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THE DEVELOPMENT OF IRON SMELTING TECHNIQUES IN GREAT BRITAIN

INTRODUCTION

The knowledge of iron metallurgy reached Britain around about 500 B. C. due to the westward movement of Celtic tribes from central Europe. There is little evidence, however, that iron was much used during the next century and bronze was still the predominating metal.

Iron working on any noticeable scale did not begin in this country until after 200 B. C. Archaeological evidence for Early Iron Age iron smelting sites consists mainly of associated slag, charcoal and ore. Only very few furnaces have been found. One of the best preserved furnaces was excavated at Kestor, near Chagford in Devon [1]. It contained partially reduced ore and slag, and a mixture of charcoal and soil and measured 30—45 cm in diameter and 23 cm in depth, and appears to be a typical bowl hearth. There was a stone to one side which might have served as a rest for the bellows. About 60 cm away was another bowl hearth which did not contain any slag and which was probably used as a reheating or forging hearth. Nearby was a granite anvil and a broken hammer--stone. This site is not closely dated and could have been occupied any time afted 400 B. C. Similar remains of bowl hearths have been found in Merthyr Mawr Warren, Glamorgan [2], dated to about IVth to Ist century B. C.; at Chelm's Combe, Cheddar [3] (150 B. C. — A. D. 50. See Figure 1); and at Rudh' an Dunain cave in Skye, Scotland (Ist century B. C.).

Recently, G. Jobey, while excavating an Early Iron Age site dated

[1] *Cf.*: Lady Aileen F o x, "Transactions of Devon Association", LXXXIX, 1957, pp. 18—77.

[2] *Cf.*: Sir Cyril F o x, "Archaeologia Cambriensis", LXXXII, 1927, pp. 44—66.

[3] *Cf.*: T. K. P e n n i m a n, I. M. A l l e n and A. W o o t t o n, "Sibrium", IV, 1958—9, pp. 97—126. These remains can be seen in the Museum at Wells, Somerset.

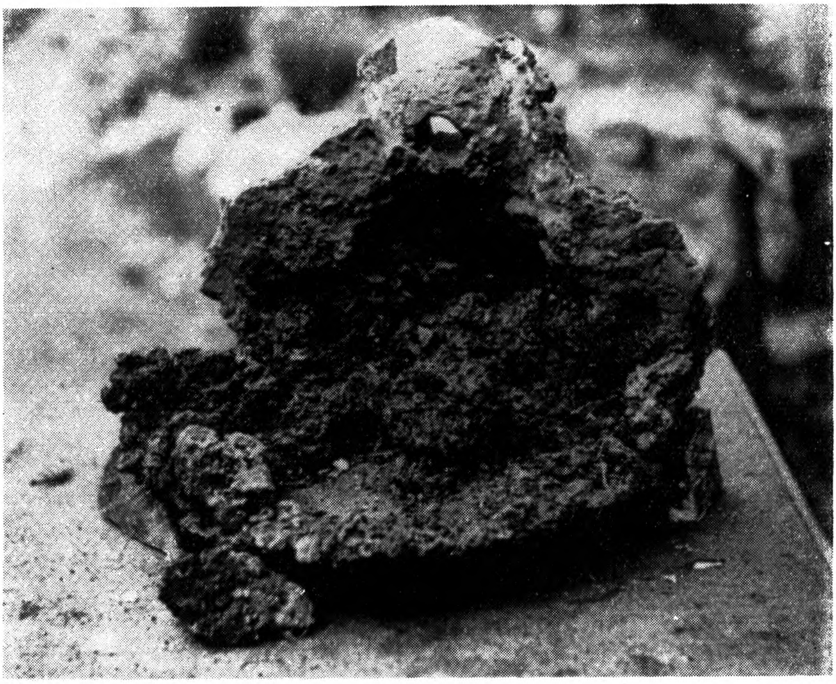

Photo Prof. M. J. O'Kelly

Fig. 1. Part of the lining and contents of a bowl furnace from Chelm's Combe, Somerset. 30 cm dia.

to between 300 and 100 B. C. at West Brandon, Durham, found the remains of two rock-cut bowl hearths [4]; one contained baked clay (from the superstructure) and prills of slag amongst the charcoal. The remains and a reconstruction are shown in Figure 2. The dimensions are similar to that found at Kestor. The reconstruction is based upon experimental work conducted on this type of furnace by E. J. Wynne in the Department of Metallurgy at Newcastle [5].

The results of excavations allow us to reach the following conclusions about the state of the iron industry before the Roman period. It was on a very small scale. The present size of slag-heaps is of the order of pounds rather than the hundreds of tons of the Roman period. The smelting furnaces seem to have been exclusively of bowl-hearth type of about 30 cm in diameter and 23 cm deep; they were either clay lined, rock-cut or built of stone slabs. Air was supplied by bellows inserted into a clay tuyere many of which have been found on various sites. The inner diameter of the holes in the tuyeres varies from 1 to 2 cm.

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[4] *Cf.*: G. Jobey, "Archaeologia Aeliana", XL, 1962, pp. 1—34.

[5] *Cf.*: E. J. Wynne and R. F. Tylecote, "Journal of the Iron and Steel Institute", CXC, 1958, pp. 339—348.

One feature of the more primitive furnace is to allow the slag to trickle into a space below the bloom (initially filled by charcoal) and there form an *Ofensau* or furnace bottom of solid slag. A number of these have been found which clearly derive from bowl-type furnaces. One very large undated piece found at Aylsham in Norfolk resembles the type of *Ofensau* found in Jutland and North Germany which is formed below a shaft furnace (Figure 3). This is, so far, the only British example of this type of product.

The exact size of the bloom produced by these early furnaces is not known but it cannot have been much more than a kilogram (Table I).

By the time of arrival of the Romans, iron working was widespread, if on a small scale. Soon the output was to increase considerably to satisfy the demands of the Roman military establishments. In some cases, as at Corstopitum, the authorities seem to have bought their material from the natives, since there is little evidence of smelting in the form of slag. But the presence of hammer scale in the workshops and forges shows that smiths worked the raw blooms into the implements required. Mining was in most cases by the open-cast method, as in the previous period. Only one case of the deep mining of iron is recorded, and this seems to be an exploratory working at Lydney, Glos. The ore was mainly obtained by surface working as in Somerset and the Forest of Dean, and by digging pits down to beds of nodular ore as at Ashwicken, Norfolk.

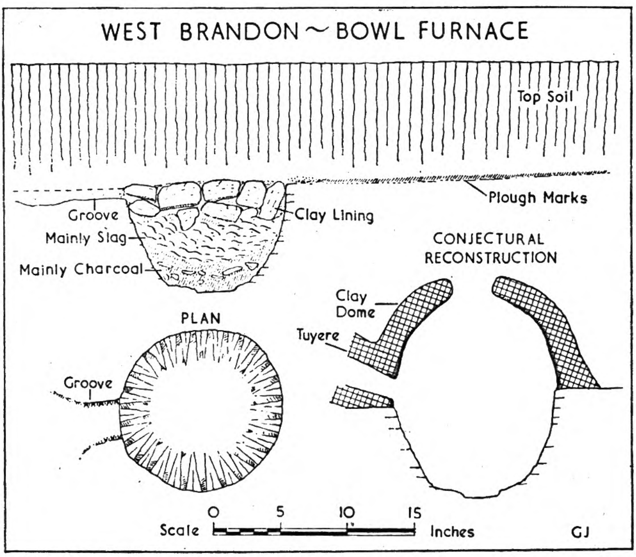

Fig. 2. Remains of West Brandon, Durham, bowl furnace. (Courtesy G. Jobey and "Archaeologia Aeliana")

Table I

Weights of individual iron blooms

Provenance	Date	Weight Kg	Bellows power
Swallowcliffe Down, Wiltshire	300—150 B.C.	0.23	Hand or foot
Ewell, Surrey	200 B.C.—150 A.D.	0.34	„
Wookey Hole, Somersetshire	150 B.C.—50 A.D.	2.05	„
Hengistbury Head, Hants	Ist cent. A.D. (?)	0.91	„
Forewood, Crowhurst Park, Sussex	E.I.A. — Roman	1.25	„
Nanny's Croft, Arundel	Roman	0.30	„
Corbridge, Northumberland	IIIrd—IVth cent. A.D.	6.80	„
Catterick, Yorkshire	Roman	7.70	„
Coed Newydd, Anglesey	Roman	3.60 *	„
Carrigmuirish, Ireland	500—1000 A.D.	3.60	„
Fermanagh, Northern Ireland	Medieval	5.50	„
Tudeley, Kent	*ca.* 1350 A.D.	13.60	„
Byrkeknott, Durham	1409	89.00	Water
Rievaulx, Yorkshire	1541	131.00	„
Pyreenees	XVIIIth century	80.00	„
Pyreenees	XIXth century	150.00	„

* Possibly welded.

The number of known Roman smelting sites from which to obtain information on details of technique is not yet large, but one important fact distinguishes Roman technique from the earlier process in which the slag remained at the bottom of the furnace. By the Roman period the slag was tapped from the furnace in a fluid state, as shown by evidence from Pickworth and Ashwicken.

Excavations carried out at the beginning of the present century yielded many remains of furnaces of this period, but these were very fragmentary and it was not possible to identify a Roman type.

The smelting furnaces excavated at Ashwicken in 1957/8 were shaft furnaces and may have been blown by induced draught [6]. Five of these

[6] *Cf.*: R. F. Tylecote and E. Owles, "Norfolk Archaeology", XXXII, 1960, pp. 142—162.

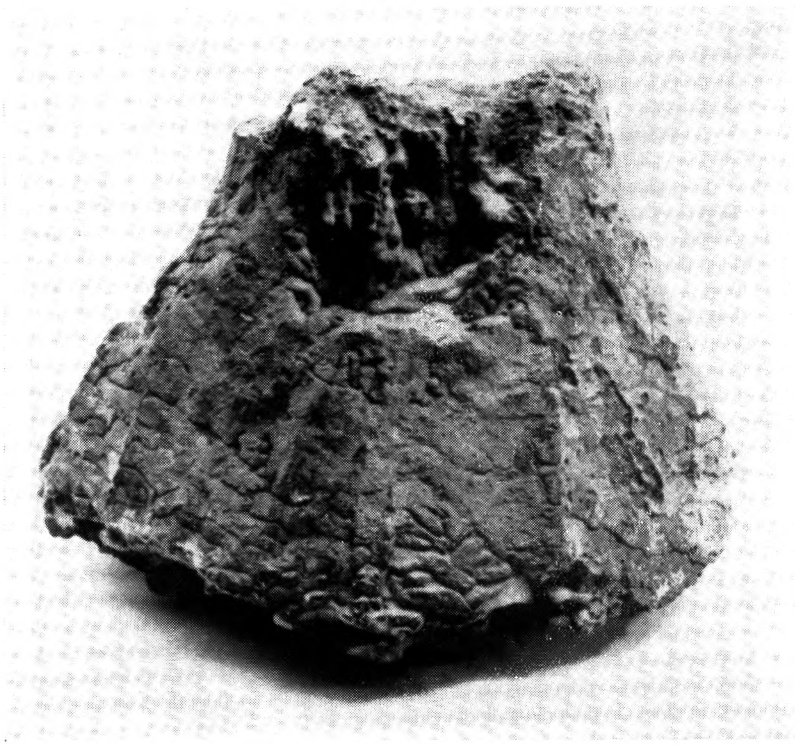

Fig. 3. Furnace-bottom from Aylsham, Norfolk. Max. dia 32 cm

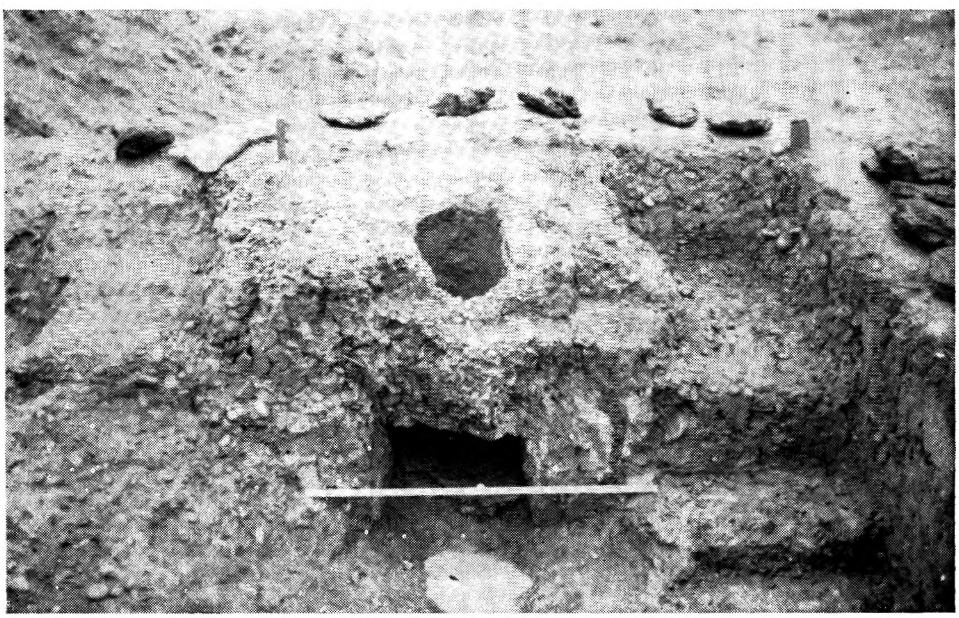

Fig. 4. Roman shaft furnace at Pickworth, Lincolnshire. Scale = 1 m. (Excavated by Ian Smith)

were found together, 30 cm in internal diameter and *ca.* 1.4 m high. The inner walls of the shaft were vertical, except near the bottom where they were slightly expanded. The slag was tapped, the bloom removed and the air drawn or blown in, all through one opening which formed

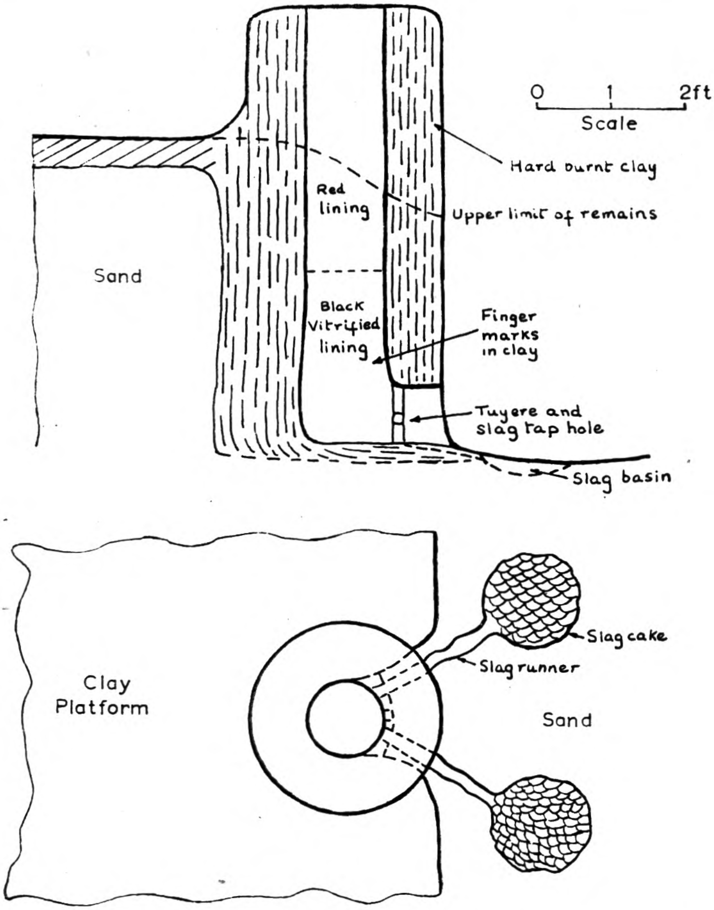

Fig. 5. Section and plan of Roman shaft furnace found at Ashwicken, Norfolk. (Courtesy "Norfolk Archaeology")

an arch at the bottom, having the full width of the furnace. A slag "runner" was found in position in one of the furnaces, showing that slag had been tapped a short distance away from centre of the furnace into the sand at a slightly lower level (Figure 5).

The original height of the furnace was probably 1.5—2 m. This would be sufficient to obtain a good draught through a 60 cm thick bed of charcoal and ore and permit the smoke to be blown clear of the pit in which the furnaces were built (Figure 5). The ore consisted entirely of partially oxidised carbonate nodules and measured about 5×2 cm; charcoal was of similar size. The ore was first roasted to remove the moisture and carbon-dioxide and make it easier to break into the required size. The furnaces found by Ian Smith at Pickworth, Lincolnshire, were exactly the same, as shown in Figure 4.

It was beginning to look as though the shaft furnace was the predominate Roman type when James Money, digging at Withyham in the Sussex Weald found a furnace which has Roman associations but which is of a type normally associated with the Saxo-Norman to medieval period in this country. What is more important is that it is the most complete of its kind with three tuyeres in place, and it may have had a fourth.

The furnace is placed at one end of a shallow pit about 3.5 m long and 1 m wide. It consists of thick clay lining which has clearly been built round a horse-shoe shaped framework of stakes probably woven with wattle like a basket. It would seem that the clay has been fired either from within the framework or from without (excavation at the time of writing is not yet complete). The three tuyeres are placed at 90° to each other and appear to have been inclined downwards. There are the remains of a clay front wall (see Figure 6), and a central slag tapping pit seems to have been provided in front of this. In vertical section the furnace would appear to be egg-shaped. It is important that the dating be confirmed and a radiocarbon dating is being done. It is possible that this will be supplemented by an archaeo-magnetic date, but it is desired to preserve the structure as much as possible.

The size of bloom produced by these furnaces seems to have been about 7 to 9 Kg. When it was desired to make larger pieces such as anvils and beams, many of these blooms were welded together in a large forging furnace. Figure 7 shows one of the beams found at Catterick, North Yorkshire, which probably supported the bronze water-boiler above the bath-house stoke hole. It is about 2 m long and must weigh over 230 Kg. The centre section has deteriorated somewhat due to long exposure to high temperatures under oxidising conditions.

There is no evidence that the more advanced techniques of the Romans were carried on in the Dark Age and Medieval period. It seems that the Saxon techniques started where the Early Iron Age people left off. Excavations in Ireland have revealed the remains of bowl type furnaces on almost all sites dated to between the VIth and the XIIIth centuries, which points to widespread local iron working. From Scotland we have evidence of a number of similar sites. In Wales few sites of this period have been examined, but the early Welsh Homesteads on Gelligaer Common [7] dated to the XIII—XIVth centuries contain evidence of iron working. In England there is little evidence of Dark Age iron working. Excavation in Saxo-Norman levels at Great Casterton, Rutland, produced tap slag.

[7] *Cf.:* Lady Aileen Fox, "Archaeologia Cambriensis", XCIV, 1939, pp. 163—199.

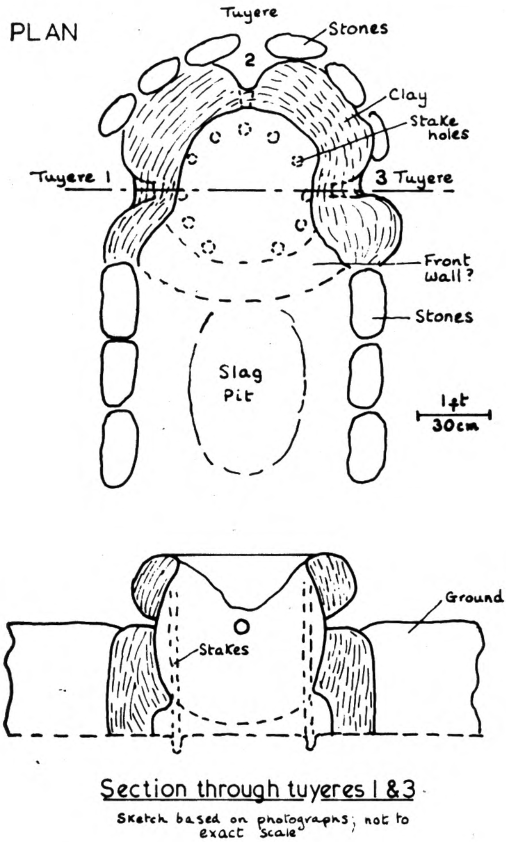

Fig. 6. Reconstruction of developed bowl furnace found at Withyham, Kent. (Based on remains excavated by J. H. Money)

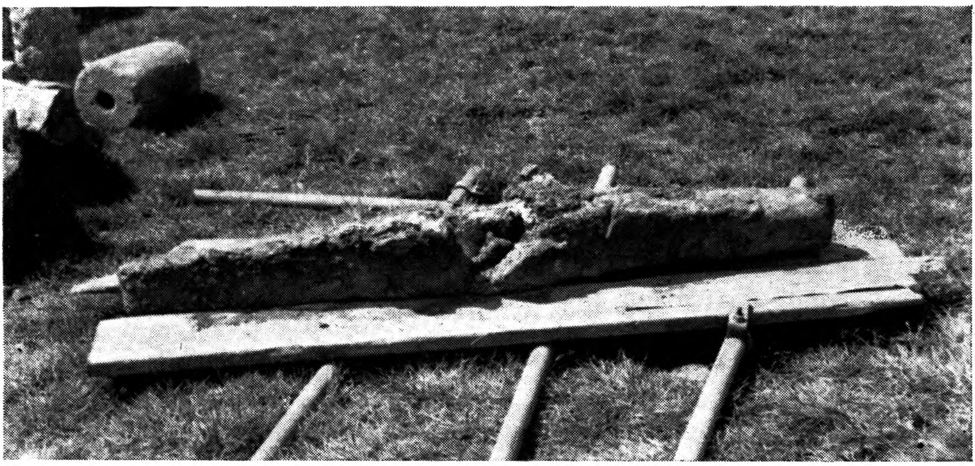

Fig. 7. Welded beam from Roman site at Catterick Bridge, Yorkshire, Length 2.7 m

Another site of this period, recently excavated by the author at West Runton near Cromer, produced quantities of tap slag, a roasting floor and the remains of a furnace together with masses of charcoal. Nodular ore had been used, which had been dug out of the great number of pits about 3 m in diameter and 2 m deep, which abound in the glacial sands of the area. A very similar site has been excavated by Alan Burchard at Stamford, Lincolnshire, and belongs to the same period. The furnace appears to be either a low shaft furnace or a bowl furnace, with slag tapping facilities. It has an internal diameter of only 20 cm and was probably blown from the side opposite that used for slag tapping. A roasting hearth was found nearby.

In the XIth century a considerable concentration of iron smelting is to be found in the river valleys in the south of England and the references to mills suggests that water-power was already in use in about 1086—88 A. D. when the Domesday accounts were compiled, almost cer-

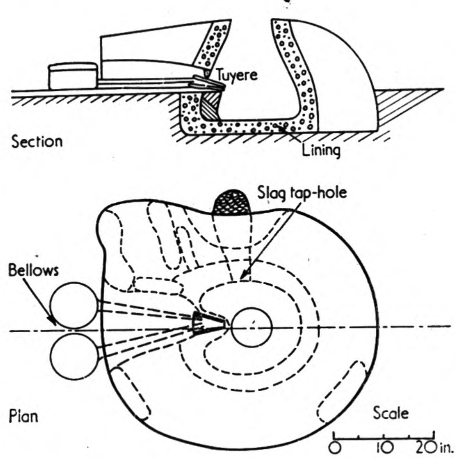

Fig. 8. Reconstruction of Early Medieval furnace at High Bishopley, Durham

tainly for driving the bellows since mechanical hammers did not come into use until about the XVth century. The bloomeries at Pucklechurch near Bristol probably had an output of 900 blooms, as they rendered 90 blooms *per annum*. Each of these would weigh about 14 Kg. This would make it one of the largest iron making areas of Norman Britain, with an output of about 12 tons *per annum*.

A XIIIth century site excavated at High Bishopley [8], Durham, revealed two bowl hearths from which slag was tapped, and the lower part of a kidney-shaped furnace with a well-vitrified clay lining. A suggested reconstruction (Figure 8) gives a low domed furnace of Engsbachtal

[8] *Cf.*: R. F. Tylecote, "Journal of the Iron and Steel Institute", CXCII, 1959, pp. 26—34.

type, blown with a forced draught. This type is well-known in the Siegerland in La Tène times and was used by Anglo-Saxon peoples in North Germany. But, like all enclosed furnaces for smelting iron, it had the disadvantage of making the extraction of the bloom difficult and it gave way to the Catalan hearth-type furnace used exclusively in Britain for the later Medieval bloomeries.

Another bloomery site of the XIIIth century was excavated by Alan Aberg in Baysdale, North Yorkshire, in summer 1964. At least four hearths were uncovered; these were built of clay and stone, and were of Catalan type with hand-blown bellows and slag-tapping facilities. They are of the same type as found in Glaisdale, further south. The latter consisted of partly rock-cut, partly stone-lined, hollow about 2×1 m. The hearth was at one end and had its slaggy accretion still *in situ*. The slag was tapped into a hollow in front of the hearth. These are precisely the same type as that found by Money at Withyham where they are believed to be Roman.

An account roll relating to a manual or foot powered bloomery at Tudeley, Kent, working the Wealden deposits, relates to the periods 1329—34 and 1350—54, i. e. before and after the Black Death [9]. This site is the best documented of the pre-water power period, but unfortunately no remains have been found. The resulting shortage of labour which followed the Black Death undoubtedly assisted the move to exploit the sources of water power which had already begun in the earlier period. A detailed account, covering one year, of a bloomery in Weardale, Durham, using water power, has been left to us in an account roll of 1409 [10].

This begins the large scale working of iron. The bloom size had now grown from 5 Kg to 100 Kg (Table I) and, if the process had been allowed to develop in this country, by the XVIIIth century we would no doubt have reached the 150 Kg bloom of the Catalan forges in the Pyreenees.

However this development was terminated by the introduction of the blast furnace from the Continent in about 1500. In all but the more inaccessible areas, the bloomeries were converted into fineries for the conversion of cast iron to wrought iron. Only in places like the Lake District do we find new bloomeries being commisioned after this date.

THE COMPOSITION OF DIRECT SMELTING SLAGS AND RESIDUES

Very many more analyses have been carried out on slags and cinders (partially reduced ore) than on metal. One reason for this is that slags survive in good condition with less chemical alteration than the metal

[9] *Cf.*: M. S. Guiseppi, "Archaeologia", LXIV, 1912, pp. 145—164.

[10] *Cf.*: R. A. Mott, "Journal of the Iron and Steel Institute", CXCVIII, 1961, pp. 149—161.

itself. We do know, however, that some cinders have weathered to some extent and show signs of hydrated iron oxides which were not there originally. Also, we must be on our guard for the possibility of alkalis being leached out. Whereas this has little importance chemically, it will have the effect of raising the free-running temperature.

In slags and cinders of Roman date, only one determination of the alkali content has been made — in the slag found in the beam from Corbridge. In this case it is unlikely that the alkali has been leached out as the slag was well surrounded by iron. The figure obtained, 0.278%, therefore seems a valid one. (Some recent figures show as much as 1.7%).

A slag from Bryn Gefeiliau, near Cricceith, Caernarvonshire, was found to contain 14.5% of zinc, probably in the form of oxide. This is unusual, and the fact that it did not contain either copper or lead shows conclusively that it is not the product of smelting for either of these two metals. It is clear from the size of the site that it is an iron smelting site in which iron ores containing appreciable quantities of zinc have been used. Some of this would be volatilised in the course of smelting, and the rest has gone into the slag, no doubt helping to lower its free-running temperature.

With this exception, the composition of Roman slags is normal and is very much the same as those from pre-Roman times and medieval times.

There are some conclusions we can reach, however. First, the lime content is uniformly low, in no case exceeding 3.7%. Since such low values could easily come from the ore, we see that no attempt has been made to add additional lime as a flux.

The phosphorus pentoxide content of the slags from undisputedly Roman sites, with two exceptions, is within the limits 0.1 — 0.9% (Figure 9). The exceptions, 1.72 and 2.27%, come from Templebrough and Ashwicken. The latter seems to have used nodular ore exclusively and the former at least partly. The available evidence does not allow us to state that by the Roman period ores lower in phosphorus were being used, since we have too little pre-Roman material.

But the evidence of the iron produced does show that the irons themselves contained less phosphorus. We can therefore conclude that better ores have been sought and used or that some change in the process has altered the phosphorus partition coefficient. At Camerton, metal and slag were analysed and we appear to have a metal/slag partition coefficient of the order $\frac{0.05}{0.20}$ = *ca.* 0.25 or 1/4; taking the further example of the Corbridge beam, we find the coefficient is $\frac{0.04}{0.078}$ = *ca.* 0.5. So, with this slight evidence we can expect to find that the phosphorus content of the metal is about 1/2 to 1/4 that of the slag.

It would appear that where there was no choice of ore, as at

Ashwicken, high phosphorus ores were smelted, resulting in metal with high phosphorus content. Where there was a choice as in most parts of the country, Roman period smelters seem to be more discriminating than earlier people and have selected the better ores.

In all cases the true tap-slags have high iron oxide contents of the order of 70%, and low silica contents of 10—20%. In some cases a good deal of lining has gone into the slag, as in two examples from Wilderspool, one from Chichester and another from Camerton. The cinders should have undergone little change and therefore be very close in composition to that of the roasted ores. The presence of Fe_2O_3 shows

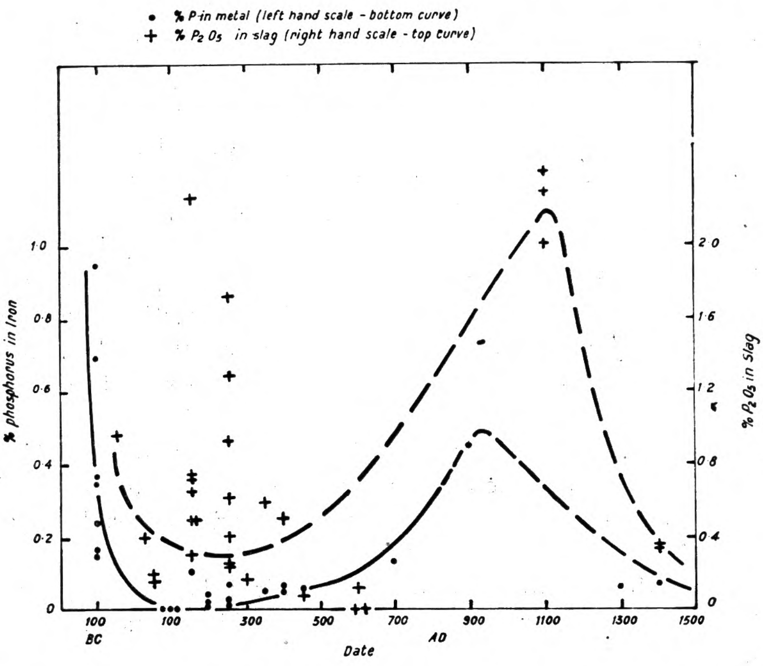

Fig. 9. Variation in phosphorus content of slag (top) and metal (bottom)

that the slag contains a proportion of the magnetic oxide of iron. This is a normal characteristic of slags and the proportion of Fe_2O_3 varies between 7 and 25%. To some extent this signifies the degree of reducibility within the furnace — highly reducing conditions giving lower Fe_2O_3 contents. However, these conditions change from time to time during the smelt, and it is possible to obtain a large range of values from one smelt. There is therefore little significance to be attached to the FeO/Fe_2O_3 ratio.

The other product which sometimes resembles slags and cinders is hammer scale. This material forms during heating under oxidising conditions prior to forging and during the forging process itself. It consists, while adherent to the metal of ferrous oxide (FeO) and magnetite (Fe_3O_4) in varying proportions. On its removal from the metal during hammering or upon quenching in water it may oxidise to a higher state, i. e. FeO may go to magnetite, and magnetite to ferric oxide, Fe_2O_3. Furthermore, changes may take place in these thin scales after deposition in the ground. These scales have a well marked granular structure, and by this structure they can be identified, as it is quite distinct from forge cinder or smelting slag.

Two examples have come to the author's notice:

a) the first one is a magnetic hammer scale from the IInd century site at Ashwicken; is contains 85.8% of Fe_3O_4, and the structure consists essentially of grains of magnetite cemented together with fayalite; this was found loose in pockets in the ground and it is clear that it has not changed very much from the state in which it was deposited;

b) the other specimen came from the IInd century site at Huckhoe, Northumberland, and was found as a deposit in the rock-cut hearth which was definitely used for smithing and also probably smelting; here, the material is mainly ferric oxide, also cemented with fayalite but now non-magnetic.

When scale is shed from iron during reheating, and taken up to a temperature of the order of 1200°C, its characteristic structure is lost and it becomes difficult to distinguish from a smelting slag. Such slags were found at Huckhoe, causing doubt as to the exact function of the hearth.

Sweepings from the floor of the forge at Benwell fort, Newcastle, were examined, and found to be mostly granular but uncemented pieces of magnetite. A small amount was cemented and appeared very similar to that from Ashwicken.

The silica in the fayalite cementing films in this material comes from the slag in the metal and possibly from sand used as flux in the smithing operation.

The metal composition shows substantial variations in phosphorus content only. The amounts of the other elements have remained constant due to the fact that the only fuel used throughout the period has been charcoal and, apart from phosphorus and trace elements, the composition of the ores used is not reflected in the metal.

Figure 9 shows the change in phosphorus content. While the number of metal specimens that have been analysed is small, the high figure for phosphorus in the Saxo-Norman period is borne out by the values for phosphorus in the slags. Indeed, there is a good correlation between phosphorus in slag and metal. We can conclude, therefore, that the use of high phosphorus ores was fairly general in the pre-Roman Iron Age and that a different type of ore was in common use during the Roman period, although there are notable exceptions. There was a general tendency for the use of high phosphorus ores to increase in the Dark Age — Early Medieval period to be followed by a search for ores containing lower phosphorus in the Later Medieval period. This may have been due to the use of nodular Coal Measure iron ores which seem to have lower phosphorus contents than their Lower Greensand and Wealden counterparts.

INTRODUCTION OF THE BLAST FURNACE

The blast furnace was introduced from abroad because it had evolved from a type of bloomery furnace which had not been used in Britain since the Roman period. The shaft furnace of the Ashwicken type died out here, but in Central Europe and Scandinavia it persisted in spite of its disadvantages. By the XVIIIth century the Swedish Osmund furnace had a height of 1.8—3 m while the *Stückofen* or high bloomery furnace of Austria had reached a heigh of 5 m by the XIXth century [11].

As far as Britain is concerned, the first blast furnace definitely known to be in existence was at Newbridge, Sussex, at the end of 1496 [12]. This appears to have received the encouragement of the Crown, for in 1496, Henry VII commissioned Henry Fyner to engage in the production of iron ordnance for the war against Scotland. The name, Fyner, is interesting, since fining is the term used for the process of converting cast iron to wrought iron in use at this time, and it suggests that the process of fining, and hence iron casting, must have been carried on for a short time at least before 1496.

Table II

Early blast furnace yields

Furnace	Date A. D.	1 kg Fe/100 kg ore (as mined)	Probable 1 kg Fe/100 kg Fe in ore
Newbridge(Suss.)	1548	12	27
Newbridge (Suss.)	1674	33	74
Frith (Suss.)	1648	41	92
Heathfield (Suss.)	1738	27	60
Hales (Worcs.)	*ca.* 1700	29	65

According to Schubert, the first gun in English history definitely known to be of cast iron was manufactured at Newbridge in 1509 [13]. We know that many of those responsible for the production of iron ordnance had French, Dutch (or German) and Belgian names, and it is not un-

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[11] *Cf.*: J. Percy, *Metallurgy; Iron and Steel.* London 1864, p. 310.

[12] *Cf.*: H. R. Schubert, *History of the British Iron and Steel Industry.* London 1957.

[13] Compare the same book as cited in footnote 12.

reasonable to suppose that the technique was introduced from this area of the Continent.

Typical figures for the yield of the blast furnace process, which have been taken from Schubert [14], are given in Table II. It is clear that by the middle of the XVIIth century is was possible to achieve a true yield of 92%, which may be compared with a bloomery yield of 55% at about the same period. The figure of 92% was not, however, universal but it is probable that the variation was mainly due to the working of different types of ores.

FURNACE CONSTRUCTION AND PROFILE

The earliest furnaces seem to have had the type of profile shown in Figure 11 (No. 1). In fact, neither picture nor description of any British furnace are preserved from the period up to 1600. After this we have sufficient details to enable us to build up a fairly accurate picture. There are about 20 furnaces in existence covering the period 1650—1800, and so we can discuss this period from actual evidence.

The British furnace up to about 1600 was stone-built with square or pyramidal shaft and stone lined. The hearth and bosh form, shown in Figure 11 (No. 1), was soon amended, since the stone lining between the crucible (or hearth) and the bosh quickly wore away. The next amendment was to use a circular crucible, and the furnace at Coed Ithel, Monmouthshire (1651—1796), which was recently excavated shows the result of this second amendment (Figure 10).

The problem now was the junction between the circular crucible-cum-bosh and the pyramidal shaft. A satisfactory join between these two was no easy matter as the example of Coed Ithel shows. Other furnaces of this period have lost their hearths, but it would seem that the normal bosh angle was about 77°. Coed Ithel shows evidence of the junction of bosh and inwall having been raised to a line half way up the furnace. This may seem unusual and it was not the case at Rockley (1652) where the bosh ceased only 3.3 m up the furnace. Although the hearth is missing, all the indications go to show that here the hearth was of the earlier type shown in Figure 11 (No. 1).

Careful selection went into the hearth material which was a very pure siliceous sandstone in large blocks up to 13 cm thick. By contrast the shaft lining was made of smaller material, not exceeding 7 cm thick, and of a less refractory stone.

The furnace body proper was usually made of carefully dressed blocks of the local stone. To economise, the space between the inner and outer faces of dressed stone was filled with mortared rubble, leaving

[14] *Cf.* footnotes 12 and 13.

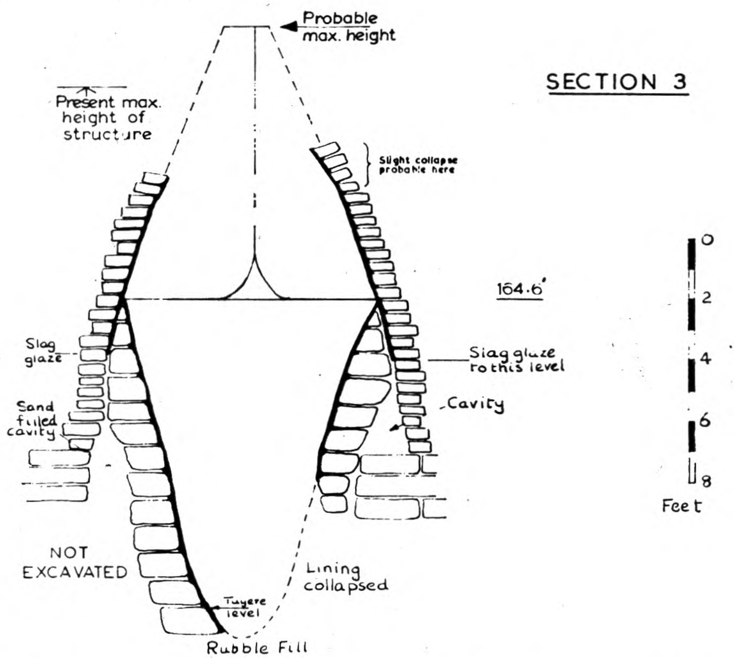

Fig. 10. Section of blast furnace at Coed Ithel, Monmouthshire (probably about 1650)

a cavity between the inner face and the lining which was filled with sand or crushed red brick.

The importance of proper ventilation was realised quite early and this was achieved at Melbourne by providing a space under the hearth and horizontal ventilating channels with vertical connections in the furnace body itself.

The early (1636) representation of a furnace on a fireback from Sussex shows a timber reinforcement on the outside of the furnace, binding it together. Later however, this seems to have been omitted or replaced by an iron framework built into the rubble core, as at Low Mill.

The earliest furnaces had the minimum number of bottom openings, i. e. one for blowing and the other for tapping. In most furnaces these were supported by cast iron lintel beams as shown in Figure 12. However, some furnaces such as Low Mill and Duddon (1736) had arched openings. The exterior of Duddon was built of dry stone, although the lining — of brick — is more recent. Low Mill, which has three openings, was built in about 1761 and has an interior firebrick lining. In this latter it has much in common with Maryport, which was built in 1752, and it would seem that firebrick for lining came into use round about this time. Older furnaces would often be relined after this with firebrick. The circular shaft also came in at this time.

While the circular inwalls and brick linings seem to be universal after 1750, the number of openings certainly was not by any means settled. While Low Mill (1761), has three, Chesterton, not built until 1790, and certainly designed for steam-blowing, has only two. It would appear that some designers built three openings automatically, either for symmetry or because the possibility of steam-blowing through multiple tuyeres was in their minds.

Both the furnaces built in the period 1750 and 1760, Low Mill and Maryport, had one thing in common, the steep sided bosh-cum-crucible. It seems that this design had become the norm, although there may be a certain amount of speculation about this as so many furnaces have lost their hearths.

Tuyeres were usually made of two or more semi-circular pieces of sandstone, shaped to a cone on the inside (see Figure 13 — Melbourne). They were not inclined — all we have are clearly horizontal.

Steam-blowing was being considered in the second half of the XVIIIth century, but the first move was away from the expensive leather bellows to the cast iron blowing cylinders of Wilkinson. Maryport, always in difficulties with its water, changed over to more efficient iron bellows in 1777, but does not seem to have had the sense (or capital?) to go in for

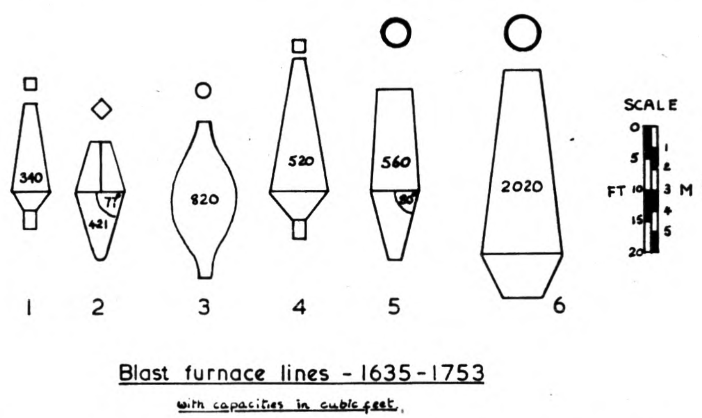

Fig. 11. Lines of blast furnaces, 1635—1761: 1) Park End, 1635; 2) Coed Ithel, 1652; 3) Forest of Dean, 1711; 4) Lamberhurst, Kent, 1695; 5) Low Mill, Yorkshire, 1761; 6) Maryport, 1753

steam-blowing. Since the earliest experience with steam was for pumping, it is not surprising that iron-masters with water supply problems should first apply steam to pumping water back from a pond below the wheel to the mill-pond above, as A. Derby did in 1742. The first application of steam to blast furnace blowing was at Brosely in Staffordshire in 1776.

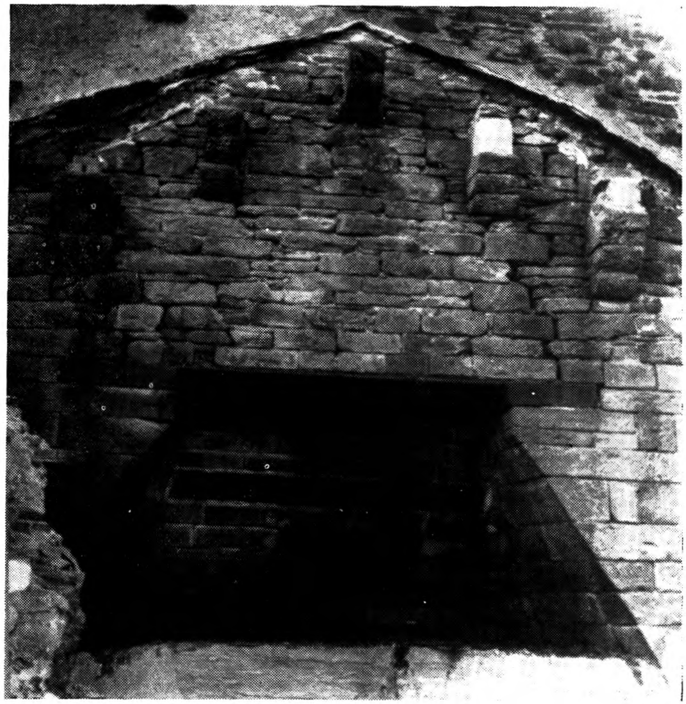

Fig. 12. Cast iron lintel beams over tapping opening at Maryport (1753—1783)

Fig. 13. Tuyere of furnace at Melbourne, Derbyshire (1725—1780)

The increase in furnace size is shown in Figure 11. Since Maryport turns out to be the largest furnace of the mid-XVIIIth century it is not surprising that it suffered chronically from insufficient blast, a problem that was to lead to it being closed down in 1783, having probably had the shortest life of any English blast furnace of this period.

In conclusion we can say that the average English blast furnace at the end of the XVIIIth century, consisted of a square stone carcass with a fire-brick lining (Table III). The inside was circular with a steep bosh. It was supplied with air through a single tuyere. Rapid developments were taking place regarding fuel and steam for blowing.

CHARGING AND SLAGGING PRACTICE

Ores available for iron-making very widely in Britain from the high grade hematites of Cumberland to the limonites of South Wales and the Forest of Dean and the lower grade bedded carbonates of Northants and Lincolnshire. The first furnaces, in the Weald, must have used the nodular carbonate ores available in that region, and when the move to the coalfields took place in the XVIIIth century this became the most widely used type of ore.

The first furnaces were charged with a mixture of half bloomery slag and half ore. In these cases there is no mention of limestone and it is clear that some of the iron was extracted from the low melting point fayalitic bloomery slags, converting them to more acid slags with a higher melting point. We have no analyses of slag which can be dated with certainty to the XVIth century, but analyses of slags from XVIIth—XVIIIth century furnaces show that these used only relatively small additions of lime (Table IV).

The furnace at Ambergate clearly used no lime additions and relied upon the Al_2O_3 content of the ore. This is probably true of Maryport also. On the other hand small additions of lime were being made at Rievaulx, Duddon and Melbourne, although the slag from Duddon may be XIXth century. Large lime additions did not come into British practice until the late XIXth century.

As pointed out in the third section the slag volume was now much reduced, and the low iron content (2—9%) of the slags did not represent a great loss.

The attempts to use coal and coke instead of charcoal belong to the XVIIIth century. Success was first achieved by A. Derby in Coalbrookdale, and the Ambergate slag shown in Table IV is a product of coal or coke smelting, as fragments of coke were found within the slag. The low sulphur content shows careful selection and it was the knowledge of low sulphur coals which Derby had gained from his early experience in the malt industry (he was apprenticed to a malt-mill maker) that

Table III

Details of XVIIth — XVIIIth Century Furnace Remains

<table>
<tr><th>Date</th><th>Date built</th><th>Date last worked</th><th>Inwall</th><th>Hearth</th><th>Bosh</th><th>Tuyere holes</th><th>Blowing apparatus</th><th>Fuel</th><th>Output tons/week</th><th>Capacity cub. m</th></tr>
<tr><td>Rockley</td><td>1652</td><td>after 1736</td><td>stone square</td><td colspan="2">? square</td><td>1 (+ 1 later)</td><td>water/ /bellows</td><td>charcoal</td><td></td><td></td></tr>
<tr><td>Coed Ithel</td><td>1651 (?)</td><td>1796 (?)</td><td>stone square</td><td colspan="2">stone circular</td><td>1</td><td>water/ /bellows</td><td>charcoal</td><td></td><td>11,9</td></tr>
<tr><td>Sharpley</td><td>1652</td><td></td><td></td><td>stone circular</td><td>stone circular</td><td>1</td><td>water/ /bellows</td><td>charcoal</td><td></td><td></td></tr>
<tr><td>Gunn's Mill</td><td>1683</td><td></td><td>stone square</td><td></td><td></td><td>1</td><td>water/ /bellows</td><td>eharcoal</td><td></td><td></td></tr>
<tr><td>Melbourne</td><td>1725</td><td>ca. 1780</td><td></td><td>stone square</td><td>stone square</td><td>1</td><td>water/ /bellows</td><td>charcoal</td><td></td><td></td></tr>
<tr><td>Duddon</td><td>1736</td><td>ca. 1866</td><td>brick circular</td><td></td><td></td><td>1</td><td>water/ /bellows/ /cylinder</td><td>charcoal</td><td></td><td></td></tr>
<tr><td>Maryport *</td><td>after 1752</td><td>1783</td><td>brick circular</td><td colspan="2">circular</td><td>1</td><td>water/ /bellows/ /cylinder</td><td>coke</td><td></td><td>57,1</td></tr>
<tr><td>Bonawe</td><td>1753</td><td>1874</td><td>stone circular</td><td></td><td></td><td>1</td><td>water/ /bellows</td><td>charcoal</td><td></td><td></td></tr>
<tr><td>Loch Fyne</td><td>1753</td><td>1813</td><td>circular</td><td></td><td></td><td>1</td><td>water/ /bellows</td><td>charcoal</td><td></td><td></td></tr>
</table>

Dovey	1755		circular			1	water/ /bellows	charcoal		
Low Mill	1761		brick circular	circular		2	water/ /bellows	charcoal		15,9
Ambergate	1764		circular	circular		?	water/?	coal/coke		
Brymbo	1798		circular			1	steam	char+coke	30	
Morley Park	1780	1874	circular			2	steam	coke	13	
Chesterton	1783 (?)	before 1870	brick circular			1	steam	?		
Charlcott		after 1825				2	water/?	charcoal	7	
Brecon	1720					1	water/?	charcoal		
Whitecliffe	after 1798	1810	brick circular			2	steam			
Llanelly	1795	1815	circular			1	steam			

* Demolished in 1963.

Table IV

Blast furnace slag analyses (%)

	Melbourne 1725—*ca.* 1780	Duddon 1736—*ca.*1866	Rievaulx 1577—1647	Rockley 1652—1736	Ambergate 1764—?	Maryport 1753—1783	Low Mill 1761—?	Cannock 1563—?
SiO_2	41.6	56.4	45.3	45.9	53.7	64.5	57.8	49.7
Al_2O_3	22.7	12.4	22.5	19.1	36.6	4.0	18.6	23.2
Fe_2O_3	2.6	FeO(2.6)	3.7	2.4	8.2	(FeO)12.0	(FeO)16.2	(FeO)4.37
CaO	14.1	14.6	22.8	18.4	1.0	5.0	0.7	11.9
MgO	14.2	3.6	3.7	9.2	0.30	3.3	—	7.2
P_2O_5	0.023	—	0.055	0.5	0.09	—	—	0.07
S(Sulphide)	0.117	—	0.032	0.10	0.01	0.9	—	0.1
S(Sulphate)	0.11	—	0.19	0.058	0.024		—	
MnO	3.01	9.8	1.17	2.95	0.09	5.3	(TiO_2)1.2	3.3
Total Fe	1.80	2.0	2.60	1.70	5.70	9.3	12.6	3.4
Alkali	—	—	—	—	—	—	2.7	—

enabled him to be finally successful. The following figures show the sulphur contents of some British coals and especially that of the Shropshire coal that Derby used.

Coals

	%S	%P
Shropshire (Coalmoor)	0.52	0.016
Forest of Dean (Coleford)	1.48	—
Bristol (Parkfield)	2.07	—

Maryport furnace was probably designed for use with coke, and certainly so used. It was the largest furnace of its period (11 m to charging floor). The sulphur content of the slag is 0.9, and that of the iron 0.073%. Thus showing very satisfactory elimination which was no doubt assisted by the high FeO content of the slag.

The composition of the cast irons themselves is given in Table V. Early irons had a tendency towards low Si and were therefore nearly white. This would not have mattered much if they were destined for the forge — as indeed was much early blast furnace iron.

However the low sulphur and high carbon contents of the charcoal irons ensured that the iron generally solidified as a grey iron, as for example in the case of the Sussex fireback. The other irons, although cold blast irons, had high silica content, which in spite of their much reduced carbon content, ensured a grey iron. The reason for the higher silica contents of the XVIIIth century Cumbrian irons no doubt lies in their rather acid slags.

According to Jars[15], who visited Clifton furnace in 1765, the coking was carried in heaps just like charcoal burning. The heaps were 4 m diameter × 1.5 m in height, covered with straw, earth and coal dust. But at Maryport the coke was made in ovens, parts of which still remain today. In either case, the resulting sulphur content must have been very low. However, Jars mentions that the Clifton iron did not make good wrought iron.

BLOWING, BLAST HEATING, AND ANCILLARIES

The cost of maintenance of the enormous leather bellows was tremendous. These reached a length of 5.5 m in the Forest of Dean by 1711, and probably had a length of 7.3 m by the latter end of the XVIIIth century. They were supplying air at a rate of 5,100 l/min., sufficient for a production of 10 tons/week. The first use of the Newcomen steam engine was to pump water back into an upper pond from a lower pond

[15] *Cf.*: G. Jars, *Voyages Métallurgiques.* Lyon 1774, vol. 1, pp. 235—237.

Table V

Analyses of cast irons (%)

	Sussex Fireback XVIIth cent. Cha coal	Sharpley Pool. 1652 Cha coal	Duddon Bridge 1736—*ca.* 1866 Charcoal	Nibthwaite ?XVIIIth cent. Charcoal	Maryport 1753—1783 Coke (a)	Maryport 1753—1783 Coke (b)	Barepot XVIIIth cent. Coke	Clifton XVIIIth cent. Coke
Com.	0.32	3.9 (Com. + Graph.)	1.65	3.73 (Com. + Graph.)	2.72 (Com. + Graph.)	0.48	1.24	0.48
Graph.	2.89		2.65			2.12	1.56	2.73
Si	0.62	0.49	0.65	0.85	2.49	3.26	2.10	1.54
Mn	0.77	0.05	0.10	0.05	1.10	0.40	2.45	0.71
S	0.082	0.068	0.023	0.029	0.073	0.12	0.15	0.16
P	0.56	0.31	0.124	0.11	0.22	0.06	0.36	0.37

(1734) then direct on to the wheel. The average annual purchase of leather at Coalbrookdale was over 225 kg in the years 1741—48.

Cylinder blowers, either water wheel or steam operated, seem to have been introduced in about 1776. In this year Wilkinson introduced his cylinder blower, powered by a Boulton and Watt engine, at the Willey furnace at Brosely, Staffs. Cylinder blowers with a water wheel were installed at Maryport in 1777; these were capable of output of 85,000 l/min. It is doubtful whether enough water was available to operate them at their maximum capacity but it shows the sort of increase that was available. Presumably this quantity of air was available from the blowing engine which was designed in 1793 for the Hollins Wood furnace. This enabled the output to be increased to about 50 tons/week. By the end of the century it had reached 70 tons/week. Morton concludes that with the increased blast pressure produced by the cylinder bellows it was possible to smelt with coal before the advent of blast heating.

In 1828 Neilson was granted his patent for the use of the hot blast. Originally he intended to use blast furnace gas for heating a stove placed on top. But this was found to be too complicated and blast heating was carried out at ground level using various types of pipe stoves with independent heating by coal. The heating of the blast decreased the fuel/iron ratio enormously as the figures for the Clyde ironworks show:

1829	Cold Blast		Coke	8	tons coal / 1 ton Fe
1830	Hot Blast	(150°C)	Coke	5	tons coal / 1 ton Fe
1833	Hot Blast	(320°C)	Coal	2½	tons coal / 1 ton Fe

Of course, these figures do not take into account the raw coal used in the blast stoves.

So far nothing has been said about ore roasting. It it well known that pre-roasting of ore has been carried out from the Roman period, and roasting hearths were found on the Saxo-Norman smelting sites excavated at West Runton and Stamford in 1964. In the intervening period not much is said about this question, but in the late XVII century we begin to find large kilns like lime-kilns by the side of the furnaces, which have certainly been used for roasting. The use of carbonate nodules from the coal measures made roasting very desirable for two reasons, that of removing carbon-dioxide and thereby making the iron more reducible, and secondly, making it more friable and therefore more easily broken up to a consistent size.

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I would like also to acknowledge the help of the many who have assisted with the excavations, lent photographs and provided information. This paper is very much the result of co-operative work, which in many cases is still continuing. It will therefore be appreciated that the conclusions are to a great extent very tentative.