Chinese blast furnaces from the 10th to the 14th century

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ABSTRACT: The Chinese 'Commercial revolution' of the 11th century was accompanied by a number of important technical developments. In the iron industry, the last major advances in blast furnace design were made. Water power was widely used for the blast, and coal and coke began to take the place of charcoal for the fuel. New blast furnace structures came into use, in some cases foreshadowing early European designs and those known from the traditional Chinese iron industry of the 19th and 20th centuries. This article reviews the available evidence on the construction and operation of iron blast furnaces in the Song and Yuan periods (960–1279, 1279–1368), with special reference to the use of mineral fuel.

EDITORIAL NOTE: The editors welcome the opportunity to publish this survey, with its valuable bibliography, despite its prior appearance in *East Asian Science, Technology, and Medicine*, 18 (2001), 41–74 (published 2002). The present version adds two illustrations and omits detail considered to be peripheral to the interests of the readership of *Historical Metallurgy*.

Blast furnace excavations

Excavations of ironworks sites of the Song and Yuan periods have been reported in seven Chinese provinces (see Fig 1 for a map of the eastern China region).[1] Of these a few are reported in sufficient detail to give us some idea of how blast furnaces in this period were built, and how they differed from what is known from periods before and after.[2]

A very large blast furnace, 6 metres tall, from the Song period is still standing today near Handan, Hebei. The photograph (Fig 2) was published, with a short description, in a newspaper in 1959,[3] and has often been reproduced.[4] In the Song this was Cizhou, a major iron-producing prefecture; in AD 1078 Cizhou and the adjacent prefecture Xingzhou between them supplied more than 75 per cent of all quota deliveries of iron to the state.[5]

I have heard that a major investigation of this furnace has recently been completed. Until a report is published we have very little to go on, but it seems to be rather like some of the traditional Chinese blast furnaces which are known from the 19th and 20th centuries. Perhaps we see in Figure 2 the internal stone shaft of a furnace like that shown in Figures 3–4, without its wooden frame and tamped-earth fill. Nearby, in Anyang and Lin Counties, Henan, several other large blast furnaces have been investigated, but the results have not yet been published in detail (Anon 1978b, 148–9; Li Jinghua 1992, 47, 48).

Blast furnaces built into hillsides

Song and Yuan remains of a curious type of blast furnace, built directly into a hill to obviate the need for a strong outer construction, have been reported in the provinces of Henan, Jiangxi, and Heilongjiang.[6] The only ones which have so far been described in adequate detail are some 12th-century sites in Acheng County,

Figure 1: Map of eastern China, showing most of the place names mentioned in the text.

Heilongjiang. Although virtually nothing is known about the place from written sources, this was clearly a major iron-production region. A survey found a very large mine site, remains of housing estimated to be adequate for 1000 workers, and more than 50 iron-smelting sites within 10km from the mine. As the authors of the report suggest, the ironworks were no doubt spread so far from the mine in order to make more efficient use of forest resources for fuel.

Figures 5–7 show three blast furnaces found at one of these sites. This type seems to be best suited to the loess regions, with their cloven topography. At a level place above a sheer cliff a few metres high, a shaft was dug, 2–3m in depth. From the side of the cliff a horizontal tunnel was dug to the shaft and reinforced with granite slabs. The whole was lined with smaller stones, mortared with clay, then plastered with a refractory clay. A second tunnel was often dug under the bottom, probably to allow heat to escape and to alleviate cracking of the furnace bottom. In furnace operation the high heat has baked the surrounding untouched loess soil to a hard red layer up to 0.5m thick (Wang Yongxiang 1965, 125, 127–9).

Presumably the shaft was completed with a stone wall at the point where the tunnel reached it, with holes provided for the blast and for tapping slag and molten

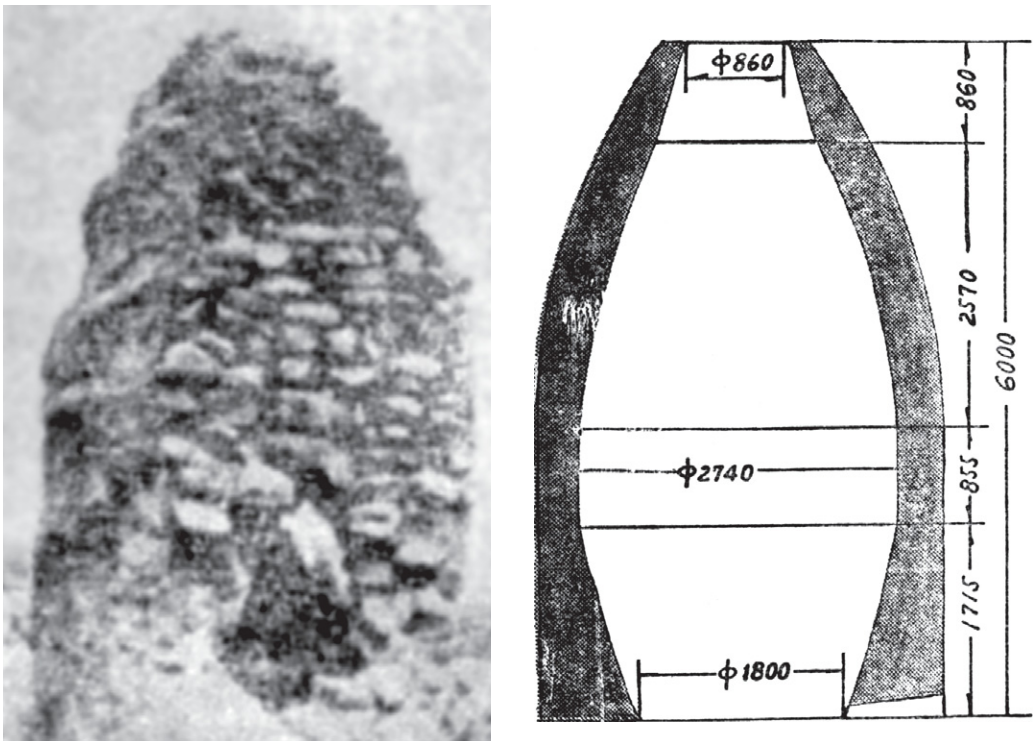

Figure 2: A Song-period blast furnace, still standing at Kuangshancun near Handan, Hebei. ***Left:*** *Photograph, originally in* Guangming ribao*, 13 December 1959, here reproduced from Liu Yuncai 1978, 23, fig 8.* ***Right:*** *Liu Yuncai's reconstruction of the furnace. Cf Figures 3–4.*

Figure 3: Blast furnaces in western Hunan, 1958, photographed by Rewi Alley (1961, No. 10). Cf Figure 4.

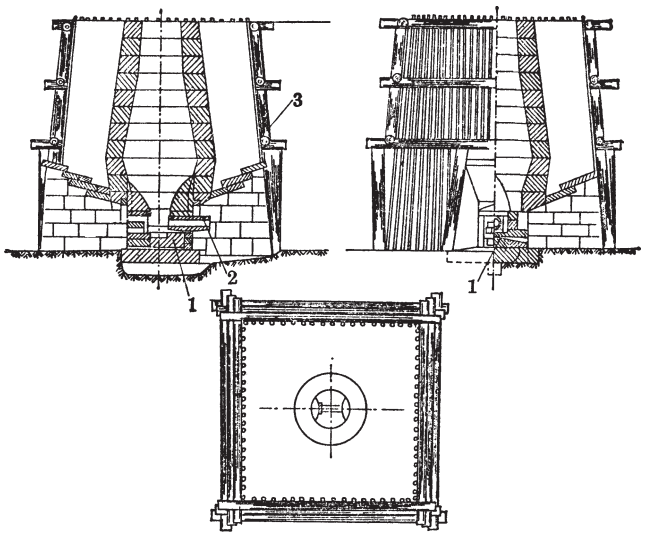

Figure 4: Diagram of a blast furnace in Sichuan, c 1958, reproduced from Yang Kuan 1982, 185, fig 47. Cf Figure 3.

iron. This wall, the weakest part of the furnace and subjected to the highest temperatures, would have been replaced often, while the rest needed only to be relined occasionally with a new layer of refractory clay.

In the Heilongjiang furnaces the height is always about 2–3m, with a rectangular shaft having cross-sectional dimensions ranging from 50 to 80cm. These are very small, and perhaps had the same operating characteristics as the later 'dwarf' furnaces, such as those of Dabieshan (Wagner 1984; 1985, 12–21, 48–59; 1997, 16–21, 58–63). They would be best suited to small-scale production in isolated regions, and it is a surprise to see them in use in a large-scale iron-production region like that in Heilongjiang.

At an ironworks site near Anyang, Henan, believed to have been in operation from the Song through the Ming period (10th–17th century), three much larger blast furnaces of the same type have been excavated. These are 2.4–4m in diameter, and the incomplete remaining height of each is about 4m (Li Jinghua 1992, 47–8). We must hope that more will be published on these in the near future. This type of blast furnace appears to be mentioned, very briefly, in the famous 17th-century technical compendium *Tian-gong kai-wu*. The sentence

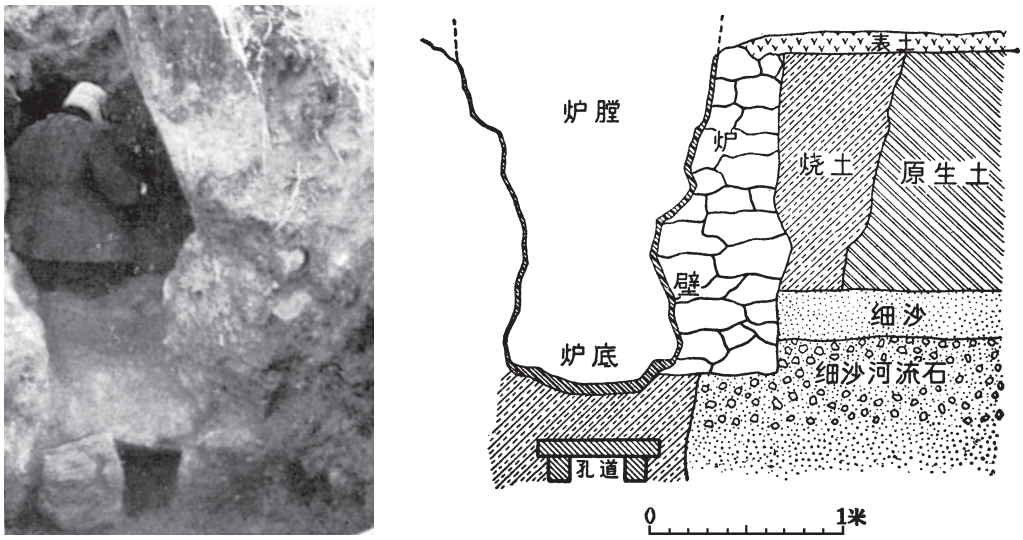

Figure 5: Photograph and diagram of blast furnace No. 2 at Dongchuan in Acheng County, Heilongjiang, reproduced from Wang Yongxiang 1965, 127, fig 5, pl 7.4. The scale shows 1m.

in question can be translated:

> …The [iron-smelting] furnace is often made in a pit at the side of a mountain; or else it is enclosed by a framework of heavy timbers.…[7]

This is the suggestion of Li Xiaoping (1995, 110), and differs from all published translations.[8]

Evidence for the use of mineral fuel in iron smelting.

The Northern Song period saw a crisis in the supply of wood for fuel and the widespread use of mineral coal. It was used both in domestic heating and in industry, including the iron industry.[9] There are some signs to indicate that coal may have been used in iron smelting as early as the 4th century AD, when the Buddhist traveller Daoan reported of a place in modern Xinjiang:

> At a mountain 200 *li* north of Quci [Modern Kucha, Xinjiang] there is at night a blazing light, in the daytime only smoke. People take the stone coal [*shitan*] of the mountain to smelt the iron of the mountain, reliably filling the needs of the Thirty-Six States [roughly modern Xinjiang].[10]

But this is the only mention before the Song, when we suddenly have many references. Both the fuel crisis and the new use of coal in iron smelting are clear in a poem, 'Stone coal', by the great poet Su Shi (Su Dongpo):[11]

> Earlier there was no stone-coal in the city of Pengcheng. It was only in the twelfth month of the first year of Yuanfeng [January, 1079] that someone was sent to investigate in the southwest of the prefecture. North of Baituzhen they smelt iron with it and make extraordinary weapons 'to pierce rhinoceros hide'.
>
> [*The city*:]
> Didn't you see her,
> Last winter, when travellers were stopped by the rain and snow,
> And city-dwellers' bones were torn by the wind?
> With a half-bundle of damp firewood, 'bearing her bedding at dawn'.[12]
> At twilight [again] she knocked on the gate, but no one wanted her trade.
> [*The coal mine*:]
> Who would have thought that in those mountains

Figure 6: Photograph of two blast furnaces No. 5 (left) and 4 (right) at Dongchuan in Acheng County, Heilongjiang, reproduced from Wang Yongxiang 1965, pl 7.1. See also Figure 7.

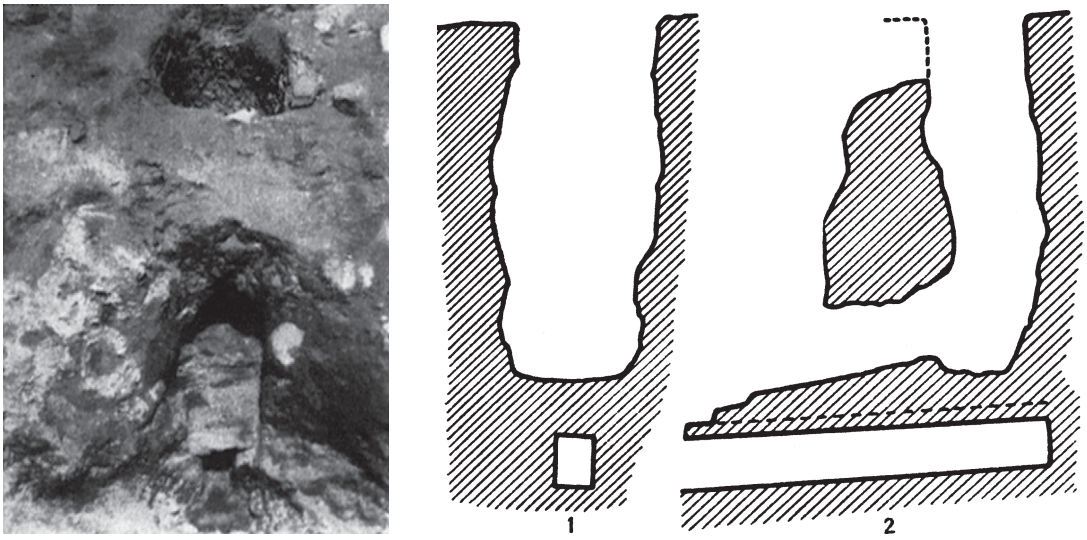

Figure 7: Photograph and diagram of blast furnace No. 5 at Dongchuan in Acheng County, Heilongjiang, reproduced from Wang Yongxiang 1965, 128, fig 6, pl 6.3. See also Figure 6.

lay a hidden treasure,
In heaps, like black jewels, ten thousand cartloads of coal.
Flowing grace and favour, unknown to all.
[*The blast furnace*:]
The stinking blast — *zhenzhen* — disperses;
Once a beginning is made, [production] is vast without limit.
Ten thousand men exert themselves, a thousand supervise.
Pitching ore into the roiling liquid makes it even brighter,
Flowing molten jade and gold, its vigorous potency.
[*The region*:]
In the Southern Mountains, chestnut forests can now breathe easy;
In the Northern Mountains, no need to hammer the hard ore.
They will cast you a sword of a hundred refinings,
To chop a great whale of a bandit to mincemeat.

There is other text-based evidence as well,[13] but this poem inspires confidence that the author had actually seen a blast furnace fuelled with coal or coke, heard the *zhenzhen* of the bellows, smelled the sulphurous smoke, and seen the glowing molten metal being tapped. (It is perhaps possible that he had merely heard a vivid description, but in any case the blast furnace is instantly recognizable). There is also evidence from chemical analyses of artefacts: high sulphur levels, which strongly suggest the use of coal in smelting, are found in numerous iron artefacts of the Song period (Anon 1978b, 152; Hua Jueming 1989).

More definite evidence is provided by radiocarbon dating of the carbon in three cast-iron artefacts of the Song and Yuan periods.[14] These give dates of 11540, 12400, and 13840 years bp respectively. Clearly these much-too-early dates indicate that some of the fuel used in the production of the artefacts was mineral coal (with effectively infinite age). Qiu Shihua and Cai Lianzhen (1986, 362) calculate that the blast furnace in which the iron was produced was charged with a mixture of three-tenths charcoal and seven-tenths coal. This is quite possible, but it must be remembered that another furnace was also involved: a cupola furnace was in all probability used to re-melt the pig iron from the blast furnace in order to cast the artefacts. What is certain is that mineral fuel was used in at least one of the furnaces. The sources above, together with consideration of the organization and economics of iron production in the period (discussed in Wagner 2001b), suggests that mineral coal was very likely to have been used in the large-scale blast furnaces. Cupola furnaces use far less fuel than blast furnaces, and re-melting and casting was probably done in smaller-scale local foundries. These would have been more likely to use charcoal, a much more convenient fuel, as long as local ecological conditions permitted.

What problems were involved in the change from charcoal to coal, and how were these problems solved? There is no straightforward way of answering this question, for we do not have, for any period, the sort of technical evidence — written or archaeological — which is needed. But we shall see that in any case the problems were not all purely technical.

One way of using coal in iron smelting is the crucible smelting process, used in Shanxi in recent centuries (Wagner 1997, 48–57). At present, however, there is no reliable textual evidence of this process as early as the Song, and no material evidence at all.[15] On the other hand, since there is no doubt that coal or coke was used in blast furnaces, we can learn something by looking briefly at the transition from charcoal- to coke-fuelled blast furnace operation in Britain and America from the 17th to the 19th centuries.

Digression: the early use of mineral fuel in English iron-smelting

Most of the early pioneers of the use of mineral coal in iron smelting, especially Dud Dudley and Abraham Darby, are well known to readers of this journal, and need not be dwelt on here.[16]

A simple way of using mineral fuel in smelting, which may have been used very early on, was to mix small amounts of coal or coke in the charcoal charged into the blast furnace.[17]

An early pioneer who is not well known was Prince Rupert (Rupprecht von der Pfalz, 1619–82), a cousin of Charles I and a member of the Royal Society.[18] His experiments with the use of coal in iron smelting were reported by Erik Odhelius (1661–1704), one of Sweden's most important metallurgists, who visited England in 1686 and 1691–2.[19] Odhelius' manuscript report on the European metals industries is still extant, but has never been published. Brief extracts from his description of Rupert's experiments are found in Emanuel Swedenborg's *De Ferro* of 1734[20] and in the report of a Swedish Royal Commission in

1744. The latter reads:

> More than 50 years ago, in the blast furnaces of Sussex, Prince Robbert attempted to smelt iron ore with stone coal, but he was unsuccessful, for the furnace became fouled with tar, and the iron was so brittle from sulphur that it was necessary to give up. Later, at the Coalebrooksdal [*sic*] works, the art of blast furnace operation with stone coal as if it were charcoal has been fully accomplished. However there have still been problems: [1] that the stone coal does not draw [*ie* smelt] as much as half the ore that charcoal does,[21] or rather, the proportion of the iron which it steals through its large sulphur content; and [2] that the iron which remains cannot be used in the forge, except in a small quantity together with good iron, if it is to be useful. On the other hand it is said to lend itself fairly well to all kinds of foundrywork.
>
> Time will tell whether this art can be brought to a higher level. The Commission believes, however, that it is not really possible, because of the great enmity between iron and sulphur which cannot be removed against their nature.[22]

It is curious that Rupert's experiments should have been conducted in Sussex, where charcoal was plentiful and coal not available (Hodgkinson 1994); but here (in the forested region of The Weald) was in the 17th century where most of England's blast furnaces were located.[23] Presumably the choice of venue was determined by the presence of an ironmaster who was willing to co-operate.

Prince Rupert's trouble with tar fouling the blast furnace suggests that he used raw bituminous coal rather than coke, and the same may have been the case in Dud Dudley's earliest experiments (Morton 1966; Morton and Wanklyn 1967). Use of raw coal can also lead to serious problems of 'scaffolding', in which parts of the furnace burden adhere to the furnace wall and build up, then suddenly fall, sometimes with disastrous results (Percy 1864, 521–6).

Coke was used in England in a variety of applications — including copper- and lead-smelting — from the early 17th century, and it appears to be certain that Abraham Darby used coke rather than coal in his blast furnace (Mott 1959a; Rehder 1987; 1998). Coke is less reactive than charcoal, and therefore requires a higher temperature in the blast furnace.[24] This in turn means greater fuel consumption and a larger volume of blast. The coke-fuelled furnace burden is less permeable, so that a greater blast *pressure* is also required.[25] The greater fuel consumption shows up clearly in Darby's account books, and the need for greater blast volume and pressure can be seen in the considerable efforts made at Coalbrookdale to increase the available water power.

The remark about foundrywork in the Swedish report points up the most important reason for Abraham Darby's success: he was an honest Quaker, and a better businessman than Dud Dudley and the others. He did not make extravagant claims for his iron, but used it in the humble applications for which it was suited. His pig iron undoubtedly contained too much sulphur to be an appropriate raw material in wrought iron production, but it is likely to have been an excellent iron for making castings. The higher temperature in the blast furnace led to a higher silicon content in the iron, so that it became possible to make thin grey cast iron products. And it happens that the local ore contains a good deal of manganese, which combines with sulphur and renders it harmless in cast iron. Darby's ironworks became famous for the production of large thin-walled iron pots; they were superior to thicker pots, and were much more economical because they used less, and cheaper, iron.

On the other hand the 'red shortness' (brittleness at high temperatures) caused by sulphur in wrought iron and steel is not affected by manganese, and the production of wrought iron required pig iron with low sulphur. The solution to the problem — more limestone in the blast furnace charge — was and is simple enough in principle, but took some time to discover and longer to exploit. Limestone ($CaCO_3$) has two functions in a modern blast furnace: as a flux, adjusting the melting point of the slag to a practicable temperature, and as a desulphurizer, removing sulphur to the slag through the reaction

$$S + CaO + C = CaS + CO$$

(Wagner 1997, 22–23). The quantity of limestone used in early blast furnaces was normally too small to have much effect on sulphur, but that was unimportant as long as the fuel was charcoal. At some time it was discovered that more limestone could help with the sulphur problem in coke-fuelled blast furnaces, but the amounts required raised the melting point of the slag considerably. The essential problem in removing sulphur from pig iron was thus the attainment of still higher temperatures in the blast furnace. The use of coke had already raised the temperature of the furnace, but not yet enough. Abraham Darby's pig iron was not used as raw material for wrought iron production until after the installation of a Newcomen steam engine to increase

the water power for the blast furnace, making much higher temperatures possible (Rehder 1987, 42–3; 1998, 31–32).

Mineral fuel in Song–Yuan iron smelting

What does this digression into 18th-century Shropshire tell us of the technical possibilities available to Song and Yuan blast furnace operators?

As the radiocarbon studies suggest, they may have mixed some coal or coke into the charcoal charged into the blast furnace. This would have meant a saving of charcoal and some reduction of overall fuel reactivity, leading to an increase in operating temperature and a modest increase in the silicon and sulphur contents of the pig iron produced.

A 19th-century blast furnace in southern Hunan (just south of Leiyang) which seems to have been fuelled with raw bituminous coal is described by von Richthofen.[26] It was 6m high, with a sandstone shaft, wooden outer frame, and stamped earth in between.

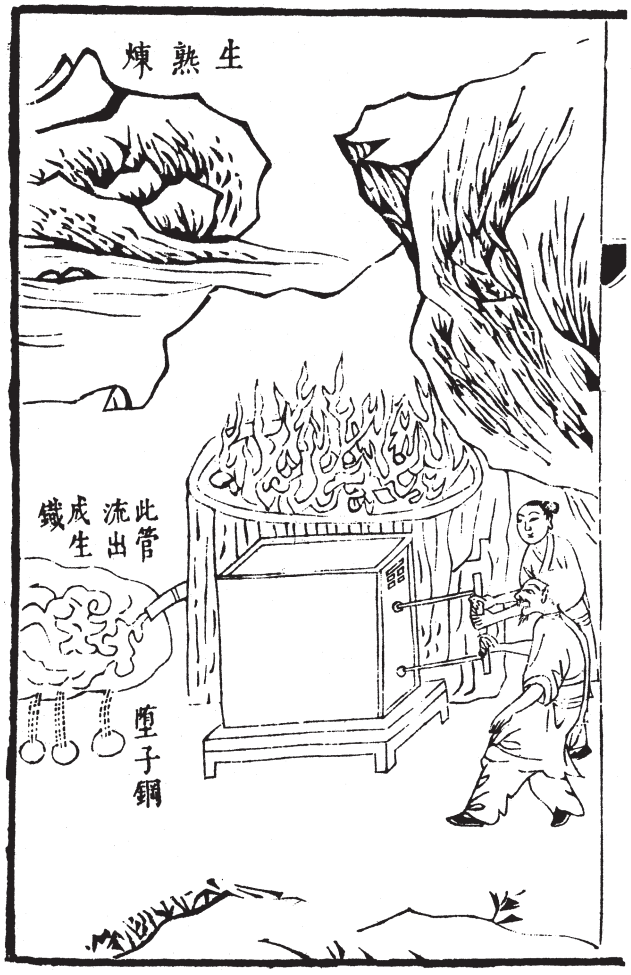

Figure 8: Illustration of a blast furnace in the 17th-century technological compendium Tian-gong kai-wu*, by Song Yingxing.*

(Some similar furnaces, in operation in Hunan in 1958, are shown in Figures 3–4.) The bellows was driven by three men. His description of the physical appearance of the fracture of the pig iron produced suggests that it was probably fairly high in sulphur; nevertheless the pig iron was fined to wrought iron, which was sold.

This example shows that a blast furnace of a type known from the Song period could be operated with bituminous coal as the fuel, though we do not know how the technical problems, discussed above, were solved. The mention in Su Shi's poem of the 'stinking blast' suggests the smell of hydrogen sulphide, an indication perhaps that coal rather than coke was used in this blast furnace — though we should not base too much reasoning on a single line in a poem.

Rostoker and Bronson (1990, 66), discussing the same question, point to some traditional Chinese blast furnaces which were wide-mouthed and shallow. In such furnaces, they suggest, the problems of aggregation and scaffolding would have been much less severe than in the more usual type of blast furnace. They refer specifically to an illustration of a 17th-century blast furnace given by Song Yingxing in his *Tian-gong kai-wu*, reproduced here in Figure 8.[27] The text does not tell us what fuel was used here, but it is interesting that Song Yingxing never mentions coke, and may not have known of it. On the other hand a very similar early 20th-century blast furnace in central China, shown here in Figure 9, was fuelled with coke (Lux 1912), and many other traditional blast furnaces of somewhat similar shape were fuelled with charcoal (Wagner 1984; 1985; 1997).

The use of coke for various other purposes was known from early times in China. The earliest reference to it is from the early 4th century AD,[28] and Hartwell (1963, 69–70; 1966, 55–7) points to two clear references to its use in the Song specifically in iron smelting. Coke was also the fuel used in a number of traditional Chinese blast furnaces in the 19th and 20th centuries (Tegengren 1923–24, 2, 316, 317, 339, 354), and it seems likely that this was the commonest fuel for those Song blast furnaces which did not use charcoal.[29]

The Song blast furnaces which we know of were large shaft furnaces, sometimes with an unusual construction but with a familiar internal form, and the lessons learnt in our discussion of English coke-fuelled blast furnaces should hold for these. The transition from charcoal to coal or coke would have required higher temperatures and therefore a larger fuel consumption and greater blast

Figure 9: An ironworks in central China (either Jiangxi or Hunan), photographed c*1910. Reproduced from Lux 1912, 1407, fig 5.*

volume and pressure. This may have been a major reason for the new emphasis on water power in iron smelting in the Song period (Needham 1965, 369–80). Those furnaces which were constructed by digging into the ground would have had better thermal insulation than the freestanding furnaces with which we are more familiar, and this may have reduced the blast requirement to some extent.

The pig iron produced probably contained a high level of sulphur, unless the effectiveness of limestone as a desulphurizer was understood and applied. But this use of limestone would have necessitated even higher temperatures, and an even more powerful blast. With human-powered bellows, or with the light undershot water-wheels which seem to have been the rule in China in this period, it seems doubtful that the necessary temperatures for desulphurization were reached. It is important to keep in mind that I am guessing here: the question cannot be answered with confidence until slag analyses become available from relevant blast furnace sites.

Sulphur levels even as low as 0.1% make wrought iron or steel almost unusable. Therefore, if effective desulphurization was not practised in the coal- or coke-fuelled blast furnace, their product was probably not used as the raw material for making wrought iron, but was used in foundrywork.

In an iron foundry, on the other hand, the higher silicon content which we should expect in pig iron from a coal- or coke-fuelled blast furnace would normally be an advantage, reducing bubbles in the casting and making a grey-cast structure more likely. The higher sulphur content would not necessarily be a disadvantage. If there is approximately twice as much manganese as sulphur in the iron, the two combine to form harmless microscopic inclusions of manganese sulphide, MnS (Angus 1976, 20). Even without manganese, the only important effect of sulphur in cast iron is to encourage a white-cast structure, which is very hard and brittle. In many applications, white-cast iron is fully acceptable or even superior to grey-cast (Massari 1938; Rostoker *et al* 1984; Wagner 1993, 345).

We do not know whether the Song-period iron smelters ever used wide-mouthed shallow blast furnaces like those illustrated in Figures 8–9, and in any case we

know next to nothing about the technical characteristics of such furnaces. They are so different from modern blast furnaces that we cannot assume that any of our modern knowledge of blast furnace operation holds, regarding temperatures, blast requirements, or the silicon and sulphur contents of the pig iron produced. In this situation of double ignorance there is nothing to do but to leave the question of this type of furnace on one side and hope for future enlightenment.

Conclusions

A charcoal iron industry does not inevitably cause deforestation. This depends very much on the long-term strategies of the ironmasters, and the extent to which they are able to defend their forest resources from other users of fuel; there are numerous examples in Chinese history of successful forest conservancy over generations.[30] The problem in all charcoal iron production is that, even with the best possible forest management, there is a definite upper limit on sustainable iron production per unit area of forest land. To produce more, it was necessary either to start up elsewhere or to find an alternative fuel. Both alternatives seem to have been tried in response to increasing demand in the Song: iron production increased in the heavily-forested south, and coal came into use in the north. The details of these developments are not clear from available sources, but in broad outline this seems to be what occurred.

If it is true, as I have suggested above, that pig iron from coal- or coke-fuelled blast furnaces was not suitable for conversion to wrought iron, then the new fuel could not replace charcoal, but could serve as a supplement in the production of cast-iron products to fulfill a growing demand. A shift seems to be visible in the Song and Yuan away from the use of cast-iron implements in favour of the use of wrought iron,[31] but in a time of population growth and expanding and intensifying agriculture, there surely remained a considerable market for cheaper cast-iron implements. Demand must have been growing for numerous other cast-iron products as well, for example pots of all sizes, from ordinary cooking pots to enormous salt-boiling cauldrons. Iron coins, too, were made of high-sulphur cast-iron (Wayman and Wang 2003).[32] I have been focusing here on the 11th century; a century later the precipitation method of copper production demanded large quantities of cheap iron, which could no doubt have been supplied by coal- or coke-fuelled blast furnaces.[33]

Acknowledgements

This article will in revised form become part of the volume on ferrous metallurgy of *Science and Civilisation in China*, which I am currently engaged in writing. Much of the research for it was done at the Needham Research Institute in Cambridge: in 1990–91 under a grant from the Julie von Müllen Foundation, in 1993–6 under a grant from the Leverhulme Trust.

As an experiment I placed an earlier draft of the article on the World Wide Web and asked for comments and advice from three Internet discussion lists.[34] The response was quite heartening, and I especially wish to thank Martha Goodway, Peter Hutchison, Peter King, and Alan Williams for useful comments. As always, errors, misunderstandings, and infelicities of expression are all mine.

Notes

1. Yang Kuan (1982 166–71) gives a general survey. **Anhui:** Hu Yueqian 1959; **Jiangxi:** Li Xiaoping 1995; Peng Zhensheng and Li Xiaoping 1992; Deng Daolian 1991; **Fujian:** Chen Zhongguang 1959; **Heilongjiang:** Wang Yongxiang 1965; **Henan:** Anon 1978b 148–50; Li Jinghua 1992; Wu Kunyi and Yu Xiaoxing 1984; **Hebei:** Ren Zhiyuan 1957; Tang Yunming 1959; Wang Zhaosheng 1994; **Guangdong:** Liu Yuncai 1978, 22 (note important correction, Yang Kuan 1982, preface, p 9).
2. For blast furnaces of the Han period see Wagner 2001a; for the traditional Chinese blast furnaces of the 19th and 20th centuries see Wagner 1984; 1985; 1997.
3. Chen Yingqi in *Guangming ribao*, 13 December 1959. This was in a period of paper shortage in China, in which the export of newspapers was stopped, and I have not been able to find a copy in any European library.
4. For example Liu Yuncai 1978, 23, fig 8; Wagner 1985, 47, fig 24.
5. In Cizhou, 1,971,001 *jin*; in Xingzhou, 2,173,201 *jin*; total quota deliveries to the state, 5,501,097 *jin* (*c* 1180 + 1300 out of 3300 metric tonnes). Wagner 2001b.
6. Li Jinghua 1992, 47, 51, 54; Peng Zhensheng and Li Xiaoping 1992; Li Xiaoping 1995; Wang Yongxiang 1965.
7. *Tian-gong kai-wu*, ch 14, Zhong Guangyan 1978, 363.
8. Sun and Sun 1966, 248; Li Chiao-ping 1980, 351; Yabuuchi Kiyoshi 1969, 270; Zhong Guangyan 1978, 366.
9. Peter J Golas in Needham 1999, 195–6; note also Nicholas K Menzies in Needham 1996, 654 ff; Xu Huimin 1987.
10. Wang Guowei 1984, 40. Note the detailed discussion of this passage by Read (1940, 123–5).
11. *Jizhu fenlei Dongpo xiansheng shi,* 25, 5a–b.
12. The woman is selling her body to obtain firewood. The phrase in quotes comes from the ancient Chinese *Book of odes*: two concubines, 'carrying in their arms their coverlets and chemises', stand in the early dawn, watch the stars disappear, and compare their lot to that of their lord's principal wife. See Karlgren 1950, 12–13; Karlgren 1942–6, 104.
13. See for example Hartwell 1963, 61–72; Hartwell 1967a, 118ff; Wang Ling 1982; Hua Jueming 1989; Xu Huimin 1987.
14. Qiu Shihua and Cai Lianzhen 1986. Note also Igaki 1994;

Saito 1994.

15. A number of writers have *assumed* that crucible smelting was the earliest iron-smelting process used in China, but there has never been any real evidence for this view. Needham 1958, 14; Wertime 1961, 48; Hartwell 1963, 71–2; Hartwell 1967a, 119.
16. The original article in *East Asian Science, Technology, and Medicine* 18 (2001), 54–57, gives a longer discussion. On the history of the use of coal in iron smelting in the West see especially Ashton 1925; Birch 1967, 22–33; Chaloner 1950; Chevalier 1949; Clark 1993; Cox 1990; Dobson 1982; Dudley 1665; Flinn 1962; Gericke 1999; Gille 1946; Harris 1988, 30–37; 1998, 238–61; Hyde 1977, 23–29; Ince 1991; King 1996; 2002a; Morton and Wanklyn 1967; Mott 1935; 1959a; 1959b; Pfannenschmidt 1977, 128–31; Raistrick 1989; Rehder 1987; 1998; Riden 1992; 1994; Treadwell 1974; Trinder 1988; Wertime 1961, 228–9; Yates 1974. A forthcoming article by Peter King (2002b) uses hitherto little-used sources to shed new light on the question. On the recent more positive view of Dud Dudley see especially Morton 1966; Morton and Wanklyn 1967. Negative evaluations are for example Ashton 1925; Mott 1935; Gale 1979, 16–18; Gille 1946, 101.
17. Birch (1967, 26) notes an agreement of 1728 among Yorkshire ironmasters which explicitly takes such a practice into account. He sees this only as providing for 'a possibility for the future', but the wording of the agreement makes it seem more like a well-known existing practice.
18. Patrick Morrah's biography of Prince Rupert has a chapter on his scientific and technical accomplishments (1976, 387–99), with numerous references to archival sources, but he does not mention the iron-smelting experiments. Other biographies, including that in the *Dictionary of National Biography*, barely mention the technical side of his career. It is interesting to note that in the English Civil War, Dud Dudley held a commission in the regiment of Rupert's brother, Prince Maurice (DNB, 6, 100; Morton and Wanklyn 1967, 62).
19. See, in English, Birch 1955, 24; Flinn 1959; Heckscher 1954, 87; in Swedish, Hofberg 1906, 2, 228; Heckscher 1935–49, vol 1, part 2 496, xxviii; Rydberg 1951, 142–3. Note that Odhelius' visits to England took place after Rupert's death in 1682, so his report cannot be from direct observation.
20. Swedenborg 1734, § 12, p 158; 1762, 96–7; Sjögren 1923, 190.
21. See note 25 below.
22. The Commission's complete report on the European iron industry is published in Anon 1918; the passage translated here is on page 135.
23. Riden 1994, 16. Peter King informs me that, while this statement concerning the *number* of blast furnaces is probably correct, the iron industry of The Weald was in decline by the 1670s and was of little importance in the 18th century (personal communication, 10 March 2000).
24. Technical studies of blast-furnace operation (summarized in Wagner 1997, 22–23) indicate that there is a 'zone of relatively constant temperature' midway up the furnace shaft. The equilibrium temperature for the reactions which proceed in this zone is directly dependent on the reactivity of the fuel. In modern blast furnace practice high temperatures are desirable, and efforts are made to limit the reactivity of the fuel.
25. Rehder (1987; 1998) gives a lucid discussion of these points, in part based on records of 19th-century blast furnace operations which often shifted back and forth among different fuel types as prices changed. Here the fuel and air requirements using coke were each almost twice the requirement when charcoal was used.
26. von Richthofen 1877–1912, 3, 455–6; *cf* Tegengren 1923–24, 2, 338. On the district, but not the ironworks, see also von Richthofen 1872, 5–7; von Richthofen 1907, 375ff; Dickson 1864, 168–9.
27. *Tian-gong kai-wu*, ch 14 (Zhong Guangyan 1978, 361–7, fig 97); *cf* Sun and Sun 1966, 248–51, fig 14-10; Li Chiao-ping 1980, 350–53, 374–5, fig 14-10.
28. Letter from Lu Yun to his brother, translated by Peter J Golas in Needham 1999, 193–4; see also Read 1940, 125–6.
29. It has sometimes been suggested that the coking process may have been forgotten after the Song, perhaps because Song Yingxing does not mention it (Elvin 1975, 91); but various entirely traditional methods were in use in the early 20th century, and there is no reason to suppose that the process was forgotten and reinvented. Lux 1912; Woo 1906.
30. Nicholas K Menzies in Needham 1996, 607ff *et passim*; note also Wagner 1985, 33–7.
31. For example the iron artefacts found in a Yuan shipwreck excavated in Ci County, Hebei, are mostly of wrought iron, except a few for which cast iron is technically a more appropriate material. Zhu Jinsheng 1978; Anon 1978a.
32. Analyses of 39 Song-period coins, reported by Michael L Wayman and Helen Wang, show sulphur contents from 0.15 to 2.05%. Even the lowest of these is remarkably high. On the iron coinage of the Song period see for example Hartwell 1967b; L S Yang 1952, 27–9.
33. Peter J Golas in Needham 1999, 370–86.
34. Archaeometallurgy <arch-metals@mailbase.ac.uk>; East Asian Archaeology <eaan@ccat.sas.upenn.edu>; East Asian Science <easci@ccat.sas.upenn.edu>.

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