The performance of Abraham Darby I's coke furnace revisited, part 2: output and efficiency

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ABSTRACT: There were specific physical and chemical reasons why early coke furnaces underperformed their charcoal competitors in both fuel usage and output, but they do not fully explain why Abraham Darby I's furnace performed as poorly as earlier commentators or the company's books of accounts have suggested. It is proposed that Darby's potential output was twice as high as was actually achieved and his potential coke usage per ton of iron significantly less than has been reported. The difference was because Darby worked under new operational disadvantages in his foundry-orientated business compared to a blast furnace producing pig iron for the forge. He had to spend longer getting his metal out of the furnace because he was filling foundry moulds, rather than casting large pigs, he frequently held his furnace hot whilst waiting for the furnace pool to fill up again and he was deliberately making a higher silicon-content iron.

Introduction

In a companion paper (Williams 2017) it was argued that in the 18th and early 19th centuries, charcoal furnaces produced grey iron, rather than the more-required white, sometimes deliberately, sometimes simply because of the materials that they had to hand. The silicon content of the iron and its consequent tendency to greyness was decided by the thermodynamic activity of the silica in the ore and by the length of time the charge was in the furnace stack, which was in turn a function of the ratio of charcoal to ore used. This applied equally to a coke fuelled furnace, but the density of coke naturally led to a longer dwell time and, additionally, the state of the silica in the ash from the coke, not present in charcoal, was conducive to its ready reduction. This latter feature made the production of a grey iron possible with almost any ore, even the lime-containing ores of the coal measures. Contrary to the prevailing wisdom, the hearths in the early coke furnaces did not need to be hotter than their charcoal equivalents, but the temperature did fall off less quickly as the gases ascended, thus providing conditions that were further enhanced for silica reduction. However, there were other physical and chemical differences between charcoal and coke, and the burdens which operators were obliged to run as a result, that did naturally make the output of a coke furnace lower than that of a similarly-sized charcoal one. What these influences were is explored in the body of this paper. With either coke or charcoal, the output of a blast furnace was a function of its *volume,* but it also depended on the grade and function of the iron being made.

The thermal efficiency with coke, influencing the fuel consumption, was much lower because of the flatter temperature gradient and the consequent higher temperature of gases leaving the top of a coke furnace. The thermal efficiency with coke was a function of furnace *height*.

Abraham Darby's first furnace has always been assumed to have been of the same size as contemporary charcoal furnaces and therefore the fact that its recorded output was lower than theirs has entirely been taken to be due simply to a property of the different fuel (Mott 1957b, 8; Rehder 1987, 39). However, his continuously *running* output was almost certainly not as low as analyses have suggested. His furnace was thermally inefficient, having to work harder to reduce iron with coke, but it also suffered operationally as a result of being used to make castings, as opposed to being able to pour all its output onto the floor at one time, as furnaces making pig iron for the forges did. The manner in which Darby was obliged to operate whilst making castings is explored in the body of the paper. Furthermore, water supply became the limiting factor in Abraham Darby's campaign length, whereas for charcoal furnaces fuel supply was the principal limitation. They found it convenient to stop work as water supplies ran low, but Darby had no fuel constraint, so just how did he operate his furnace as the water levels dropped?

To operate efficiently, blast furnaces needed to be run continuously at the optimum conditions for the iron that they wanted to make. In other words the excessive consumption of coal, as evidenced by the Coalbrookdale account books (Shropshire Record Office 6001/329-31), was not just a consequence of the chemical and physical properties of the new fuel but of a lot of operational issues as well. So now the principal question is what might have been the working output of Darby's furnace had its production not been limited by water and operational factors, as if it had been able to run much more like a charcoal furnace of the time, when that furnace was fully supplied with both charcoal and water? Two 19th-century studies are particularly useful in the analysis.

The thermochemistry of Isaac Lowthian Bell

The first English thermo-chemist who applied his knowledge to the workings of the blast furnace was Isaac Lowthian Bell, who was metallurgist at the Clarence Iron Works in the north east of England in the 1860s and wrote copiously on the subject. He compared the theoretical heat requirements of coke and charcoal per ton of iron produced (Table 1; Lowthian Bell 1884, 275). He was followed by Gruner, who used Lowthian Bell's data for furnaces in the north east of England to demonstrate his theory that the efficiency of a blast furnace could be understood in terms of the ratio of carbon monoxide to carbon dioxide at the furnace top. Gruner (1873, 133) did not do the calculations for charcoal, but showed that he agreed roughly with Lowthian Bell's calculations for coke. Lowthian Bell's calculations were somewhat crude and involved some questionable assumptions, but they may be regarded as representative. They were also not for furnaces working under exactly the same conditions, but Table 1 indicates that a ton of coke iron needed 34% more heat energy in its manufacture than one made using charcoal. The big differences were in the requirements of the larger amount of higher temperature slag, the greater evolution and decomposition of carbon dioxide from ore and limestone, the greater amount of silica reduction and the amount carried off in the top gases.

Williams (2017) argues that Darby's 1709 furnace

Table 1: The calculations of Lowthian Bell (1884, 275) detailing the different heat requirements of furnaces burning charcoal and coke when producing 20kg of iron.

	Heat required (kilocalories per 20kg iron produced)		
	Charcoal (A)	**Coke** (B)	**Difference** [(B-A)/A]%
Fusion of slag	8,811	14,520	65
Decomposition of water in blast	1,700	2,444	44
Expulsion of carbon dioxide in minerals	962	4,013	317
Decomposition of carbon dioxide in minerals	992	4,160	319
Evaporation of water in fuel	1,674	324	-81
Reduction of ore	32,100	33,108	3
Carbon impregnation	1,920	1,440	-25
Decomposition of silicic, phosphoric and sulphuric acids	522	4,174	700
Transmission through walls	2,615	3,658	40
Fusion of pig iron	6,600	6,600	0
Carried off in tuyere water	1,176	1,818	55
Carried off in gases	3,480	7,542	117
Total	62,552	83,801	34

probably ran at much the same hearth temperature as contemporary charcoal furnaces, using a similar slag basicity (although a greater quantity). With coke however the temperature fell off much less sharply as the shaft was ascended, so gases exited at a much higher temperature. If heat losses in the gases accounted for 9% in the figures for Lowthian Bell's furnaces, with Darby's furnace height of less than 25 feet, they would have been a lot more.

Raising the height of a coke furnace resulted in this heat being better captured in the falling burden. Lowthian Bell (1884, 97) noted that the temperature of escaping gases were 452°C in a furnace of 48 feet (14.6m), but only 332°C in one of 80 feet (24.4m). Separately he noted 300°C in a 57 foot (17.4m) furnace and 200°C in a 70 foot (21.3m) furnace, the two sets of figures being under different circumstances (*ibid*, 114). Parity with carbon usage in charcoal furnaces was reached around these taller heights, but the lower the coke furnace the greater was the difference in the consumptions between the two fuels. Gruner discussed the probable maximum height that coke furnaces needed to be in the 1870s and despite the above, concluded that 55 to 60 feet (18.3m) was a *practical* maximum (Gruner 1873, 7 and 75), giving an optimum combination of output, fuel efficiency and ease of operation. Charcoal furnaces peaked at a height usually less than 30 feet (9.8m) even in mid 19th-century Europe, apart from Russia. Modern coke furnaces are mostly around 100 feet (30.5m).

All other heat except that lost through the top and walls was involved with maintaining the chemical reactions and the production of iron and therefore, for any given burden, proportional to the amount of it produced. When iron was not being produced, much less heat needed to be generated, hence Angerstein's observation in the mid-1750s (Berg 2001, 325) that furnaces could mark time with very little expenditure of fuel (see below).

The work of John Birkinbine

The experiments of John Birkinbine (1880, 169-175) in Philadelphia are the most complete report of the differences in the practical working of a blast furnace running alternatively charcoal and coke as fuels. Rehder (1987, 37-45) has provided some analysis of Darby's operating conditions using Birkinbine's results. He did not however provide a completely accurate criticism of their worth. Birkinbine ran coke for just ten days, not running the furnace down first, but simply piling the coke on top of the previous charge of charcoal. He had some difficulties which made the test less than ideal. He noted himself that the first few days with coke were partially consumed in trials and were therefore 'unfair to this fuel'. He had to substitute smaller tuyeres which should have increased back pressure but in fact did not, even though pumping more air. Birkinbine started with charcoal and returned to charcoal at the end of the experiments, giving data for 30 days of both batches. The two lots of charcoal data are considerably different (Table 2). The first batch of charcoal 'was deteriorated by the reloading, hauling by wagons and railroad and the inclemency of the weather'. The consumption, admitted Birkinbine, was 'above the proper working of the plant, nor was the output as great as it has been'.

Table 2: The results of Birkinbine (1880, 175) in comparing charcoal and coke in the Pine Grove Furnace, PA in 1879.

	Charcoal 1	**Charcoal 2** (A)	**Coke** (B)	**Difference** [(B-A)/A]%
Fuel per ton of iron, pounds	2,581	2,650	3,494	31.8
Production, tons per week	95	102	70	-31.4
Lime:Ore (%)	22	24	44	83.3
Air per minute, cubic feet	1,806	2,301	2,485	8.0
Air per ton of iron, cubic feet	197,081	216,243	323,845	49.8
Air per pound of fuel, cubic feet	77.8	81	92.7	14.4
Blast pressure, pounds per square inch	0.77	1.23	1	-18.7
Tuyere area, square inches	47.7	42.5	28.9	-32.0
Least dwell time, hours	12.5	9.5	20.5	115.8
Duration of experiment, days	28	31	10	
Calculated fuel, tons per week	108.5	119.6	108.2	-9.5
Air:Air to produce CO (%)	98	102	116	

The irons made by the two main fuels were different, although Birkinbine was not absolutely clear when he said, 'there was no attempt to make a gray iron for foundry purposes, as the market for charcoal pig is entirely confined to charcoal forges, and for the iron made with…coke…the demand was for mill iron'. Presumably 'mill iron' at that time in America meant pig iron for the Bessemer process. Bessemer iron did not fit exactly into the grading system. It required quite a lot of silicon (*c*1.5%) but had to be low in phosphorus. Different irons of course demanded different amounts of fuel and resulted in different production rates, so part of Birkinbine's differences between charcoal and coke can be explained by that. Bessemer iron required less silicon than Darby's pot iron (*c*2.5%+).

Table 2 compares the working of coke against the second, 'proper' charcoal, but with the first there for useful caution. With coke, a 32% increase in fuel per ton of iron made resulted in a production of only two thirds the amount, with the iron being in the furnace twice as long.

When Rehder suggested that the Birkinbine data could be wholly applicable to an understanding of Abraham Darby's first coke furnace, he was not completely accurate. He noted that the 'furnace size and shape was not greatly different from 18th-century practice' (Rehder 1987, 38). In fact the Pine Grove furnace was over 50% higher than the Coalbrookdale one. Birkinbine reported that he raised it from 28 feet (8.5m) to 36.5 feet (11.1m). The height of the 1709 furnace has long been lost, but it has been assumed that it was a standard unit of its day and thus probably only 24 feet (7.3m) or less in height (Mott 1957a, 74). This agrees with Schubert's views on furnace heights at the time (Schubert 1957, 206). Discussing Birkinbine's results, Lowthian Bell (1884, 130) said 'the furnace dimensions were below that which will be recognised as required for successful melting with mineral fuel'. Lowthian Bell's smallest furnace was 48 feet (14.6m) high.

Also, Birkinbine's input materials were significantly different from those of Darby. From his density measurements, Birkinbine's fuel was a typical 19th-century coking coal, whereas we know from Charles Wood that Darby's was much closer to charcoal in its bulk density and therefore in its reactivity (Gross 2001, 223). Darby's ores were typical carbonates of the coal measures with iron contents of about 35% (pre-roasting). It has not been possible to identify the nature of Birkinbine's ores for it is evident from the geological survey of Pennsylvania (Rogers 1840,161-163) that the area around Pine Grove Furnace provided both hydrated and carbonated ores. Birkinbine quoted a yield of 38% iron which might have been true of either type.

Birkinbine showed that coke resulted in a production rate 31% slower than charcoal and it needed 32% more of it to produce a ton of iron (Table 2). Significant though these coke disadvantages are, they are much smaller than those which apparently beset Darby in the early days. Darby's output was disproportionately less and his coke usage huge in comparison. Mott's figures suggest that, relative to contemporary charcoal practice, Darby's production was 65% slower and his fuel usage 100% higher.

However, Birkinbine used a preheated blast which is much more important to Rehder's comment regarding applicability. When hot blast first appeared in 1829, it was revolutionary and seldom can a capital development have spread so quickly. Nielson's first experiments with the Clyde blast furnace were completed in 1831. By 1833, 67 blast furnaces throughout Britain were using it (Dufrenoy *et al* 1837, 389). In many instances hot blast could simultaneously result in dramatically reduced overall coal consumption and it better allowed the use of un-coked coal. It also reduced lime consumption, increased iron output, increased iron grade, *ie* made it more grey, and reduced air consumption. Birkinbine used a blast of 320°C, really only a warm one, but the very first experiment at the Clyde Iron Works in 1831 used a blast of 230°C and reduced furnace coke consumption by over 35% (Percy 1864, 398).

Back calculating to Darby's output

We can compare Darby's output with Birkinbine's by adjusting for the different conditions noted above. We have the effects of hot blast, as above. For furnace size and grade of iron there is Gruner (1873, 2), who reckoned that for the production of a foundry iron with hot blast 260 cubic feet (7.4 cubic metres) of furnace volume were required to produce 1 ton of iron per day, whilst for a middle grade (*ie* less silicon) it was nearer 235 cubic feet (6.7 cubic metres). By applying the three factors in the right order, we can convert Birkinbine's output back to something representative of Darby's (Table 3). By this method Birkinbine's output of 70 tons per week is calculated to be equivalent to 9 tons per week of Darby's, a considerable difference in output which might be used further to question Rehder's suggestion above that the operations were very comparable.

Another method of calculating a theoretical output is to assume that the limiting factor was carbon combustion.

Table 3: The relationship between Birkinbine's output and that of Abraham Darby's smaller, cold-blast furnace.

	Tons of iron per week	Data source
Birkinbine's output per week	70	Birkinbine 1880, 175
Reduced for size of furnace	15.6	Gruner 1873, 2
Reduced for absence of hot blast	10.9	Percy 1864, 398
Reduced for grade of iron	9.3	Gruner 1873, 2
If coke burnt at same rate as charcoal	8.7	This paper
Reported peak month output before installation of horse gin 1723	5	This paper, Table 4
Reported peak monthly output after installation of horse gin 1736	8	This paper, Table 4
Darby's output 1754	12	Berg 2001, 330; Gross 2001, 223

Within the limit of experimental accuracy, Birkinbine's furnace appeared to have burnt the coke at much the same *rate* as it burnt charcoal. Iron output differed, ratio of fuel to iron differed, but carbon burnt per week was remarkably similar (Table 2). The figure for coke was the same as for the poor charcoal, and well within errors associated with the carbon content of the fuels in comparison with the good charcoal. This might have been the result of a fixed property of any size of furnace, or it might have more to do with a phenomenon discussed in Appendix 1, where the suggestion is made that in order for small cold-blast furnaces to have generated the necessary heat for the chemical reactions, a small proportion of the carbon needed to have been burnt 'permanently' to carbon dioxide rather than solely to carbon monoxide.

If 'fixed' carbon consumption may be used as a yardstick, we can again calculate what Darby's output would have been by reference to contemporary charcoal furnaces. Mott (1957a, 72) reckoned that charcoal blast furnaces in Darby's time (and of the same size as his) produced about 14 tons per operating week, again confirmed by Schubert (1957, 353) with an expenditure of about 2.5 tons of charcoal per ton of iron. Prior to 1720, the accounts show that Darby used 12 tons of coal per ton of iron. This is equivalent to a coke usage of 4 tons, conversion at that time being about 3:1 (Hall 1924, 5; Mushet 1840, 55). At the same carbon combustion rate as the charcoal furnaces, that would put Darby's theoretical output again at nearly 9 tons per operating week.

Darby's reported output

Mott (1957a, 69) calculated Darby's output in the 1720s at 4.5 tons average per week by assuming that the furnace worked for 45 weeks in the year and dividing annual output by this period, whilst noting that the accounts showed that output varied considerably from month to month. Raistrick (1970, 105) published in graphical form the outputs in the four-weekly periods in which they were recorded in the accounts books. King (2003) digitalized original data from these accounts which allows reproduction of four-weekly output in tabular form (Table 4). An overlap with Raistrick's graphs allows them to be compared and validated. The data is for the Old (1709) Blast Furnace for two-year periods before and after the installation of the horse gin, which pumped water back into the furnace pool, in 1734. In peak months before this installation, the maximum output was 5 tons per week, rising to 8 tons per week after the installation, which is noted for comparison in Table 3.

Why therefore did Darby's furnace not produce at the calculated 9 tons per week rate before the installation of the gin? The surmise is that its running rate was always potentially of this order, but that the furnace was not in a position to run at this rate all the time, even when water was freely available. Darby's furnace had to operate in a way that few furnaces had to before, remembering that true foundry work before Darby was a very minor part of total iron production. A furnace casting pig iron for the forges, or indeed casting over half a ton of iron into a mould to make a gun, spent as little time as possible emptying itself. It more or less dumped its entire crucible of metal onto the floor through a tap hole and launder, and then got on with making more iron. But as Karsten (1841, 151) remarked, 'when the iron has to be used for castings, it is necessary to follow the work of the moulding shop and hold off casting until the moulds are ready'.

Table 4: Twenty eight-day outputs of the Coalbrookdale old blast furnace before and after the installation of the horse gin (data from King 2003).

	Period of	**1722**		**1723**		**1736**		**1737**	
	28 days	tons/ week	% pots	tons/ week	% pots	tons/ week	% pots	tons/ week	% pots
Winter	1	2.5	0	5.0	18	6.0	34	7.7	27
	2	5.0	44	4.8	23	6.8	34	9.1	27
	3	4.7	50	4.2	34	6.2	4	8.7	24
	4	2.2*	36	3.6	59	8.7	23	8.1	22
	5			3.4	50	8.0	23	7.9	25
	6	2.2	38	0.6	39	7.9	28	7.0	24
Summer	7	1.4†	32	0.9	0	5.3	40	7.1	30
	8	0.0	0	1.2	0	1.5#	39	7.3	25
	9	1.6	0	1.6	4			8.2	29
	10	3.1	54	2.5	45			0.9*	35
	11	2.8	46	2.4	32	3.2	33		
	12	3.9	30	2.6	36	5.7	42	5.8	24
Winter	13	5.0	27	3.0	41	6.8	33	6.8	32

* = one period of 56 days, † = a period of 38 days, # = one period of 84 days.

Darby had to empty his furnace slowly, putting small amounts of iron into a ladle and stopping the tap hole with clay repeatedly, or he had to bale the metal out of the forehearth (Fig 1). Whilst this was happening, the blast had to be turned off. A typical forge cast took place twice a day, half a ton or so at a time, and emptied the crucible completely. Darby must have cast several times a day, quite possibly shutting the furnace down for over half an hour each time. Compared to continuous blast, it would have been inefficient working, involving loss of time and extra fuel. Karsten (1841, 153) noted that in order not to chill the crucible under these circumstances, nor to get slag into the metal, the hearth always needed to be kept between a half and three quarters full, particularly when using coke. This alone would imply stopping the furnace every three hours.

Tapping the iron in small quantities, irregularly, also inevitably resulted in higher metal losses in launders, ladles (the so-called skulls) and through oxidation, none of which would have appeared as iron in the production statistics. Darby cast cooking pots in green sand moulds, many of them made using pig iron separately re-melted in air furnaces (King 2013, 139), but many moulds, including pot moulds (perhaps the larger ones), were brought into the blast furnace area for casting. The company also made bigger castings, much bigger vessels and, from the 1720s, cylinders for steam engines. These moulds would have to be built up in front of the furnace and often the furnace would have had to wait whilst they were finished. Included for interest in the output table (Table 4) is the percentage of pot castings made direct from the furnace, in addition to those from those made with the air furnaces; but deducing some inverse correlation between output and pot production would be fanciful without taking into account the other complicating factors.

Running a furnace at anything other than its optimum output was difficult and inefficient. The careful balance of heat production, iron and silicon reduction and hearth temperature with ore to fuel ratio and air blast was not something that operators changed lightly. Darby needed a specific grade of iron to make his pots, a very grey-tending one, with a carbon equivalent in excess of 5% (Williams 2013, 130). It must have been very easy to get this wrong by varying the operating conditions.

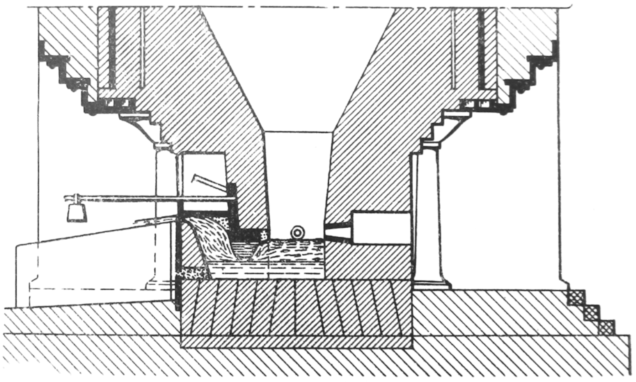

Figure 1: Blast furnace with a fore-hearth on its left hand side. It allowed iron to be baled out with hand held ladles to make small castings (after Johanssen 1925, 139).

So what happened then in those four-week periods when production was recorded as only 1 ton per week or less? The answer has to be that this small production just happened to be at the beginning or end of the period, when otherwise the furnace was on hold, without any attempt to produce iron, while the pond was allowed to refill. Angerstein (Berg 2001, 329) noted specifically in the Coalbrookdale context, that 'in England it is now known … that the furnace can be damped down, which preserves the heat in the furnace with very little fire for several weeks, so that the campaign can be restarted without renewing the furnace lining and with a smaller expense for blowing in'.

Both Hassenfratz (1812, 242-244) and Karsten (1841, 85, 234) explained how this was done. Basically the air inlets and outlets (*ie* the top) were closed off with just the smallest apertures to let some air in and some gases out. The task was to make sure that the furnace did not cool down below a certain temperature where damage to the lining would start to occur. This was the short term solution. If the furnace was to be shut down for more than a few days, the charge was run down, the furnace filled solely with fuel and the same procedure adopted; Recovery from this clearly took longer. In both cases there was the expenditure of some extra fuel over and above that needed for smelting alone which would have been responsible for some of the extra consumption reported by Mott.

Output and furnace height

Hitherto, the assumption by all historians of the blast furnace seems to have been that blowing in more air was the answer to improving the output of coke furnaces, but that is just not so. Simply blowing in more air might produce more iron, but not of the quality necessary to make pots (Williams 2017). Dufrenoy *et al* (1837, 329) noted that 'for iron for casting the descent must be slower and use a lesser quantity of air'. A furnace had to be fed with the proportional volume of air, so the production of a higher quantity of any particular grade of iron was only obtained by building a bigger furnace, that is, a furnace of a greater volume. Most reported dimensions are of furnace height, but we can make some approximations to estimate volume. Karsten (1841, 300) reported the differences that furnace shape made to the colour of iron produced, noting that tall thin furnaces produced a greyer iron than short fat ones, but ratios of height to width were generally not hugely different from furnace to furnace, so it is probably no great approximation to say that in general a furnace's output was directly proportional to the cube of its height.

Thus if output is T, and the height of the furnace is H

$$T=KH^3$$

where K is the constant of proportionality. If the output of the 24 foot Coalbrookdale furnace was 8 tons per week, a figure averaged from peak months after the horse gin was installed (Table 4), K calculates at 5.8×10^{-4} tons per week per cubic foot.

For the production of the same foundry grade of metal, the increased outputs at Coalbrookdale in 1754 of 12 tons per week, as reported by both Angerstein (Berg 2001, 330) and Wood (Gross 2001, 223) (Table 3), suggest that at least one of the Coalbrookdale furnaces had been enlarged to a height of 27.5 feet (8.4m). Charles Wood said that the furnace was much the same size as the other furnaces around. In his diary he included a plan of the nearby Leighton furnace with the annotation that it was 30 feet (9.1m) high (Gross 2001, xvi).

Water was pumped back into the furnace pool at Coalbrookdale from 1734 by a horse gin, which was replaced in the early 1740s by a Newcomen engine. The extra water would have extended the period of operations still further, but would not in itself have influenced the maximum output of the furnace. So the significant difference between outputs of the peak winter months before and after the horse gin was installed in 1734 must also be an indication that the opportunity was taken then to increase the furnace size. Given that in these early days the furnaces were completely relined each year, a small extension at the same time might not have been a huge undertaking (cf Birkinbine's claim above that he increased the height and capacity of his furnace before undertaking his trials).

For the later Coalbrookdale Company furnaces at Horsehay with an initial 1755 output of 16 tons per week (Mott 1957c, 280), a height of 30 feet (9.1m) would be required. Horsehay was purposely built for the forge market to take advantage of Abraham Darby II's breakthrough in removing sulphur (Williams 2017) so the implication of sending this output to the forges is that the iron would have been of a lower grade, *ie* have contained less silicon, just as Tylecote (1991, 215) reported. Such output *might* have been obtained from a furnace of lower height, but there was also the question of the single technological change made in the interim, with Horsehay needing a higher slag quantity and a higher hearth temperature in comparison with the Coalbrookdale furnace of 1709 to achieve the lower sulphur content needed for forges. Mott believed that the two stepwise growths in output that he noted at Horsehay from 16 to 25 tons per week between 1761 and

1767 (1957, 280) and to 35 tons per week between 1773 and 1796 (Mott 1959, 46) stemmed from the provision of extra blast from improved steam engines. However, if the present argument is accepted it cannot have been just improved blast, the furnaces must also have been simultaneously enlarged on each occasion. Their heights, which do not seem to have been recorded at any time, when calculated in the same way, would have been 30, 35 and 39 feet (9.1, 10.7, 11.9m) respectively.

Consequences for the comparative economics

Exploring in this detail why Darby's first furnace was so much less productive and efficient than a charcoal furnace of the same era means that we will need to revisit the cost of his iron. Much of Hyde's (1977, 67) argument for it being merely a matter of economics why coke iron was not used for making bar iron before the 1750s was based on a computation of the cost of Darby making it, in turn calculated from the Coalbrookdale account books. If however Darby's furnace had been run solely for producing pigs for the fining trade, then his production would have been higher, his fixed costs (per ton) much lower, and his fuel bill less. All of this would have meant that his overall cost would have been significantly lower. However, this author contends that it was the contribution of sulphur to the fining issue, rather than the economics of production, that was the real reason why it took so long for the forges to purchase pigs made using coke.

Further observations on the question of height

The need of a coke furnace for a greater height than a charcoal one as a result of coke's lower reactivity leads to a further observation. We are told that in various circumstances in the 17th and 18th century, people failed to make coke work (*eg* Powle 1677/1678, 934 and Riden 1991, 75) and that this was because people used relatively unreactive coke in furnaces which were not tall enough. Darby insisted on the use of clod coal because its coke was the most reactive he could find. Dufrenoy *et al* (1837, 296) observed that the furnaces in South Wales were taller than those in Shropshire and Staffordshire. It is here suggested that this was because of the lower reactivity of the coke that was produced there, and that the 24 foot (7.3m) furnaces designed for use with charcoal were simply not high enough to permit the use of anything but the lightest and most reactive of cokes.

Before John Baildon started to build the first coke dedicated iron works in Prussia/Silesia in 1794, conditions for the use of coke were earlier established through trials in an otherwise charcoal furnace at Malapane, now Osimek (Johannsen 1925, 146). They failed to begin with, but when William Wilkinson visited in 1789, he recommended that the furnace be raised from 7.5m (25 feet) to 9.1m (30 feet) and the experiments then succeeded. The furnace eventually built at Gleiwitz (Gliwice) in 1796 was 43 feet (13m) feet high (Wiebmer 1874, 253), much the same size as that at Carron which was where Baildon came from.

Summary and conclusion

The difficulties that Abraham Darby faced when he first smelted iron with coke were not simply a reflection of the new fuel, but also of the manner in which he was obliged to run his furnace in order to make cast goods. The potential continuous running output of his first furnace is deduced at some 8-9 tons per week but the nature of his casting operations obliged him to accept an output much less than this in practice, whilst competitive charcoal furnaces making iron for the forges were not so constrained.

On top of this, the problems of water supply, and of the resultant intermittent working, also lowered output and increased coke usage. That water supply was a serious impediment was shown by the improvement which was realized when firstly the horse gin and later the steam engine was employed to return the available water to the mill pool.

In beginning to quantify how output varied with furnace size and how fuel usage varied with furnace height, we can begin to deduce that some hitherto unsuspected furnace enlargements must have taken place continuously as the businesses expanded. Thus we can suspect that the Coalbrookdale furnaces were enlarged between 1740 and 1754 and the Horsehay furnaces received several enlargements as the second half of the 18th century progressed.

Appendix I: The consumption of air in the blast furnace and its implication for carbon combustion

Birkinbine's (1880) paper hints at a phenomenon which has not been discussed in any paper of which the author is aware, but would certainly be of relevance to the manner in which cold-blast furnaces sometimes worked. The classical chemistry of the blast furnace, reported by

Table 5: Rates of charcoal and air 'consumption' for various European furnaces at the beginning of the 19th century (data from Hassenfratz (1812, 51) quoting Marcher).

Furnace location	**Iron** (pounds per day)	**Charcoal** (pounds per day)	**Ratio charcoal:iron**	**Ratio carbon:oxygen**	**Oxygen above requirement for CO** (%)	**Height of furnace** (feet)
Neuberg	3200	7072	2.2	2.0	152	16
Vordenberg	5000	7400	1.5	1.8	131	17
Rauscher	5100	7038	1.4	1.6	122	18
Rauscher	5200	7072	1.4	2.0	152	18
Rauscher	5600	7168	1.3	2.0	150	18
Rauscher	6000	7980	1.3	2.5	189	19
Rauscher	7000	8190	1.2	2.3	171	19
Eisenerz	8000	14640	1.8	1.7	125	19
Turach	2600	6994	2.7	2.3	173	19
Turach	6300	7371	1.2	2.3	176	20
Saint Leonard	3100	8060	2.6	2.0	147	20
Hesse	3500	5880	1.7	2.2	165	20
Gollrath	3400	7276	2.1	2.2	163	21
Huttenberg	6100	11224	1.8	1.8	134	22
Saint Gertrude	4800	8784	1.8	1.9	139	23
Saint Gertrude	5700	8892	1.6	2.3	170	23
Lichenstein	3000	4800	1.6	4.8	359	24
Mossins	7900	11850	1.5	1.7	128	27
Feystritz	8000	7920	1.0	5.4	408	28
Feystritz	8600	11180	1.3	1.7	125	29
Bohemia	4000	7520	1.9	3.4	258	32

Percy (1864, 349) onwards has it that carbon dioxide is produced at the tuyeres when oxygen is in excess, but all of it reverts almost immediately to carbon monoxide as carbon becomes the excess reactant, and it is this carbon monoxide that does most of the reducing of the iron oxides as it moves further up the stack. The heat generated for the necessary reactions above is thus provided by the oxidation of carbon to carbon monoxide near the tuyeres.

However, where air quantities have been reported in early furnaces, considerably more air was *apparently* blown in than was necessary to convert all the carbon consumed (coke or charcoal) to carbon monoxide, the implication being, if true, that carbon dioxide was produced that did not have the time/temperature conditions to revert to carbon monoxide before reaching the part of the furnace where it was stable. Birkinbine's results suggested this (which stimulated discussion reported with the paper) and air quantities published by Marcher (Hassenfratz 1812, 51) reported even greater surpluses with cold-blast charcoal furnaces in German-speaking Europe at the beginning of the 19th century, but not all air pumped would actually have passed through the furnace (Table 5). Wood reported that the 20 foot (6m) bellows at Coalbrookdale in 1753 'blow hard and have a good blast' (Gross 2001, 223). He subsequently calculated the air production of such bellows as 800 cubic feet (23 cubic metres) per minute each (Gross 2001, 170). Wood did not note the then Coalbrookdale fuel consumption, but reported Bersham's coal consumption as 6 tons per ton of iron (Gross 2001, 224). Using this latter figure and a coal:coke ratio of 3:1, the above figures calculate to an air blast of twice the volume necessary to convert the carbon actually consumed to carbon monoxide.

There were many ways in which air leaving the bellows had the opportunity to escape before ascending the furnace shaft; in particular, before the hot blast was introduced with water cooled tuyeres, they were left deliberately loose fitting in order to let escaping air help to cool them (tuyeres for hot blast furnaces came to be water cooled and were then sealed in, but Birkinbine did not report on this). In the case of Birkinbine, one assumes that leakages would have been consistent between charcoal and coke, particularly as the air pressure in the furnace was no more with coke than with charcoal.

Lowthian Bell's calculations of the thermal requirements for the production of charcoal iron suggest that 20kg of iron would require a thermal input of 62,552 kilocalories (Table 1). If all that were to be supplied by the burning of charcoal to CO, it would require the consumption of about 1.5 tons of charcoal per ton of iron. Birkinbine's charcoal consumption was 1.2 tons per ton of iron, but this was associated with the use of a warmed air blast, extra energy being supplied by this means.

It can also be seen that of Marcher's summary of 21 cold blast furnaces (Table 5), almost half used less charcoal than the above 1.5 ton requirement. We do not know how many of these furnaces were making iron for the forges and how many for foundry use, but Fournel (1842, 4-5) quoted for two furnaces in the Haute Marne 1.29 tons of charcoal for making a ton of forge iron and 1.85 tons for making a foundry ton. Remembering the injunction that the more air blown in, the more the iron that came out of the furnace was suited for forge application, it could be deduced that at the highest limit of thermal efficiency, when it was not necessary to hold the charge in the furnace for an artificially long time to produce a grey iron, the blast furnace apparently burnt less charcoal than was theoretically needed to supply all the required heat via the production of carbon monoxide.

Moving on to coke and taking Lowthian Bell's energy requirements for a furnace using that fuel, Birkinbine's iron production calculates to a needed combustion to CO of about 2 tons of coke to make a ton of iron, but he actually only used 1.6 tons (Table 2, 3,494 pounds). Similarly, Mushet (1840, 65) claimed that a ton of forge iron in South Wales around 1800 was produced with 1.5 tons of coke but he also noted (separately) that different types of coke produced different quantities of iron. Coke from clod coal required 2.15 tons to smelt a ton of iron, that from splint required 2.66 tons (Mushet 1840, 291). One could see that the difference was to do with the low height of furnaces at the time, the less reactive splint coke losing more of its heat energy through the exhaust gasses.

So, there is some indication that at the upper limit of efficiency some cold blast furnaces, burning both charcoal and coke, used less fuel than was theoretically necessary to produce the iron that they did. However, that presupposes that the carbon was burnt only to carbon monoxide. Burning a certain weight of carbon to carbon dioxide produces three times more heat than does burning that weight to carbon monoxide. The suggestion from Karsten (1841, 240), that if a furnace blew in too much air then unreduced ore would start to appear in the hearth, suggests that it was perfectly possible to blow in so much air that it would force the production of permanent carbon dioxide, *ie* carbon dioxide that would not be reduced back to carbon monoxide further away from the tuyeres. Birkinbine's ratio of air pumped to carbon burnt was 14% higher with coke than charcoal (Table 2). The reported figures suggest that with coke (and ignoring air losses), carbon dioxide constituted something approaching 15% of the carbon dioxide/carbon monoxide mixture initially ascending the shaft from the tuyeres.

The Bauer Glaessner diagram (Fig 2) illustrates that a CO/CO_2 mixture containing up to 25% of CO_2 can still be reducing to iron oxide between 800 and 1,000°C. Only beyond this percentage does too much carbon dioxide result in the gas mixture not being able to reduce the ore. Reduction by solid elemental carbon can continue, even in an atmosphere of pure carbon dioxide at a high enough temperature, but the solid components need to be very intimately mixed together. This condition is only created in the blast furnace by the decomposition of carbon monoxide (to carbon dioxide and carbon) at the lower temperatures in the upper part of the blast furnace. The reduction by solid carbon, known as direct reduction, as opposed to the indirect reduction by carbon monoxide, is a well-accepted feature of the functioning of the blast furnace. The decomposition of carbon monoxide is catalysed at the surface of the ore, on which it descends into the hotter part of the furnace, there to reduce either silica or iron oxide and to produce more carbon monoxide. The

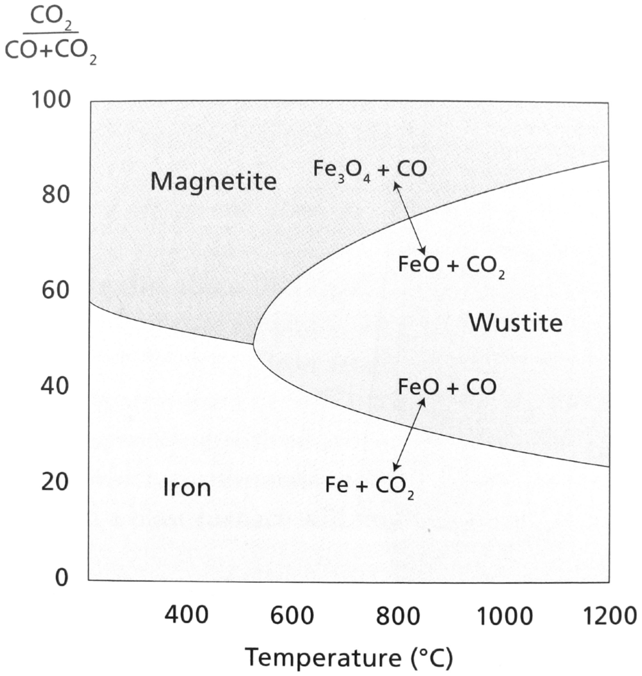

Figure 2: The Bauer Glaessner diagram (after Geerdes et al 2015, 119).

carbon so-used still needs to have been burnt to carbon monoxide first and it therefore will have already taken part in the production of heat at the tuyeres.

There have been many attempts to explain the theoretical basis for the benefits of hot blast over cold blast (Percy 1864, 418-428; Lowthian Bell 1884, 80-93; Johnson 1918, 30-35; Turner 1908, 129-144). None of them spotted the above apparent excess air usage in cold blast furnaces, but it looks as if under some circumstances the use of a hot blast removed any need for the generation of permanent carbon dioxide to provide the required heat and thus allowed more efficient use of 100% reducing gases. In contrast to the general cold or warm blast conditions in small furnaces, when Lowthian Bell (1884, 97) reported the consumptions of two of the hot-blast Clarence furnaces he gave air consumptions that were 14% short of those necessary to burn the carbon consumed even to carbon monoxide. The oxygen that consumed the rest of it would have had to come from the ore, from direct solid-solid reaction as above, or where ore and coke just touched. This suggestion can of course only be tentative. Lowthian Bell's calculations were crude and only applied to the particular ores and practice. His data for charcoal came from furnaces working in Styria and that for coke from tall furnaces working in the north east of England and the actual amount of air that made it into the furnace under any of the situations is pretty much unknown; nevertheless, the suggestion is more than theoretically possible.

If 'permanent' carbon dioxide generation did occur, carbon consumption would rise proportionately with air blow to the plateau where carbon dioxide began to be produced and then rise no more, despite more air being blown in (Fig 3). The very similar rates of carbon consumption reported by Birkinbine for charcoal and coke, yet with different air consumptions, might be due to both needing to work close to the carbon dioxide plateau, but with coke some way further along it.

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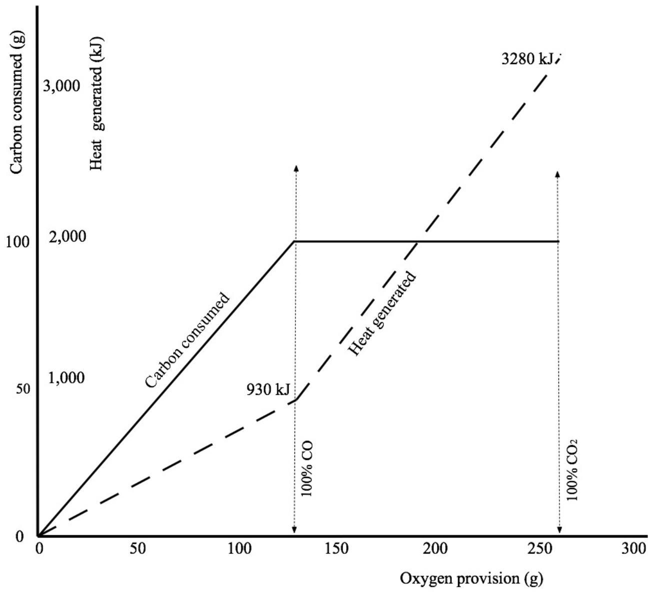

Figure 3: Carbon consumed and heat generated by increased oxygen provision.

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