio Woodland ceramics, using general purpose Fugi ROXG film, verified his results.

Some medical films designed for high detail work, such as Kodak XTL used for specimen radiography and Kodak Ortho M used for mammography applications, provide the sharpness that is required in ceramic applications when they are used without fluorescent screens. However, XTL must be used with fluorescent screens in a medical setting because it is too slow relative to medical X-ray tube limitations. Fluorescent screens are plates that convert X-rays into light energy, which can expose the film much more quickly (see below). Since fluorescent screens decrease image sharpness, the use of XTL is not recommended. Another mammography film, Kodak Min-R, also provides excellent image sharpness without fluorescent screens but is not recommended for ceramic work because its film contrast is lower than Kodak Ortho M.

In an industrial setting, the films Kodak Industrex M, single coated R, and double-coated R, are very fine grained and give the image sharpness that is necessary to resolve temper particles and microcracks. Industrex M, the least fine grained of these, was found to be more than sufficient for studies using the eye alone on Ohio Woodland ceramics. It was also found adequate for low magnification ($< 14\times$) microscopic studies of rock temper mineralogy, although single-coated R is less grainy. The two Industrex R films have the disadvantage of requiring three to four times the exposure of Industrex M and are not recommended for unmagnified ceramic work. Kodak Industrex T is similar to M in graininess but allows an approximately 55% reduction in exposure time. We have not compared the two for documenting ceramic temper and cracks, but this would be worthwhile.

Factors affecting image distortion

Object and film orientation: Unless stereopairs are being made, the specimen and the film should be positioned as perpendicular to the line of X-rays as possible. This is necesary to avoid image distortion—elongation or contraction of the image along the axis of tilt. With curved ceramic specimens, this is not fully possible. Although a specimen's centre can be made perpendicular to the line of X-rays, the periphery will increasingly curve away from it.

When the source is above and the specimen and film are on a table below, this problem can be reduced for a small or large sherd by bending and attaching the film around its convex side and laying its convex side down. This reduces obliqueness to the line of X-rays by taking advange of the spread of the X-ray cone from the source. This trick cannot be used for whole vessels that are radiographed from without because interior, concave film attachment is required. When radiographing whole vessels, optimal object and film orientation can be ensured only by radiographing a small arc of curvature at a time and by making separate exposures for different adjacent sections of the arc.

Table 2. Specific gravity of some common minerals for ceramic temper compared to each other and clay

Mineral	Specific gravity
Orthoclase	2·56
Plagioclase	2·55–2·70
Chert	2·55–2·63
Quartz	2·65
Clay	*2·65*
Calcite	2·71
Dolomite	2·80–2·99
Biotite	2·69–3·16
Muscovite	2·76–3·00
Amphibole	3·00–3·50
Augite	3·20–3·60
Olivine	3·26–3·40
Zircon	4·02–4·86
Ilmenite	4·44–4·90
Magnetite	4·96–5·18

*Specific gravity data are from Hodgman (1948: 1250–1265).

Factors affecting radiographic contrast

Radiographic contrast—the contrast that can be obtained in a radiograph between the images of different phases of an object—can be optimized in only two basic ways. The first is by controlling subject contrast—the range of remnant radiation intensities that is transmitted through the specimen. This can be achieved operationally in many particular ways, only some of which are useful in ceramic radiography. The second means for optimizing radiographic contrast is by choosing an appropriate film for recording and interpreting variations in the remnant radiation as different grey levels.

In ceramic radiography, one of the principle problems to be overcome is low subject contrast. Temper particles and clays may differ only slightly in elemental composition and specific gravity, which govern the relative degrees to which they adsorb X-rays and create images of different grey levels (Table 2). Clays, themselves, are essentially indistinguishable X-radiographically, making coil or slab joins or other indicators of vessel formation difficult to discover. Cracks and microcracks are more easily documented.

Peak kilovoltage: One of the easiest ways to control variation in the remnant radiation of different phases of a specimen and to optimize subject contrast is to adjust the kVp applied to the X-ray tube. Higher subject contrast is obtained with a lower kVp. For example Figure 5(a) shows a typical Ohio Woodland sherd that has been radiographed at a moderate, 50 kVp. Figure 5(b) shows the same sherd radiographed at a lower, 30 kVp. Note the greater contrast between the grey levels of the background clay and the rock temper particles in the lower kVp radiograph. A similar result for higher kVp is shown in the comparison of Figures 8(f) and (g).

The rationale for this can be seen in Figure 3. As kVp is increased, the X-ray spectrum that is generated comes to encompass additional X-rays of a shorter wavelength, higher

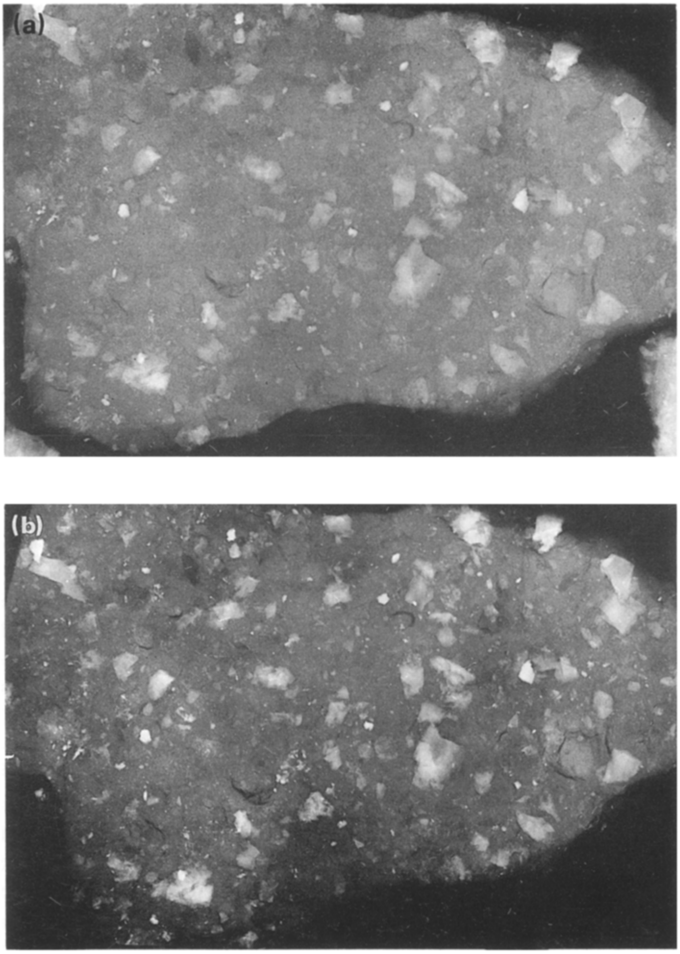


Figure 5. Higher radiographic contrast between phases of a specimen can be obtained by using a lower kVp. (a) An Ohio Woodland sherd from the W.S. Cole site. Radiographed at 50 kVp, 3 mA. (b) The same sherd radiographed at 30 kVp, 4 mA. Radiographic contrast between the grey levels of temper particles and the background clay are greater in the second case.

energy, and greater penetrating power—hard radiation. The total intensity (percentage) of these more penetrating X-rays in the spectrum increases. Because clay and temper particles are similar in specific density, this harder radiation will pass through both to a somewhat similar extent, creating similar remnant radiation and low subject contrast. The film behind both phases will be exposed to a similar degree, producing poor radiographic contrast between them. When a lower kVp is used, the generated X-ray spectrum is predominated by longer wavelength, lower energy, less penetrating X-rays. If these have barely enough energy to pass through the least dense phase of the specimen—here, usually the clay—they will be stopped in significant quantity by the more dense phases—here, usually the temper particles. The result will be greater variation in the remnant radiation and higher subject contrast. With an appropriate film, radiographic contrast will also be high.

Another, mathematically-based way of expressing this condition is to say that the adsorption coefficients of clay and rock temper are very similar at a high kVp but become more distinguishable at a lower kVP.

In sum, to optimize subject contrast among phases in a low subject contrast specimen like a pottery sherd, one should use the lowest kVp that satisfies three conditions. (1) It should generate X-rays of enough energy that they can barely pass through the specimen. This can be determined quickly by trial and error, varying kVp and using long exposures. For example, Carr & Gruber (Battelle Columbus Laboratories) found that Ohio Woodland ceramics less than 5 mm in thickness required *c*. 20 kVp to generate X-rays of great enough energy to pass through them. For sherds of thicknesses up to 15 mm (the thickness examined), 30 kVp was sufficient. (2) The kVp should allow reasonable exposure times within the mA limits of the machine. For example, in Carr's studies with Industrex M-2 film, he had to raise the minimum required kVp from 20 to 30 to keep lab time down. (3) Subject contrast should not be made so great that thin specimens of variable thickness produce a radiograph with underexposed (thicker) and overexposed (thinner) areas. This can interfere with identifying phases (Rye, 1977: 210).

It is not possible to generalize the kVp that is required to pass through sherds of particular thicknesses or even a substance whose precise composition and specific density is known. Trial and error determination is necessary and the above numbers can be used only as a beginning point for developing appropriate radiographic technique in particular instances. The reason for this lies not in the physics of X-ray adsorption but, rather, in variation among X-ray machines. Different machines apply voltages of different wave forms to the X-ray tube. The wave form may be unrectified, rectified or filtered. Since the different wave forms produce different X-ray spectra at the same kVp, subject and radiographic contrast and radiographic density will vary among machines even when using the same technique.

Peak kilovoltage relative to rock temper particle volumetric density: The kVp that is optimal for distinguishing rock temper particles in a radiograph depends on their volumetric density. Higher kVp are required to resolve particles when they become abundant enough that, for a given sherd thickness, their images begin to overlap often and they, rather than the clay, become their own background. The higher kVp reflects the greater specific density and adsorption coefficients of the temper particles compared to clay and the need for higher-energy, more penetrating X-rays to pass successfully through a specimen. For the Ohio Woodland sherds with which Carr worked, using Industrex M-2 film, 30 kVp was found optimal for differentiating igneous rock temper particles from a background of clay in thinner or low temper density specimens. In contrast, 50 kVp was required to differentiate temper particles from each other for specimens that were thick and/or that had higher temper density such that particles created their own background.

Tube source: The spectrum of X-rays that are emitted by an X-ray machine and that influence subject contrast can be optimized by selecting the tube source as well as the kVp. Tubes with targets of either tungsten or molybdenum are common. Molybdenum targets are used in mammography medical applications where normal and abnormal tissues with low subject contrast must be distinguished. Tungsten targets are used in both medical and industrial applications.

If the radiographic facilities available to the archaeologist are in a hospital rather than industrial setting, using a machine with a molybdenum tube can be preferable to one with a tungsten tube, all else equal. A molybdenum tube generates an X-ray spectrum that is dominated by a very large peak of soft radiation at 17 keV, which a tungsten tube does not. If the pottery sherds to be studied are thin enough for X-rays of this energy level to pass through them, then the molybdenum spectrum should provide greater subject contrast. This conclusion is borne out by a comparison that we made between the radiographic contrasts provided by a molybdenum and a tungsten tube for one thin Ohio Woodland sherd [Figure 8(c),(d), below]. It is substantiated by parallel work with materials of lower specific gravity (Rini *et al.*, 1973; Marshall *et al.*, 1975). This advantage, however, is not realized for sherds above a *c.* 5 mm thickness, which do not allow the 17 keV peak to pass through either their clay or temper phases (see above). Finally the advantage of the molybdenum over the tungsten tube assumes the use of no filters of aluminium or other materials. When filters are used, as is common in medical applications to reduce patient dosage, either kind of tube may offer greater subject contrast, depending on the filter thickness and thickness of the specimen (Bernstein *et al.*, 1977). This qualification, however, is not pertinent to ceramic radiography, where patient dosage is not at issue, filters are not needed to reduce dosage, and they only decrease subject contrast (see below).

Window: Producing an X-ray spectrum that is predominated by soft radiation, through kVp and tube choice, is one general means for increasing subject contrast. A second strategy is to modify the emitted spectrum. This can be done by selecting an X-ray machine with an appropriate window and by using various filters, screens, and/or a diaphragm.

The X-ray machine window, through which X-rays are transmitted (Figure 1), can be made of beryllium, glass, aluminium, or steel. Beryllium allows the most primary radiation, both soft and hard, to pass through. Glass, aluminium, and steel increasingly cut out the soft, long-wavelength radiation, which is least penetrating. They increasingly leave the harder, shorter-wavelenght radiation, which is most penetrating. These changes in the spectrum of the emitted radiation in turn affect the subject contrast that can be obtained, in the same way that spectral changes by kVp do. The more that the spectrum is predominated by harder, penetrating X-rays, the lower the subject contrast. In rock tempered ceramics, the harder radiation will pass through the temper and clays to a similar extent, producing similar amounts of remnant radiation for both and exposing the film behind both similarly. However, if softer, less penetrating waves predominate the spectrum, these will be stopped differentially by the clay and temper, creating greater subject and radiographic contrast between them. Consequently, an X-ray machine with a *beryllium* window, which transmits the most soft radiation, is preferable to one with a glass, aluminium, or steel window.

Importantly, many medical X-ray machines with tungsten targets have glass or aluminium windows, and are not optimal for ceramic studies. They are designed to protect the patient from harmful, soft radiation by absorbing it in the window, to the disadvantage of not maximizing subject and radiographic contrast. In comparison, some industrial tungsten target X-ray machines have beryllium windows. These are better suited for examining subtly differentiated materials like ceramics. The contrast problem caused by using a medical, tungsten-target X-ray machine with an absorbing window in one factor that led to inadequate radiographic contrast in Braun's (1982) experimental work.

In the medical setting, X-ray machines with a molybdenum tube always have a beryllium window. This is necessary to allow the softer spectrum of radiation generated by the molytube to be transmitted and taken advantage of in mammography work. The same conditions are useful in ceramics studies.

Filters and screens: Subject contrast can be increased or decreased by modifying the emitted X-ray spectrum with filters and screens (Figure 1) as well as the window of the X-ray machine. Filters are sheets of metal if—usually aluminium, molybdenum, or steel—of a chosen thickness, which are placed in front of the window of the X-ray machine. They

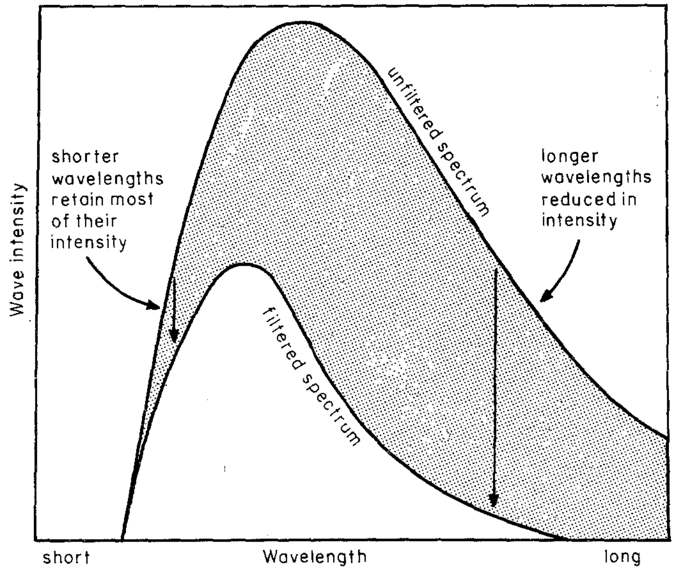


Figure 6. A metal filter, placed in front of the window of an X-ray machine, will absorb longer wavelength waves more so than shorter wavelength waves. This will change the emitted X-ray spectrum as shown.

increase the percentage of harder radiation in the emitted X-ray spectrum by adsorbing longer-wavelength, softer, less penetrating radiation more so than shorter wavelength, harder, more penetrating radiation (Figure 6). The spectrum is hardened also by the increase in kVp which must be made to compensate for filter absorption and to maintain proper exposure. This spectral shift is opposite that needed to increase subject contrast in most ceramic studies, as shown by Braun (1982: 186). Consequently, filters are not generally useful for ceramic research.

An exception is when ceramic specimens are quite variable in thickness and all portions need to be exposed simultaneously and uniformly—e.g. to examine a fracture pattern in a base or rim section that thins and thickens. As in industrial applications, filters can be used in this circumstance to obtain a more uniformly exposed radiograph. Filters achieve this by (1) lessening subject contrast between the thick and thin portions by hardening the radiation, and (2) by reducing *undercut* scattered radiation in thinner sections so that they do not overexpose. Carr found that cordmarks and decorative surface variations on Ohio Woodland ceramics did cause disuniform exposure when maximizing subject contrast. However, these were not too distracting to count and measure temper particles or examine coiling patterns and did not justify a reduction in contrast through filtration.

In medical applications, aluminium and molybdenum filters are frequently used to harden radiation in order to reduce exposure and patient dosage (e.g. Bernstein *et al.*, 1977). This reason is not relevant to ceramic studies. Those who do ceramic research in medical settings should inquire whether the X-ray machines they use have filters and whether the filters can be removed for their work.

Screens are of three varieties: front lead foil screens, front and back fluorescent screens, and back lead screens (Figure 1). All three are sometimes called *intensifying screens*.

A back screen of lead is useful in most industrial, medical and ceramic studies. It absorbs secondary, scattered radiation from the floor or table beneath the specimen, called backscatter. If not minimized, this radiation can cause a general fog over the radiograph and reduce radiographic contrast, especially at the low kVp used in ceramic studies.

To minimize backscatter, the back screen must remain in close contact with the film above it. This can be a problem when working with large curved sections of vessels. In such cases, Carr found that when a vessel section and the film were positioned a few inches away from a back screen, quite visibly lower contrasts were obtained compared to when there was immediate contact with the back screen. The reduction in contrast was on an order one would obtain by increasing kVp detrimentally 50–100%. This problem can be overcome when practical by bending lead sheeting to the shape of the vessel section and placing it below the vessel (Rye, 1977: 211). Thus, in ceramic work, backscatter is a significant problem and using back lead screens is essential.

Front lead screens are used in industrial work to increase contrast when working above *c.* 130 kVp. They increase contrast in two major ways: (1) by absorbing softer radiation which predominates in scattered radiation, especially scatter from the specimen itself, and (2) by intensifying primary radiation more than scattered radiation. In most ceramic applications, lead front screens are not useful. This is so because kVp must be increased for the primary radiation to penetrate both the lead screen and the specimen. The higher kVp decreases subject contrast more than the screen increases radiographic contrast in the two ways mentioned.

Fluorescent screens are plates that are coated with phosphor compounds and positioned above and below the X-ray film (Figure 1). They absorb X-rays and convert them into light, which exposes the film. Fluorescent screens offer the advantage in medical applications of reducing exposure time by factors of 10 to several hundred, depending on the kind of screen and kVp. Patient dosage is thereby decreased.

Fluorescent screens are not recommended for ceramic work for two reasons. First, they decrease image sharpness. This results from the fact that the light emitted by a screen as it is bombarded by an X-ray spreads beyond that X-ray and exposes the film over a wider area. The defocusing effects of using fluorescent screens can be seen by comparing Figures 8(b) and (c). Both radiographs were made with mammography film of similar grain. However, the one made with a fluorescent screen does not have as sharply defined temper particles as the radiograph made without a screen. Second, fluorescent screens can cause *screen mottle*—an uneven exposure that results from random variations in the number of X-rays absorbed in different areas of a screen. Both problems can interfere with identifying and counting temper particles or microcracks, as found by Braun (1982: 186).

Diaphragms: Diaphragms come in two forms. The simplest is a sheet of lead with an opening. It is placed between the X-ray machine's window and the specimen (Figure 1). The opening is made of a size and shape such that it reduces the cone of emitted X-rays to a field similar to the size and shape of the object being radiographed. In this way, scattered radiation from outside the object is minimized and radiographic contrast is increased. The effect can be very significant in low kVp work such as ceramic radiography. Here, external scattered radiation can be as plentiful as primary radiation.

The second kind of diaphragm is known as the Potter–Bucky diaphragm. It is useful for eliminating scattered radiation from both the specimen and outside the specimen. The diaphragm is comprised of a series of parallel strips that function like window blinds relative to the X-ray source. Each strip is set at a slight angle from vertical, toward the source. The diaphragm is placed between the specimen and the film and moves back and forth so as not to show on the radiograph. Since primary radiation parallels the strips whereas scattered radiation comes at all angles, the diaphragm transmits predominantly primary radiation and very little scattered radiation. Subject contrast is thereby increased.

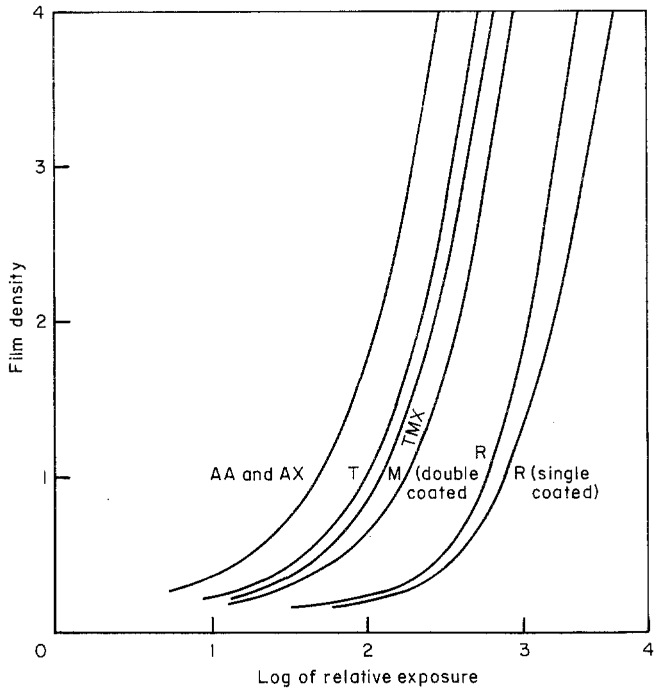


Figure 7. Characteristic curves of various Kodak films for industrial radiography using 200 kVp, a 0·005 in. front lead screen, 0·1 in. back lead screen, and manual film processing. (Adapted from Kodak.)

Although the Potter–Bucky diaphragm is most useful in low kVp work where scattered radiation is a problem, its relevance in ceramic work is questionable. Image clarity is sacrificed to some degree because the diaphragm is placed between the specimen and the film. Also, the radiographic image will be somewhat magnified, which may or may not be desirable.

Film type: Each of the above technical choices allows the researcher to optimize radiographic contrast by adjusting subject contrast. The second means for improving radiographic contrast is by choosing a film with an appropriate film contrast.

The characteristic curves of some available industrial films (Figure 7) show that film contrast is not a critical factor in film choice. The slopes of the characteristic curves for Kodak Industrex AA, T, MTX, M and R are each similar at 200 kVp. The advantages of one over the other is in film grain, the image sharpness that is rendered (see above), and exposure time. It is true that the characteristic curves of these films at 200 kVp give only an approximate estimate of their relative contrast at the 30–50 kVp at which ceramic work will usually be done: the slope of a characteristic curve is a function of kVp. However, for the two high detail films in Figure 7 which are most useful for ceramic radiography, Industrex M2 and single coated Industrex R, experimentation on Ohio Woodland pottery has shown that the higher detail film Industrex R offers no observable contrast advantage over M2 for documenting rock temper particles at 50 kVp.

Medical films are not easily contrasted with industrial films or each other using characteristic curves. There are two reasons. First, the slow, high-detail medical films that are useful in ceramic applications are meant to be applied with fluorescent screens, in order to reduce patient exposure. Thus, in medical applications, it is the characteristic curve of a film-screen combination, rather than a film alone, that is relevant. In contrast, in ceramic applications, where exposure time is less critical and screens only reduce image sharpness, the characterisitic curve of the film, alone, is pertinent. The latter curves are unfortunately not important commercially and are not available. Second, contrast differentials among medical films as a function of kVp are not especially relevant when fluorescent screens are used. Screens tend to give a similar light output for a wide range of kVp inputs (J. Blonowitz, Kodak, pers. comm.). Consequently, characteristic curves for screen-film combinations, which might be useful to the archaeologist working in a hospital setting, are not readily available, either.

To explore the relative merits of medical and industrial films in their contrast, with and without fluorescent screens, several Ohio Woodland sherds were each radiographed using several different techniques. Representative results for one of the sherds are shown in Figure 8(a)–(g). Several observations can be made and conclusions drawn, starting with lower contrast films and ending with the highest. (1) When used as intended with fluorescent screens, the general purpose medical film Fugi ROXG with a Lanex fine detail screen [Figure 8(a)] and the mammography film Min-R with a fluorescent screen [Figure 8(b)] have much lower contrast than films for mammography [Figure 8(d)] and XTL for high detail specimens radiography [Figure 8(e)] used without screens. (2) The lower observed contrast is in part a result of using the screens, as argued above. (3) When used with or without screens, mammography film Kodak Min-R has lower contrast than some other mammography films such as Kodak Ortho M (Eastman, Kodak, 1981: 9). With screens, Min-R has a characteristic curve with an average gradient of about 2·0, whereas Ortho-M has a curve with an average slope of about 3·0 (J. Blonowitz, Kodak, pers. comm.). (4) When used without fluorescent screens, a general purpose medical film has a characteristic curve with an average slope of approximately 1, whereas mammography films have curves with average slopes of approximately 2·5–2·8 and Industrex M and R average about 4 (W.V. Bowles, Kodak, pers. comm.). Consequently, mammography and industrial films have a large advantage over general purpose medical films in the contrast that they offer when used without fluorescent screens. (5) Mammography film [Figure 8(c)] and XTL [Figure 8(e)] used without fluorescent screens offer lower contrast than Industrex M [Figure 8(f)]. This observation agrees with the approximate slopes of the characteristic curves of mammography films and Industrex M and R just cited. (6) Given that Industrex AA and T have characteristic curves similar to Industrex M and R, the contrast that they offer should also be greater than that of mammography films and XTL. (7) XTL used without a fluorescent screen provides a contrast almost as good as Industrex M2. However, it has the advantage that it can be developed in a 90 second processor, which many hospitals have, whereas M2 cannot. Since development time rather than exposure time is the slowest part of radiographic lab work, XTL is competitive with the Industrex M2 and R.

These results, along with considerations of film sharpness (above), would suggest at face value that XTL, M2, or R should be used in ceramic studies. In addition, one would want to use an X-ray machine with a molybdenum target. However, the selection process is more complex. As remarked earlier, one must consider whether the work setting is the hospital or industrial laboratory and the differences in their goals and equipment limitations. In particular, many hospital X-ray machines are designed to make radiographs using a high mA (*c.* 100 mA) and short exposure time, whereas industrial X-ray machines are often designed to make radiographs using a low mA (2–5 mA) and long exposure time. This difference reflects the importance of minimizing patient exposure and overcoming patient movement in the medical setting versus the concern for image sharpness which is

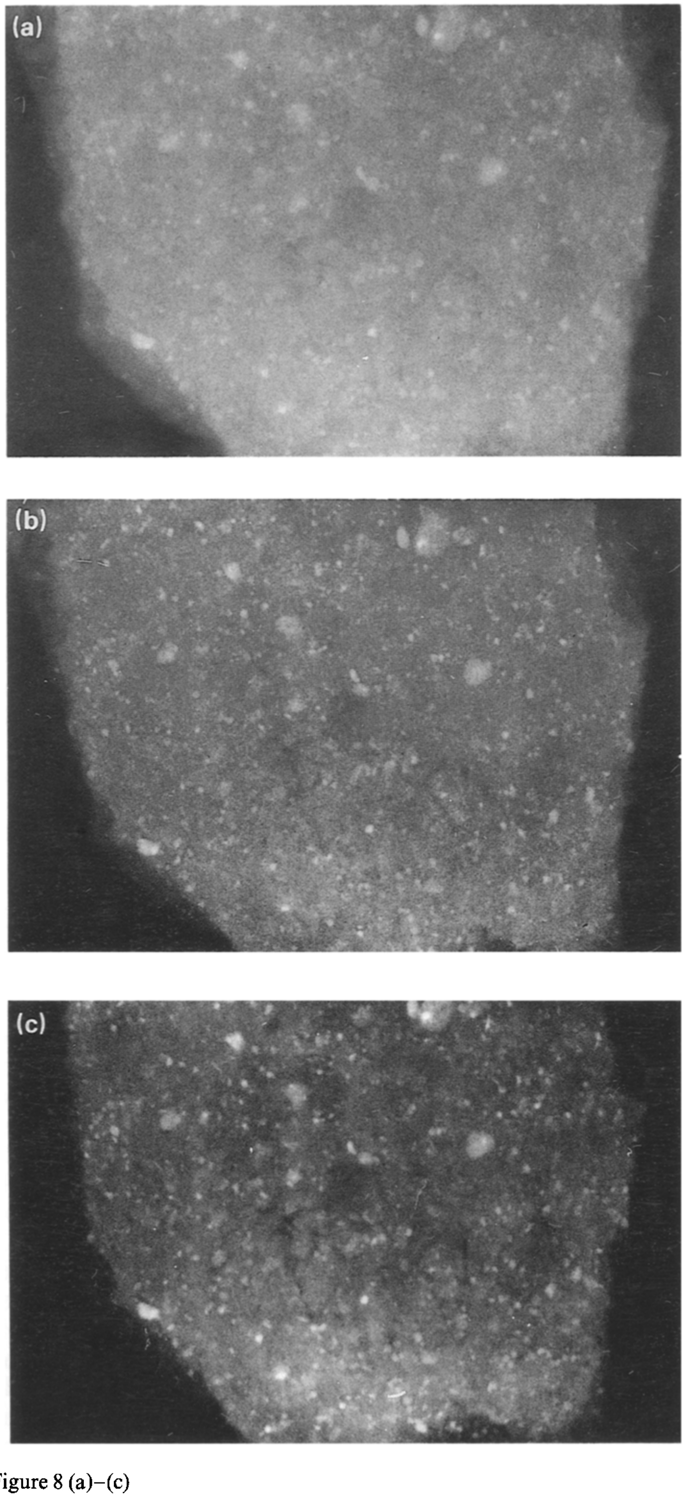


Figure 8 (a)–(c)

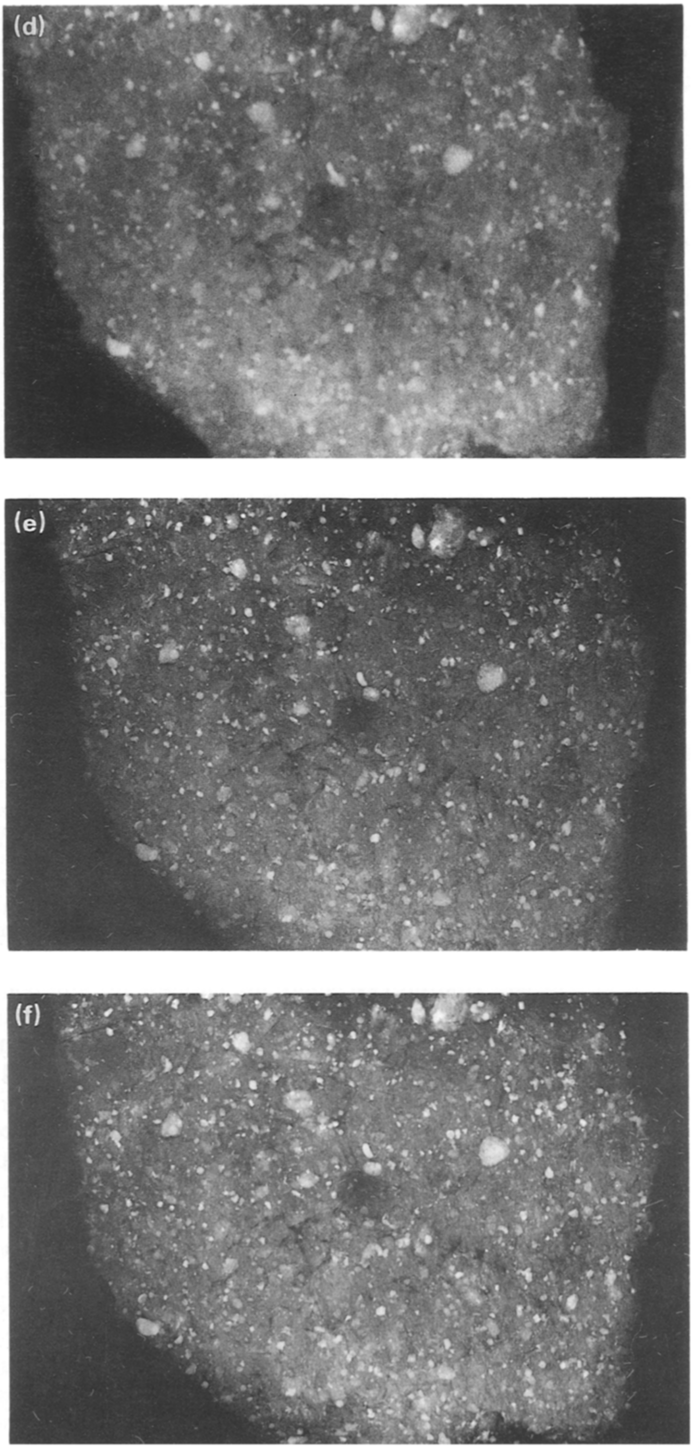


Figure 8 (d)–(f)

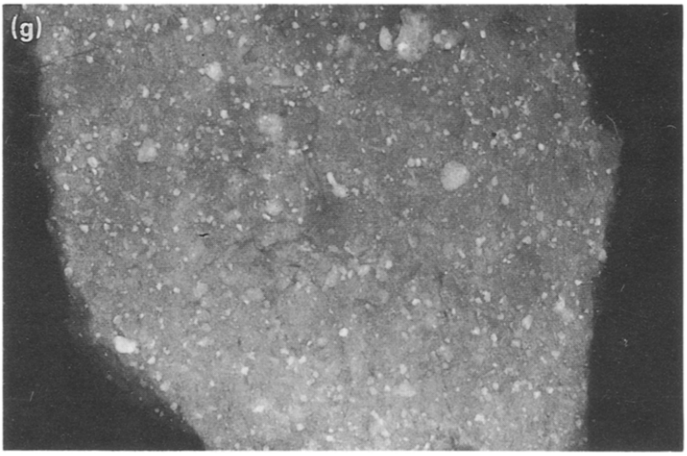


Figure 8 (g)

Figure 8. Comparisons of radiographic techniques for their effects on image sharpness and contrast using a Baum phase Ft. Ancient, igneous rock tempered sherd from southern Ohio. (a) General purpose medical film Fuji ROXG with a Kodak Lanex Fine screen. 40 kVp, 200 mA, 0·025 s, tungsten target. (b) Mammography film Kodak Min R with a Min R fluorescent screen. 50 kVp, 50 mA, 0·2 s, tungsten target. (c) Mammography film without a fluorescent screen. Tungsten target. (d) Mammography film without a fluorescent screen. Molybdenum target. (e) High detail specimen radiography film Kodak XTL without a fluorescent screen. 50 kVp, 3 mA, 5 min, tungsten target. (f) Industrial film Kodak Industrex M-2 without a front screen. 50 kVp, 3 mA, 6 min, tungsten target. (g) Industrial film Kodak Industrex M-2 without a front screen, 110 kVp, 30 mA, 15 s. Exposures (a–d) were made by Riddick & Carr at Washington Regional Medical Center, Fayetteville, AR. Exposures (e–g) were made by William V. Bowles, Kodak Research Laboratory, Rochester, NY. Differences in contrast obtained for exposures made with different X-ray machines (a, b, c versus d versus e, f, g) are only approximate. Differences in secondary scattered radiation levels among machines, which is an important contributor to radiographic contrast at low kVp, has not been controlled.

attained with slow films in an industrial setting. Several consequences follow. (1) It is not possible to use the slow, high detail industrial films, M2 and R, in a hospital setting without screens. The long exposures that would be required to use these films would quickly expend the life of a medical tungsten or molybdenum tube and would probably not be allowed by hospital personnel. To use them with fluorescent screens, however, would significantly and undesirably decrease their sharpness. Thus, these films can be used to an advantage only in an industrial laboratory setting. (2) It is not possible to use the slow, high detail medical film, XTL, in a hospital setting without a fluorescent screen, for the same reason (J. Blonowitz, Kodak, pers. comm.). Again, to use a screen would decrease image sharpness, which makes this film choice less desirable. Thus, XTL, too, is useful only in an industrial laboratory setting. However, given that industrial laboratories usually do not have 90 second automated developers which can be used with XTL and that XTL has a somewhat lower contrast than M2 and R, the latter are preferable in an industrial setting. (3) In a hospital setting, mammography films used without fluorescent screens (in order to increase image sharpness) and exposed with a molybdenum tube (in order to increase radiographic contrast) provide optimum techniques when sherds are less than 5 mm thick. For thicker sherds, either a tungsten or molybdenum target tube can be used. (4) With these choice limitations, the industrial laboratory is preferable to the hospital setting in providing high contrast and sharp radiographs for ceramic research.

Film cassettes: At kVp's less than about 60, secondary, scattered radiation from the film cassette, machine, and other equipment can sometimes be as important as film type in determining radiographic contrast (J. Blonowitz, Kodak, pers. comm.). In hospitals, both metal and plastic film cassettes are used. Plastic cassettes are usually used in mammography work in order to reduce scatter and increase radiographic contrast. They are to be preferred in ceramic work regardless of the film type chosen. Metal cassettes are often used for general purpose radiography, where scatter and contrast are less important, and should be avoided. In industrial laboratories, the problem of metal cassettes does not typically arise. Film is often bought and used directly in sealed paper "ready packs," or is bought in sheets that are placed in cardboard cassettes.

Xeroradiography: The problem of low subject contrast can be overcome in some, but not all, ceramic studies by using the new technique of xeroradiography (Heinemann, 1976; Christensen *et al.*, 1978: 308–328). Xeroradiography is used in the medical sciences to document subtle density differences in soft body tissues, especially in mammographic applications (Fingerhut & Fountainelle, 1974; Wolfe, 1976). This is achieved not by using a film with a greatly sloping characteristic curve and high contrast, as in mammography X-ray film. The average characteristic curve slope of a xeroradiographic plate is only about 0·2 (Wagner *et al.*, 1974). Instead, high contrast is *simulated* in xeroradiography by an edge-enhancement process. Borders between areas that differ in density are distinguished greatly in shade whereas the areas, themselves, are distinguished to a much lesser degree.

Edge enhancement is made possible by using a selenium sulfide coated plate which has been electrostatically charged (positive or negative), rather than the silver halide plate used in X-radiography. When subjected to X-rays with a specimen above it, different parts of the plate lose their charge in proportion to the remnant radiation. This latent image of residual charges is then developed with oppositely charge blue pigment particles (toner) and made permanent by transferring them to paper. A blue on white or white on blue image results, depending on whether the plate was initially charged positively or negatively. Edge enhancement at the border between two areas of different exposure results when toner particles are attracted from the edge of the area of greater exposure and less residual charge to the edge of the area of lesser exposure and greater residual charge.

The edge enhancement feature of xeroradiography makes it ideal for defining the boundaries between uniform phases of a specimen. The key words, here, are boundaries and uniform phases. In ceramic studies, examples of such tasks include defining the interior wall outlines of hollow, closed items (Alexander & Johnston, 1982; Foster, 1983), delineating voids at the seams between coils or slabs of a vessel (Adler, 1983; Glanzman & Fleming, 1986), documenting cracks (Heinemann, 1976), and delimiting the outlines of large, compositionally uniform temper particles such as large limestone or shell temper particles or voids where these have been leached out (Adler, 1983).

Xeroradiography is not well suited, however, to studies that require continuous image representation as opposed to edge enhancement (Alexander & Johnson, 1982). Nor is it suited for documenting small anomalies which have a high border to internal area ratio. Edge enhancement causes small anomalies to form blurred images, which may not be distinguishable from the background. Finally, xeroradiography is not meant for distinguishing by "grey level" broad homogeneous areas which differ in composition or thickness from each other. In ceramic research, documenting the characteristics of rock temper in vessels is an example of a task posing each of these problems. (1) When temper volumetric density is high and particle images overlap greatly, edge enhancement imaging does not allow one to distinguish cases of overlap of two particles from the simple adjacency of three particles, whereas continuous imaging does. (2) With edge enhancement, the multiple crystal facets that a rock temper particle can have are easily confused for separate, adjacent particles. With continuous imaging, these circumstances can be distinguished. (3) Smaller temper particles may not appear in a xeroradiograph when they do in a high contrast X-radiograph (e.g. Figure 9). (4) With xeroradiography, rock temper particles of different mineral compositions will be represented by similar "grey levels", whereas with X-radiography, they will often be distinguished (Figure 9). Consequently, xeroradiography does not have the potential for identifying the approximate mineralogy of rock temper particles that X-radiography does.

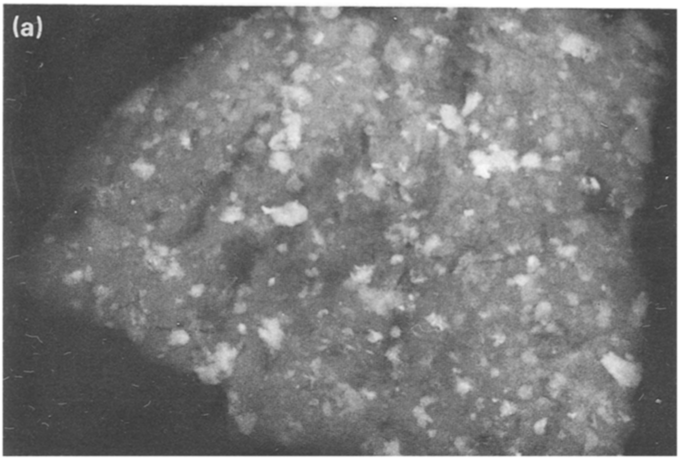
CAT scanner: Subtle anomalies in the density of a specimen—much lower than those that can be documented by conventional radiography—can be detected by another X-ray based procedure, computerized axial tomography or CAT scanning. CAT scanning allows one to create an image of density differences within a 1·5–13 mm thick-section. The image of the thick section is produced by computer-aided triangulation.

A CAT scanner is comprised of a conventional tungsten X-ray tube which rotates around the object. Primary radiation is emitted from different angles in burst and an array of detectors monitors the residual X-radiation received at those angles. Phases of different density within a thick section of the object are reconstructed and displayed from this information. Specifically, a thick section is defined as a three-dimensional matrix of cells. For each cell, the degrees to which it has absorbed X-rays from several angles are used to calculate its linear attenuation coefficient. This is then displayed as a grey level on film or a monitor, producing a coarse-grained image of phases within the slice.

The CAT scanner is potentially important for ceramic analysis because it increases subject contrast through triangulation. Also, its sectioning capability greatly reduces the problem of overlapping temper particle images and hidden particles, which is encountered in a standard radiograph. Unfortunately, however, the spatial resolution of a CAT-scan is poor; the matrix of cells that define a slice is coarse. Coils, unique joins of various kinds, and temper particles are not distinguished clearly enough for a CAT scan to be useful (Figure 10). In some instances, a CAT scan through the centre of a whole vessel can be used to determine its construction stages, as experiments by Riddick have shown. Different portions of a wall may differ in their average density and grey level. The contrast is not nearly as good as with Xeroradiography, however.

Exposure

In ceramic work aimed at documenting rock temper particle size, volumetric density, and/or composition, exposure should be selected in relation to several factors. (1) The grey level of the background clay should be held constant from radiograph to radiograph as much as possible. This is essential if a grey level comparison of rock temper particles to each other and to the background clay is to be used—on either an absolute or ordinal scale—to identify the approximate mineral composition of the particles. It is also helpful when identifying and sorting sherds from multiple vessels in a mixed archaeological deposit to their vessels of origin by their temper volumetric density, size, and mineralogy (Carr, 1987). When clay grey level is held constant, the *overall* grey level of a sherd's radiograph becomes a function of temper volumetric density and composition. Thus, it becomes easy to make an overall visual assessment of these parameters for a sherd and its differences from or similarity to other sherds. This facilitates segregating sherds from



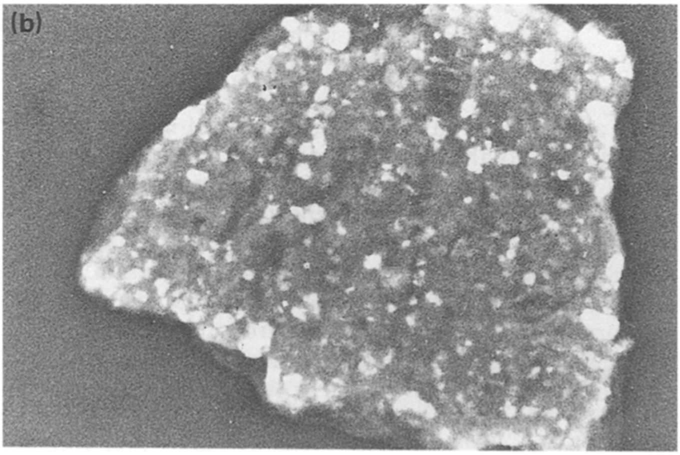


Figure 9. (a) X-radiograph of a Ohio Woodland pottery sherd made with mammography film Kodak Min-R, a fluorescent screen, a tungsten target, 80 mAs, and 32 kVp. (b) Xeroradiograph of the same sherd made with a high plate charge in negative mode, 120 kVp, 200 mA, and 0·1 s. Note, first, how some smaller temper particles that appear in the X-radiograph do not show in the xeroradiograph; second, how overlapping particles can be distinguished by their grey level in the X-radiograph when they merge together with one grey level in the xeroradiograph; and third, how temper particles have different grey levels—indicating their different mineralogy—in the X-radiograph, whereas they have only one nondiagnostic "grey level" in the xeroradiograph.

different vessels visually and quickly, as opposed to quantitatively and slowly, using these parameters. (2) The grey level of the background clay should be made somewhat above 50% between white and black, as exemplified in Figure 4(a). In a lighter radiograph, most rock temper particles will have a similar grey level and their compositional distinctions will be obscured. This prohibits using the radiograph to determine the approximate mineralogy of the particles. Also, particle images that overlap may be difficult to distinguish and size. Finally, small particles with radiographic densities similar to that of the background clay may be lost. As the clay grey level approaches the black end of the

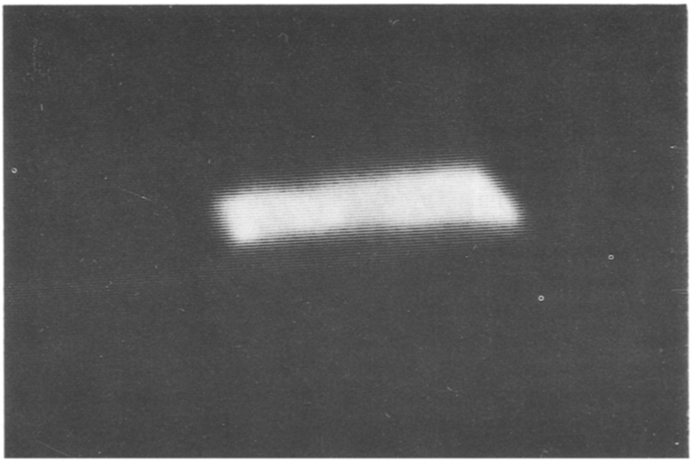


Figure 10. A CAT scan of the Ohio Woodland pottery sherd shown in Figure 9. The scan was made with a Picker International 1200SX with the section perpendicular to the sherd's curvature. Note that temper particles are almost indistinguishable in the scan as a result of poor image sharpness.

spectrum, again, small particles which contrast little from the clay may become indistinguishable. Each of these effects were observed in various exposure tests made with Ohio Woodland ceramics. (3) Somewhat denser radiographs are sometimes required for sherds that have high enough volumetric densities of temper particles that particle images overlap and form their own background. This is necessary to maximize particle distinction, particularly if most particles are similar in composition. In sum, a useful radiographic exposure for examining temper characteristics should have a somewhat darker balance.

To ensure the proper exposure of sherds, they must be sorted and radiographed by thickness. Thickness, in part, determines the remnant radiation that is available for exposing the film:

$$I = I_0 e^{-ax} \tag{4}$$

where I_0 is the remnant radiation, I is the primary radiation, a is the absorption coefficient of the material at the given kVp, and x is specimen thickness. When relatively low contrast film, higher kVp, and other low contrast techniques are used, the thickness grades can be relatively wide. For example, Braun (1982: 186) selected 5 mm gradations when using Kodak XRP-1 and 60–65 kVp. When working with higher contrast Industrex M2 and 30 kVp, Carr needed to use much narrower grades to obtain exposures that were approximately uniform in background clay grey level among sherds. The classes were 1·4 mm wide for sherds in the 3–7·7 mm range, 2 mm wide for sherds in the 7·7–12 mm range, and 3 mm for sherds in the 12–15 mm range. (Class end points were varied freely within these ranges, depending on the specific sherd thicknesses in sherd lots.)

Figures 11 and 12 are exposure charts that Carr developed for Ohio Woodland ceramics for 30 and 50 kVp studies. The charts indicate the minutes of exposure time at 4 and 3 mA, respectively, and 31 in. *ffd* that were found to give an optimal radiographic density to the background—clay or particles— for sherds of given thicknesses. For the 30 kVp chart, the range of variation in sherd thickness that gave marginally similar background clay grey levels, such that temper particles could easily be distinguished from their clay matrices, is also shown for all exposure times. These limits represent Carr's personal grey-level tolerances for adequately distinguishing particles, as well as variation in film development. To

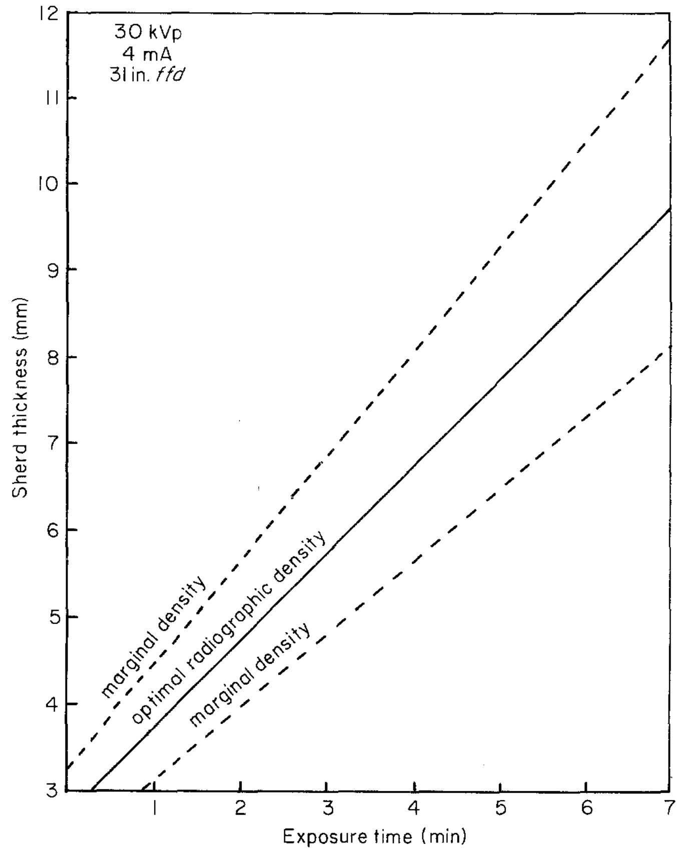


Figure 11. Exposure chart for sherds that have lower temper particle densities or are thinner, such that particle images do not overlap much.

obtain more acceptable radiographs, Carr routinely used sherd thickness ranges one-half of those shown in Figure 11. Those attempting to survey and/or identify rock temper mineralogy with radiographs should be at least this stringent. The decision of whether to use a 30 or 50 kVp technique depended on sherd temper density and sherd thickness, as discussed above.

For routine work with small sherds that varied little in thickness, it was easiest to sort sherds into the thickness classes mentioned above and to use the exposure time of the mean thickness for each class, as specified by the appropriate chart. Multiple sherds of a class were then radiographed together. For large sherds or vessel sections that varied much in thickness and did not fit into one class, I used the chart to determine areas of similar enough thickness that each could be radiographed optimally with a single exposure time, and to determine that time.

The charts in Figures 11 and 12 can serve others as a useful starting point for establishing their own exposure charts. Some may find that they cannot be used as given, for as mentioned above, different X-ray machines can emit different spectra of X-rays at the same kVp, depending on the waveform of their current. Also, tubes of various ages may emit more or less intense X-rays.

Exposure charts are easy to make and help to minimize laboratory errors in exposure. Ceramic radiographers are encouraged to develop their own charts relevant to the spectral

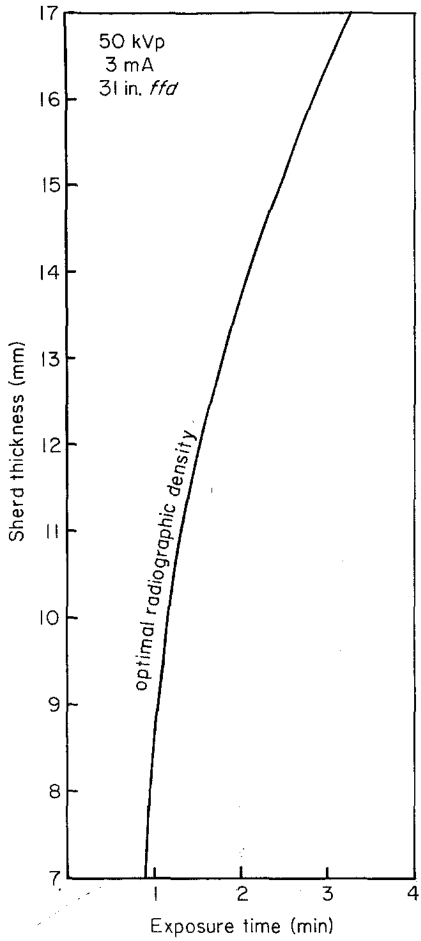


Figure 12. Exposure chart for sherds that have higher temper particle densities and/or are thicker, such that particle images overlap much.

outputs and other technical parameters unique to their work. The charts shown here were created simply by radiographing 32 sherds of known thicknesses (3–15 mm) at multiple exposures, ranging from well underexposed to well overexposed. Acceptable exposures for each sherd were then selected and plotted against thickness. A best fit linear regression and a confidence band for acceptable exposure were then constructed visually.

For these or other exposure charts, exposure time can be adjusted so as to maintain the same exposure factors and radiographic density by using eqn (1), above. For example, to halve exposure time, one could increase the milliamperage two-fold or decrease the focal spot-to-film distance by a factor of $1/\sqrt{2}$. To adjust the charts for a change in kVp, Table 3 can be used.

Operations

A number of procedures can help to make for efficient use of laboratory time, which is expensive. (1) Sherds which have been sorted according to provenience, type, or some other classification during their initial study should be reorganized as they will be radiographed—by thickness class first and then other classes—before going to the

Table 3. mAS multiplying factors to be used when kilovoltage is changed

Old kVp	New kVp										
	50	55	60	65	70	75	80	85	90	95	100
50	1·00	0·69	0·50	0·39	0·30	0·29	0·19	0·14	0·12	0·10	0·09
55	1·45	1·00	0·73	0·56	0·43	0·34	0·27	0·21	0·18	0·15	0·13
60	2·00	1·37	1·00	0·77	0·60	0·47	0·37	0·29	0·25	0·21	0·19
65	2·58	1·77	1·29	1·00	0·77	0·61	0·48	0·37	0·32	0·27	0·24
70	3·33	2·29	1·66	1·29	1·00	0·79	0·62	0·48	0·42	0·35	0·31
75	4·21	2·89	2·10	1·63	1·26	1·00	0·79	0·60	0·52	0·44	0·39
80	5·33	3·66	2·66	2·06	1·60	1·26	1·00	0·76	0·66	0·56	0·50
85	6·95	4·78	3·48	2·69	2·00	1·65	1·30	1·00	0·87	0·74	0·65
90	8·00	5·50	4·00	3·10	2·40	1·90	1·50	1·15	1·00	0·85	0·75
95	9·41	6·47	4·71	3·64	2·80	2·23	1·76	1·35	1·17	1·00	0·88
100	10·66	7·33	5·33	4·13	3·20	2·53	2·00	1·53	1·33	1·13	1·00

From Cahoon (1956: 57).

laboratory. (2) For smaller pottery sherds, multiple sherds of the same thickness class can be radiographed at once on 8 × 10 in. or larger sheet film. Lead letters or numbers can be used to mark sherds of a single provenience. It is not practical to label every sherd within proveniences. Sherd order and position can be used for this. (3) Sherds to be radiographed together on a single sheet should be prearranged on a dummy piece of paper of the same size as the film before lab work. Sherds can then be transferred quickly and mechanically from the paper to the film. The lead characters to be used should be written on the paper. (4) Each exposure should be numbered with lead characters, which tie it to a log of its content and machine settings, in order to keep matters straight during exposure and development. (5) For a whole vessel or large vessel section where only a portion will be radiographed at one time, the outline of the area to be exposed should be marked with gummed stickers. Film, pre-cut to the appropriate size, can then be quickly placed relative to the stickers and secured with masking tape. (6) Lab work will go most effectively when there are two persons, one to set up shots and a second to develop film. This is so because the two operations have different schedules: exposure time versus several development times when development is manual. (7) In a laboratory with manual development, development will be slower than exposure. Consequently, exposure should proceed from shots that require shorter setup or exposure times to longer shots. Shots of multiple sherds on sheet film, which involve little set up time, should precede shots of whole vessels or vessel sections, which require extra film attachment and sherd positioning time. In a hospital setting with an automated 90 or 150 second processor, set up will be the most time-consuming activity and the order of shots does not matter. (8) Shots requiring the same kVp should be done together so that only the mA need be changed for each exposure. This will reduce mistakes.

Sequencing of dating and radiographing

When radiography or other methods are used to track ceramic technological change hrough time in order to develop a ceramic chronology (e.g. Braun, 1982; Carr, 1985, 986), it is preferable to date ceramics as directly as possible. Small quantities of food arbon residues on the interior surface of a sherd or organic temper can be dated by AMS methods to achieve this (de Atley, 1980; Bill *et al.*, 1984; Johnson *et al.*, 1986; vans & Meggers, 1962). Thermoluminescence can similarly be used when dating accuracy and precision can be ensured. In either case, however, the samples of carbon or ceramic to be dated should be removed from specimens before they are radiographed. Exposure of organics to X-rays at the typical kVp's and times used in ceramic research *may* cause carbon-14 decay and older date estimations (H. Haas, pers. comm.). Similarly, ceramic thermoluminscence *may* be reduced, producing younger date estimations (Rye, 1977: 208). Though theoretically expectable, the extent to which these processes are troublesome has not yet been investigated.

The effect of radiography on the results of other radioactive and molecular based techniques, such as those which aim at material identification from trace residues, is not known.

Costs

The cost in labour and materials to radiograph a collection of ceramics depends on several primary variables: whether small sherds or larger vessel sections or whole vessels are being studied, the number of specimens that can be exposed at once, the thickness of the specimens, the speed of the film, and whether automated development is possible. Each of these factors can alter costs by two-fold or more. In our work on Ohio ceramics, a typical 8 h day of radiographing about 60% small sherds with sheet film (less time-consuming) and 40% larger sections with roll film (more time consuming) and using the technical parameters in Table 1 allowed us to make about six exposures h^{-1}. At the conservative equivalent of 40 sherds per sheet film exposure and $250 of material and labour costs per 8 h day, this translates to *c.* 13¢ per sherd.

To work in a commercial setting with overhead costs is more expensive. A package of Kodak M2 ready pack 8 × 10 in. sheet film with 50 sheets (1·1 days supply) currently costs $123·25; M2 70 mm × 200 ft roll film runs $205·36. Commercial industrial labour and overhead costs typically run $500–750 day^{-1}. These costs are much less than those of making thin sections for an equivalent number of sherds. However, they still encourage one to develop a research relationship with a laboratory whereby overhead costs can be dropped and only X-ray technician and material costs are charged.

Laboratory accessibility

Most hospital radiology laboratories that might help an archaeologist radiograph ceramics must schedule work in off times, such as during the night.

Viewing

Light table: Radiographs should be viewed with incandescent rather than fluorescent lighting. Fluorescent lighting does not provide the intensity that is necessary to see the full dynamic range of a properly exposed radiograph, which has a somewhat dark balance in order to distinguish temper particle overlap or composition. Also, fluorescent lighting produces a narrower colour spectrum than incandescent lighting, and is thus apparently not as helpful to the eye in defining subtle distinctions in radiographic density. More satisfactory is dense incandescent lighting which is cooled by fan to prevent heat-warping of the radiograph. Carr used 4 100 W bulbs, which lighted a 20 × 25 in. area.

Standard light tables use plates made of either of two media to provide diffuse light: a translucent plastic or ground glass. Neither are sufficient. Plastic will melt under the heat of dense incandescent lights. Ground glass overcomes this problem but has a grain that will show in a radiograph and confuse the definition of subtle borders and small particles. More satisfactory viewing is provided by a plate made of two layers of clear glass with a plastic translucent tracing "paper" in between. Plastic tracing papers come both with and without grain and it is essential to use the latter.

Multiple exposures and stereopairs: When pottery is thick enough or has a high enough temper density, particle images can overlap in a radiograph and obscure each other. Also, some facets of multifaceted particles with low subject contrast relative to the background clay may be hard to see. In these cases, it is useful to make two radiographs of each sherd, with the sherd positioned at slightly different angles from vertical. This repositioning creates different patterns of overlap among particles, which allows one to count and size particles more accurately. It also helps one to see all facets of a particle and to correctly size it. Thus, more accurate estimates of temper volumetric density and size distribution can be derived.

Operationally, repositioning sherds can be done most satisfactorily by placing them and the film on a lead-covered plate which tilts about 5 degrees from the vertical in two directions, and then radiographing the sherds twice at the two different tilts. The sherds should be positioned convex side down, in order to reduce the object-to-film distance. Alternatively, one can radiograph the sherds on both of their sides. Sherd curvature, off centres-of-gravity, and irregular outlines will usually ensure a different tilt. This method is less preferable to the extent that it increases the object-to-film distance for one of the exposures. For whole vessels or large sections which are radiographed with roll film, a simple rotation of the vessel a few degrees in the direction of the film's length will suffice.

A more elaborate way to improve the view of overlapping or multifaceted particles is to make stereopair radiographs. Stereopairs can be created by taking two shots of a specimen with a shift in the position of the X-ray tube (Cahoon, 1956: 95–96; Bryant & McIntire, 1985) or a shift in the position or angle of the film and specimen (Krinitsky, 1970: 25–28). The appropriate amount of shift varies with the focal spot-film distance and with the stereoviewer to be used.

Experiments by Gruber & Carr showed that stereopairs were helpful in documenting temper particles only when they were large ($>c.$ 2 mm in diameter) and high enough in density to form their own background. In this case, the problems of particle overlap and indistinguishable facets were overcome by the sense of perspective and redundant imaging offered by stereoradiography. The technique was found superior to examining a single radiograph or sequentially examining double radiographs of repositioned/tilted sherds. Stereopairs offered no great advantage over single or double radiographs when trying to resolve isolated temper particles in ceramics with low temper density. They were also not effective for ceramics predominated by small temper particles, which cannot take on much three dimensionality. In general, the extra labor involved in mounting stereoradiographs does not justify their use in ceramic temper analysis.

Conclusion

Diagnostic ceramic features such as temper particles, voids at joins, and fracture systems are visible in a radiograph because they differ from the clay matrix in their potential for allowing X-rays to pass through them. Compared to anomalies in other materials however, those in ceramics are often subtle. They may produce little radiographic contrast or be fine-grained. Application of several standard industrial and newer medical products and methods allows these difficulties to be overcome. (1) High contrast, fine-grained industrial films such as Kodak M-2, and medical mammography films, help to amplify and resolve subtle ceramic features. These films should be used without front lead or fluorescent screens in order to retain their contrast and sharpness advantages. (2) Recently developed medical X-ray tubes with a molybdenum rather than tungsten target and without filters generate spectra that are predominated at low kVp by softer, longer wave length X-rays. These X-rays increase radiographic contrast for ceramics that are thin enough (less than c. 5 mm in thickness) to transmit them. (3) Mammography units with molybdenum targets and more generally, X-ray units that are designed for low kVp applications, are usually equipped with small focal spots. These units are capable of creating sharper images and are preferable for ceramic work. (4) The new method of xeroradiography simulates higher contrast conditions with edge enhancement. It is well suited for defining hidden interior wall outlines, voids at vessel joins, and large, compositionally uniform (e.g. limestone, shell) temper particles. X-radiography is more appropriate for defining temper particles that are small, form overlapping images, and/or are polymineral in kind. It is also preferable for identifying the approximate mineralogy of rock temper particles. (5–9) Radiographic contrast can also be increased by using an X-ray machine with a beryllium window which transmits soft radiation; a low, 20–50 kVp setting which generates soft radiation; and back lead screens, plastic film cassettes, and a simple cut-out diaphragm, which reduce scattered radiation. (10–11) Image sharpness can be increased by using a large film-to-focal spot distance and by reducing the object-to-film distance. The latter can be achieved by positioning a sherd convex down on the film or, for large sherds, by taping the film to the sherd's contour. (12) Image distortion can be avoided by positioning a sherd convex down and, for large sherds, by making separate, perpendicular exposures for different sections of its arc. (13) Radiographs should be made with a somewhat dark balance and viewed with a strong incandescent light in order to maximize perceived contrast.

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