Blast furnaces in Song–Yuan China

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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, with special reference to the use of mineral fuel.

Blast furnace excavations

Excavations of ironworks sites of the Song and Yuan periods have been reported in seven Chinese provinces.[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 in Figure 1 was published, with a short description, in a newspaper in 1959,[3] and has often been reproduced.[4] In the Song this was Cizhou 磁州, a major iron-producing prefecture; statistics preserved in the *Song huiyao jigao* indicate that in A.D.1078 Cizhou and the adjacent prefecture Xingzhou

[1]Yang Kuan (1982: 166–71) gives a general survey. **Anhui:** Hu Yueqian 1959; **Jiangxi:** Li Xiaoping 1995; Peng Zhensheng & Li Xiaoping 1992; Deng Daolian 1991; **Fujian:** Chen Zhongguang 1959; **Heilongjiang:** Wang Yongxiang 1965; **Henan:** Anon. 1978b: 148–50; Li Jinghua 1992; Wu Kunyi & 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 陳應祺 in *Guangming ribao* 光明日報, 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]E.g. Liu Yuncai 1978: 23, fig. 8; Wagner 1985: 47, fig. 24.

邢州 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 1 the internal stone shaft of a furnace like that shown in Figures 2–3, without its wooden frame and tamped-earth fill. Nearby, in Anyang 安陽 and Lin 林 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 Henan, Jiangxi, and Heilongjiang.[6] The only ones which so far have been described in adequate detail are

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[5]In Cizhou, 1,971,001 *jin* 斤; in Xingzhou, 2,173,201 *jin*; total quota deliveries to the state, 5,501,097 *jin* (ca. 1180 + 1300 out of 3300 metric tonnes). *Song huiyao jigao* 宋會要輯稿, *Shihuo* 食貨, **33**: 13a, 27b; cf. Hartwell 1963: 180. Hartwell believes that these figures represent an in-kind tax of 10 per cent which was collected from one of several sectors of the iron industry. Under this assumption and several others he calculates that total annual iron production in Northern Song China was on the order of 125,000 English tons (ca. 115,000 metric tonnes, 1.2 kg per capita). Though this figure seems quite credible, Hartwell's method is seriously flawed, as Yoshida Mitsukuni (1966: 517–23; repr. 1972: 364–70; see also Wagner 2001b) has argued, and his calculation is not reliable.

[6]Li Jinghua 1992: 47, 51, 54; Peng Zhensheng & Li Xiaoping 1992; Li Xiaoping 1995; Wang Yongxiang 1965.

some 12th-century sites in Acheng County 阿城縣, Heilongjiang. Though virtually nothing is known about the place from written sources, this was clearly a major iron-production region of the Jin 金 or Jürched state. A survey found a very large mine site, remains of housing estimated to be adequate for 1,000 workers, and more than 50 iron-smelting sites spread out up to about 10 km 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 4–6 show three blast furnaces found at one of the 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, 2–3 metres 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 a half metre 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 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 2–3 metres, with a rectangular shaft having cross-sectional dimensions ranging from 50 to 80 cm. These are very small, and perhaps had the same operating characteristics as the later “dwarf” furnaces, such as those of Dabieshan.[7] They would be best suited to small-scale

[7]See e.g. Wagner 1985: 12–21, 48–59; 1997: 16–21, 58–63.

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; perhaps future research into the channels by which technology was transferred between the Song and the Jin will produce an explanation.

At an ironworks site near Anyang, Henan, believed to have been in operation from the Song through the Ming period, three much larger blast furnaces of the same type have been excavated. These are 2.4 – 4 m in diameter, and the incomplete remaining height of each is about 4 m (Li Jinghua 1992: 47–8). We must hope that more will be published on these in the near future.

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This type of blast furnace appears to be mentioned, very briefly, in the famous 17th-century technical compendium *Tian-gong kai-wu* 天工開物. This is the suggestion of Li Xiaoping (1995: 110). The sentence 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 encompassed using a framework of heavy timbers. . . .
>
> 其爐多傍山穴為之，或用巨木匡圍．[8]

Some published translations ignore the mention of a pit (*xue* 穴) here.[9] One translator gives instead, "It is generally located near the mine, and sometimes made with a frame of heavy timbers. . . . " (Li Chiao-ping 1980: 351). This is a possible translation, and takes the "pit" into account, but in the light of the archaeological material Li Xiaoping's interpretation fits better into the context.

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[8]*Tian-gong kai-wu*, ch. 14, Zhong Guangyan 1978: 363.

[9]Sun & Sun 1966: 248; Yabuuchi Kiyoshi 1969: 270. Zhong Guangyan (1978: 366) does translate *xue* (as *shan dong* 山洞), but does not attempt to explain it.

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.[10]

There are some signs to indicate that coal may have been used in iron smelting as early as the 4th century A.D., when the Buddhist traveller Daoan 道安 reported of a place in modern Xinjiang:

> At a mountain 200 *li* 里 north of Quci[11] 屈茨 there is at night a blazing light, in the daytime only smoke. People take the stone coal [*shitan* 石炭] of the mountain to smelt the iron of the mountain, reliably filling the needs of the Thirty-Six States [i.e. the Western Region].[12]

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 famous poem, “Stone coal”, by Su Shi 蘇軾:[13]

> 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 [Xuzhou]. North

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[10]Peter J. Golas in Needham 1999: 195–6; note also Nicholas K. Menzies in Needham 1996: 654 ff; Xu Huimin 1987.

[11]Modern Kucha (Kuche 庫車), Xinjiang; see Feng Chengjun & Lu Junling 1980: 55.

[12]*Shui jing zhu* 水經注, ch. 2 (Wang Guowei 1984: 40), quoting *Shishi Xiyu ji* 釋氏西域記. On this lost book see Cen Zhongmian 1966: 213. Note the detailed discussion of the passage by Read (1940: 123–5).

[13]*Su Dongpo ji* 蘇東坡集, 3: 90; cf. Sivin 1973.

of Baituzhen 白土鎮 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”.[14]
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 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.

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[14]The woman is selling her body to obtain firewood. The phrase *bao qin chou* 抱衾裯 comes from *Xiao xing* 小星, “Little stars”, ode no. 21 of the *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. In the next line *qiao men* 敲門, “knocking on the gate”, can also mean “dowry”.

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.

彭城舊無石炭, 元豐元年十二月, 始遣人訪獲於州之西南,
白土鎮之北, 以冶鐵作兵, 犀利勝常云.
君不見前年雨雪行人斷, 城中居民風裂骭, 濕薪半束抱衾裯,
日莫敲門無處換. 豈料山中有遺寶, 磊落如䃜萬車炭.
流膏迸乳無人知, 陣陣腥風自吹散. 根苗一發浩無際,
萬人鼓舞千人看. 投泥潑水愈光明, 爍玉流金是精悍.
南山栗林漸可息, 北山頑礦何勞鍛. 為君鑄作百煉刀,
要斬長鯨為萬段.

There is other text-based evidence as well,[15] 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 recognisable.)

[15]See e.g. Hartwell 1963: 61–72; Hartwell 1967a: 118ff; Wang Ling 1982; Hua Jueming 1989; Xu Huimin 1987.

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.[16] These give dates of 11540, 12400, and 13840 years b.p. 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 calculate that the blast furnace in which the iron was produced was charged with a mixture of three-tenths charcoal and seven-tenths coal (Qiu Shihua & Cai Lianzhen 1986: 362). This is quite possible, but it must be remembered that another furnace was also involved: a cupola furnace was in all probability used to remelt 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 organisation 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 remelting 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.

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The question to be asked now is what problems were involved in the change from charcoal to coal, and how these problems were 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.

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[16] Qiu Shihua & Cai Lianzhen 1986. Note also Igaki 1994; Saito 1994.

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 the use of this process as early as the Song, and no material evidence at all.[17]

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 century.[18]

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

The first economically successful use of coal in iron smelting in the West was by Abraham Darby at Coalbrookdale, in Shropshire. Here, at the Ironbridge Gorge Industrial Museum (a marvellous open-air museum covering many acres), visitors today can see the remains of Darby’s blast furnace, with a sign informing them that *on this spot*, in 1709, the Industrial Revolution began.

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[17]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.

[18]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; Flinn 1962; Gericke 1999; Gille 1946; Harris 1988: 30–37; 1998: 238–61; Hyde 1977: 23–29; Ince 1991; King 1996; Morton & 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. A forthcoming article by Peter King (2002) uses hitherto little-used sources to shed new light on the question.

Before Darby a number of other entrepreneurs had attempted to use coal or coke in iron smelting. One simple method 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.[19]

The first person to claim success in smelting iron with mineral fuel alone was Dud Dudley (1599–1684), in his *Metallum Martis* of 1665. The consensus of metallurgical historians today appears to be that he did succeed in producing iron with coal; but he was certainly not an economic success, presumably because his iron was of inferior or unreliable quality.[20]

Another early pioneer was Prince Rupert (Rupprecht von der Pfalz, 1619–82), a cousin of Charles I and a member of the Royal Society.[21] His experiments with the use of coal in iron smelting were reported by Erik Odhelius (1661–1704), one of Sweden’s

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[19]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.

[20]On the recent more positive view of Dud Dudley see especially Morton 1966; Morton & Wanklyn 1967. Negative evaluations are e.g. Ashton 1925; Mott 1935; Gale 1979: 16–18; Gille 1946: 101.

[21]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 & Wanklyn 1967: 62).

most important metallurgists, who visited England in 1686 and 1691–2.[22] 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[23] 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 [i.e. smelt] as much as half the ore that charcoal does,[24] 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.
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> 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

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[22]See, in English, Birch 1955: 24; 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.

[23]Swedenborg 1734, § 12, p. 158; 1762: 96–7; Sjögren 1923: 190.

[24]See fn. •• below.

> great enmity between iron and sulphur which cannot be removed against their nature.[25]

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 known as The Weald) was in the 17th century where most of England's blast furnaces were located.[26] Presumably the choice of venue was determined by the presence of a cooperative ironmaster.

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 & 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).

Bituminous coal is (to make a long story very short) a polymer of large and complex hydrocarbons, typically about 75 per cent carbon.[27] The "coking" of bituminous coal is (like the charring of charcoal) a process of pyrolysis (destructive distillation) which can provide useful organic distillates (coal tar) as well as the coke,

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[25]The Commission's complete report on the European iron industry is published in Anon. 1918; the passage translated here is on p. 135.

[26]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 1670's and was of little importance in the 18th century (personal communication, 10 March 2000).

[27]This introduction to the chemistry of coal is based especially on Grayson 1985: 285–9; Mott 1936; Percy 1861: 78–107, 144ff; Pitt & Millward 1979; Rehder 1987; 1998; Rosenqvist 1974: 223–7; Rostoker & Bronson 1990: 66–69.

which is typically over 90 per cent carbon. Traditionally coke was made by a process very like the charring of charcoal, and both processes were seen as "the burning away of impurities". In the respective modern processes the pyrolysis uses a less expensive and more manageable heat source than the coal or wood being distilled.

Coke is preferred to bituminous coal in both domestic and industrial applications because it "burns clean": the combustion products do not smell of sulphur, and do not contain heavy hydrocarbons which muck up furnaces and flues and pollute the air.

Anthracite, or "smokeless coal", is a kind of coal in which the geological processes which turn vegetable matter into coal have proceeded much farther, so that it contains over 90 per cent carbon and not more than a per cent or two of hydrogen. It cannot be coked, and for most purposes does not need to be. Because of its very low reactivity it is difficult to use in a blast furnace (Yates 1974).

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.[28] 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*

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[28]Technical studies of blast-furnace operation (summarised 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 control the reactivity of the fuel.

is also required.[29] 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 desulphuriser, removing sulphur to the slag through the reaction S

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[29]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.

+ 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 in charcoal-fuelled blast furnaces. 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 耒陽) which seems to have been fuelled with raw bituminous coal is described by von Richthofen.[30] It was 6 m high, with a sandstone shaft, wooden outer frame, and stamped earth in between. (Some similar furnaces, in operation in Hunan in 1958, are

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[30]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.

shown in Figures 2–3.) 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" (*xing feng* 腥風) 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 宋應星 in his *Tian-gong kai-wu* 天工開物.[31] 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.[32] On the other hand a very similar early 20th-century blast furnace in

[31]*Tian-gong kai-wu*, ch. 14 (Zhong Guangyan 1978: 361–7, fig. 97); cf. Sun & Sun 1966: 248–51, fig. 14-10; Li Chiao-ping 1980: 350–53, 374–5, fig. 14-10.

[32]Hartwell (1963: 69) suggests that Song Yingxing describes the making of coke from coal in chapter 11 of *Tian-gong kai-wu* (Zhong Guangyan 1978: 288–92). Perhaps this hypothesis is inspired by the fact that the passage entitled "Coal" (*meitan* 煤炭) occurs in a chapter on "Calcining" (*fanshi* 燔石), but it is difficult to sustain when one actually reads the text. Cf. Sun & Sun 1966: 205–6; Li Chiao-ping 1980: 291–3; Yabuuchi 1969: 219–20.

central China, shown here in Figure 7, 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 purposes was known from early times in China. The earliest reference to it is from the early 4th century A.D.,[33] and Hartwell points to two clear references to its use in the Song specifically in iron smelting.[34] 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.[35]

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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 volume and pressure. This may have been a

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[33]Letter from Lu Yun 陸雲 to his brother, *Taiping yulan* 太平御覽, ch. 605: 5a, translated by Peter J. Golas in Needham 1999: 193–4; see also Read 1940: 125–6.

[34]*Xu Zizhi tongjian changbian,* 164: 12b; Ouyang Xiu 歐陽修, “Qi tiaozhi duzuo yuan 乞條制都作院”, in *Ouyang Wenzhong ji*, 118: 6b–8 and *Ouyang Yongshu ji* , 14: 8–10; Hartwell 1963: 69–70; 1966: 55–7.

[35]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.

major reason for the new emphasis on water power in iron smelting in the Song (Needham 1965: 369–80). Those furnaces which were constructed by digging into the ground must have had much better thermal insulation than the free-standing 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 desulphuriser 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 Song China, it seems doubtful that the necessary temperatures for desulphurisation 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 per cent make wrought iron or steel almost unusable. Therefore, if effective desulphurisation 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) (e.g. 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 iron smelters ever used wide-mouthed shallow blast furnaces like the one illustrated in *Tian-gong kai-wu*, or the one in Figure 7, 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.

Concluding remarks

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.[36] 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

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[36]Nicholas K. Menzies in Needham 1996: 607ff *et passim*; note also Wagner 1985: 33–7.

products to fill 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,[37] 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. Acceptable iron coins, too, could probably be made of high-sulphur cast iron, though I should like to see some analyses of Song iron coins in order to be sure.[38] 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.[39]

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As an experiment I placed the penultimate draft of the article on the World Wide Web and asked for comments and advice from three Internet discussion lists.[40] The

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[37]For example the iron artefacts found in a Yuan shipwreck are mostly of wrought iron, except a few for which cast iron is technically a more appropriate material. Zhu Jinsheng 1978; Anon. 1978a.

[38]On the iron coinage of the Song period see e.g. Hartwell 1967b; L. S. Yang 1952: 27–9.

[39]Peter J. Golas in Needham 1999: 370–86.

[40]Archaeometallurgy <arch-metals@mailbase.ac.uk>; East Asian Archaeology <eaan@ccat.sas.upenn.edu>; East Asian Science <easci@ccat.sas.upenn.edu>.

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.

References

Alley, Rewi. 1961. *Together they learnt how to make iron and steel. Some early types of furnaces used in 1958–9, in China.* An unpublished album of 299 photographs; this and most of the original negatives are in the collection of the Needham Research Institute, Cambridge.

Angus, H. T. (ed.) 1976. *Cast iron: Physical and engineering properties*. 2nd ed., London: Butterworth.

Anon. 1918. "Järnhandtering i Europa under midten af 1700-talet." *Blad för bergshandteringens vänner*, 1916/18, **15**: 125–40.

Anon. 1978a. "Cixian Yuan-dai muchuan chutu tieqi jinxiang jianding 磁縣元代木船出土鐵器金相鑑定 (Metallographic examination of iron artefacts unearthed from Yuan-period shipwrecks in Ci County, Hebei). By the Editorial Committee for "The History of Metallurgy in China" 中國冶金史編寫組 and the Metallography Group, Capital Iron and Steel Company Research Institute 首鋼研究所金相組. *Kaogu* 考古 ("Archaeology"), 1978.6: 400–401 + pl. 10. Tr. by DBW, Dien et al. 1985: 1946–8.

Anon. 1978b. *Zhongguo yejin jianshi* 中國冶金簡史 (A concise history of metallurgy in China). By an ad hoc editorial group under the Beijing University of Iron and Steel Technology 北京鋼鐵學院《中國冶金簡史》編寫組. Beijing: Kexue Chubanshe.

Ashton, T. S. 1925. 'The discoveries of the Darbys of Coalbrookdale.' *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, 1924/25, **5**: 9–14.

Birch, Alan. 1955. "Foreign observers of the British iron industry during the eighteenth century." *Journal of economic history*, **15**.1: 23–33.

Birch, Alan. 1967. *The economic history of the British iron and steel industry, 1784–1879: Essays in industrial and economic history with special reference to the development of technology*. London: Cass.

Cen Zhongmian 岑仲勉. 1966. *Zhong-wai shi-di kaozheng* 中外史地考證 (Researches on Chinese and foreign historical geography). Orig. Zhonghua Shuju, 1962; repr. Hong Kong: Taiping Shuju 太平書局.

Chaloner, W. H. 1950. "Further light on the invention of the process for smelting iron ore with coke." *Economic history review*, 2nd ser., 1949/50, **2**.2: 185–187.

Chen Zhongguang 陳仲光. 1959. "Tongan faxian gudai liantie yizhi 同安發現古代煉鐵遺址" (An ancient iron-smelting site discovered in Tongan County, Fujian). *Wenwu* 文物 ("Cultural relics"), 1959.2: 75.

Chevalier, Jean. 1949. "La mission de Gabriel Jars dans les mines et les usines britanniques en 1764." *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, 1947–9, **26**: 57–68. English tr. by J. F. Petree.

Clark, Catherine. 1993. *English Heritage book of Ironbridge Gorge*. London: Batsford / English Heritage.

Cox, Nancy. 1990. "Imagination and innovation of an industrial pioneer: The first Abraham Darby." *Industrial archaeology review*, **12**.2: 127–44.

Deng Daolian 鄧道煉. 1991. "Jiangxi Yongping tieye yizhi chutan 江西永平鐵冶遺址初探" (Preliminary study of ironworks sites in Yongping County, Jiangxi). *Jiangxi wenwu* 江西文物 (Cultural relics of Jiangxi), 1991.3: 33–5.

Dickson, W. 1864. "Narrative of an overland trip, through Hunan, from Canton to Hankow." *Journal of the North China Branch of the Royal Asiatic Society*, N.S., **1**: 159–73.

Dien, Albert E., Jeffrey K. Riegel, & Nancy T. Price (eds.). 1985. *Chinese archaeological abstracts,* vols. 2–4. Los Angeles: Institute of Archaeology, University of California. (*Monumenta archaeologica*, vols. 9–11.)

DNB. *Dictionary of national biography, from the earliest times to 1900.* Orig. 1885–1901; facs. repr. Oxford: Oxford University Press, 1973.

Dobson, Philippa 1982. *The 250th anniversary of the first successful use of coke in ironmaking: A select bibliography*. London: School of Library and Information Studies, Ealing College of Higher Education. (*Ealing miscellany*, 25).

Dudley, Dud. 1665. *Dud Dudley's Metallum Martis, or, Iron made with pit-coale, sea-coale, &c. And with the same fuell to melt and fine imperfect mettals, and refine perfect mettals*. London: the author, 1665. Repr. West Bromwich, 1851.

Elvin, Mark. 1975. "Skills and resources in late traditional China." Perkins 1975: 85–113.

Feng Chengjun 馮承鈞 & Lu Junling 陸峻嶺 (eds.). 1980. *Xiyu diming (zengdingben)* 西域地名（增訂本）(Historical place-names of the Western Regions, revised). Orig. 1930; 1st rev. ed. 1955; 2nd rev. ed. Beijing: Zhonghua Shuju.

Flinn, Michael W. 1959. "The travel diaries of Swedish engineers of the eighteenth century as sources of technological history." *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, **31**: 95–109.

Flinn, Michael W. 1962. "William Wood and the coke-smelting process." *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, **34**: 55–71.

Gale, W. K. V. 1979. *The Black Country iron industry: A technical history*. 2nd ed., London: The Metals Society. 1st ed. 1966.

Gericke, Hans Otto. 1999. "Die Verwendung von Koks bei der Erzverhüttung im mitteldeutschen Raum um 1584." *Technikgeschichte*, **66**.2: 87–113.

Gille, Bertrand 1946. "L'Utilisation de la houille en sidérurgie (Notes d'histoire de la technique métallurgique, II)." *Métaux et civilisations: Les métaux dans l'histoire, les techniques, les arts*, **1**.5: 99–104.

Golas, Peter J. *see* Needham 1999.

Grayson, Martin (ed.). 1985. *Kirk-Othmer concise encyclopedia of chemical technology*. 3rd ed., New York: Wiley.

Harris, J. R. 1988. *The British iron industry, 1700–1850*. Basingstoke & London: MacMillan Education.

Harris, J. R. 1998. *Industrial espionage and technology transfer: Britain and France in the eighteenth century*. Aldershot, Hants.: Ashgate.

Hartwell, Robert M. 1963. *Iron and early industrialism in eleventh-century China*. Ph.D. dissertation, University of Chicago.

Hartwell, Robert. 1966. "Markets, technology, and the structure of enterprise in the development of the eleventh-century Chinese iron and steel industry." *Journal of economic history*, **26**.1: 29–58.

Hartwell, Robert. 1967a. "A cycle of economic change in imperial China: Coal and iron in northeast China, 750–1350." *Journal of the economic and social history of the Orient*, **10**: 102–59.

Hartwell, Robert. 1967b. "The evolution of the early Northern Sung monetary system, A.D. 960–1025." *Journal of the American Oriental Society*, **87**: 280–89.

Heckscher, Eli F. 1935–49. *Sveriges ekonomiska historia från Gustav Vasa*. 4 vols., Stockholm: Albert Bonniers Förlag. Vol. 1, part 1: *Medeltidshushållningens organisering 1520–1600*, 1935; vol. 1, part 2: *Hushållningen under internationell påverkan, 1600–1720*, 1936; vol. 2, parts 1–2: *Det moderna Sveriges grundläggning, 1720–1815*, 1949.

Heckscher, Eli F. 1954. *An economic history of Sweden*. Cambridge, Mass.: Harvard University Press. (*Harvard economic studies*, 95). 2nd printing 1963. Orig. *Svenskt arbete och liv från medeltiden till nutid*, 1941.

Hodgkinson, Jeremy. 1994. "Fordley North Park: Coke smelting in the Weald?" *Journal of the Historical Metallurgy Society*, **28**.1: 11–13.

Hofberg, Herman. 1906. *Svenskt biografiskt handlexikon: Alfabetiskt ordnade lefnadsteckningar af Sveriges namnkundiga män och kvinnor från Reformationen till nuvarande tid. Ny upplaga*. 2 vols., Stockholm: Albert Bonniers Förlag.

Hu Yueqian 胡悅謙. 1959. "Fanchang xian gudai liantie yizhi 繁昌縣古代煉鐵遺址" (An ancient iron-smelting site in Fanchang County, Anhui). *Wenwu* 文物 ("Cultural relics"), 1959.7: 74.

Hua Jueming 華覺明. 1989. "The use of coal, briquetting and agglomeration in ancient Chinese metallurgy." Unpublished typescript, 1989, in the files of the Needham Research Institute, Cambridge. 5 pp.

Hyde, Charles K. 1977. *Technological change and the British iron industry, 1700–1870*. Princeton, N. J.: Princeton University Press.

Igaki, Kenzo. 1994. "14C dating study of ancient iron artifacts." In *BUMA-3: The Third International Conference on the Beginning of the Use of Metals and Alloys, 18–23 April 1994*, Sanmenxia; pp. 38–9.

Ince, Laurence 1991. "The introduction of coke iron at the Stour forges of the Knight family." *Journal of the Historical Metallurgy Society*, **24**.2: 107–13.

Jizhu fenlei Dongpo Xiansheng shi 東坡先生詩 (Poems of Su Shi 蘇軾, classified and annotated). Ed. by Wang Shipeng 王十朋. Facs. repr. of a Song edition with title *Zengkan jiaozheng Wang Zhuangyuan jizhu fenlei Dongpo shi* 增刊校正王狀元集注分類東坡先生詩, *Sibu congkan* 四部叢刊.

Karlgren, Bernhard. 1942–6. “Glosses on the Book of Odes.” *Bulletin of the Museum of Far Eastern Antiquities*, 1942, **14**: 71–247; 1944, **16**: 25–169; 1946, **18**: 1–198. Repr. in a single vol., Göteborg: Elanders Boktryckeri, 1964.

Karlgren, Bernhard (tr.). 1950. *The book of odes: Chinese text, transcription and translation*. Stockholm: Museum of Far Eastern Antiquities.

Ke Jun (ed.) 柯俊. 1986. *Zhongguo yejin shi lunwenjii* 中國冶金史論文集 (Essays on the history of metallurgy in China [reprints of 33 articles]). Beijing: Beijing Gangtie Xueyuan 北京鋼鐵學院. English summaries pp. A1–A74.

King, P. W. 1996. “Dud Dudley and pit-coal iron.” *The Blackcountryman*, **29**.3: 23–4.

King, P. W. [2002]. “Sir Clement Clerke and the adoption of coal in metallurgy.” forthcoming in *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*.

Li Chiao-ping [Li Qiaoping 李喬平] (et al., trs.). 1980. *Tien-kung-kai-wu. Exploitation of the work of Nature: Chinese agriculture and technology in the XVII century, by Sung Ying-sing*. Taipei: China Academy. (*Chinese culture series*, 2–3).

Li Jinghua 李京華. 1992. “Henan sheng wu xian gudai tie kuangye yizhi diaocha 河南省五縣古代鐵礦冶遺址調查” (Investigation of iron mining and smelting sites in five counties of Henan province), by Henan Provincial Institute of Cultural Relics 河南省文物研究所 and the Historical Metallurgy Group , Beijing University of Science and Technology 北京科技大學中國冶金史研究室; written by —. *Huaxia kaogu* 華夏考古 (“Huaxia Archaeology”), 1992.1: 44–62.

Li Xiaoping 李小平. 1995. “Xinyu gudai yetie kaoxi 新餘古代冶鐵考析” (A study of ancient iron metallurgy in Xinyu, Jiangxi). *Nanfang wenwu* 南方文物 (“Relics from South”), 1995.3: 108–11.

Liu Junwen 劉俊文 (ed.). 1992. *Riben xuezhe yanjiu Zhongguo shi lunzhu xuanyi. 10: Kexue jishu* 日本學者研究中國史論著選譯, 第十卷， 科學技術 (Selected translations of essays on Chinese history by Japanese scholars. Vol. 10: Science and technology). Beijing: Zhonghua Shuju.

Liu Yuncai 劉雲彩. 1978. “Zhongguo gudai gaolu de qiyuan he yanbian 中國古代高爐的起源和演變” (The origin and development of the blast furnace in ancient China). *Wenwu* 文物 (“Cultural relics”), 1978.2: 18–27.

Lux, Fr. 1912. “Koksherstellung und Hochofenbetrieb im Innern Chinas.” *Stahl und Eisen*, **22**.34: 1404–7.

Massari, S. C. 1938. “The properties and uses of chilled iron.” *Proceedings of the American Society for Testing Metals*, **38**: 217–234. Discussion, pp. 233–234.

Menzies, Nicholas K. *see* Needham 1996.

Morrah, Patrick. 1976. *Prince Rupert of the Rhine*. London: Constable.

Morton, Geo. R. 1966. “The early coke era.” *Bulletin of the Historical Metallurgy Group*, **6**: 53–58.

Morton, G. R. & M. D. G. Wanklyn 1967. “Dud Dudley – A new appraisal.” *Journal of West Midlands regional studies*, **1**: 48–65.

Mott, R. A. 1935. “Dud Dudley and the early coal-iron industry.” *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology,* 1934/35, **15**: 17–37.

Mott, R. A. (ed.) 1936. *The history of coke making and of the Coke Oven Managers’ Association*. Heffer, Cambridge, 1936.

Mott, R. A. 1959a. “Abraham Darby (I and II) and the coal–iron industry.” *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, 1957–8 & 1958–9, **31**: 49–93.

Mott, R. A. 1959b. “The Coalbrookdale Group Horsehay Works (Parts I–II),” *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, 1959, **31**: 271–87; 1961, **32**: 43–56.

Needham, Joseph. 1958. *The development of iron and steel technology in China*. London: The Newcomen Society. Second Dickinson Memorial Lecture to the Newcomen Society, 1956.

Needham, Joseph. 1965. *Science and civilisation in China*. Vol. 4: *Physics and physical technology.* Part 2: *Mechanical engineering.* Cambridge: Cambridge University Press.

Needham, Joseph. 1996. *Science and civilisation in China*. Vol. 6: *Biology and biological technology*. Part 3: *Agro-industries and forestry*, by Christian Daniels; *Forestry*, by Nicholas K. Menzies. Cambridge: Cambridge University Press.

Needham, Joseph. 1999. *Science and civilisation in China*. Vol. 5: *Chemistry and chemical technology*. Part 13: *Mining*, by Peter J. Golas. Cambridge: Cambridge University Press.

Ouyang Wenzhong ji 歐陽文忠集 (Collected works of Ouyang Xiu 歐陽修). *Sibu beiyao* 四部備要 ed.

Ouyang Yongshu ji 歐陽永叔集 (Collected works of Ouyang Xiu 歐陽修). *Guoxue jiben congshu* 國學基本叢書 ed.

Peng Zhensheng 彭振聲 & Li Xiaoping 李小平. 1992. “Jiangxi Xinyu shi Fenyi xian gu kuangye yizhi diaocha jianbao 江西新餘市分宜縣古礦冶遺址調查簡報” (Preliminary report on a survey of ancient mining and smelting sites in Fenyi County, Xinyu Municipality, Jiangxi). *Nanfang wenwu* 南方文物 (“Relics from South”), 1992.2: 8–15.

Percy, John. 1861. *Metallurgy: The art of extracting metals from their ores, and adapting them to various purposes of manufacture.* [Vol. 1:] *Fuel; fire-clays; copper; zinc; brass; etc*. London: John Murray. Facs. repr. in 2 pts., Eindhoven: De Archaeologische Pers Nederland, n.d. [ca. 1985].

Percy, John. 1864. *Metallurgy* . . . [Vol. 2:] *Iron; steel*. London: John Murray. Facs. repr. in 3 pts., Eindhoven: De Archaeologische Pers Nederland, n.d. [ca. 1983].

Perkins, Dwight H. (ed.) 1975. *China’s modern economy in historical perspective*. Stanford: Stanford University Press.

Pfannenschmidt, Carl W. 1977. *Die Anwendung des Holzkohlenhochofens seit Ende des 16. Jahrhunderts zur Erzeugung von Gusswaren erster Schmelzung und die spätere zweite Schmelzung in Flamm- und Kupolöfen bis Mitte des 19. Jahrhunderts*. Düsseldorf : Verein Deutscher Eisenhüttenleute. (Verein Deutscher Eisenhüttenleute, *Fachausschussbericht*, 9.007).

Pitt, G. J. & G. R. Millward (eds.) 1979. *Coal and modern coal processing: An introduction*. London / New York / San Francisco: Academic Press.

Qiu Shihua 仇士華 & Cai Lianzhen 蔡蓮珍. 1986 "Woguo gudai yetie ranliao de tan-shisi jianding 我國古代冶鐵燃料的碳十四鑒定" (Use of radiocarbon dating to determine the fuel used in ancient Chinese iron-smelting). Wang Zhongshu & An Zhimin 1986: 359–63.

Raistrick, Arthur 1989. *Dynasty of ironfounders: The Darbys and Coalbrookdale*. 2nd ed., York: Ironbridge Gorge Museum Trust & Sessions Book Trust. First publ. 1953; repr. David & Charles, Newton Abbot, 1970.

Read, Thomas T. 1940. "The earliest industrial use of coal." *Transactions of the Newcomen Society for the Study of the History of Engineering and Technology*, 1939–40, **20**: 119–33.

Rehder, J. E. 1987. "The change from charcoal to coke in iron smelting." *Journal of the Historical Metallurgy Society*, **21**.1: 37–43.

Rehder, J. E. 1998. 'Abraham Darby and coke in the blast furnace.' *Iron and steelmaker*, December 1998, 29–33.

Ren Zhiyuan 任志遠. 1957. "Shahe xian de gudai yetie yizhi 沙河縣的古代冶鐵遺址" (Ancient ironworks sites in Shahe County, Hebei), *Wenwu* 文物 ("Cultural relics"), 1957.6: 84.

von Richthofen, Ferdinand. [1872?]. *Baron Richthofen's letters, 1870–1872* [to the Shanghai Chamber of Commerce]. Shanghai: North China Herald, n.d.

von Richthofen, Ferdinand. 1877–1912. *China: Ergebnisse eigener Reisen und darauf gegründeter Studien*. 5 vols., Berlin: Dietrich Reimer, Bd. 1: *Einleitender Theil*, 1877. Bd. 2: *Das nördliche China*, 1882. Bd. 3: *Das südliche China*, nach den hinterlassenen Manuscripten im letztwilligen Auftrag des Verfassers hrsg. v. Ernst Tiessen, 1912. Bd. 4–5: *Palaeontologischer Theil* . . . , 1883–1911.

von Richthofen, Ferdinand. 1907. *Ferdinand von Richthofen's Tagebücher aus China*. Ausgew. u. hrsg. v. E. Tiessen. 2 vols., Berlin: Dietrich Reimer.

Riden, Philip. 1992. “Some unsuccessful blast furnaces of the early coke era.” *Journal of the Historical Metallurgy Society*, **26**: 36–44.

Riden, Philip. 1994. “The final phase of charcoal iron-smelting in Britain, 1660–1800.” *Journal of the Historical Metallurgy Society*, **28**.1: 14–26.

Rostoker, William & Bennet Bronson 1990. *Pre-industrial iron: Its technology and ethnology*. Philadelphia: privately published. (*Archeomaterials monograph*, no. 1).

Rostoker, William; Bennet Bronson, & James Dvorak. 1984. “The cast iron bells of China.” *Technology and culture*, **25**.4: 750–767.

Rydberg, Sven 1951. *Svenska studieresor till England under Frihetstiden*. Uppsala: Almqvist & Wiksell. (*Lychnos-bibliotek*, 12).

Saito, Tsutomu. 1994. “Development of new methods for isotope analysis on ancient metal objects – lead isotope and C-14 measurements.” In *BUMA-3: The Third International Conference on the Beginning of the Use of Metals and Alloys, 18–23 April 1994*, Sanmenxia; pp. 40–41.

Sivin, N. (tr.) 1973. “Coal, by Su Shih.” *Technology Studies bulletin*, **1**: 33.

Sjögren, Hj. (tr.) 1923. *Mineralriket, av Emanuel Swedenborg: Om järnet och de i Europa vanligast vedertagna järnframställningssätten* . . . Stockholm: Wahlström & Widstrand. Swedish tr. of Swedenborg 1734.

Song huiyao jigao 宋會要楫稿 (Draft collection of fragments of “Collected documents of the Song dynasty”). 1935; facs. repr., 8 vols., Zhonghua Shuju, Beijing, 1957.

Sun, E-tu Zen & Shiou-chuan Sun (trs.) 1966. *T’ien-kung k’ai-wu: Chinese technology in the seventeenth century*. University Park & London: Pennsylvania State University Press.

Swedenborg, Emanuel. 1734. *Regnum subterraneum sive minerale.* [Vol. 2:] *De ferro, deque modis liquationum ferri per Europam passim in usum receptis* . . . Dresdæ et Lipsiæ: Friderici Hekelii. Tr. Swedenborg 1762; Sjögren 1923.

Swedenborg, Emanuel. 1762. *Traité du fer*, par M. Swedemborg; trad. du Latin par M. Bouchu. Paris: Guerin et Delatour. (*Description des arts et métiers: Art des forges et fourneaux à fer*, par M. le Marquis de Courtivron et par M. Bouchu; 4ème section). [Réimp. Slatkine Reprints, Genève, 1984.]

Taiping yulan 太平御覽 (Encyclopedia of the Taiping Xingguo 太平興國 reign [976–84], prepared for the press by the Emperor). Comp. by Li Fang 李昉 (925–96). Facs. repr. from fragmentary Song eds., 4 vols., 1960; repr. Beijing: Zhonghua Shuju, 1985.

Tang Yunming 唐雲明. 1959. "Hebei Xingtai faxian Song mu he yetie yizhi 河北邢台發現宋墓和冶鐵遺址" (A Song burial and an ironworks site discovered in Xingtai Municipality, Hebei). *Kaogu* 考古 ("Archaeology"), 1959.7: 369.

Tegengren, F. R. 1923–24. *The iron ores and iron industry of China: Including a summary of the iron situation of the circum-Pacific region*. 2 vols., Peking: Geological Survey of China, Ministry of Agriculture and Commerce. (*Memoirs of the Geological Survey of China, series A*, no. 2). Part I 1921–23, part II 1923–24. English text; abridged Chinese translation by Xie Jiarong 謝家榮. Chinese title: *Zhongguo tiekuang ji* 中國鐵礦誌 , by Ding Gelan 丁格蘭 (*Dizhi zhuanbao*, A.2 地質專報甲種第二號). Xerographic repr. available from University Microfilms, Ann Arbor, Mich., order no. OP 12715.

Treadwell, J. M. 1974. "William Wood and the Company of Ironmasters of Great Britain." *Business history*, **16**.2: 97–112.

Trinder, Barrie. 1988. *"The most extraordinary district in the world": Ironbridge and Coalbrookdale. An anthology of visitors' impressions of Ironbridge, Coalbrookdale and the Shropshire coalfield.* 2nd ed., Chichester, West Sussex: Philimore / Ironbridge Gorge Museum Trust. 1st ed. 1977.

Wagner, Donald B. 1984. "Some traditional Chinese iron production techniques practiced in the 20th century." *Journal of the Historical Metallurgy Society*, **18**.2: 95–104.

Wagner, Donald B. 1985. *Dabieshan: Traditional Chinese iron-production techniques practised in southern Henan in the twentieth century*. London & Malmö: Curzon Press. (*Scandinavian Institute of Asian Studies monograph series*, no. 52).

Wagner, Donald B. 1993. *Iron and steel in ancient China.* Leiden: Brill. (*Handbuch der Orientalistik, vierte Abteilung: China*, no. 9).

Wagner, Donald B. 1997. *The traditional Chinese iron industry and its modern fate.* Richmond, Surrey: Curzon Press. (Nordic Institute of Asian Studies, *NIAS Report series,* 32).

Wagner, Donald B. 2001a. *The state and the iron industry in Han China*. Copenhagen: Nordic Institute of Asian Studies.

Wagner, Donald B. [2001b]. "Research note: The administration of the iron industry in Song China", forthcoming in *Journal of the economic and social history of the Orient*.

Wang Guowei 王國維 (ed.). 1984. *Shui jing zhu jiao* 水經注校 (Critical edition of the "Commentary on the Classic of waterways"). Typeset edition, ed. by Yuan Yingguang 袁英光 & Liu Yinsheng 劉寅生, Shanghai: Shanghai Renmin Chuanshe.

Wang Ling. 1982. "The history of the use of coal by the Chinese in early periods." Unpublished typescript in the files of the Needham Research Institute, Cambridge. 25 pp.

Wang Yongxiang 王永祥. 1965. “Heilongjiang Acheng xian Xiaoling diqu Jin-dai yetie yizhi 黑龍江阿城縣小嶺地區金代冶鐵遺址” (Jin-period ironworks sites in Xiaoling Region, Acheng County, Heilongjiang). By Heilongjiang Provincial Museum; written by —. *Kaogu* 考古 (“Archaeology”), 1965.3: 124–30 + plates 6–7.

Wang Zhaosheng 王兆生. 1994. “Longyan tiekuang kuangqu faxian Liao-dai liantie yizhi — gai kuang you waiguoren faxian de lishi jiang gaixie 龍煙鐵礦礦區發現遼代煉鐵遺址 — 該礦占峭外國人發現的歷史將改寫” (A Liao-period ironworks discovered at Longyan Iron Mine [in Chicheng 赤城 and Xuanhua 宣化 Counties, Hebei]: The history of the mine’s discovery by foreigners is to be rewritten). *Wenwu chunqiu* 文物春秋 (Annals of cultural relics), 1994.1: 83–5.

Wang Zhongshu 王仲殊 & An Zhimin 安志敏. 1986. *Zhongguo kaoguxue yanjiu – Xia Nai xian-sheng kaogu wushi nian jinian lunwenji* 中國考古學研究—夏鼐先生考古五十年紀姑擠蚺撊迴 (“Archaeological researches in China: A collection of papers in commemoration of the fiftieth year of Prof. Xia Nai’s work in archaeology”). Comp. by an ad hoc editorial committee 《中國考古學研究》編委會; preface by —. Beijing: Wenwu Chubanshe.

Wertime, Theodore A. 1961. *The coming of the age of steel*. Leiden: E. J. Brill.

Woo, Yang Tsang. 1906. “The manufacture of coke in northern China.” *Transactions of the American Institute of Mining Engineers*, **36**: 661–4.

Wu Kunyi 吳坤儀 & Yu Xiaoxing 于曉興. 1984 “Xingyang Chucun Yuan-dai zhuzao yizhi de shijue yu yanjiu 滎陽楚村元代鑄造遺址的試掘與研究” (Trial excavation and study of a Yuan-period foundry site at Chucun in Xingyang County, Henan). Repr. Ke Jun (1986: 171–9 + Eng. abstract p. A63). Orig. *Zhongyuan wenwu* 中原文物 (“Cultural relics from the Central Plains”), 1984 (*tekan* 特刊): 60–70.

Xu Huimin 許惠民. 1987. “Bei Song shiqi meitan de kaifa liyong 北宋時期煤炭的開發利用” (The exploitation and use of coal in the Northern Song period). *Zhongguo shi yanjiu* 中國史研究 (Studies in Chinese history), 1987.2: 141–52.

Xu Zizhi tongjian changbian 續資治通鑑長編. (Collected data for a continuation of the *Comprehensive mirror for aid in government*). Comp. by Li Dao 李燾 (1115–1184). Edition Zhejiang Shuju 浙江書局, 1881.

Yabuuchi Kiyoshi 藪內清 (tr.). 1969. *Tenkō kaibutsu* 天工開物 (Japanese translation of *Tian-gong kai-wu*, by Song Yingxing 宋應星). Tōkyō: Heibonsha, 1969 (*Tōyō bunko* 東洋文庫, 130).

Yang Kuan 楊寬. 1960. *Zhongguo tufa yetie lian-gang jishu fazhan jianshi* 中國土法冶鐵煉鋼技術發展簡史 (A brief history of the development of Chinese regional siderurgical techniques). Shanghai: Renmin Chubanshe.

Yang Kuan 楊寬. 1982. *Zhongguo gudai yetie jishu fazhan shih* 中國古代冶鐵技術發展史 (The history of the development of siderurgical technology in ancient China). Shanghai: Renmin Chubanshe.

Yang, Lien-sheng [楊聯陞]. 1952. *Money and credit in China: A short history*. Cambridge, Mass.: Harvard University Press. (*Harvard–Yenching Institute Monograph series*, 12).

Yates, W. Ross. 1974. "Discovery of the process for making anthracite iron." *Pennsylvania magazine of history and biography*, **98**.2: 206–23.

Yoshida Mitsukuni 吉田光邦. 1966. "Sodai no tetsu ni tsuite 宋代の鐵について" (On iron in the Sung period). *Tōyō shi kenkyū* 東洋史研究, **24**.4: 508–24 + Eng. abstract pp. 5–6. Repr. Yoshida 1972: 353–71. Chinese translation Liu Junwen 1992: 184–201.

Yoshida Mitsukuni 吉田光邦. 1972. *Chūgoku kagaku gijutsu shi ronshū* 中國科學技術史論集 (Essays on the history of science and technology in China). Tōkyō: Nihon Hōsō Shuppan Kyōkai 日本放送出版協會.

Zhong Guangyan 鍾廣言 (ed. & tr.) 1978. *Tian-gong kai-wu* 天工開物 (An edition and translation of *Tian-gong kai-wu*, by Song Yingxing 宋應星). Repr. Hong Kong: Zhonghua Shuju.

Zhu Jinsheng 朱金升. 1978. "Hebei Cixian Nankaihecun Yuan-dai muchuan fajue jianbao 河北磁縣南開河村元代木船發掘簡報" (Excavation of six Yuan-period shipwrecks at Nankaihecun in Ci County, Hebei). By Ci County Cultural Office 磁縣文化館; written by —. *Kaogu* 考古 ("Archaeology"), 1978.6: 388–99 + pl. 5–8.

Figure captions

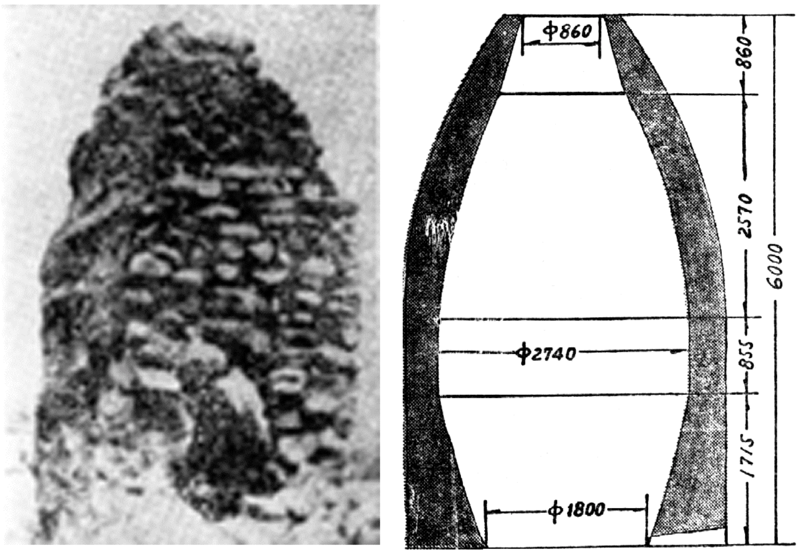


Figure 1. A Song-period blast furnace, still standing at Kuangshancun 礦山村 near Handan, Hebei. **Left:** Photograph, originally in *Guangming ribao*, 13 December 1959, here reproduced from Liu Yuncai 1978: 23, fig. 8. **Right:** Liu Yuncai's reconstruction of the furnace. Cf. Figures 2–3.

Figure 2. Blast furnaces in western Hunan, 1958, photographed by Rewi Alley (1961, no. 10). Cf. Figure 3.

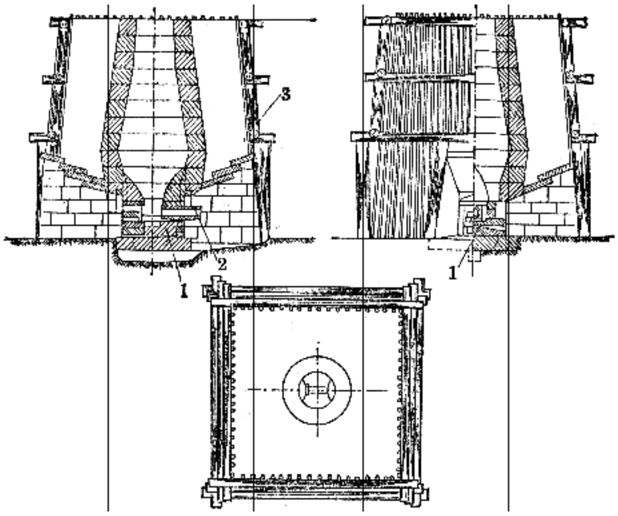


Figure 3. Diagram of a blast furnace in Sichuan, ca. 1958, reproduced from Yang Kuan 1982: 185, fig. 47. Cf. Figure 2.

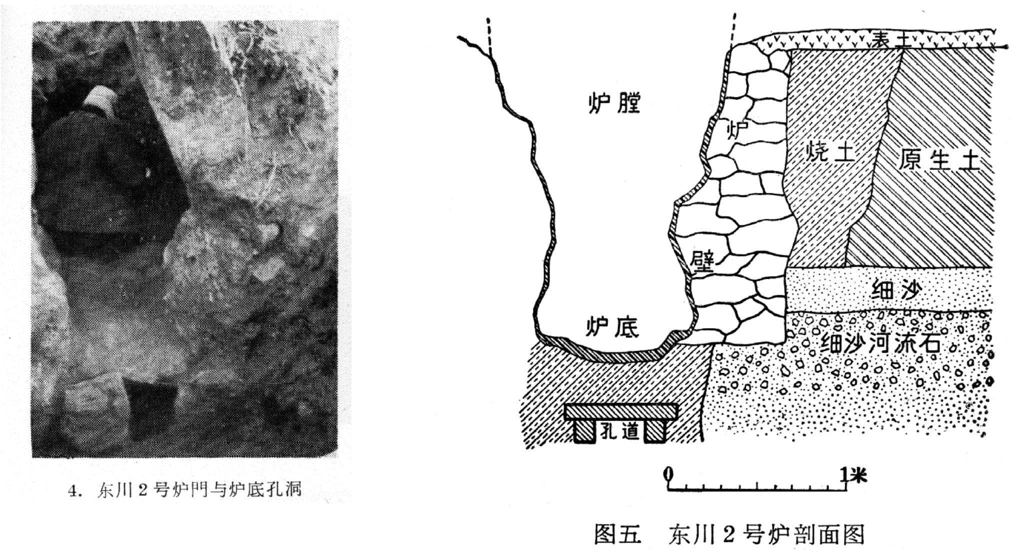
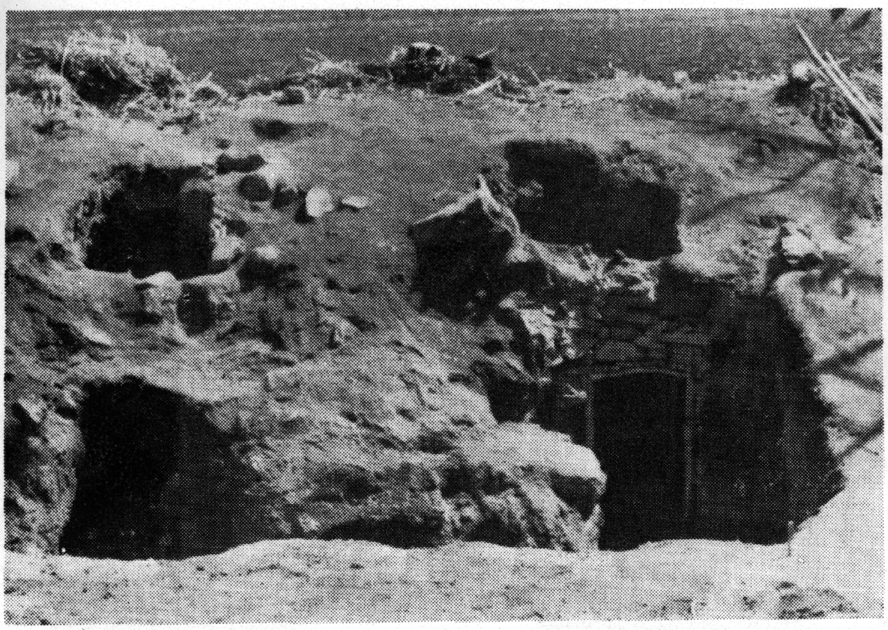
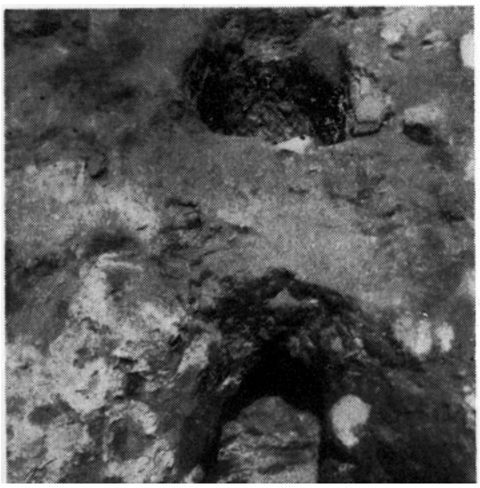


Figure 4. Photograph and diagram of blast furnace no. 2 at Dongchuan 東川 in Acheng 阿城 County, Heilongjiang, reproduced from Wang Yongxiang 1965: 127, fig. 5, pl. 7.4. The scale shows 1 m.



1. 东川4、5号炉全貌(左、5号炉,右、4号炉)

Figure 5. 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 6.



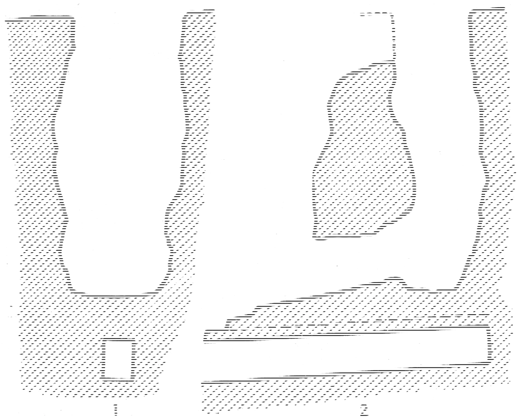


Figure 6. Photograph and diagram of blast furnace no. 5 at Dongchuan in Acheng County, Heilongjiang, reproduced from Wang Yongxiang 1965: 128, fig. 6, pl. 6.3. See also Figure 5.

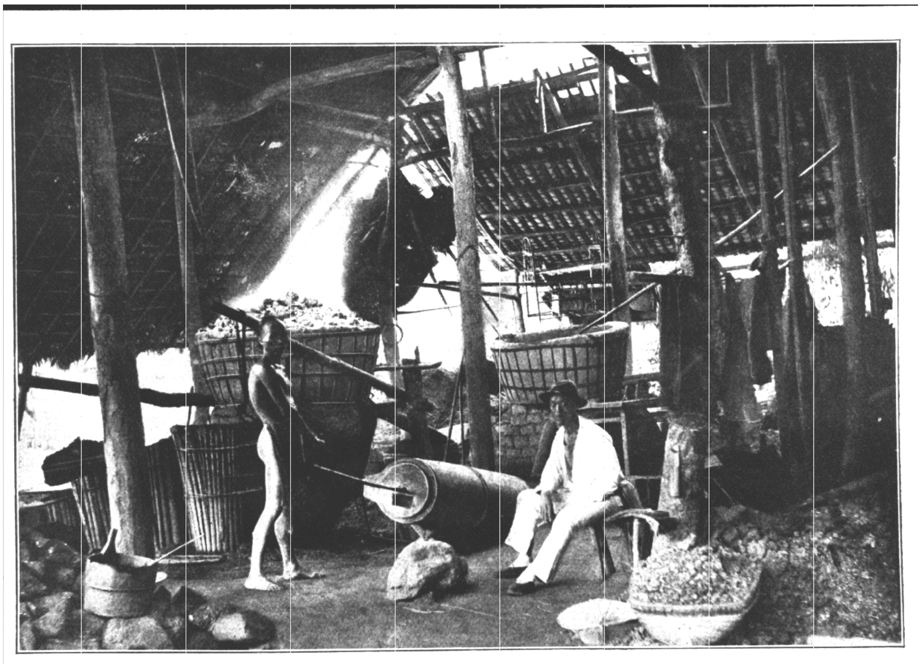


Figure 7. An ironworks in central China (either Jiangxi or Hunan), photographed ca. 1910. Reproduced from Lux 1912, p. 140.