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Reduction and oxidation in English medieval kiln practice

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SUMMARY

Although the effects of reduction and oxidation on medieval pottery are easily recognized, the technical means of producing them are less well understood. The present paper will look at some aspects of body and glaze reduction and reduction firing in open-topped kilns. Grimston reduced glazed pottery, medieval unglazed greywares and Cheam whitewares will serve as illustrative examples.

REDUCTION AND OXIDATION

If the supply of oxygen is sufficiently restricted by controlling the amount of air entering a kiln, carbon monoxide will be produced and a reducing atmosphere will be created. The carbon monoxide will take oxygen from metal oxides present in the pottery and glaze, thus reducing the amount of oxygen present in the resulting compounds. Although in medieval glazes the oxides of copper and lead are readily reduced, the reduction of ferric 'red' oxide to ferrous 'black' oxide ($Fe_2O_3+CO>2FeO+CO_2$) is the most important change in terms of its visual and physical effects. Ferric oxide is not an effective flux at earthenware temperatures. At red heat in the presence of carbon monoxide it is easily reduced to the ferrous form which is a strong flux. Ferrous oxides "are powerful fluxes, and combine with clay to form viscous, fusible silicates, ferro-silicates and alumino-silicates . . . Ferro-silicates and ferro-alumino silicates behave in a manner similar to felspar, i.e. they are moderately fusible and increase the amount of vitrified matter or "bond" in the fired ware and so slightly increase the strength of the ware" (Grimshaw 1971, 278–79). "In a reducing atmosphere the ferric oxide is reduced to ferrous oxide which, with silica, forms liquids at much lower temperatures than those required to cause ferric oxide and silica to melt . . . more liquid is produced than in an oxidising atmosphere so that lower temperatures are sufficient for making the ware dense." (Rado 1988, 100)[1].

The normal state of a wood firing kiln is neither fully oxidising nor fully reducing, but an intermittent combination of both created by cycles of stoking and burning. A neutral atmosphere tending towards reduction is to be expected unless steps are taken to make it otherwise. The composition of the kiln atmosphere will depend mainly on the method of stoking and the control of the draught. Light and frequent stoking with a strong draught favours oxidation, and heavy charges of fuel in a weak draught create reducing conditions. The type of fuel may also matter. The way the kiln atmosphere affects the clay body and glaze will depend on their chemical make-up and, additionally, on how the pottery is placed in the kiln.

Generally speaking, the surfaces of iron-bearing pottery fired in an oxidising atmosphere have warm light-brown, reddish or slightly pink tones. A reducing atmosphere will yield body colours of a cool dark to light grey. Oxidised glazes tend to fire to various shades of yellow or brown, while reduced glazes form a family of olive-green or brown-green colours. The particular colour, or range of colours, of an oxidised or reduced ware will depend upon the character of the clay used and especially its iron content, the composition of the glaze, and the technique used in firing and placing the ware in the kiln. An individual vessel or sherd will often display both oxidised and reduced features, most commonly in colour differences between fabric surface and core.

Deliberately firing pottery in a reducing atmosphere has the advantage that the body of some thinly-potted vessels may be strengthened appreciably. The clay must contain some iron. As the reducing fire proceeds, the black iron oxide produced acts as a flux sufficient to bring about partial vitrification of the fabric. In a relatively short firing the pottery is rendered stronger and less porous than it would have been in an oxidised firing. The technique, which will be discussed below, is especially suitable for unglazed pottery.

Reduction firing is usually not advantageous. A strongly reducing atmosphere can check temperature rises and may cause kiln temperatures to fall, thus cooling the kiln. Reduction, in short, wastes fuel, produces less energy and is more demanding than oxidised firing both in the time needed to finish and in the combustible materials consumed. This feature of reduction has the useful consequence, however, of halting a rapidly rising oxidising fire when a slow pace is needed. A fall in the ambient kiln temperature when the air supply is restricted is also a practical way of telling whether a kiln is reducing in the early stages of firing.

A common disadvantage of reduction is the possible formation of a 'black core' within a vessel's fabric. This is most likely to occur with clays that are rich in carbonaceous matter as are, for example, many gaults. If the oxygen in a kiln is insufficient to burn out the carbon in the body, at about 700–900°C, additional oxygen will be obtained from any red iron oxide within the fabric, thus converting it to black iron oxide (Grimshaw 1971, 716, 732; Hamer and Hamer 1991, 173–4). This oxide together with unburned carbon is largely responsible for the grey or black colour of the fabric core. In an over-rapid firing the ferrous oxide and any remaining carbon in the core of the fabric may be sealed by glazed or partially vitrified surfaces. Subsequent gas release may cause surface cratering and bloating (Col. Pl. 3a). Much medieval pottery is affected with 'black core' although usually in such a way that it causes little damage to the fabric. Strong reduction may also cause lead glaze to volatilize below 900°C.

Reduction of the glaze

During a reduction firing, lead oxide combines with silica naturally present in the iron-bearing clay to form a glaze melt, in which the reduced black iron oxide is an actively involved flux. Once any form of iron oxide is involved in vitrification it is difficult to change its properties by altering the kiln atmosphere. Consequently, in the production of a typical medieval olive-green reduced glaze the kiln must be strongly reducing before the glaze begins to melt, at least from 600°C. Reduction should continue until past the initial stages of vitrification and the formation of ferrous silicate, roughly around 900°C. If reduction is delayed beyond a point at which the iron oxide and silica combine the glaze will lack its distinctive 'reduced' appearance.

Glaze fired in a reducing atmosphere can be changed to oxidised colours by introducing a generous supply of air into the kiln before the iron oxide is locked into the glaze melt. Oxidation after the reduced iron has entered the melt in fusion with silicates is unlikely to bring about a substantial change of colour, although a slightly brownish, sometimes streaky, surface to the glaze may result. Fabric surfaces covered by a reduced glaze will usually be unaffected by reoxidation except where the margins are thin. In experimental tests, galena glaze on gault replica jugs fired in reduction before and during the melt resisted reoxidation later in the firing and again when refired in strong oxidation. Glazed sherds of Grimston green-glazed pottery retained much of the original green colour when refired in oxidation. Once the reduced iron oxide reacts with the clay to form viscous silicates the reduced green lead oxide glaze will, to a large extent, survive reoxidation (see Hamer and Hamer 1991, 174–5).

Reduction of the fabric and reoxidation

One important difference between glaze and body reduction is that vitrification of the clay body itself occurs at higher temperatures than does vitrification of the lead glaze applied to the body. The higher vitrification range of the clay fabric and its surfaces means that body colours may be altered by the kiln atmosphere after a point at which glaze colours become more-or-less fixed. Thus it is common to find a reduced olive-green medieval glaze on a partially or even fully reoxidised fabric.

Reoxidation of the fabric surfaces created by firing in a reducing atmosphere is possible up to temperatures which bring about appreciable vitrification of the clay. If the vitrification of the exposed fabric surfaces and the body is very incomplete, black iron oxide not involved in the melt may be available for reoxidation. A period of strong oxidation at the finish or during early cooling will usually give an oxidised appearance to the fabric surfaces of reduced vessels fired at earthenware temperatures. To retain a fully reduced fabric the vessels must remain in a reducing atmosphere throughout firing and cooling. Occasionally the reduced interiors of inverted vessels sealed in the kiln by glaze runs or stacking will remain unchanged. The very large quantities of reoxidised pottery recovered from excavations are indicative of the firing cycle of reduction and oxidation characteristic of medieval updraught kilns.

Firing techniques

The firing schedule of a medieval kiln is constrained at the start by the fact that the pottery to be fired is unlikely to be fully dry. How British medieval potters coped successfully with drying pottery is uncertain. Excavations at Limpsfield suggest that drying was accomplished there by placing pottery in a hot chamber adjacent to the kiln (Moorhouse 1981, 101 fig. 85, after Jope 1956, 285, fig. 266). Comparable methods of utilizing kiln warmth can be found in modern potteries. An arrangement of the Limpsfield type seems ideally suited to a fast turnover, with the preheated pottery immediately replacing a fired load as soon as it has cooled sufficiently to clear the kiln. This will also yield a significant saving in fuel. In the absence of any such drying arrangement the kiln itself must be used, thus extending firing times.

Damp vessels need a slow and gradual rise in kiln temperature, using a very low oxidising fire to drive the moisture from the pots without damaging them. A slow pace is also needed to even-out temperature gradients in the pottery fabric and temperature differences between the lower and upper parts of vessels in the stack. The latter is especially important in updraught kilns where the heat builds from the bottom of the kiln. The length of time taken for this initial period depends upon the kiln capacity, the state of the ware and the prior condition of the kiln. In larger medieval kilns it may have taken several days, and in smaller kilns less than a day.

The basic problem in the initial stages of firing a medieval updraught kiln is that of slowing down the temperature rise while maintaining a good flow of air through the kiln to facilitate the escape of moisture vapour from the pottery. This initial combination of lightly rising fire and full draught favours oxidation. To avoid the occurrence of a 'black core' capable of doing real damage to the fabric it is essential to prevent too rapid a rise in temperature in the region of 600–900°C when carbon, and perhaps sulphur, remain to be burned out. To slow down the rate of increase of temperature while maintaining an adequate amount of fuel, the draught and air at the flue may be checked, and larger pieces of wood, hardwoods or 'green' wood may be introduced. Kiln firing experiments at Bickley show that congestion in the firebox may choke the supply of air into the kiln and create reducing conditions around 600°C (Dawson and Kent 1989, 16; 1997, 3). Changes of this kind between, roughly, 500–700°C provide favourable conditions for the production of reduced glazes by creating a period of reduction just before the glaze begins to melt. It is necessary only to continue reducing into the glaze vitrification stage. When there is no longer any danger of an over-rapid rise, the draught can be opened fully. The kiln will stop reducing and an intermittent oxidising or neutral fire may take over before the firing is stopped. The pottery produced would have a reduced glaze and core with largely reoxidised fabric surfaces.

This unexceptional firing schedule illustrates one way in which the medieval manufacture of reduced pottery could have come about in the course of normal workshop practice. The essential material precondition is that the vessels be made from a suitable iron-bearing clay[2]. If the firing schedule were altered to maintain an oxidising fire up to the start of the glaze melt, then oxidised glaze would be the likely result instead, even if the clay had a significant iron content. This could, for example, be a better choice of kiln management where the clay is relatively free from carbonaceous matter and allows a more rapid rise.

REDUCTION FIRING IN OPEN-TOPPED KILNS

As it now seems, many if not the majority of medieval kiln superstructures were not of the closed or "domed" variety, but were what have become known as "open-topped" kilns (Moorhouse 1981, 97–98). Open-topped kilns are updraught top- or side-loading kilns, usually with more-or-less cylindrical walls, and have no permanent covering or dome closing the top of the kiln. The kiln is closed before each firing with a temporary capping laid over the pottery stacked inside, consisting variously of layers of tiles, sherds, turves or "clay plates" specially prepared for the job. The capping is removed once the firing has been completed and the kiln has cooled down. Open-topped kilns may have single or multiple flues. They have the advantage of being rapid to load and unload, thus permitting careful stacking and a quick turnaround to make use of the residual heat from a previous firing. They are highly successful as producers of pottery and it seems likely that many such kilns produced reduced wares.

Open-topped kiln firings by Dawson and Kent at Bickley have added much to our understanding of their operation (Dawson and Kent 1985, 1987, 1989, 1997, 1999). Perhaps the most persuasive case for the medieval use of open-topped kilns has been given by Geoffrey Bryant and is based on a series of firings of replica kilns (Bryant 1970, 1973, 1977a, 1977b. See also Mayes 1961, 1962; Moorhouse 1981, 97–9; Musty 1974, 54–6). Bryant's conclusion that they are simple to load and fire, and perform well, is confirmed by more than a dozen firings of an experimental open-topped kiln at my pottery in Cambridge. The kiln was built with the particular purpose of testing the construction of the temporary capping and its suitability for reduction firing. The experimental kiln incorporates the medieval features of opposed flues, central pedestal and a capped open top. It has mixed propane/wood firing and a cylindrical firing chamber about 1 m in height and diameter. Its firing characteristics parallel those of a wood-only kiln closely, but not completely. The principal difference is in the reduction firing of greywares, which would seem to require wood-only firing for reliable production in large quantities. To maintain an acceptable temperature gradient inside the kiln, the pottery was usually not stacked above the height of the kiln walls.

The kiln capping

The arrangement of the capping effectively controls the draught through the kiln and, in large part, determines the degree of oxidation or reduction to which the pottery is subjected. The capping of an open-topped kiln has a hot face placed directly on the pottery being fired and exposed to the intense heat of the kiln, and an insulation layer to back-up the hot face and maintain firing temperatures inside the kiln. The stability of a kiln stack of unfired pottery is usually increased by having to bear the weight of the capping material which spans and links together the individual pots. Inverted raw vessels closely stacked can support a considerable load, and the weight of the capping was never a problem in the tests to be described.

Kiln excavations can reveal much about possible capping materials. Broken pottery and waster sherds seem to have been used frequently. Experiments show that if pottery and sherds are to be used as hot face materials, the pieces must be large enough to span the individual pots in the kiln and form an adequate cover. As an insulation layer, sherds of any size can be used successfully in conjunction with tiles, large tile fragments or purpose-made capping placed directly on the pottery itself. In this position a sherd layer forms a buffer to deal with the temperature gradient between the hot face and the air temperature outside.

Fig. 1. Clay plate with grass impressions on both sides from the Eden street kiln, Kingston-upon-Thames (Museum of London Specialist Services).

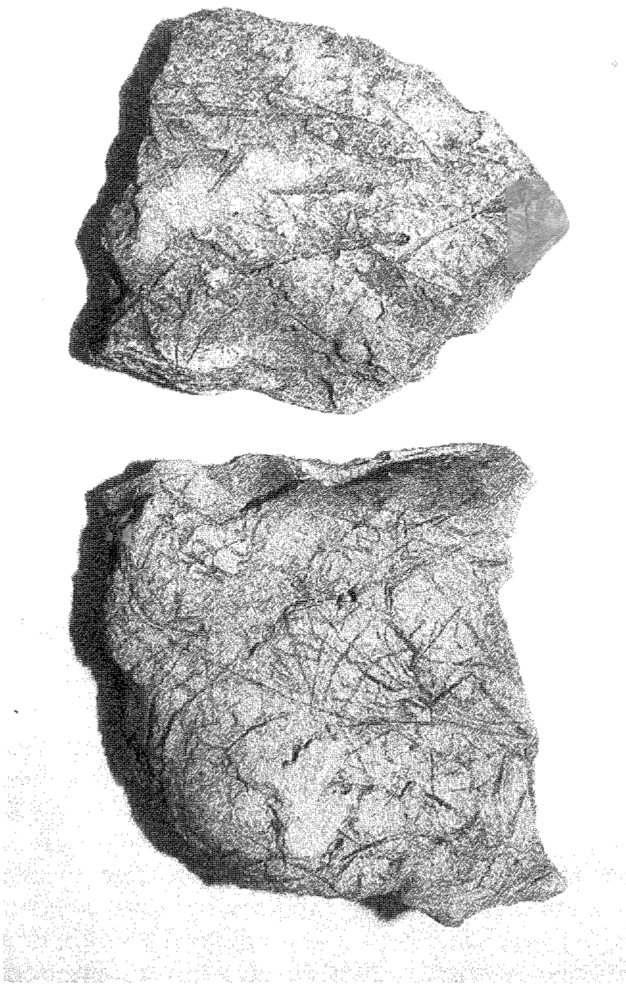

Fig. 2. Clay plates with exterior grass impressions. Top, Romano-British, Horningsea kilns. Bottom, fragment from the sealed capping of a kiln firing experiment.

Common roofing tiles have often been used in the construction of kiln flues, walls and pedestals, and probably were used in the arrangement of the capping. Kiln-associated tile finds occur, for example, at Cheam; Orchard Street, Chichester; Earlswood; Kingston; Knighton; Rickinghall Inferior and at Hanley Swan. Tests with modern red earthenware tiles show that their insulation properties are low and that they are subject to cracking. Medieval tiles are of less dense composition and are likely therefore to have been more satisfactory.

The practice of using materials prepared specifically for kiln closure was probably widespread in medieval potteries. Pieces of grass-tempered clay, so-called "clay plates" usually associated with the kiln's covering, are occasional finds at kiln sites (Figs. 1 and 2). "Clay plates" and grass-marked daub occur at, for example, Upper Heaton: "Vast quantities of broken daub plates ½" thick, covered with imprints of grass and rushes on one side and a few grass marks and palm imprints on the other, usually slightly concave side" (Manby 1965, 100); also at Brill (Jope 1954, 39); Kingston, Eden Street (Stephenson and Miller 1996); Laverstock (Musty *et al.* 1969, 147) and Chandler's Cross, Hertfordshire (St Albans Museum).

Impressions of grass, straw or other vegetable matter may occur internally as well as on the surface of fired clay pieces, as at Rattray where "grass impressions were random throughout the clay, showing that it has been deliberately mixed before use" (Murray and Murray 1993, 147). These should be distinguished from fired pieces where the grass impressions occur only on the external surfaces. The two sorts of grass-tempering seem to have had different uses.

In the case of internal tempering, the addition of grass or straw reduces shrinkage and gives some degree of stability and strength to the wet clay. It is also an effective way of producing insulating material: the vegetable matter burns out when fired, leaving a lightweight clay mass riddled with air spaces which inhibit the transmission of heat. This improvement in thermal properties is accompanied by a significant reduction in the weight of the clay.

Clay fragments with grass or straw impressions only on their external surfaces have been found on medieval and Romano-British kiln sites. Among Romano-British examples are kiln sites at Horningsea, Nene Valley, Sheringham, Overwey, and Savernake. Most appear to have been clay slabs of varying thickness, and some have cut edges and returns. If used as part of the kiln capping, large quantities would have been needed, presumably stacked ready-to-hand near the kilns. Experiments in making numbers of such slabs, about 400 mm × 300 mm, show that they are most easily made from soft clay, and then stacked in piles to await use. The wet slabs are certain to stick together and become irretrievably joined unless they are separated from each other by layers of grass or straw. The interleaving grass, which also enables the slabs to stiffen to a workable state, would seem to be responsible for the external grass impressions.

A desirable barrier between the unfired pottery in the kiln stack and the clay daub on top can also be made by first covering the stack with a layer of grass, straw, leaves, and so on, which might account for some impressions on surviving pieces of daub. This may have been the case at Upper Heaton.

Kiln firing tests

A series of experimental kiln firings were undertaken using the capping arrangements described below (see Dawson and Kent 1985 for a summary of firing tests of kiln closures at Bickley). The firing schedule had the general objective of introducing early reduction before 500°C and continuing reduction while maintaining an adequate temperature rise and glaze melt. The pottery in the glazed firings consisted of about two dozen medium-sized replica medieval vessels, galena-glazed on a mainly Grimston gault clay body. Greyware firings were of unglazed cooking pots made mainly from Chandler's Cross clay in Hertfordshire.

Diffused Capping

The capping may be placed on a pottery load so that venting of the kiln is diffused over its surface area. This is easily done by ensuring that the capping material is permeable enough to allow a draught of air from the kiln to exhaust through it. A moderate insulating covering of tiles and sherds is sufficient. This, in effect, forms a number of individual vents.

Venting the experimental kiln by a diffusing kiln closure was satisfactory in producing oxidised pottery. Heat loss through the diffused capping was much greater than when using a well-insulated single vent capping, and a diffusing arrangement could not maintain the kiln pressure of a reducing atmosphere long enough to produce a reduced load.

Central venting with loose tiles and sherds

The vent used here consisted of a fired clay disc about 300 mm in diameter with a 50–75 mm diameter opening in its centre. Discs of a similar kind have appeared on Romano-British kiln sites and, probably, on a medieval site (Swan 1984, 64–6 and pl. 21. Probable medieval kiln vents were reported at Chilvers Coton, see Moorhouse 1986, 92; and Musty 1984, 27–8). The disc is placed in the centre, directly on top of the pottery in the kiln stack. Tiles, sherds or other capping materials are built-up around it and spread out densely over the kiln top forming an insulating layer. The vent can be closed with a tile, which also acts as regulator of the draught (Col. Pl. 3b). It gave a more satisfactory control over the kiln atmosphere than did a diffusing closure. With adjustments to the firing schedule, either oxidised pottery or pottery with reduced glazes and reoxidised fabric surfaces could be produced.

Central venting with a sealed clay closure

In the experimental kiln, specially prepared "clay plates" were used for capping material either as unfired slabs in a plastic state, or as pre-fired insulating tiles. Although there is sufficient evidence from kiln sites to illustrate the basic clay-plate materials it can be unclear whether they were applied, as seems probable, as wet slabs or as previously-fired insulating plates. Accordingly, both options were tested.

In the latter option, clay plates tempered with chopped straw were previously fired to make lightweight insulating tiles about 200 × 200 × 35 mm. With the top of the pottery stack kept slightly below the level of the kiln walls, the prefabricated tiles were placed close together over the pottery to form two overlapping layers of insulation. A central vent was installed, and the tiles were covered by a thick layer of sherds. The generously insulated closure ensured that a satisfactory temperature gradient was maintained throughout the kiln. A capping of this kind could be rapidly constructed from the prepared and re-usable material at hand, and would be an effective method of production to achieve a quick turn around using the kiln warmth from a previous firing. In this arrangement, it was possible to contain a reducing atmosphere sufficiently to produce reduced glazes, although most body surfaces were largely reoxidised.

With a wet clay closure, the soft slabs were placed on top of a layer of tiles and sherds, which acted as a hot face and prevented the wet clay from having any direct contact with the raw pots. Once in place the slabs were smoothed together by hand to seal the kiln top around the central vent (Col. Pl. 3c). During firing the clay cover was disposed to crack in drying out which allowed flames to break through at various points on the surface, although prior to cooling the most serious cracks could be repaired by using plastic clay. Cracking was inhibited by joining together firm semi-dry slabs instead of daubing with wet clay. At the close of firing the kiln was stoked with softwood, then sealed. When the kiln cooled to below 125°C, the capping was removed and the hard-fired pieces saved for re-use as insulating material. The discarded remainder of the capping consisted of friable and incompletely fired clay, and would seem unlikely to survive in the ground for any great length of time.

Closed in this way, the kiln contained a reducing atmosphere well enough to produce partial loads of unglazed greywares. Some partly reoxidised pottery occurred in layers just beneath the capping, the remainder having a reduced grey-black fabric. Reduced olive-green colours occurred routinely on glazed vessels.

A roughly comparable method of closure was used in a recent experimental firing of a wood-fired kiln at Priory Farm, Suffolk (Adrian Thorpe, pers. comm.). The kiln, built by Gilbert Burroughes, was a scaled-down version of the Rickinghall kiln (see Anderson *et al.* 1996, 5–6 and fig. 2; see also *MPRG Newsletter* **32**, 1998). The double-flued kiln superstructure had an open top closed with a daubed clay capping through which vents had been cut to control the draught. The capping was supported by a load of unglazed pottery covered with layers of straw immediately below the daubed clay. Frequent repair of cracking in the clay cover was needed during firing, and at the finish the kiln was stoked and sealed. The pottery produced was fully reduced.

The results of these firing tests would indicate that the use of a temporary capping in open-topped kilns is consistent with the production of pottery with reduced glazes and reoxidised or reduced fabrics. In the somewhat special case of reduced greywares, a reducing kiln atmosphere must be maintained during firing and cooling. The kiln should be stoked and sealed at the end of the firing and the capping made as airtight as possible to prevent reoxidation of the pottery. It is probably the case that to make reduced greywares simply and easily, wood-firing is needed and that the pots should be piled in the kiln to create a dense stack filling the whole of the firing chamber.

EXAMPLES OF MEDIEVAL REDUCED AND OXIDISED WARES

Grimston reduced pottery

This pottery valuably illustrates some typical characteristics of medieval reduced wares. Early, unglazed, Grimston 'Thetford-type' ware characteristically has a grey-to-black reduced core with dark reduced surfaces, or brown-to-buff oxidised surfaces. The fabric is sandy, often coarse or gritty, and sometimes contains small cavities which appear to be the burned-out remains of organic matter or trapped gas pockets.

The fabric of Grimston glazed pottery of the 13th to 15th centuries is less open and probably fired to higher temperatures. Typically the olive-green glaze covers a reduced grey or black body with brown-to-buff or brick red surfaces where exposed to a reoxidising kiln atmosphere. This usually occurs beneath handles or on the interior of a vessel. Not all Grimston pottery is fully reduced and oxidised glazes occasionally occur (see Clarke and Carter 1977; Jennings 1981; and Leah 1994).

The regular production of mainly reduced ware for more than three centuries is probably explained by the kiln site's location within an area containing outcrops of gault clay[3]. The Grimston gault is a black-to-dark grey iron-bearing clay with a significant decomposed organic content. Some of the oxygen needed for this decomposition was probably taken from ferric oxide originally in the clay, leaving a stable black oxide flux responsible for the ease with which the clay reduces in the kiln. Local reduction from carbon burning-out in the body may also be a contributing factor.

Gault is a variable clay, although most outcrops found today near Grimston will produce acceptable pottery with a clear, reduced lead glaze (Col. Pl. 4a).

The Grimston gault clay has a top temperature limit somewhat above 1000°C and will begin to deform much beyond that. The most probable firing range for the glazed pottery would be between 900 and 1000°C. It seems likely that, at some time during their long history, the Grimston potters took advantage of a more refractory and light-firing Lower Cretaceous clay to be found at nearby Leizate. A blend of the two makes a good throwing clay and, when reduced, both fabric and glaze are characteristic of Grimston products.

Because of its iron and decomposed organic content, the Grimston gault is easily reduced. With this type of clay, an over-rapid temperature rise in the early stages of firing is likely to lead to a 'black core' condition, attested by numerous waster sherds to have been a standing problem at Grimston and at the medieval tileworks nearby in Bawsey. Judging from the vessels themselves, the Grimston potters appear to have adopted the remedy of checking damaging temperature rises by severely restricting the draught, probably after stoking, thus causing the kiln to reduce. With the reduction-prone gault clay, the creation of a sustained reducing atmosphere at this point in the firing cycle would almost certainly have resulted in the type of green or green-to-brown glazed pottery actually produced (Col. Pl. 4b). Reoxidation during the finish and in cooling is evident on most Grimston glazed pieces.

During the lifetime of the industry it was probably not the deliberate intention of the Grimston potters to produce reduced wares. There is no evidence in the pottery itself of an intervention in the firing cycle to create reducing conditions beyond their normal occurrence. It is more likely that they made the kind of pottery that could be produced successfully within the limitations of their clay resources, kilns and working experiences. Grimston pottery probably was the natural outcome of a medieval firing cycle of oxidation, reduction and reoxidation, together with a near-total reliance on the gault.

Greywares

Unlike the products of the Grimston kilns, many of the ubiquitous medieval 'greywares' of the 12th and 13th centuries may have been produced by an intervention in the firing process specifically designed to create fully reduced pottery. The reason was noted earlier: iron-bearing pottery fired in a reducing atmosphere at low temperatures will be stronger and less porous than it would have been if fired in an oxidising atmosphere. This happens because the reduced ferrous 'black' oxide is a strong enough flux under reduction at red heat to initiate partial vitrification of the fabric or a high degree of sintering. This fluxing advantage does not occur when the oxide is in the ferric 'red' state and the oxidized fabric will, accordingly, be less strong and dense (Tite *et al.* 1982, 65; Rice 1987, 354).

This fabric strengthening technique is known to have been used in at least two widely separated areas of pottery production. In New Mexico, Anasazi grey and white ware produced from 600–1300 AD was deliberately fired to about 800–900°C in reduction to increase the pottery's density and strength (Dr Eric Blinman, Museum of New Mexico, pers. comm.).[4]

For the same reason, as it appears, Romano-British grey pottery was fired in strongly reducing kilns from which oxygen was deliberately excluded during cooling. The methods used to produce the Anasazi and Roman reduced pottery are remarkably similar. A Roman kiln was fired as far as possible in reduction, and stoked with a fresh supply of fuel immediately before sealing the flue and vents at the end of the firing. The burning fuel continues to consume any available oxygen inside the sealed kiln and prevents reoxidisation of the pottery. In an Anasazi trench kiln, immediately at the close of firing, the pottery and surrounding embers are covered with layers of soil, thus creating reducing conditions by eliminating air from the fuel and vessels, and halting further oxidation (Swink 1997, 17)[6]. Bryant (1973a, 156–57) gives a summary of this method of producing Roman greyware in an open-topped kiln. Commenting on the experimental Claxby reduction firing, he writes "One of the pots showed no signs of leakage after holding water for a week — the same pot, fired to the same temperature but oxidised, would have been very porous" (Bryant 1973b, 10).

For much of the medieval period South Hertfordshire greyware producers supplied the London market with a distinctive range of cooking pots, jugs and bowls (Col. Pl. 4c). This hard and often thin-walled pottery was probably fired to some temperature between, roughly, 800° and 900°C, although the duration of the firing remains unknown. The fabric is usually anisotropic. Although anisotropy may be regarded as a general indication of low-fired pottery, it does not exclude a high degree of sintering or partial vitrification of the clay matrix. The vessels are reduced, mainly with grey surfaces, core and margins, moderately dense, and often have a slightly metallic ring when tapped. They share these characteristics with much Romano-British greyware.

Earlier and contemporaneous shell-tempered pottery dealt with thermal shock by the addition of crushed shell inclusions, forming a thick open-textured fabric whose sintered structure was elastic enough to absorb differential stress. The result was pottery capable of surviving repeated heating, but remaining porous, heavy and easily broken. The makers of shelly ware faced a dilemma: to withstand exposure to cooking fires, shell additions were needed, but these very inclusions prevented strengthening the vessels by firing them at temperatures higher than the, roughly estimated, 700–800°C limit imposed by the use of lime. Beyond this limit, calcium carbonate decomposes to the oxide; rehydration of the fired pots causes expansion of the temper and spalling of the surface. Although much shelly ware has a reduced core, this restriction may have impeded the fluxing action of any ferrous oxide in the fabric.

South Hertfordshire greywares demonstrate a technically superior solution. Thermal shock is inhibited by the presence of well-graded largely sub-rounded sand creating an open texture[5]. The main cause of thermal shock in cooking pots is the differential stress imposed on the fabric, for example between surface and interior, or one part of a vessel and another. If temperature differences can be kept uniformly to a minimum throughout a pot, the chances of damage are greatly reduced. One way of doing this is to make the walls of the pot rounded and uniformly thin, and to make the fabric a better conductor of heat. Thus a damaging differential is avoided by minimizing the distance the heat has to pass through the fabric, and by increasing the rate at which it is transmitted. If the fabric is marginally vitrified the transmission will be rapid and, in addition, the pot will be stronger (see Schuring 1989, 185ff; and Kilikoglou *et al.* 1998).

The key to the South Hertfordshire potters products seems to be their reliance on strong early reduction to create a ferrous-oxide body flux, and a determined attempt to maintain a reducing atmosphere throughout firing and cooling. It would seem likely that the kiln management techniques needed to produce them closely followed those used in the production of Roman greywares.

Experimental reproduction of these hard greywares indicates that firing the pottery to temperatures permitting a high degree of sintering or even partial vitrification is crucial for their production (Col. Pl. 5a). Tests using clay samples from Chandler's Cross, Nettleden and Potters Green, Hertfordshire, show that greywares can be produced within the range of 780–940°C. The length of firing, temperature attained and extent of reduction will depend ultimately on the refractoriness of the clay. With many clays, strengthening can occur at the lower terminal temperatures. Measures must be taken to prevent or minimise reoxidation towards the end of the firing and in cooling. Reduced surfaces may occur on a semi-oxidised core indicating, probably, a neutral firing finished with a period of reduction before closing-up the kiln. Differences in fabric colour and composition among S. Hertfordshire greywares are probably due to variations in clays at source, differences in clay preparation and in firing techniques at different kiln sites (see Turner-Rugg 1993, 32).

Cheam whitewares

During the later medieval period, the drift of change in kiln practice suggests a movement away from reduction in manufacturing and towards predominately oxidised firing. At the close of the period, Surrey white-firing and red-firing clays may have been fired together in the same kilns to produce oxidised redware and whiteware (Pearce 1997, 3–6, 79). The failure of the iron-bearing gault redware clays to reduce can be attributed to the way in which the late medieval kilns were operated and, probably, to changes in their construction (see Orton 1982, 83–4). Firing largely in oxidation brings with it the advantages of faster firing, a decarbonised fabric and, in large kilns, fuel economy. In addition the objectives of strengthening pottery and making it less porous can be reached by firing mainly in oxidation to significantly higher temperatures, usually with a more refractory clay.

The products of the Cheam kilns are good examples of an advanced manufacture in which great attention was paid to the technical details needed for efficient mass-production (see Pearce and Vince 1988, 68–77). Cheam drinking jugs illustrate, almost in an extreme way, how form and decoration can be put to the service of manufacturing efficiency. The biconical form, invariably bisected at its girth into upper and lower parts of unequal length, allow pairs of inverted and upright jugs to be tightly stacked together in the kiln with an appreciable saving of space (Col. Pl. 5b). The flanged top rim gives a firm purchase for other vessels placed on top or underneath, enabling the use of columnar stacking. Rod handles are placed so that they interlock snugly with other handles when stacked together and permit columns to support each other. The placing of the glaze, usually a brief bib touched on the front of the jug, inhibits glaze runs to the rim or base and allows physical contact between jugs in unglazed areas. The use of a biconical form gives load strength to tightly packed columns with little risk of deformation during firing[7].

The Cheam Parkside kiln is an orthodox Musty type 2c kiln with opposed flues and oval central pedestal, interpreted by Orton to have an open-topped superstructure (Orton 1991, 327). There is no evidence of 'clay plates' or other capping materials used to form a sealed closure, although quantities of tile, some of it glaze-marked, were found on the site (Marshall 1924, 82). The mainly oxidised-to-neutral firing of its contents is consistent with a temporary capping of tiles and/or sherds forming a permeable insulating layer.

The ten controversial clay cylinders found inside the Parkside kiln (Marshall 1924) are probably the remains of a kiln accident in which the kiln was seriously overfired, causing some of them to collapse and fall into the channels surrounding the pedestal where they became bent and deformed under the intense heat. They may have functioned as orthodox firebars although there are no signs of attachment (Orton 1991, 325; the remains of the cylinders are now housed in the Sutton Library). If used instead as tubular kiln props in conjunction with tile shelving they could have supported several layers of closely packed vessels and increased the capacity of the kiln. This admittedly speculative arrangement would also provide an unobstructed flame path around the interior circumference of the kiln to take full advantage of radiant heat from the kiln walls, and would respond well to oxidised firing.

The probable firing range for most products of the Parkside kiln and group 1 of the Cheam High Street kilns (see Orton 1982, 76–77) falls between 900 and 1050°C. Experimental refiring of group 1 High Street sherds shows that a temperature of at least 1055°C may be reached without deformation, and the top temperature limit of the clay is probably higher. Sherds of closely-related Kingston-type ware from the Eden Street kiln were refired to 1040°C without any deformation and could easily have exceeded this. Both Cheam and Kingston sherds were taken well beyond Orton cone 06, which falls at about 1000°C given a 150°C rise per hour. Since this gives the clay a generous firing range of 100° or so, the idea that Surrey whiteware clay has a short firing range probably needs revision (see Orton 1982, 80; Holling 1971, 64).

Cheam whiteware is by no means always white and has the colour variations characteristic of most oxidised and semi-oxidised wares. Fabric samples from both kilns suggest that the pottery was generally fired in a neutral or semi-oxidising atmosphere, with intermittent periods of reduction leaving their traces in the occasional grey core and fabric surface. Variations in the appearance of glazes and fabrics can easily result from comparatively slight differences in the way in which a kiln is stacked and fired. In a medieval updraught kiln, completely oxidised firing must have been difficult to achieve, nor was it needed to produce the higher-fired utilitarian pottery found at Cheam.

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Endnotes

1. Pottery reactions are functions of both time and temperature. Consequently estimates of firing temperatures can be no more than approximate unless the duration and rate of temperature rise are also given, and this is often unknown (see Grimshaw 1971, 569; Shepard 1956, 272ff; for useful commentaries on reduction and allied topics see Grimshaw 1971; Hamer and Hamer 1991; Noble 1966, Rhodes 1977, and Rye 1981).
2. Atomic absorption spectrometry analysis for iron of illustrative body sherds (expressed as %Fe/%Fe_2O_3): Grimston glazed ware 4.02/5.75 (glaze itself not analysed); S. Herts greyware: Potters Green: 4.07/5.82, Nettleden: 3.6/4.52 and Chandler's Cross: 4.82/6.89 (Dr M. J. Hughes, Dept. of Scientific Research, British Museum).
3. X-ray diffraction analysis of Grimston gault clay: Kaolinite 30%, Mica (=illite) 41%, and Vermiculitic phase 29% (Dr C. Jeans). AAS analysis of Grimston clay (%Fe/%Fe_20_3): 4.21%/6.00% (Dr M. J. Hughes).
4. "Laboratory experiments currently being conducted by Lawrence Sitney at Los Alamos National Laboratory have demonstrated the importance of this reduction (Sitney *et al.* 1995). Under reducing conditions, a well-fired ware can be produced at 800°C, while a temperature closer to 1000°C is required to produce the same degree of sintering under oxidising conditions" (Swink 1997, 19).
5. About 500 m from the Chandler's Cross greyware kiln site (NGR-TQ065 988) clay strata are exposed in the Westwood quarry. The sandy, iron-rich red clays are plastic enough to be thrown on the wheel, although often contain gravel and stone which must be removed.
6. 'The simple atmosphere control provided by the smothering soil which limits oxidation to the outer surface of the pottery, while maintaining a reduced core, appears to be crucial for vessel strength as well as appearance'.
7. The rough resemblance between Cheam and Siegburg drinking jugs suggests a self-conscious attempt by the Cheam potters to make something that looks like the imported model. Yet it may be that the influencing factor was not so much the appearance of the vessels as the novel manufacturing techniques to a degree responsible for their appearance. For example, the efficient stacking regime in Siegburg 14th century stoneware kilns seems mirrored in the Cheam kilns (see Gaimster 1997, 46 and fig. 2.21; 165–6).

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Résumé
Bien que les effets de réduction et d'oxydation sur la céramique médiévale soient aisément reconnus, les moyens techniques de les produire sont bien moins compris. Ce papier examinera certains aspects de la réduction du vase et du vernis ainsi que la réduction de la cuisson dans les fours à alandier. La céramique glaçurée "Grimston", les céramiques médiévales "greywares" non glaçurées et les céramiques "Cheam whitewares" seront utilisées comme exemples illustratifs.

Zusammenfassung
Obwohl die Auswirkungen von Reduktionsbrand und Oxydation auf mittelalterliche Töpferware leicht erkannt werden können, sind die technischen Maßnahmen, diese Effekte zu erreichen, weniger verstanden. Dieser Aufsatz behandelt einige Aspekte der Gefäßkörper und Glasurreduktion und des reduzierten Brandverfahrens in oben offenen Brennöfen. Grimston reduziert-glasierte Töpferware, mittelalterliche unglasierte Grauware und Cheam Weißware werden als illustrative Beispiele herangezogen.