The Bristol brass industry: Furnace structures and their associated remains

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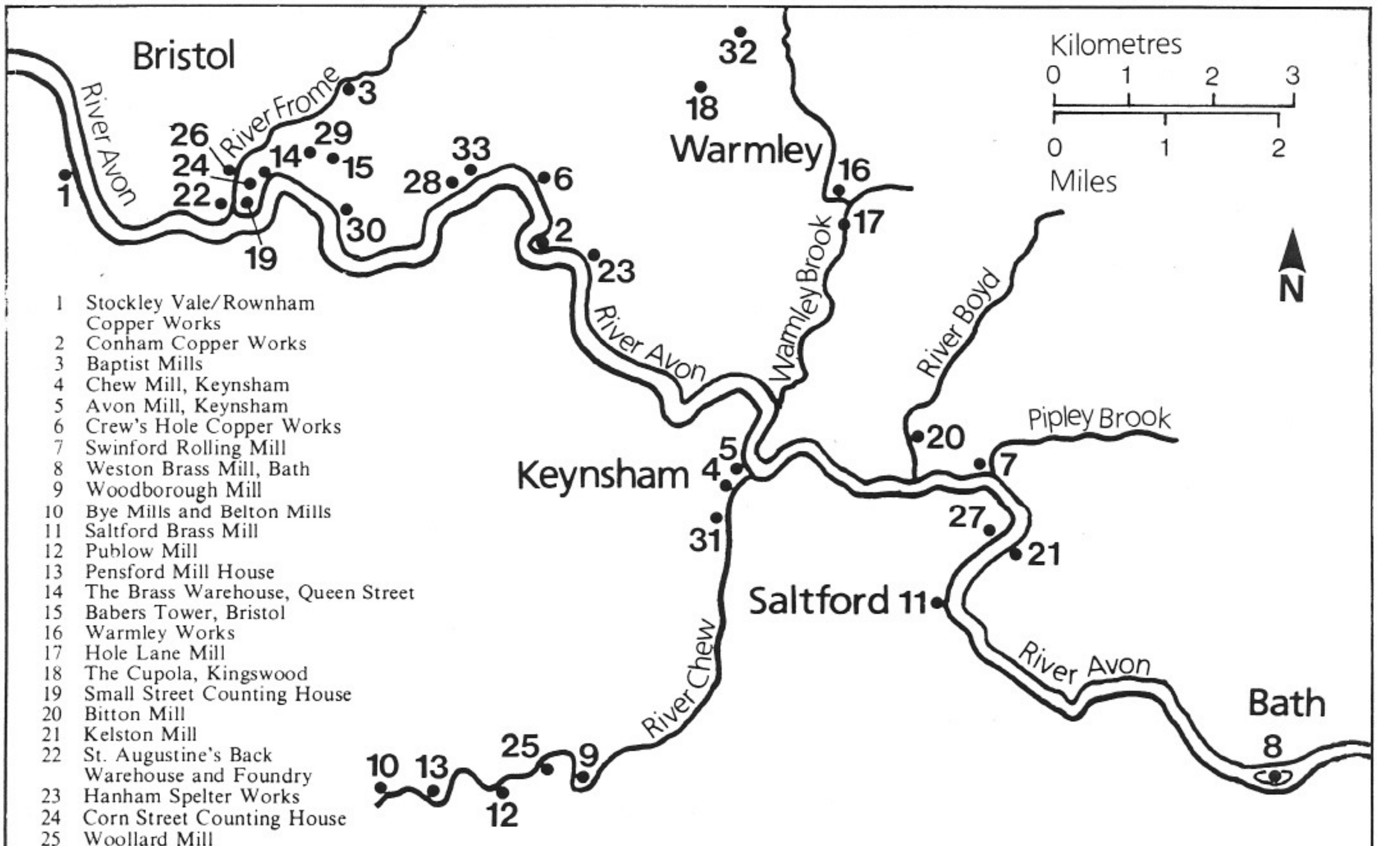
Remains of the once-extensive Bristol brass industry can still be seen at several sites on the banks of the Avon and its tributaries between Bath and Bristol.[1] They are relics of the production of brass and its manufacture which flourished during the eighteenth century to become the most important industry of its kind in Europe, superseding continental centres of similar production. By the close of the century Bristol itself was challenged by strong competition and the adoption of new techniques in Birmingham, and thereafter suffered a slow decline. Still using its eighteenth-century water-powered methods the Bristol industry just managed to survive into the twentieth century, finally closing in the 1920s.[2]

The factors which gave impetus to the growth of the Bristol industry when previous English efforts had failed appear to have been complex. Political and economic developments of the time contributed to varying extents. So too, did the availability of raw materials and good sources of fuel and waterpower, but technical innovation in the smelting of copper, which was being evolved locally, provided a major component of the initial success.[3] It laid foundations for Bristol's domination of the industry throughout the greater part of the eighteenth century.

Significantly, it was Abraham Darby who was responsible as 'active man', together with Quaker partners, for launching the Bristol company in 1702. After some five years' experience in employing coal-fired techniques in the non-ferrous metals industry he left Bristol to concentrate his efforts at Coalbrookdale on the smelting of iron by using coal as his fuel.[4]



1	Stockley Vale/Rownham Copper Works
2	Conham Copper Works
3	Baptist Mills
4	Chew Mill, Keynsham
5	Avon Mill, Keynsham
6	Crew's Hole Copper Works
7	Swinford Rolling Mill
8	Weston Brass Mill, Bath
9	Woodborough Mill
10	Bye Mills and Belton Mills
11	Saltford Brass Mill
12	Publow Mill
13	Pensford Mill House
14	The Brass Warehouse, Queen Street
15	Babers Tower, Bristol
16	Warmley Works
17	Hole Lane Mill
18	The Cupola, Kingswood
19	Small Street Counting House
20	Bitton Mill
21	Kelston Mill
22	St. Augustine's Back Warehouse and Foundry
23	Hanham Spelter Works
24	Corn Street Counting House
25	Woollard Mill
26	Lewin's Mead Wire Works
27	The Old Leather Mill, Saltford
28	Netham Brass Works
29	Redcross Street Warehouse
30	Cheese Lane Works, Bristol
31	South Mill, Keynsham
32	Soundwell Brass and Zinc Works
33	Blackswarth Lane Works

Fig. 1 Sites associated with brass making, manufacture and marketing in the Bristol area, (in chronological order from the 1680s.)

Well before the formation of the brass company, in the late seventeenth century, there had been Bristol achievement in the smelting of lead with coal fuel in a reverberatory furnace: the 'cupilo' as it was known locally. The innovation of a chimney, creating adequate through draught had enabled the process to work successfully.[5] This Bristol innovation had predated, by some ten years or so, the much-quoted 'introduction' of the same furnace by the emerging London Lead Company in the 1690s.[6] By this time Bristol smelters had transferred their skills to the smelting of copper in their new coal-fired furnaces, paving the way for a good local supply of this metal when brass manufacture was established just after the turn of the century. There were early difficulties with quality but these were soon overcome.

Contemporary Swedish observers described these new copper-smelting processes and the furnaces in some detail for the benefit of industrial enterprise in their own country.[7] In doing so they provided a sound basis for interpretive accounts of early copper smelting published elsewhere, even though no known remains survive of the furnace structures.[8] By contrast, contemporary records of the techniques and structures employed by the emerging brass company are more fragmentary and less detailed. It is clear that the brass manufacturers continued to develop the use of coal as their fuel at Bristol, justifying a record of any surviving details as a contribution to the history of coal technology and furnace construction. An interpretation of surviving furnace structures also reveals a basis of success for this eighteenth-century Bristol industry.

For production of brass at its main works at Baptist Mills, on which the outlying mills depended for their basic material for manufacture, the Bristol industry relied from its outset on technical expertise imported from the continent. It is well recorded that Abraham Darby brought some of these skilled men to Bristol[9] and others appeared to have arrived much later; facts that can be corroborated from local records and the traditions of present-day descendants of those early arrivals.[10] The furnaces used were directly derived from those of continental construction, employing the same basic principles as the methods described by Theophilus believed to have been writing in the early twelfth century. His references to the construction of a small clay-built furnace with a natural draught induced from below up through the top opening are the earliest of their kind. On a larger scale, Biringuccio and Ercker were describing similar kinds of structures in the sixteenth century.[11]

The ancient method had evolved by trial and error, without being understood. Throughout the era of the alchemists, who were trying to transmute base metals to gold, the colour and properties of brass had obvious attractions. By the outset of the eighteenth century and the start of the Bristol industry, understanding had progressed only little. Brass was still considered by many to be copper of a different colour, whilst calamine $ZnCO_3$, the carbonate ore of zinc used to produce the alloy, was not recognised as a metallic ore but rather as a 'semi-mettle', a type of earth or stone with the property of changing the colour and increasing the weight of copper.[12]

The cementation process

The process and furnace used at the Esher brass mill, the main precursor of the Bristol establishment, had been briefly described by Houghton in 1697. Clearly, both processes and furnace were following the continental practice which was better described by Christoph Weigels in 1698:[13]

> 'The art of brass making requires a great space of ground which must however be roofed over, so that the ascending vapour may be drawn up through the roof. For greater safety, moreover, the laths upon which the tiles rest are fashioned in iron and not in wood. The furnaces are set in the ground in such a fashion that the wind forces the flames of the fire through the holes which are beneath the furnace and brings coals to burning. In such a furnace they are accustomed to put round eight great crucibles, and when these are hot to remove them speedily from the fire and pour the calamine into them; but they have certain measure by which they reckon how much shall be needed that each crucible shall get its due portion; this being in weight round sixty-eight pound. Hereafter they add to the calamine in its pit, a measure of eight pound of copper beaten small and lay it on the top; then do they return the crucibles to the fire and heat them to redness, and they remain at this great temperature during nine hours. Thereupon the servants try the metal with an iron rod to see if it be melted aright, and let the same stand further for an hour in its flux to refine it. Then do they lift the crucibles one after another out and pour them together into a pit, when they desire the brass for casting. And when the metal is still warm they do break it into pieces, but in such a wise that these all remain close together. Then the brass takes on by reason of this hammering a most fine yellow colour, very pleasing to the eye. When they wish to form the metal into pots and other vessels, or to draw it out into wires, they pour the crucibles instead onto great stones which are prepared for this purpose . . .'

From the descriptions available, it can be ascertained that the early eighteenth-century brass-making furnace was a comparatively small beehive structure, perhaps 1.5m-2m in height and a little over half that width. It was housed completely below working level and normally operated from above, where materials, equipment and processes were organised. The furnace chamber was divided horizontally in two sections at a little below half its height, the lower part providing air access through a large culvert, usually extending to the exterior of the building, and it also served as an ashpit. The horizontal division was formed by firebars or a cast-iron plate. Either would be covered with fireclay pierced with a ring of holes to allow air access, between which a circle of crucibles were placed containing the raw materials for brassmaking. The crucible number varied with different accounts and places but usually seven or eight are specified, often with an extra empty crucible placed centrally and kept heated ready to replace a broken pot. The top section of the upper

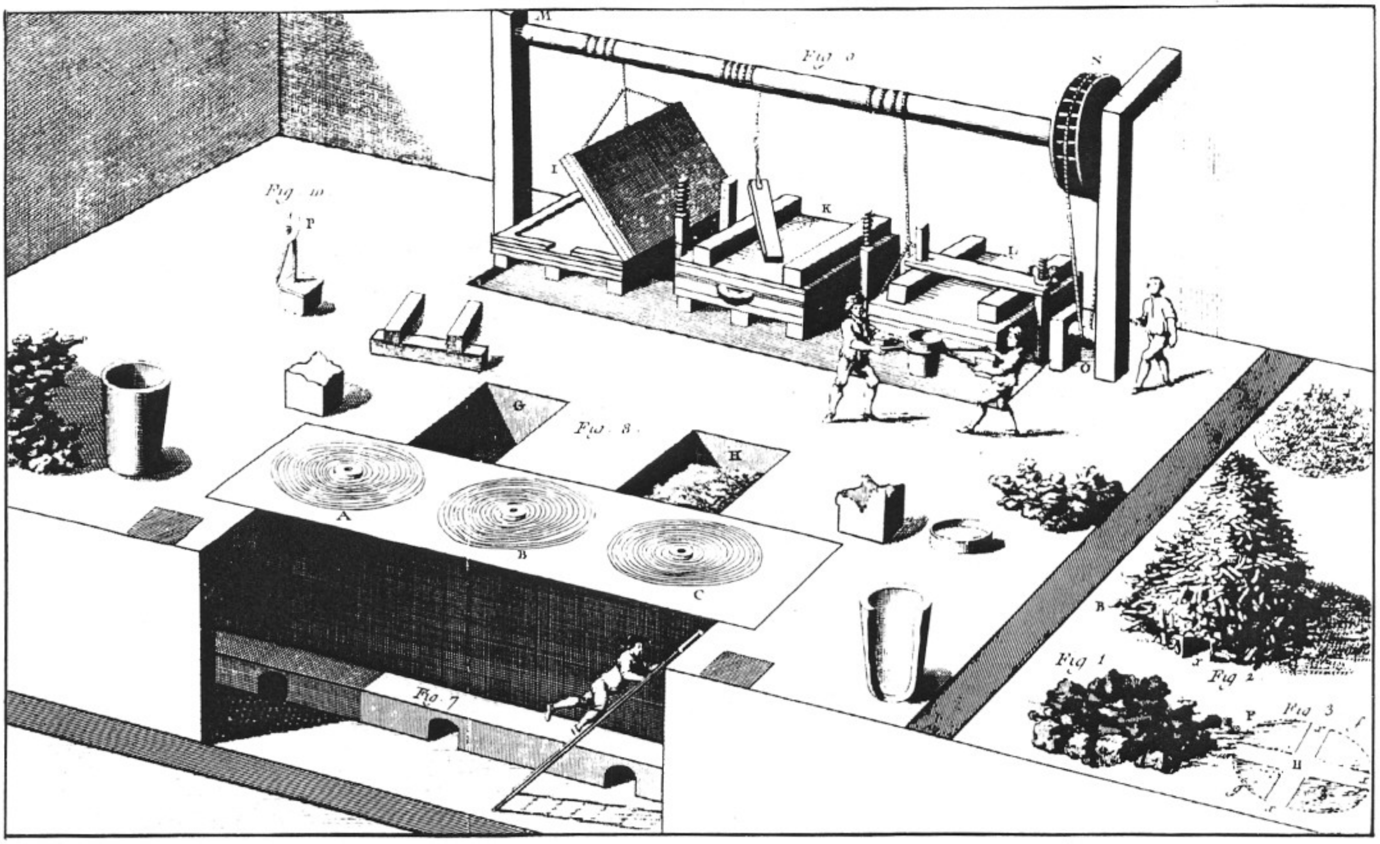


Fig. 2 Typical continental brass production, on which the improved Bristol version was based, is shown in this Diderot Encyclopedia illustration of 1763. Normal access to the three furnaces for brass making was through their top openings at A, B and C. (see Fig. 3). Their ash pits and air ducts could be reached by the ladder revealed by the cutaway illustration. The stone slab moulds for casting plate are shown to the rear.

chamber was constricted to a domed shape, supporting a circular cover of brick bound with iron bands. It could be left off or partially removed, or was sometimes perforated to allow the regulation of draught. This opening gave the only normal working access to the furnace.[14] (Figs. 2 and 3).

In the crucibles, the raw materials consisted of small broken pieces of copper placed between layers of finely crushed calamine which had been calcined to an oxide, together with powdered charcoal and, sometimes, scrap brass was added. The mix was heated to a temperature above 900°C, high enough to separate the zinc from its oxide by which time, the zinc had vapourised. The vapour permeated the surface of the copper pieces which, to retain the maximum surface area, had to be kept just below melting point for the zinc vapour to be successfully absorbed to its limit.[15] By 1723, the Bristol company was granulating its copper for brass-making, thus improving the surface absorbtion and increasing the total yield of brass in the traditional cementation furnace.[16]

The part that the Bristol industry played in the development of the use of coal as the fuel for brass production cannot be fully evaluated on present evidence, but a contribution appears to have been made. In most early descriptions where it is mentioned at all, the fuel placed round the crucibles in the upper chamber was described as charcoal, although use of coal is recorded in the late seventeenth century at Stolberg, in Germany. In descriptions of those furnaces and in those of England at the time, there appears to have been little provision for any special kind of chimney. In some cases it was necessary to use water-powered bellows to provide a draught, rather than the induced draught as described by Christoph Weigels.

At Bristol there is no evidence of a forced draught being required. In contrast, a distant view of Baptist Mills of the 1730s[20] showing the site of brass production exhibits several large cones similar to the glass cones of Bristol, which were developed to use coal fuel in glassmaking. A modified structure of this type became standard practice at later brass works, being referred to by Hatchett at similar works at Birmingham by the end of the eighteenth century.[21] By comparison with Christoph Weigels' description of German works in 1698 (above), it is clear that the cone housing was a comparatively new development, which undoubtedly improved the ability to induce and control a more efficient draught and so control the furnace temperatures more effectively.

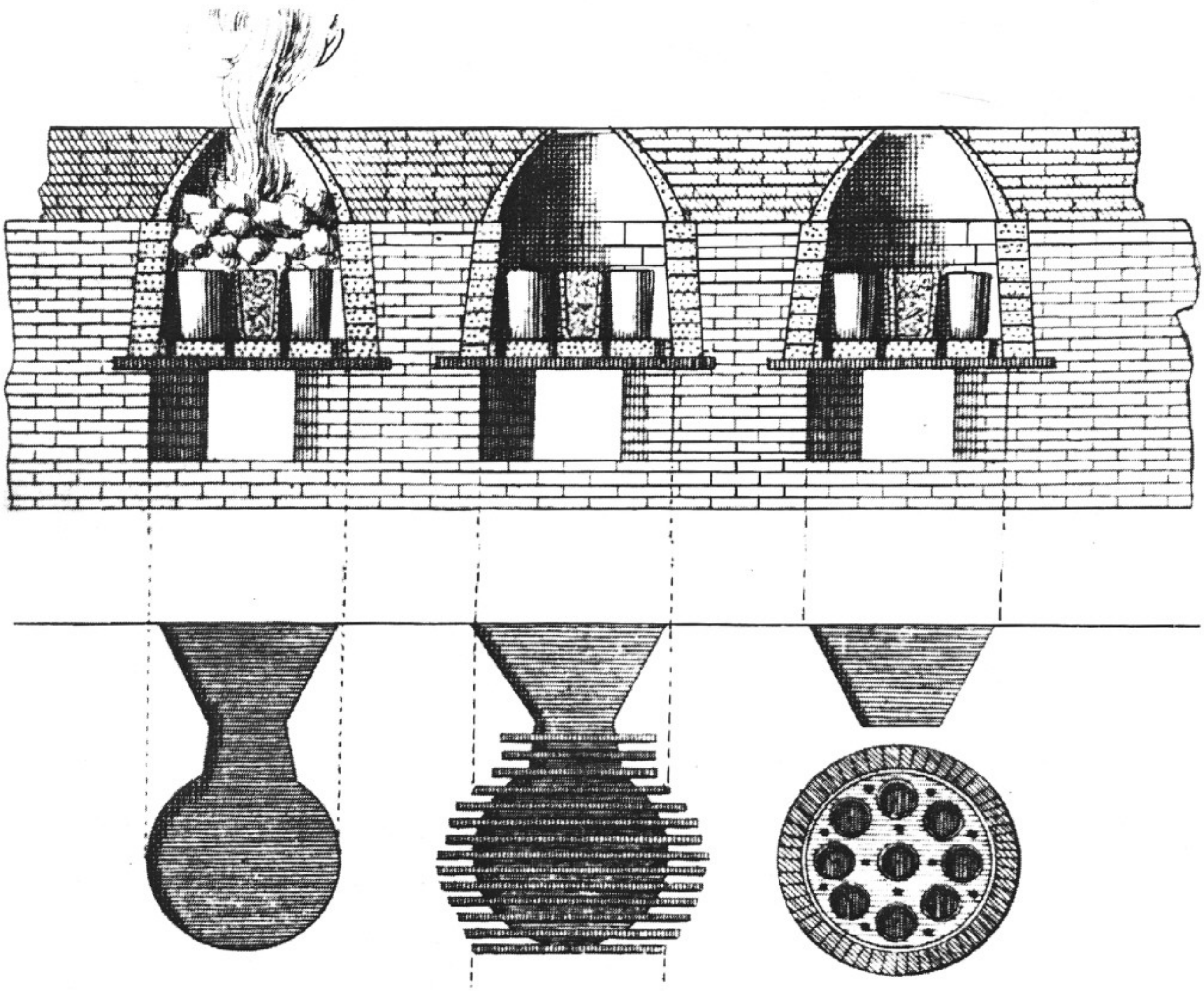


Fig. 3 Sections and plans of a bank of three typical cementation brass furnaces as seen by J Galon at Namur in the late 1740s.[14]

The Bristol works also housed its furnaces in banks of three, constructed back to back in groups of six in each one of its brass houses. These were described by Kahlmeter in 1725,[22] suggesting that by that date each group of six furnaces was probably housed under a cone structure. Joseph Harris gave an eye-witness account of inspecting the Baptist Mills furnaces somewhat later[23] when he described three furnace tops at floor level probably in one side of the house. Looking down into one of the chambers he saw, at a depth of about 3½ ft, that there were six pots circled round a central one. At the time of his visit in August 1748, it may just have been possible for him to have seen an additional demonstration of brassmaking at the new works being established by William Champion at Warmley, two to three miles distant.[24] The structures he would have been able to see would have been very similar to those of Baptist Mills where William's father, Nehemiah Champion had been manager.

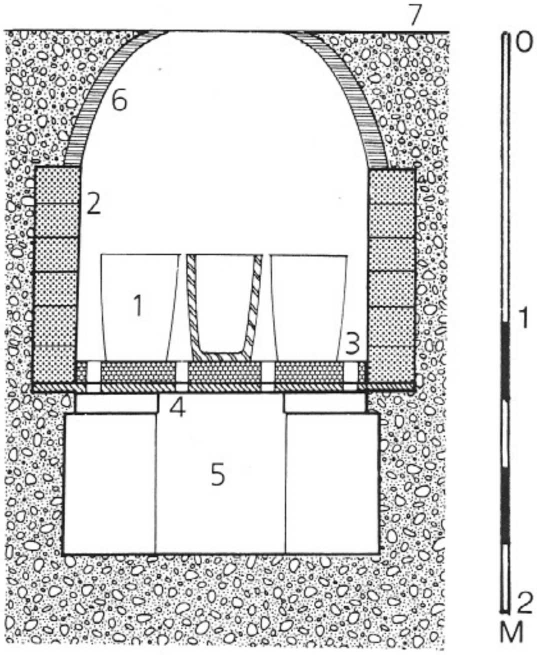
Evidence for this 'cementation' production of calamine brass, essentially medieval in concept, has been in the past entirely of a documentary nature. The method was superseded during the nineteenth century by melting copper with metallic zinc, once supplies of this latter commodity were widely available, making for a far simpler and quicker technique.[25] No furnace remains from the earlier method were known to have survived.

Cementation furnace remains

Early in 1986, adjacent to the 'listed' Clocktower building, the main surviving structure of William Champion's industrial estate, building operations in the early stages of excavating foundations uncovered a series of arches.

Local residents drew the attention of local authority officials to the historic interest of the site but appear to

Fig. 4 The best preserved of the three furnace sections at Warmley, situated at A in Fig. 7 inset.



1 Crucible 2 Refractory bricks
3 Refractory furnace bottom
4 Cast iron perforated plate
5 Ash-pit|draught hole
6 Refractory furnace domed top
7 Surrounding masonry

Fig. 5 Only the vertical part of the structure survived, revealing the full width of the ledge of the bedplate support.

have met with little or no response. By chance, two members[26] of the Bristol Industrial Archaeological Society visited the site over the Easter Holiday, and immediately realised that the foundations had been driven through a set of three furnaces which they thought were probably calamine-brass cementation furnaces. Only about one third of a vertical section of each furnace had survived the foundation trenches, and the remainder of the weekend was spent in cleaning up these structures, measuring and photographing, and investigating to see if there were further remains of importance. (Fig. 4).

The writer was able to confirm that the remaining features were consistent with those of cementation furnaces. (Fig. 5). They comprised segments of three vertical cylindrical constructions of crumbling brick, each segment divided approximately at half its height by a wide brick ledge, which would have supported firebars or a pierced cast-iron furnace bedplate.[27] The upper sections had been truncated at approximately 0.60m in height from the ledge, and were without batter, but it could be expected that this removed upper part would have formed the domed top and opening to take the round brick lid. The estimated diameter of the upper section was approximately 1.25m, below the ledge it would have been about 20cm less. The depth of the lower half of the structures could not be measured as they were already embedded in the concrete of the foundations. The remaining segments conformed to circular structures placed equidistant within rubble infill, with culverts leading in the same direction from each one. Overall, from the one segment to the missing, but estimated, outer part of the far distant furnace measured about 6.9m. No time was available to excavate the exterior of these structures as they were buried in deep hard-packed rubble.

Within two days of the writer's inspection the remains had been surrounded by concrete-block foundation walls and could no longer be photographed. Efforts to delay building work, or to arrange removal of one of the segments could not be made quickly enough. In less than a week, all was covered in concrete. (Figs. 6 and 7)

Other remains discovered in the area had been of less consequence, but what there was had corroborated the general interpretation. Interspersed with the rubble infill near the furnace area were many fragments of a stony material notable for its blue colouration in varying degrees. Analysis (see Appendix I) confirmed suspicions of the writer that this colour resulted from the presence

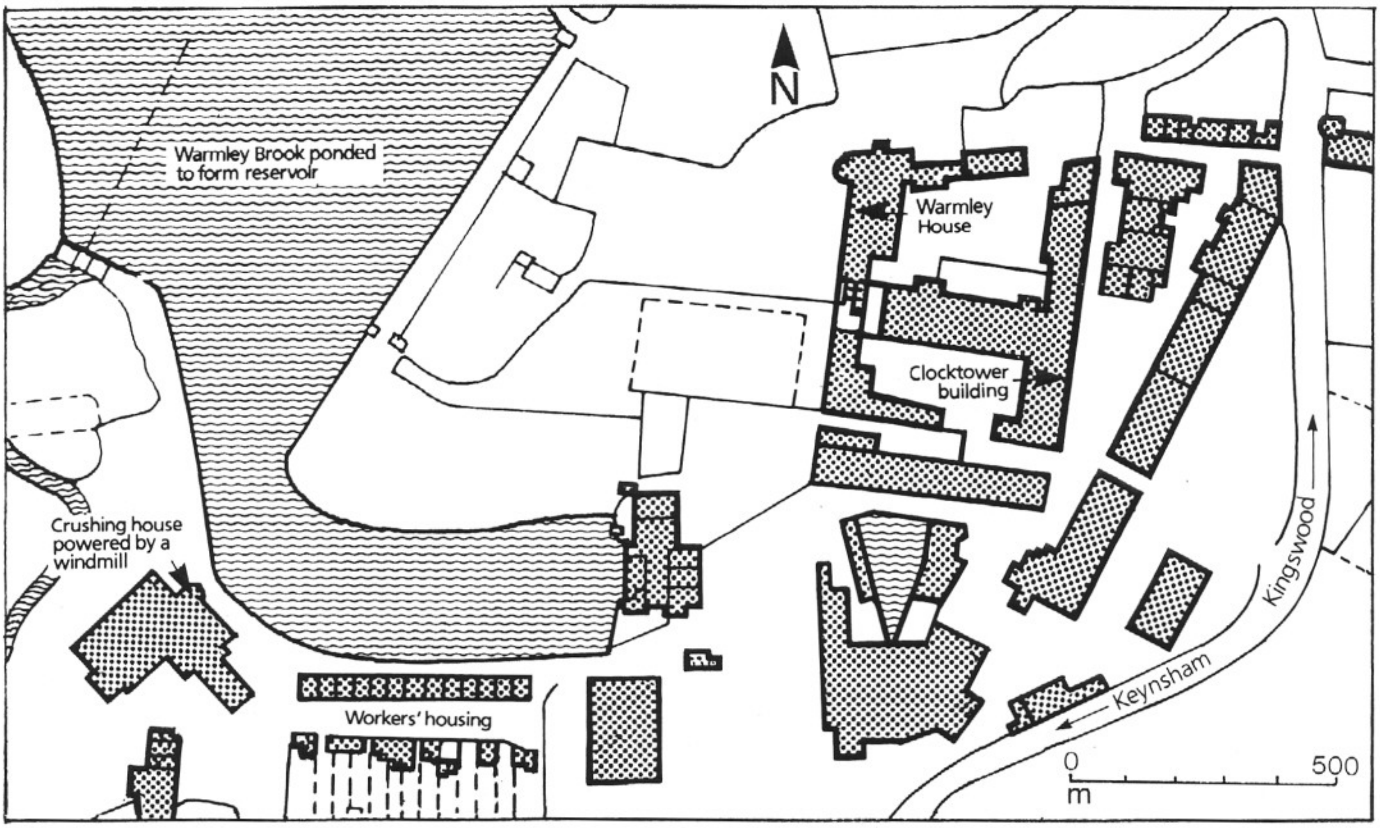


Fig. 6 Plan of part of the Warmley Company estate derived from the Tithe Map 1740.

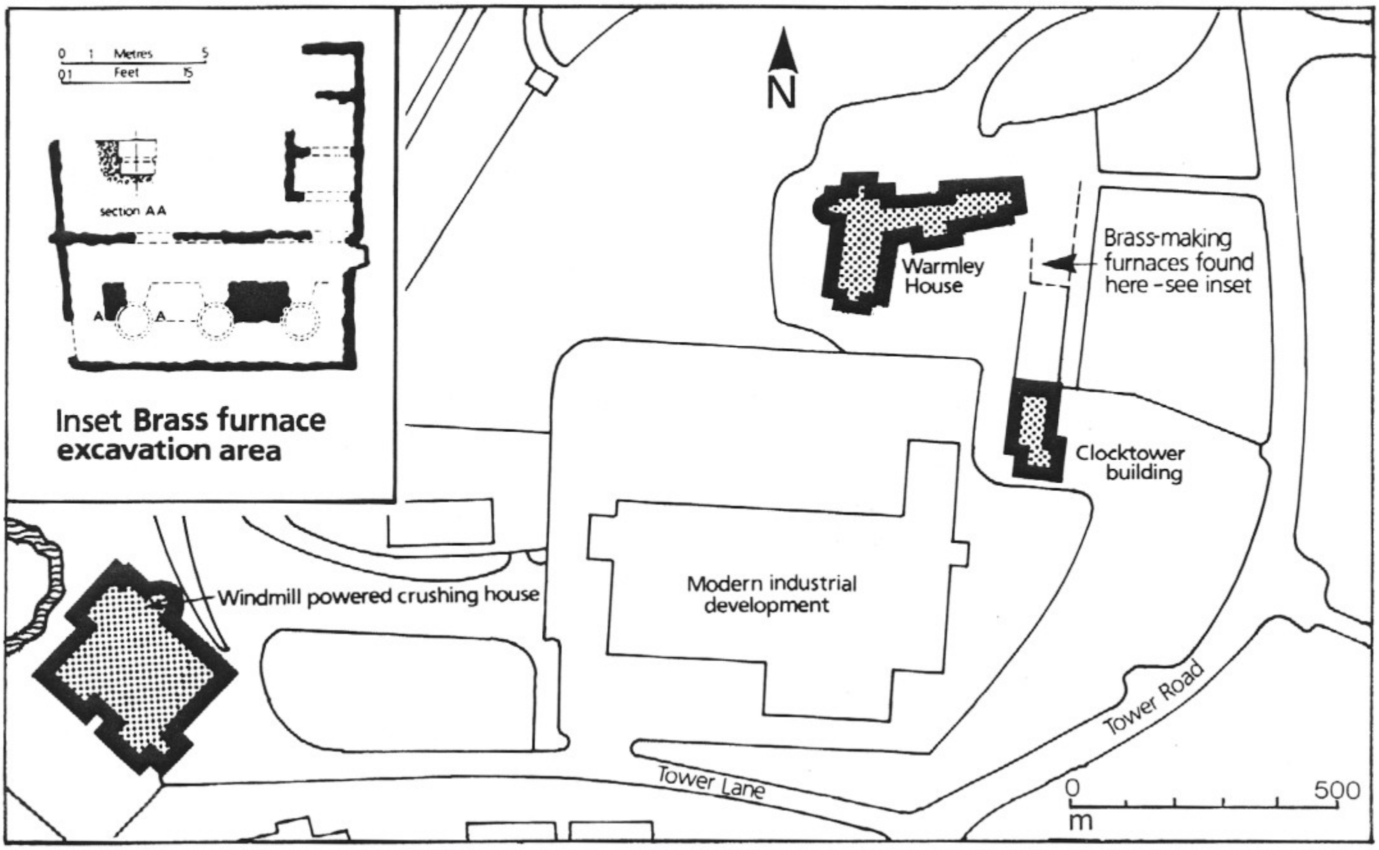


Fig. 7 Modern plan of the area shown above with surviving features in bold, and indicating the position of the brass making furnaces.

of zinc in some form, an indication possibly first referred to by Galon in the late 1740s when describing techniques of brass production at Namur. At the Warmley site there appeared to have been a coal bunker to one side of the furnace area, with a large amount of coal dust still present. A little further away there were thick slabs of granite and some broken pieces at a level above the tops of the furnaces. These could have been the 'great stones' described by Christoph Weigel, above, and also referrred to by Joseph Harris.[27] Used in pairs with iron spacing bars between, they were the traditional method of creating a suitable mould in which to cast large flat plates of brass, a technique brought from the continent where granite from Brittany and Normandy was employed. The casting of such plates was the main product of the early eighteenth-century brasshouse, which William Champion was known to have included in his extensive industrial estate. There, the Warmley works was organised to include his new process of zinc smelting as well as the whole range, from the smelting of copper to the final fabrication in the production of brass wares. Because of the high costs of processing metallic zinc, traditional methods were retained for the normal production of brass using the cementation furnaces. Annealing furnaces would also have been required, but no remains of such structures, or of those for zinc smelting have been revealed at Warmley so far.

The battery mills

The most conspicuous remains of the older works of the Bristol industry which started at Baptist Mills are the structures still surviving of the coal-fired annealing furnaces used during the manufacture of hollow-ware, the main product of the works. The processes of rolling brass slab, for production of sheet metal, which was then hammered, or **battered,** to shape under water-powered hammers, were all carried out at a series of water-powered mills between Bath and Bristol. All had their own coal-fired annealing furnaces as standard equipment, as frequent annealing was required at all stages of the work to soften the metal which had become work-hardened under the severe mechanical treatment.[28] Such sites once existed at Weston, Bath; Chew Mill and Avon Mill, Keynsham; and Woodborough Mill near Woollard; as well as the later Warmley site of William Champion and his battery mills at Bitton and Kelston. Two outer shells of such furnaces still survive at Kelston but at Saltford battery millsite a furnace still stands which is almost complete. It accompanies a similar structure, though partly ruined, all that remains from the four furnaces which were once in use at Saltford, a battery mill which continued to work and use these furnaces until 1925.

Until comparatively recent times it had not been possible to make a detailed investigation of the unique surviving structure at Saltford. The base was buried in flood-carried silt and the furnace chamber stacked with rubbish, so that previously-published descriptions have been far from complete. New Saltford ownership brought fresh opportunities. The rubbish was cleared and permission obtained to remove the layers of silt from the furnace base and its surroundings. This was carried out under the direction of Dr Paul Craddock during August 1980 with assistance from Brenda Craddock, Rod Clough and R Whittaker, the writer and members of the Bristol Industrial Archaeological Society.

The results revealed structures which confirmed tape-recorded details given by Tom Shellard, shortly before his death in the early 1970s in which he recalled memories of working under his foreman father at the mill in his youth.[29]

From these descriptions it had been apparent that the furnace had been a muffle with an interior wall which Tom Shellard remembered having to keep sealed by smearing with refractory clay. This inner arched wall, forming the furnace chamber is now missing, having disintegrated, but clearance of the furnace bed revealed grooves in the brickwork from which the arch would have sprung. A few refractory bricks of half normal width which fitted these grooves were still lying in and about the furnace. The reconstruction drawing shows how this inner arch may once have appeared (Fig. 9), although no precise details of it are known.

Fig. 8 The bed of the annealing furnace showing the groove from which sprang the muffle arch, and part of the firebox, top left. Scale, metre.

Further removal of silt revealed the two fire boxes situated at either side of the furnace bed, both extending from front to rear in, what would have been, cavities surrounding the missing protective arch. They would have been fired from the rear face through cast-iron doors, some fittings of which had still survived in place. The ashpits descended to floor level, well below the bed of the furnace, creating two troughs extending the whole length of either side. (Fig. 11). Although

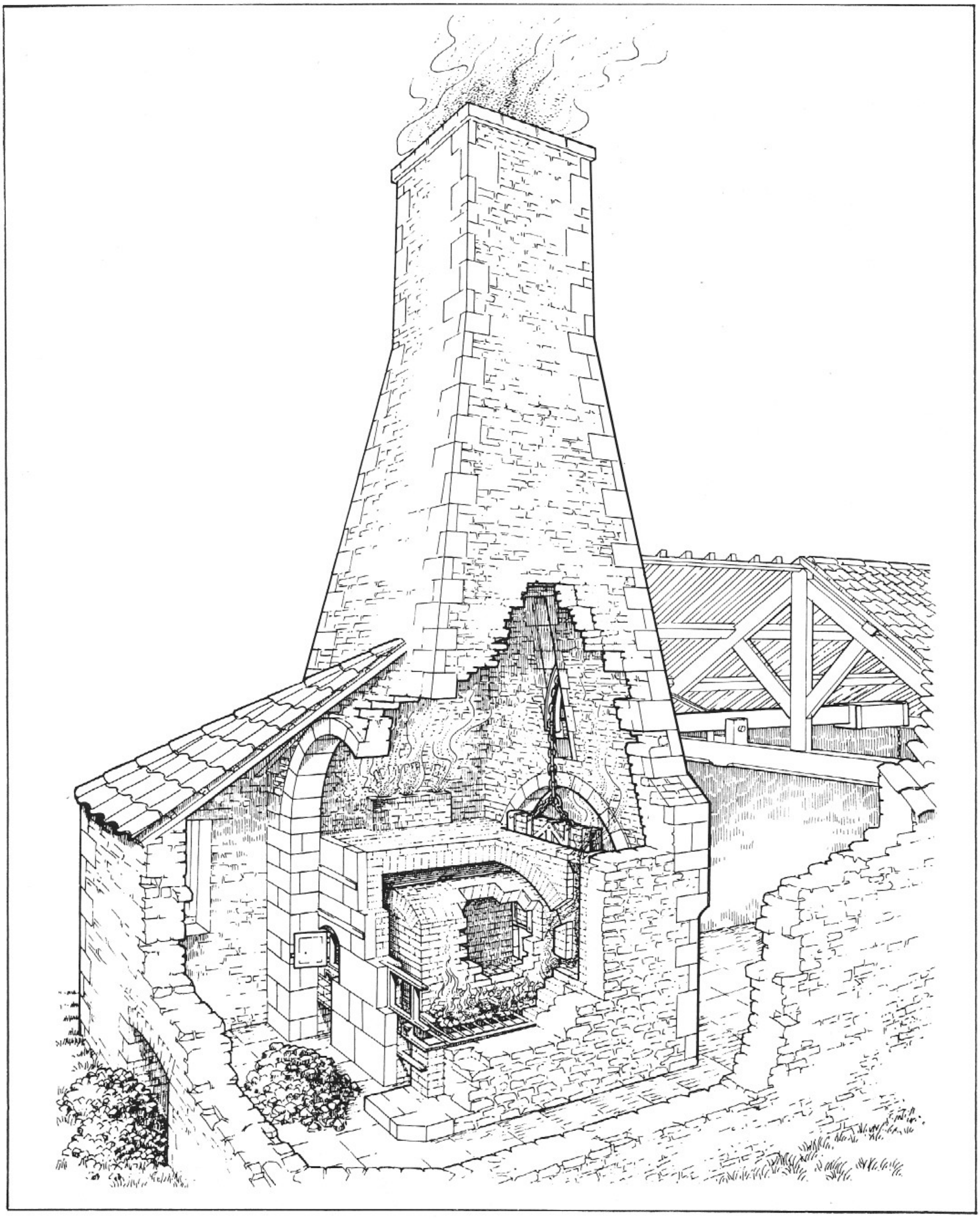


Fig. 9 A conjectural drawing of Saltford brass annealing furnace with its firebrick furnace door hanging from the arch-head of the balance-beam. The inner arch of the muffle is in place with the fireboxes stretching along either side of it controlled by the flue ducts. The furnace was fired from the near face, where the coal was stored and where the ashpits were cleared.

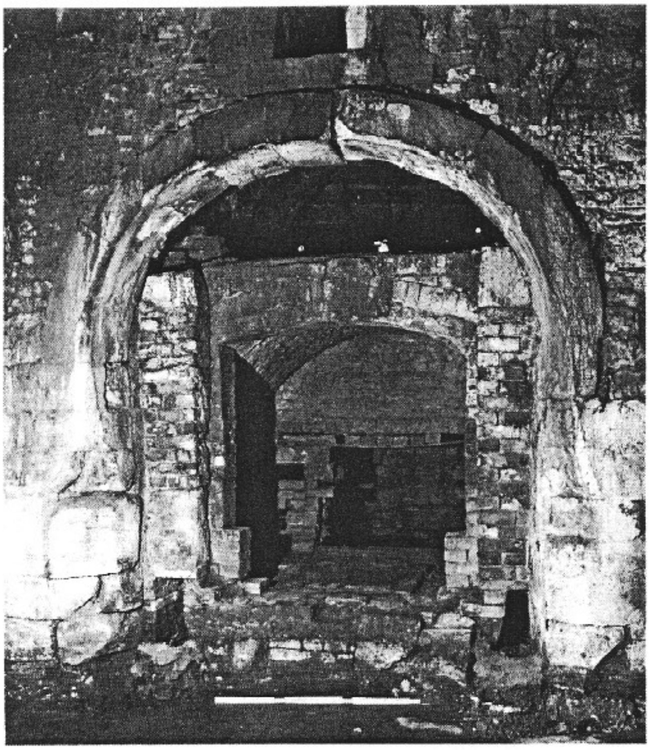


Fig. 10 Saltford annealing furnace from the front, before repair of the gaping hole in the rear face.

Fig. 11 Rear of annealing furnace showing door position and ashpit of left-hand firebox.

gaping dangerously at the time of excavation the rear face of the furnace was originally blind apart from the firing apertures. This damaged section has now been repaired to match photographic evidence. (Figs. 10 and 16).

The furnace would have been loaded from the front by trolley from a revolving turntable according to Tom Shellard's memory. The turntable is no longer there, neither is the heavy firebrick door bound with iron bands but it is possible to see where it slid into place, suspended from a long timber balance beam. This horizontal beam held the door from an arch-head type hoist by protruding through a vertical slot pierced through the wall of the chimney, which accommodated its balancing movement. (see Figs. 12-14). A wooden box at the opposite end of the beam counterbalanced the weight of the door, enabling it to be opened quite easily by pulling the box down with a length of chain. The vertical chimney slot is still a distinctive feature of the structure, and the balance beam, which had crashed to the ground just prior to the excavation, has now been repaired and placed in position. (Fig. 12). An original beam is also still in place at the time of writing in front of the ruined furnace, although threatened by possible collapse.(Fig. 14).

The repairs carried out, however, have consolidated the best and most complete of these surviving furnaces to the point where it is no longer in danger of collapse as it was when carrying out the exploratory work. The re-erection of the balance beam was regarded as something of a milestone because it illustrated the wide contrast in the ages of techniques to be found at the mill. A similar mechanism can be seen in the furnace drawings of Georg Bauer (alias Agricola) in his De Re Metallica of 1556,[30] so that the use of a balance beam for opening heavy furnace doors can be regarded as medieval in concept.(Fig. 15). At Saltford it was employed in the most up-to-date techniques of late eighteenth-century annealing incorporating the use of coal as a fuel.

No known written sources refer to this type of furnace with its carefully designed muffle cavities housing combustion, and providing protection from sulphurous coal fumes for the brass being worked; the remains themselves and recorded memories provide the only evidence. The structures can be dated back to the late eighteenth century by the more scanty outer structures surviving at Kelston Mills, less than a mile away. This site was built by William Champion in 1764 at a time of intense activity, innovation and expansion within his company.

After Champion had over-reached himself in his activities and had been declared bankrupt in 1769, the old Bristol company eventually occupied the Kelston site but at a time when they were lacking in technical innovation, running down their works, and gradually withdrawing in face of growing competition from Birmingham.[31] It is most likely, therefore, that William Champion himself was responsible for the introduction of the Kelston furnaces and that subsequent examples were copies of those he had constructed. At Saltford, on a site belonging to the old Bristol company from 1721, it is relevant to note that overall dimensions are similar to those of the Kelston structure but the design

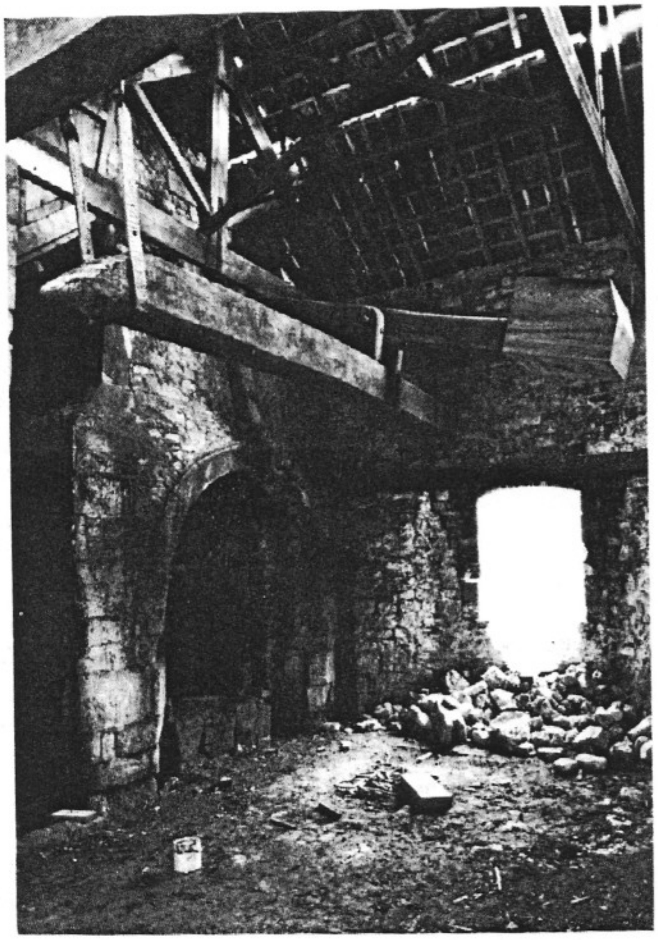


Fig. 12 The balance beam and box replaced in its original position after the collapse of its supporting timbers.

Fig. 13 One of the two shells of annealing furnaces surviving at Kelston. Of slightly different design to those at Saltford.

Fig. 14 The balance beam of the second partly ruined Saltford annealing furnace. This has now collapsed.

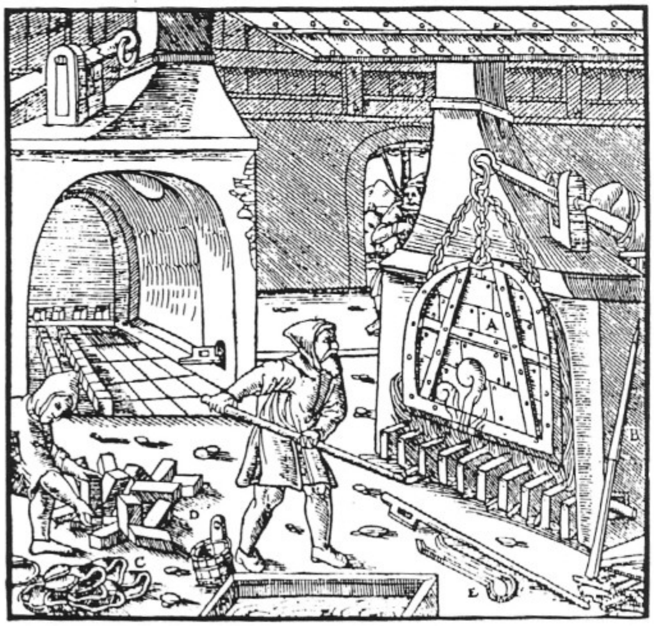


Fig. 15 An Agricola illustration showing the use of a balance beam to open the door of a furnace.

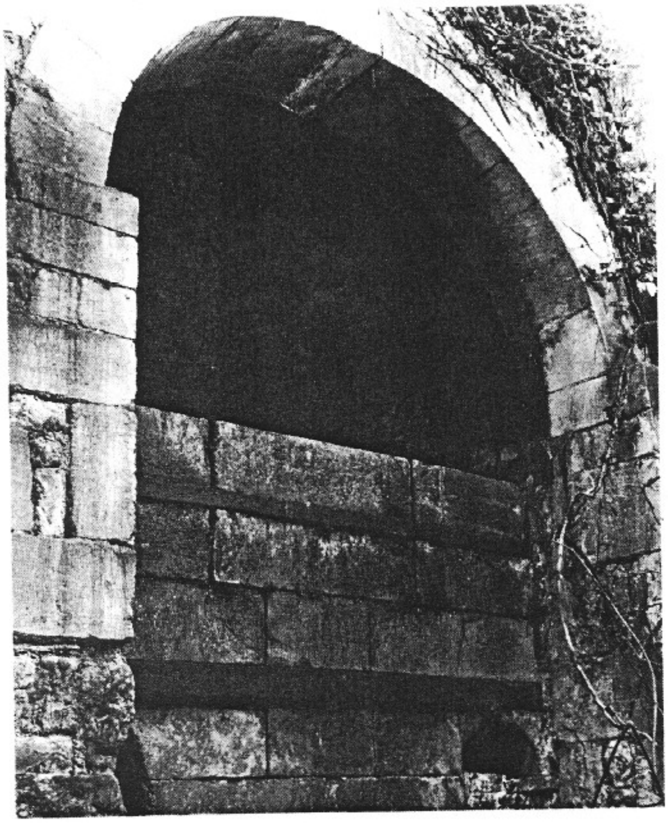


Fig. 16 The rear view of Kelston annealing furnace, giving a pattern for the repair of the collapsed rear face of the Saltford furnace.

differs slightly in the batter of the chimney and other small details. (Fig. 13).

The old Bristol brass company had long acquired the facility of coal-fired annealing in an earlier type of furnace. William Champion's father, Nehemiah, as manager of the old company and successor to Abraham Darby, had patented **'A New Way of Nealing the Plates and Kettles with Pitt Coale, which softens and makes the Brass as Tough and Fine-coloured as any Nealed with Wood and Wood Coale.'** as far back as 1723 in Patent Specification No 454.[32]

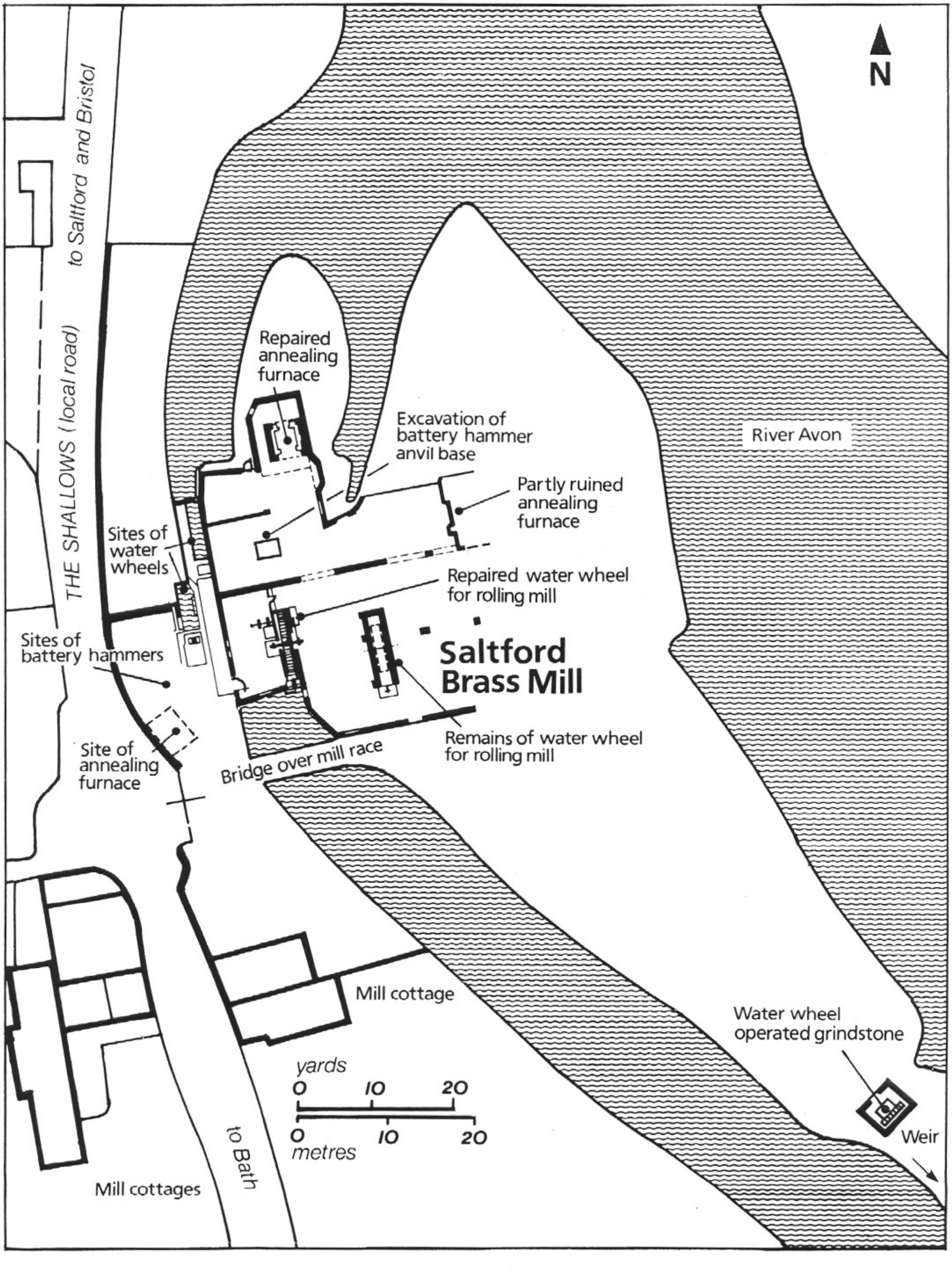
This process was regarded as important enough to be recorded in some detail by Emmanuel Swedenborg in his **De Cupro** of 1734.[33] He noted that the brassware to be annealed was placed in wheeled cast-iron containers which were then completely sealed with clay. The furnace interior was 5ft square with a 4ft high arched roof and 1½ft thick side walls. The furnace gases entered the chamber through apertures in these side walls and was drawn up and reverberated from the arched roof down on the protected containers below. The door could be raised and lowered by a chain suggesting, together with other details in the design, that the later development had evolved from this early innovation. As originally introduced, the Bristol coal-fired annealing process appears to have taken place in a type of reverberatory furnace, in which there had been much previous local development in the smelting of non-ferrous metals.

No remains of this earlier type of structure have been discovered so far, but this is the type of furnace which must have existed at Saltford before the erection of the present structures. The mill there was established by the old Bristol brass company, probably in 1721, the time when coal-fired annealing appears to have been introduced.

By comparison, it can be inferred that, for the most part, continental establishments of the eighteenth century annealed their wares singly on a waist-high blacksmith-type charcoal hearth which was blown by water-powered bellows. Written descriptions rarely make any mention of continental annealing methods but a number of illustrations of the period show this type of operation,[34] which can also be seen in reconstruction at the copper-battery mill display at the Westfälisches Freilichtmuseum, Hagen. There is reference to some coal-fired annealing at Stolberg, near Aachen, the continental centre of hollow-ware manufacture, but there the best work is stated to have been annealed in wood-fired furnaces.[35] Not until the nineteenth century are large continental enclosed furnaces taking multiple loads described by Andrew Ure[36] and even then no mention is made of the type of fuel used.

There is similar lack of evidence for the use of such furnaces in this country, other than at Bristol. Only at Holywell in Flintshire has the excavation of the eighteenth-century brass battery works revealed ground-level remains which **may** possibly be similar in structure.[37] Here, it should be noted that the mill was established by John Champion, brother to William, who was himself closely connected with the Bristol industry. The inferences point to the local techniques of coal-fired annealing in a muffle furnace being entirely Bristolian in origin and only slowly adopted elsewhere.

The interest and importance of the surviving furnace remains at Saltford was further augmented by small-scale trial excavations during late May and early June, 1986. This work was carried out at the request of English Heritage HBMC, when the Avon County Planning Department and the local Wansdyke District Council were strongly in favour of converting that area of the mill to holiday flats although it had by then been scheduled as an Ancient Monument. The limited excavation revealed the timber anvil-mounting of a water-powered hammer in its stone-lined setting, and other minor features, which sufficed to indicate the quality and historic importance of material still encompassed in the site. The remains of the Bristol brass industry at Saltford Mill are the most complete, and comprise the last surviving site of the industry, typical of the era when the Bristol industry was leading the world in its own particular sphere of technology. No such remains exist elsewhere and as unique survivals, deserve to be protected for future study and interpretation of the Bristol brass industry.


N
to Saltford and Bristol
THE SHALLOWS (local road)
Repaired annealing furnace
Excavation of battery hammer anvil base
Partly ruined annealing furnace
River Avon
Sites of water wheels
Repaired water wheel for rolling mill
Sites of battery hammers
Saltford Brass Mill
Site of annealing furnace
Bridge over mill race
Remains of water wheel for rolling mill
Mill cottage
Water wheel operated grindstone
Weir
yards
0
10
20
0
10
20
metres
to Bath
Mill cottages

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Appendix I

Report on the examination of blue material from industrial remains at Warmley

Introduction

The sample was examined by x-ray diffraction, and a polished thin section was prepared and examined by optical microscopy and the scanning electron microscope (SEM).

Chemical analysis of the sample in the SEM (Table 1, Col. 1) showed it to contain around 40 wt. % zinc oxide, ZnO, 10% Al_2O_3 and 50% SiO_2. Neglecting the zinc oxide, the analysis corresponds to a siliceous fireclay, low in fluxes such as FeO, MgO, CaO and K_2O (Table 1, Col. 2). Fig. 1 shows the microstructure of the sample. Large ceramic fragments, about 1mm diameter and relatively low in zinc, are set in a white matrix containing approximately 60 wt. % ZnO. The matrix also contains common sub-angular quartz grains, around 0.1mm diameter. More detailed examination of the low-zinc fragments (Fig. 2) shows that they contain grains of zinc spinel, $ZnAl_2O_4$, with subordinate zinc orthosilicate (willemite), in a matrix of silica and a potassium silicate glass. The zinc-rich compounds are concentrated around cracks and voids in the low zinc fragments (Figs.1, 2). The $ZnAl_2O_4$ is often enclosed or rimmed by Zn_2SiO_4, suggesting that the silicate phases formed after the spinel. The high zinc matrix is composed predominantly of Zn_2SiO_4. The composition of the matrix, excluding quartz grains, is given in Table 1 col. 3 and recalculated zinc-free in Table 1, col. 4. It again corresponds to a fireclay, this time less siliceous because the quartz particles have been excluded.

Table 1

	1	2	3	4	5	6	7
SiO_2	49.0	80.3	23.6	59.7	2.6	27.7	72.2
TiO_2	0.6	1.0	0.7	1.8	1.1	-	1.5
Al_2O_3	10.5	17.2	13.7	34.7	52.6	-	10.9
FeO	0.9	1.5	1.1	2.8	0.5	3.3	0.8
MgO	0.2	-	0.4	1.0	0.9	0.9	0.2
CaO	0.2	-	0.2	-	-	-	1.8
K_2O	0.4	0.7	0.2	-	-	-	6.8
ZnO	39.0	-	60.0	-	41.6	66.9	3.6

1. Large area SEM/EDXA analysis of ceramic.
2. As 1. recalculated to 100%, neglecting ZnO.
3. Analysis of Zn-rich matrix, excluding quartz grains.
4. As 3. recalculated to 100%, neglecting ZnO.
5. Zincian spinel, $ZnAl_2O_4$. NB SiO_2 may be interference from matrix.
6. Zinc orthosilicate, Zn_2SiO_4.
7. Interstitial glass phase.

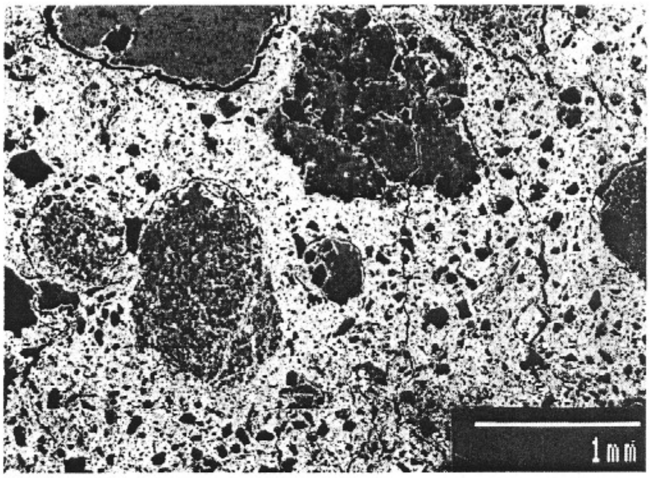

Fig. 1 SEM photomicrograph showing overall structure of ceramic. Large dark areas are relatively poor in zinc; note concentrations of zinc show white along cracks. Matrix is rich in zinc and contains numerous fine quartz grains (black) (Robinson back-scattered electron detector).

Interpretation

The sample appears to have been a fireclay ceramic which has been permeated by zinc vapour during use. Initially zinc spinel formed followed by zinc silicate. In the porous ceramic matrix, reaction has proceeded to the extent that most of the original fired clay material has formed zinc compounds. However, in less porous areas of the ceramic (possibly grog filler, or more likely mudstone fragments which are common in some fireclays) the impregnation proceeeded less rapidly, and is at an early stage relative to the ceramic matrix.

The ceramic is likely to have been either a crucible used in brass cementation, or a zinc distillation retort. It is unclear which, but on at least some fragments of a cementation crucible copper contamination would be expected. None was detected in the present case but a single example is not conclusive. The sample appears to match the expected composition of a distillation retort; for example Smith (1918) notes that zincian spinels were formed in retorts during use. A further possibility is that the ceramic represents a fragment of furnace brick or lining; this is less likely, as the furnace would have been isolated from the bulk of the zinc vapour by the crucible/retort containers. However, repeated use at high temperatures over very long periods of time might have resulted in such a material being formed. At present we are limited by the lack of comparative material.

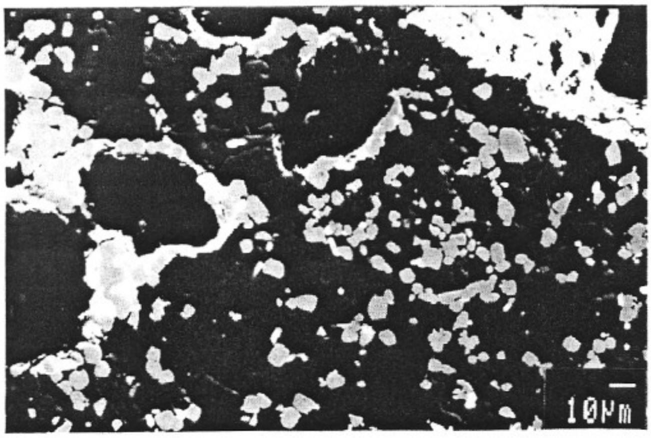

Fig. 2 Detail of low-zinc area with high-zinc matrix copper right. Common grains of $ZnAl_2O_4$ spinel, mid-grey occur throughout, and are concentrated with Zn_2SiO_4 (white) around pores (black) on the left and upper centre of photomicrograph. The low-zinc matrix consists of a two-phase mixture of silica and a potassium aluminosilicate glass; these are both dark shades of grey and only just resolvable.

I C Freestone

Appendix II

The Composition of Bristol Brass

The Material

During the excavations and restorations at Saltford Mill, two pieces of sheet brass were recovered. One was very thin (<0.5 mm) but the other was more substantial (>2 mm). Metallographic examination of a polished section showed that it was extensively worked and annealed, and not a cast plate.

A sample was also taken from a nest of three unfinished brass bowls recovered from the River Avon just downstream of the Brass Works at Bath which operated in the late 18th-early 19th century but was closed by 1812.

The Blaise Castle House Museum, Bristol holds an extensive collection of local brassware. From this a selection of brass pans was sampled varying in size from domestic cooking pans to large milk pans used by the dairy trade and other large vessels made for export to Africa, America and the Far East (Day 1973 pp 169-170). Unfortunately few of the pans were marked or easily dateable beyond the 18th or 19th century, although most should lie between 1750-1850.

Samples were also taken from a selection of the brass heads of the standards belonging to the local friendly societies and used at the head of their annual processions. The ornamental brass heads on the standards are only found in the South West, especially in the Bristol region dating from the late 18th to early 19th century and it seems logical that the brass was produced locally.

Finally, a late 17th century sheet brass chestnut warmer and an 18th century sheet brass spit jack both local, conclude the items sampled for analysis.

Technical

The samples were taken with a steel scalpel, or drilled with a small hand-held modeller's drill mounted with a size 60 (1 mm diameter) bit. Between 2 and 15 mg of clean metal turnings were collected in each case. The samples were analysed by atomic absorption spectrometry using the methods detailed in Hughes **et al** 1976. The analyses have a precision of ± 1% for the copper and zinc, and about ± 20% for the minor and trace elements. Most elements could be detected down to at least 0.005% in the metal. The elements Co, Au and Mn could not be detected at this level. The detection limit for tin varies and is quoted (<) in each case.

Discussion

The metals are of brass, with the exception of the large copper pan, T9174. Although all the brasses only contain small amounts of lead and traces of other metals, they do fall into two quite distinct groups, probably reflecting the method by which the brass was made. One group is high in zinc (>.30%) and these have rather low lead contents and relatively small traces of iron, tin and other trace elements.

Table 1: Bristol Brasses

Lab.	Description	Provenance	Cu	Pb	Sn	Ag	Fe	Sb	Ni	Au	Co	As	Mn	Cd	Bi	Zn
103	Brass sheet	Saltford Mill	67.5	1.10	.05	.010	.085	.030	.075			.100		.200	.035	31.000
104	Bowl	Bath Mills, Bath	66.5	2.70	.05	.050	.060	.030	.035			.200		.005	.085	30.000
113	Sheet	Saltford Mill	66.0	.65	.07	.010	.040	.015	.050			.250			.003	33.200

Table 2: Bristol Brasses from Blaise Castle House Museum

Reg. No.	Description	Cu	Pb	Sn	Ag	Fe	Sb	Ni	Au	Co	As	Mn	Cd	Bi	Zn
a) Battery pans															
TA 2235	Large pan	75.0	1.48	1.08	.080	.401	.039	.109	(TR)	.005	.097	(TR)	(TR)	(TR)	17.562
TTC 1875	Large pan	64.2	.87	(TR)	.031	.241	.019	.064			.066	(TR)	.019	.058	37.341
TA 2236	Large pan	72.3	1.77	.64	.070	.371	.038	.096	(TR)	.006	.082	(TR)	(TR)	.015	23.965
T 9174	Large pan	100.7	.14	.09	.036	.125	.046	.063		(TR)	.308	(TR)	(TR)	.027	.008
T 9173	Pan	70.4	1.49	.40	.063	.384	.026	.123	(TR)	(TR)	.045	(TR)	.006	(TR)	25.495
T 2034	Pan	66.2	.37	(TR)	.038	.107	.027	.027	(TR)	(TR)	.093	(TR)	.031	(TR)	30.398
J.T. Ralls	Pan	67.1	.50	(TR)	.026	.172	.015	.038		(TR)	.051	(TR)	.010	.024	33.223
T 9839	Pan	65.6	.88	(TR)	.018	.016	.020	.108	(TR)	(TR)	.069	(TR)	.010	.041	33.727
b) Society Standards															
T 7506	Butleigh Society Standard	75.1	2.82	.66	.077	.389	.051	.054	(TR)	(TR)	.390	(TR)	.003	.105	19.974
TA 94	Wedbury on Trym Society Standard	71.4	1.85	.38	.080	.276	.077	.069	(TR)	(TR)	.280	(TR)	.015	.068	23.988
T 7715	Chilcompton Society Standard	76.4	2.49	.59	.077	.375	.052	.059	(TR)	(TR)	.294	(TR)	.002	.099	19.050
T 7580	Wedmore Society Standard	73.1	2.30	.93	.074	.309	.040	.058	(TR)	(TR)	.300	(TR)	.007	.085	22.800
T 7583	Willsbridge Society Standard	62.7	.48	(TR)	.022	.080	.017	.033	(TR)	(TR)	.073	(TR)	.016	(TR)	37.107
T 7558	Old Wick Society Standard	77.4	1.68	.59	.077	.419	.036	.053	(TR)	(TR)	.353	(TR)	(TR)	.145	17.153
TA 207	Bilton Society Standard	75.2	2.63	.58	.093	.532	.049	.059	(TR)	(TR)	.211	(TR)	(TR)	.041	19.431
T 7515	Westbury on Trym Society Standard	76.2	2.95	.73	.078	.475	.049	.060	(TR)	(TR)	.349	(TR)	(TR)	.115	19.137
T 7557	Kingswood Society Standard	73.7	2.55	.89	.072	.624	.067	.063	(TR)	(TR)	.156	(TR)	(TR)	.067	20.093
T 7531	Iron Acton Society Standard	74.3	2.43	.32	.071	.130	.038	.041	(TR)	(TR)	.343	(TR)	.004	.096	21.482
T 7571	E & W Stow Society Standard	73.3	2.22	.71	.079	.867	.058	.051	(TR)	(TR)	.394	(TR)	.008	.127	21.343
c) Other															
T 9250	Spit jack	70.4	2.80	.15	.060	.265	.037	.028	(TR)	(TR)	.140	(TR)	(TR)	.054	23.866
T 8922	Chestnut warmer	67.5	3.10	.38	.052	.133	.047	.052			.161	(TR)	(TR)		30.474

The second group has correspondingly less zinc (<26%) and these brasses have more lead, together with substantial traces of iron and tin.

The century between 1750 and 1850 to which most of the artefacts belong witnessed a complete change in the way that brass was made in the Bristol region. In 1750 almost all brass was still made by the traditional cementation process. This is described in detail by Day (1973), but put very simply, the local calcined calamine ores were mixed with coke (or charcoal) and finely divided copper, placed in a sealed crucible and heated to about 1000°C, producing brass directly. In 1738 Champion had patented his process for producing metallic zinc by distillation but through most of the 18th century brass made from the copper and zinc metals was expensive and used mainly for costume jewellery alloys such as pinchbeck or for scientific instruments. By 1860 as Percy (1860) records brass was almost universally made by mixing the two metals, or speltering as it was and still is known (itself a highly-skilled operation, see Hull 1950). Such great differences in these two ways of making brass are reflected in the composition of the metal. Several technical authors, such as Ercker in the 16th century and Nehemiah Champion in the early 18th century, have commented on the maximum amount of zinc they could get into the copper; for Ercker it was 29% and for Champion it was 28%. The validity of these claims is reinforced by the many hundreds of Roman, Medieval and Islamic brasses analysed by the authors and others; none are known with more than 28% of zinc, although many approach that figure (Craddock 1985). Haydecke and Werner (1970) carried out experiments in which they heated first copper, and then a 40% zinc brass in the presence of zinc oxide and charcoal at 1000°C. Significantly in both instances the product was a 28% zinc brass. The figure of 1000°C is critical, below that temperature the reaction barely proceeds at all, but if much higher then the forming brass melts to form a puddle in the crucible bottom with only a very limited surface area exposed to further absorption. However, Nehemiah Champion claimed he could raise the percentage of zinc absorbed to 33% (Day 1973, pp 59-

61) and from the 16th century brasses are known containing up to 33%. (NB the 17th century chestnut warmer, T8922, with 30.5% zinc). Percy (1860 p 616 records that at the Forest Works, Birmingham in 1781, 33% was the maximum zinc content attainable.

A high iron content was another feature of cementation brass. The copper was reacted directly with the calcined ore under very reducing conditions and any iron minerals present were reduced to metal and dissolved in the forming brass. This is evident from the analyses and from contemporary comments. Thus Watson (1786) reported the claims of Emerson, the Bristol brassmaker, that his brass, made by speltering 'is quite free from knots or hard places arising from iron, to which other brass is subject and this quality, as it respects the magnetic needle, renders it of great importance in making compasses'.

The calamine ores inevitably contained some galena, although this was carefully picked out by hand as far as possible. Cementation brasses tend to have a small percentage of lead. However, zinc produced by distillation will also have some lead, as it is quite volatile. Fortunately Watson (1786) has given some indication of the levels one could expect in late 18th century zinc. He records that a cubic foot of zinc from India weighs 7,240 oz, from Goslar in Germany 6,953 oz, and from Bristol 7,028 oz. This equates roughly to 5%, 1% and 2% respectively of lead in the zinc, assuming lead was the only impurity and that the zinc was cast. If this was the case then it is possible to calculate approximately how much lead one could expect in Bristol brass. If the metal has approximately $^1/_3$ zinc, then it should contain about 0.6-0.7% of lead from the zinc on Watson's figures plus any lead from the copper. One of the pans, T9174, is of unalloyed copper and this has 0.14% lead, 0.09% of tin, and 0.125% of iron and gives a useful indication of the intrinsic purity of the copper before alloying. Thus a 70 : 30 brass made by speltering could be expected to contain around 0.1-0.2% of Pb from the copper and 0.4-0.8% from the zinc, ie around 0.5-1% of lead overall, and this is the range of lead contents in the high zinc brasses, such as T7583, T1875, T2034, J T Ralls, T9839, and the samples from Saltford (although not the brass bowls from the Avon with 2.7%). Thus the zinc, lead and iron content seem to correlate together and are indicative of the process. In this instance, those with over 30% zinc are likely to have been made by speltering, those with less than 26% by cementation. (The chestnut warmer, T8922, with 30.5% is an exception but the iron and lead contents confirm what its date dictates — namely that this must be a cementation brass).

If the zinc, lead and iron are indicative of process, what of the tin content, and other trace elements which all seem lower in the high zinc brasses? A possible explanation is that this reflects the different sources of copper that were used at different periods. Until the late 18th century copper ore from Cornwall was smelted in Bristol itself (Day 1973). After that copper ore from a variety of sources, Anglesey, then Cornwall and latterly sources from all over the world, smelted at Swansea, supplied the Bristol brass makers (Barton 1978). Cornish copper was noted for its tin content and thus the regular and quite high tin content in the low-zinc alloys probably suggest a Cornish source for the metal. However, improved copper refining at Swansea in the early 19th century drastically reduced the tin content. Thus an ingot of copper smelted by the Rose Copper Company at Swansea in 1805 using Cornish ore was found to be free of tin at least down to 0.1%. (The ingot was recovered from the wreck of EIC vessel 'Britannia' and is now in the British Museum).

Thus the relatively high tin content **could** indicate copper smelted in Bristol from Cornish ore in the 18th century.

Summary

Analysis of the brasses reveals two compositional groups, one with high zinc (>30%) and low levels of iron, tin and lead, and the other group with less, but still substantial, zinc (<26%) and higher iron, tin and lead. The first group are likely to have been made by mixing copper and zinc metals, ie speltering, and the second group made by reacting copper with calcined zinc ore and coke in a closed crucible, ie cementation. Cementation brass seems to have been made in Bristol up to the 1830's (Day 1973) and speltering continued into this century. The high tin in the copper probably denotes a Cornish source. Cornish ore was smelted in Bristol only until the late 18th century. Copper smelted at Swansea from Cornish or other ore sources in the 19th century seems to have had much less tin, thus it is possible that in general the cementation brasses are of the late 18th century, whereas the high zinc brasses are after the 1830's. However, items from both groups could easily belong to the early 19th century. Perhaps all that can be said with any confidence is that the high zinc brasses (excluding the chestnut roaster) are unlikely to be pre-19th century and the cementation brasses are unlikely to be post-1830.

D Hook and P T Craddock

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Appendix III

Unfinished brass "shells" from the River Avon, Bath.

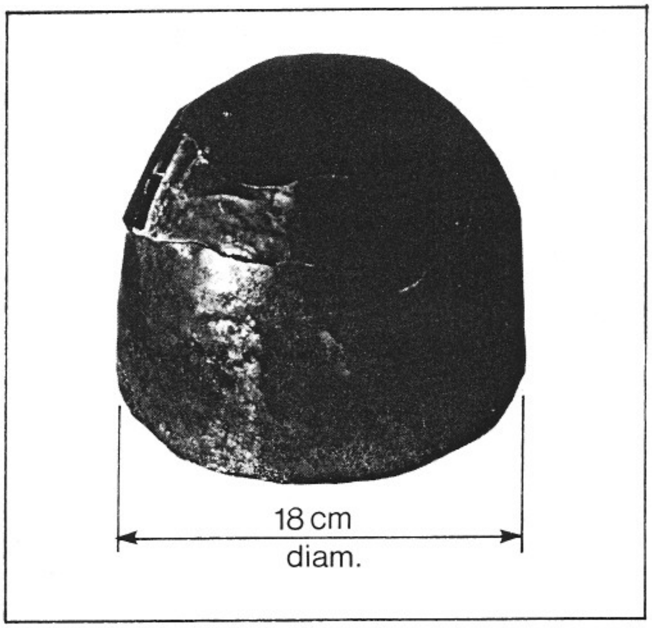

Fig. 1 *An upturned set of three damaged bowls, hammered together, as sometimes described in battery mill literature. These were recovered from the River Avon, down river of the Weston, Bath brass-mill site by Mr R Macy, formerly a river board man.*

A section was cut near a broken edge and mounted and polished in the usual way. When viewed after polishing and before etching it showed a large number of smaller cracks and some signs of the 2% lead (small black spots) *(Fig. 2).* Etching in ferric chloride showed the expected worked and annealed structure with bent twins and some slip bands near the surface. The hardness is only 112 HVI which indicates that it is not in a highly worked state. The grain size is large which shows that it had been worked only slightly before the last anneal, or had been annealed at too high a temperature. The metal is very clean, showing no signs of the sort of slag one finds in brass pins. The iron content must be low and the fact that it is not magnetic show that it must be less than 1%. I would put it much lower than this. (Craddock gives 0.06%).

If the zinc content is 30% then it is not in a highly cold-worked state which would have a hardness of at least 145 HV after only 30% reduction. Therefore it is clear that cracking was not caused by overworking. There remain three other possibilities:- fire-cracking, stress-corrosion cracking, or cracking in the river due to oxide penetration along grain boundaries. This latter is often called "jacking" and is due to the stresses caused by the volume increase of the metal under corrosion (Cu to Cu_2O etc.). Fire-cracking occurs when cold-worked brass is heated too rapidly annealing so that thermal stresses are imposed on those already present due to cold work; this is favoured by impurities such as lead.

In stress corrosion cracking the two most likely chemicals are ammonia from the stables and moist sulphur dioxide from the annealing furnaces. Before one can judge which is the most likely of the three possibilities one would like to know if there is any historical record which shows how common this sort of failure was. It would have occurred after cold working, before, or during annealing. Where were the shells left while they were waiting to be annealed?

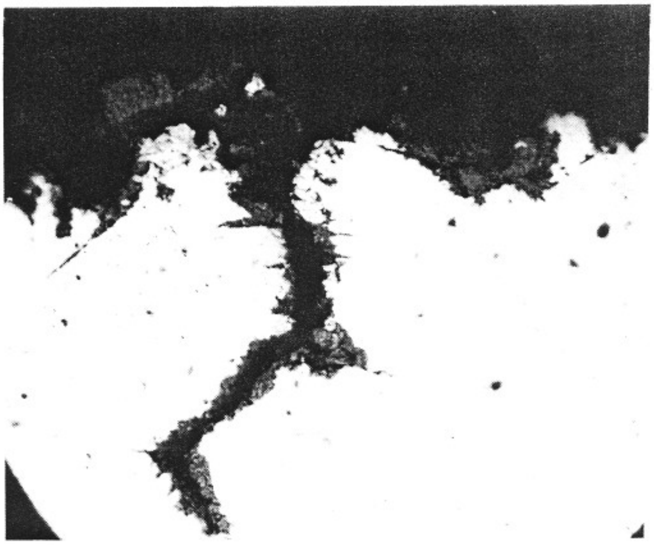

Fig. 2 *Fire-crack in brass bowl (unetched) x 400.*

I think that fire-cracking is the most likely explanation and will account best for the thick film down the crack shown in Fig. 2.

R F Tylecote

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