THE PICTURE OF THE TAOIST GENII PRINTED ON THE COVER of this book is part of a painted temple scroll, recent but traditional, given to Mr Brian Harland in Sichuan province (1946) by the philologist and epigrapher Wen You 聞宥 (1901–1985). Concerning these four divinities, of respectable rank in the Taoist bureaucracy, the following particulars have been handed down. The title of the first of the four signifies 'Heavenly Prince', that of the other three 'Mysterious Commander'.

At the top, on the left, is Liu *Tian Jun*, Comptroller-General of Crops and Weather. Before his deification (so it was said) he was a rain-making magician and weather forecaster named Liu Jun, born in the Jin dynasty about +340. Among his attributes may be seen the sun and moon, and a measuring-rod or carpenter's square. The two great luminaries imply the making of the calendar, so important for a primarily agricultural society, the efforts, ever renewed, to reconcile celestial periodicities. The carpenter's square is no ordinary tool, but the gnomon for measuring the lengths of the sun's solstitial shadows. The Comptroller-General also carries a bell because in ancient and medieval times there was thought to be a close connection between calendrical calculations and the arithmetical acoustics of bells and pitch-pipes.

At the top, on the right, is Wen *Yuan Shuai*, Intendant of the Spiritual Officials of the Sacred Mountain, Tai Shan. He was taken to be an incarnation of one of the Hour-Presidents (*Jia Shen*), i.e. tutelary deities of the twelve cyclical characters (see vol. 4, pt. 2, p. 440). During his earthly pilgrimage his name was Huan Ziyu and he was a scholar and astronomer in the Later Han (*b.* +142). He is seen holding an armillary ring.

Below, on the left, is Gou *Yuan Shuai*, Assistant Secretary of State in the Ministry of Thunder. He is therefore a late emanation of a very ancient god, Lei Gong. Before he became deified he was Xin Xing, a poor woodcutter, but no doubt an incarnation of the spirit of the constellation Gou Chen (the Angular Arranger), part of the group of stars which we know as Ursa Minor. He is equipped with hammer and chisel.

Below, on the right, is Bi *Yuan Shuai*, Commander of the Lightning, with his flashing sword, a deity with distinct alchemical and cosmological interests. According to tradition, in his early life he was a countryman whose name was Tian Hua. Together with the colleague on his right, he controlled the Spirits of the Five Directions.

Such is the legendary folklore of common men canonised by popular acclamation. An interesting scroll, of no great artistic merit, destined to decorate a temple wall, to be looked upon by humble people, it symbolises something which this book has to say. Chinese art and literature have been so profuse, Chinese mythological imagery so fertile, that the West has often missed other aspects, perhaps more important, of Chinese civilisation. Here the graduated scale of Liu Jun, at first sight unexpected in this setting, reminds us of the ever-present theme of quantitative measurement in Chinese culture; there were rain-gauges already in the Song (+12th century) and sliding calipers in the Han (+1st). The armillary ring of Huan Ziyu bears witness that Naburiannu and Hipparchus, al-Naqqās and Tycho, had worthy counterparts in China. The tools of Xin Xing symbolise that great empirical tradition which informed the work of Chinese artisans and technicians all through the ages.

SCIENCE AND CIVILISATION IN CHINA

Joseph Needham
(1900–1995)

Certain it is that no people or group of peoples has had a monopoly in contributing to the development of Science. Their achievements should be mutually recognised and freely celebrated with the joined hands of universal brotherhood.
Science and Civilisation in China VOLUME I, PREFACE

*

Joseph Needham directly supervised the publication of seventeen books in the *Science and Civilisation in China* series, from the first volume, which appeared in 1954, through to Volume VI.3, which was in press at the time of his death in March 1995.

The planning and preparation of further volumes will continue. Responsibility for the commissioning and approval of work for publication in the series is now taken by the Publications Board of the Needham Research Institute in Cambridge, under the chairmanship of Dr Christopher Cullen, who acts as general editor of the series.

中國科學技術史

李約瑟著

冀朝鼎

JOSEPH NEEDHAM

SCIENCE AND CIVILISATION IN CHINA

VOLUME 5

CHEMISTRY AND CHEMICAL TECHNOLOGY

PART 11: FERROUS METALLURGY

BY

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Dedicated to

LI JINGHUA 李京華

and to the memory of

RONALD FRANK TYLECOTE

Two archaeometallurgists, East and West, who can represent
here the hundreds of metallurgists, archaeologists, and historians
on whose work this volume is based.

*Nous nous devons premièrement à notre Patrie; mais nous nous
devons aussi au reste du monde; ceux qui travaillent pour
perfectionner les Sciences & les Arts, doivent même se regarder
comme les Citoyens du monde entier.*
René Antoine Ferchault de Réaumur (1722)

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TEXT BOXES

ABBREVIATIONS

CSJC	*Cong shu ji cheng* 叢書集成.
DMHD	*Da Ming hui dian* 大明會典.
DNB	*Dictionary of national biography* (Anon., 1885–1901).
GSR	*Grammata Serica recensa* (Karlgren, 1957). References give entry number.
HHS	*Hou Han shu* 後漢書.
HMJS	*Huang Ming jing shi wen bian* 皇明經世文編.
HS	*Han shu* 漢書.
MSL	*Ming shi lu* 明實錄.
SBBY	*Si bu bei yao* 四部備要.
SBCK	*Si bu cong kan* 四部叢刊.
SCC	Joseph Needham, *Science and civilisation in China* (1954 ff).
SHY:SH	*Song hui yao ji gao* 宋會要輯稿, *Shi huo* 食貨 section.
SHY:XF	*Song hui yao ji gao* 宋會要輯稿, *Xing fa* 刑法 section.
SHY:ZG	*Song hui yao ji gao* 宋會要輯稿, *Zhi guan* 職官 section.
SJ	*Shi ji* 史記.
SKQS	*Si ku quan shu* 四庫全書.
SS	*Song shi* 宋史.
SSJZS	*Shi san jing zhu shu* 十三經注疏.
TGKW	*Tian gong kai wu* 天工開物.
TPYL	*Tai ping yu lan* 太平御覽.
WX	*Wen xuan* 文選.
WXTK	*Wen xian tong kao* 文獻通考.
XZZTJCB	*Xu Zi zhi tong jian chang bian* 續資治通鑑長編.
YTL	*Yan tie lun* 鹽鐵論.

PREFACE

Vita pro ferro, the title of a Festschrift for the metallurgist Robert Durrer,[1] gave me a laugh when I first saw it. Now, years later, I find that I have spent half my life researching and writing on ferrous metallurgy and its history. How did this happen?

I was about 25, a beginning student of Chinese with a degree in mathematics and a brilliant future in computer systems behind me, when a teacher introduced me to *Science and Civilisation in China*. I was attracted immediately to Joseph Needham's erudition, to his clear and precise language, and perhaps most of all to his use of his scientific background in a constant concern for 'brass tacks'. At that time four volumes had appeared; I devoured these, and most of the following volumes as they appeared. Today I count Joseph Needham's work as one of the most important components of my basic sinological education, and one of the models constantly before me in my career of research and writing.

My first research was in the history of mathematics in China, but after a conversation with Professor Noel Barnard in 1978 I began looking seriously at the history of iron technology in ancient China. The need to 'get my hands dirty' soon became apparent, and in 1981 I began studying metallurgy with Dr V. F. Buchwald at the Technical University of Denmark.

When, around that time, Joseph Needham asked me to be his collaborator for Ferrous Metallurgy, I readily accepted, but felt that it was important to finish the book I was currently working on, *Iron and steel in ancient China*,[2] before starting on this chronologically broader work. That book required much longer to complete than I had ever expected – a phenomenon I had seen before with other publications, and would see again. It was essentially finished in 1990, and published in 1993.

In all that time I had been preparing on the side for this volume for SCC, gathering bibliography and reading up necessary historical and technical background. Actual writing could begin in 1994 when, thanks to the efforts of the Publications Board of the Needham Research Institute, I received a grant from the Leverhulme Trust for two and a half years of research in Cambridge. The work continued after my return to Denmark, with ups and downs due to unstable employment, and now, in 2006, I feel that the volume is as finished as I can make it.

Though I count myself among Joseph Needham's admirers, long-term readers of *Science and Civilisation in China* will notice that I disagree with him on a number of matters large and small. I cannot believe in the essential virtue of Progress, or in

[1] Guyan (1967).
[2] Wagner (1993).

modern natural science as a measure of historical value, in quite the same way that he did; and my socialism is not his socialism.

The title page of this volume presents Ferrous Metallurgy as a branch or aspect of Chemistry, but this is a categorisation that I have never found especially useful. As another of Joseph Needham's critical admirers, Francesca Bray, has pointed out, the hierarchy of knowledge on which the structure of *Science and Civilisation in China* is based, with all technology seen as applied science, was already considered old-fashioned when the first volume was published in 1954.[3] But structure is as structure does, and this old-fashioned structure, with its emphasis on the brass tacks of modern science, continues to serve well after 24 volumes published over a period of more than 50 years.

Among more specific disagreements, I find the social sciences more useful than Joseph Needham did. As a young man at a technical university I fell in with the crowd in sneering at 'the social so-called sciences', but working in the history of technology has forced me to change that opinion. There are more appeals in this volume to theoretical economic and geographical considerations, in particular, than elsewhere in his work. Other social-science approaches, especially sociology and anthropology, would also have been useful in considering some of the broader aspects of the production and use of iron, but getting a book finished means recognising some personal limitations.

Among the goals of this volume is a demonstration of some of the ways in which technologies influence the course of history. Not some monolithic Technology – Lewis Mumford's *technics*[4] – but the many technologies which people have used to satisfy their practical needs. It has been said often enough in the 20th century that *technology has consequences*, the latter seen by various pundits with either hope or despair; but for the historian it is more important to realise that *particular technologies have particular consequences*. As we shall see further on in this volume, most agricultural implements in Han China were made of cast iron (more precisely, the kind called *malleable cast iron*), while in Roman Europe at the same time they were made of wrought iron. It will also become clear that these two different technologies had significant social and political consequences, though perhaps not as direct or extreme as those which Karl Marx suggested in his aphorism about hand-mills and steam-mills.[5] At the same time, technologies are clearly shaped by the context in which they develop, and we must also ask the question, how it came to be that two societies with roughly similar practical needs adopted such different technologies to meet those needs.

Treating a technology as a historical factor requires us to understand it technically, and this volume includes a good many discussions which are based on

[3] Bray (2000, p. 67).

[4] Mumford (1934).

[5] 'The hand-mill gives you society with the feudal lord; the steam-mill, society with the industrial capitalist.' In *Misère de la philosophie*, 1847, Marx (1963, vol. 1, p. 79); tr. Marx (1936, p. 92); cf. MacKenzie (1984, p. 473).

detailed technical considerations. As in most of my publications, I attempt to explain these matters with readers in mind who know some chemistry and are accustomed to technical thinking. Others will find, I think, that they can skip the more technical discussions and still follow the basic lines of the argument.

The archives of the Needham Research Institute show that Joseph Needham began studying the history of ferrous metallurgy in China in the early 1950s. He gathered a good deal of primary and secondary source material, using his excellent contacts in China, and initiated two laboratory projects, to reconstruct Qiwu Huaiwen's 'co-fusion' steelmaking process, and to study the microstructures of ancient Chinese cast-iron artefacts.[6] His monograph *The development of iron and steel technology in China*,[7] completed in 1956, was for several decades all that was available on the subject in English. He was dissatisfied with it, however, especially after a friendly but very critical letter from the great metallurgist Cyril Stanley Smith, and in about 1959 he wrote a draft revision of the monograph which approximately tripled its size. But in the draft one can see him still struggling with the technical mysteries of ferrous metallurgy; he remained dissatisfied, and never published the revision. At about that time he quite suddenly abandoned the subject, even leaving several letters unanswered, and never returned to it.[8]

When I began studying the subject I had the great advantage that Chinese historians, archaeologists, and metallurgists had begun doing important work on all aspects of archaeometallurgy, but Joseph Needham's monograph, and later the draft revision, were my best guide to the older literature and to the Chinese primary sources.

Another useful guide was John Percy's *Metallurgy. Iron; steel* (1864). Percy was an admirable Victorian polymath, and in his book he summed up what was known of the science and technology of metallurgy in his time as well as their history worldwide. He wrote at a time of great change, but the older technologies were still alive, and he was able to describe them in useful technical detail.

Among other authors whose works guided this perplexed beginner were Ronald F. Tylecote, Noel Barnard, Yang Kuan 楊寬, Hua Jueming 華覺明, Li Jinghua 李京華, and the group which in troubled times hid under the pseudonym Li Zhong 李眾.[9] Robert Hartwell's Ph.D. dissertation on the Song iron industry (1963), and Bernd Eberstein's on Ming mining and metallurgy (1974), were also immensely valuable as starting points in dealing with those periods.

In the years that followed I have enjoyed the advice and assistance of numerous friends and acquaintances, experts in the various archaeological, historical, and

[6] See pp. 167, 257–8 below.

[7] Needham (1958).

[8] The article Needham (1980a) was largely written by Colin Ronan on the basis of the 1959 revision.

[9] The group, at the Beijing University of Iron and Steel Technology (Beijing Gangtie Xueyuan 北京鋼鐵學院, now the Beijing University of Science and Technology), was led by Ke Jun 柯俊. The most active participants were Qiu Lianghui 丘亮輝, Huang Wudi 黃務滌, Wu Kunyi 吳坤儀, and Sun Shuyun 孫淑雲. I am grateful to Mei Jianjun for this information.

technical fields that make up the background for this volume. Some of this help I have acknowledged in footnotes, and in the list further below I have tried to show my wider indebtedness.

Portions of this volume have appeared in earlier publications,[10] and I am grateful to the editors and publishers for permission to use this material here.

Thanks are also due to numerous libraries and librarians: here I shall single out the staff of the public library in the small town of Frederikssund, where I have lived since my retirement in 2003. They have been unfailingly helpful, far beyond the call of duty, in obtaining books for me on many subjects in a variety of languages, including Chinese and Japanese.

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And my greatest debt is, as always, to my dearest friend, Annie Winther.

Matters of Form

This volume of *Science and Civilisation in China* is the first to use the Pinyin transcription for Chinese instead of Joseph Needham's modification of the Wade-Giles system, in which for example Qin is transcribed Chhin. The Publications Board of the Needham Research Institute made the decision to change the transcription in April 2004; I spent two weeks changing the transcription in an almost-complete manuscript, but this I was delighted to do, as I have always felt that the previous system formed a serious barrier between Joseph Needham's work and its readers.[11]

Another change made at about the same time was to combine Bibliographies B and C into one, so that all modern publications are to be found in one list.

As throughout *Science and Civilisation in China*, years before and after the Common Era are usually indicated by – and +, so that +1200 means the year 1200 CE and –117 means 117 BCE. The + is omitted for early modern and modern dates.

Unless otherwise specified, all translations from Chinese texts are my own. Wherever possible, however, I have also cited published translations of the same text. Readers may find it useful to consult these in order to see more of the context of the passages translated here.

[10] These are listed in the bibliography under Wagner (1985–2006). In particular, Koninklijke Brill N.V., the publishers of my *Iron and steel in ancient China* (1993), kindly permitted the extensive reuse of material in that book.

[11] An artefact of the transcription change is that the abbreviation 'ch.' in bibliographical references can mean either 'chapter' or *juan* 卷 (JN's *chüan*).

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July 2006 DONALD B. WAGNER

36(c). FERROUS METALLURGY

1 INTRODUCTION

> Iron seemeth a simple metal, but in its nature are many mysteries, and men who bend to them their minds shall, in arriving days, gather therefrom great profit, not to themselves alone but to all mankind. *Attributed to Joseph Glanvill (1636–80)*

The metallurgy of iron has long presented numerous mysteries to which craftsmen and philosophers have bent their minds. The craftsmen – smiths, ironfounders, and others – accumulated over millennia the amazing variety of techniques which made this the most useful and versatile of metals. Today we see the ancient craftsmen darkly, through folklore and through scientific examination of their works, and we know little of how they thought about their work and explained it to apprentices.

The challenge of explaining what the craftsmen knew provided important impulses to natural philosophers interested in the nature of matter. The names of Wang Chong 王充, Shen Gua 沈括, Descartes, and Réaumur are perhaps the best known, though there were dozens of others. Wang Chong in the +1st century, attempting to explain thunder and lightning, found a useful model in the iron-founder's furnace.[1] Shen Gua in the +11th century speculated that steel was a kind of gluten, which could be extracted from iron as gluten is extracted from flour.[2] Descartes and other corpuscular philosophers of the 17th century found an enormous challenge to their theories in the quench-hardening of steel.[3] Réaumur in the 18th century, in a long programme of experiments on the technologies of iron and steel, 'alone proceeded to develop corpuscular theory into something useful', in fact developing techniques of great industrial importance; thus began the repayment of the philosophers' debt to the craftsmen.[4]

Ferrous metallurgy had no less influence in economics than in philosophy. Certain fundamental facts about iron and its production have had enormous consequences. First, it has for millennia been a necessity in both agriculture and war. These two fields of endeavour have very different economic circumstances: while an army needs weapons of the best quality, and governments pay what is necessary to supply them, the tools of the farmer always represent a more complex compromise between quality and cost. Thus we shall see that in the Han period weapons were nearly all of wrought iron or steel, while agricultural implements were usually of cast iron. It is safe to assume that a Han peasant would have preferred an axehead,

1 P. 252 below.
2 P. 321 below.
3 C. S. Smith (1988, pp. 71–85). On quench-hardening, and on Chinese ideas about it, see pp. 133–7 below.
4 C. S. Smith (1988, p. 85). See also pp. 161–2 below.

for example, made of steel by a smith, but the many cast-iron axeheads which have been found in Han excavations must have cost much less to produce, and no doubt were preferred for this reason alone.

Iron ores, and the fuel needed for smelting, are found nearly everywhere in the world in quantities sufficient for pre-modern production levels, and iron is relatively cheap by weight. These two facts mean that transportation costs are an extremely important factor in the geography of pre-modern iron production. In Europe, until late medieval times, iron was most often a local product, and only especially high-quality grades were traded over long distances. The situation was rather different in China. Blast-furnace iron production, which was practised from very early times in China but only much later in Europe, is efficient only at high production levels, and in addition provides great economies of scale: efficiency increases as production increases. Thus it was economic to produce for much larger markets than in Europe, with the cost of transportation and marketing a less important factor in the cost of iron.

Another implication of the widespread availability of raw materials is that, in large markets, competition between iron producers will be intense and profits low. So that whenever marketing conditions encourage large-scale production, this production will tend to be located in regions which do not have the resources to produce more profitable goods – their 'comparative advantage' is in iron production. Thus, in pre-modern China, iron production was often located in the poorest regions.

Of course numerous other factors also influenced the geographic distribution of the industry, including transportation conditions and the availability of ores with special properties. Of great importance is that, in early iron production, the limiting factor is wood for charcoal. For this reason, large-scale iron production should be located close to abundant forest resources and distant from competing consumers of fuel, especially the populations of cities. This consideration has often led to the appearance of specialised industrial villages, isolated in forests, whose activities were entirely centred about the production of iron. These were called 'iron plantations' in colonial America and *järnbruk* in 18th-century Sweden. The same sort of situation seems to have existed in the province of Guangdong in recent centuries, and in many parts of China in the –3rd and –2nd centuries.[5]

Here I have described a few technical aspects of iron production and the ways in which they influence the economics and geography of the industry. In this volume we shall see many examples of how such influences play against each other to produce different results in different times and places, in turn influencing wider historical developments.

The rôle of the Chinese state in the iron industry is one of the threads running through this volume. Any state will attempt to extract a share of all economic activity, and the early Han period saw a curious 'self-assessed' tax (about which

[5] Pp. 47–59 and 144–6 below.

virtually nothing is known) on iron production.[6] This was seemingly because the early Han state lacked both the personnel and the technical competence needed to assess the tax. One can imagine that an entirely self-assessed tax was not very effective, and the need for revenue was one of a number of reasons for the establishment in –117 of a state monopoly of all iron production and marketing. The full background for this action, and for the intense opposition which it provoked, have been a matter of dispute, and Section 5 takes up the question in detail.[7] One important reason for the monopoly was surely that the ironmasters, commanding large labour forces deep in mountain forests, were perceived as a danger to the power and prestige of the state and its servants. The monopoly seems to have brought these 'primitive "capitalists" or industrialists' (as Joseph Needham called them[8]) into the Han civil service, making them more manageable. It also brought the blast furnaces to the cities – a disposition which was economic and ecological madness, but good sense from the point of view of administration and control. Later in the Han period, the monopoly arrangements were first reformed and then abandoned, no doubt because of political and economic developments: transportation and markets were improving, making contraband production and sale easier, at the same time that the central government's decline relative to local power centres made enforcement doubly difficult. This at the same time that the forests were receding and the supply of charcoal for the state blast furnaces, in competition with the needs of urban populations, was becoming more and more costly.

The state's involvement in the industry took other forms after the Han, and there was never again any attempt to take full control of iron production and marketing. In the Period of Disunion, between the Han and Tang periods, we often hear of military ironworks, and there were also some civil ironworks established by the state, but these do not reflect a monopoly.[9] In the Tang period there seems to have been a tax on iron production, but we have no information on how it was assessed or enforced.[10]

From the Song period onward, better sources give a clearer view of the interaction between the state and the iron industry. In the Song there was a bewildering variety of *ad hoc* local arrangements to provide tax revenue and raw materials to the state and protection and legitimacy to the industry.[11] The Song central government was never very powerful, and we see in the sources constant negotiation about these arrangements between local and state interests.

The development of the use of mineral coal rather than charcoal in iron smelting, seemingly from about the +10th century, brought a major change in the geography of the industry. In the heavily forested south, charcoal continued to be used, and the

[6] P. 181 below.
[7] Pp. 221–9 below.
[8] Needham (1958, p. 7).
[9] Pp. 249–52 below.
[10] Pp. 251–2 below.
[11] Pp. 294–305 below.

best iron came from here. In the badly deforested north, most iron production used mineral coal. The problem of sulphur in the iron produced seems never to have been solved before modern times, so that most of the iron produced in the north was used for cast-iron products, in which sulphur was not a major problem, rather than being converted to wrought iron and steel.

The government's need for high-quality iron and steel weapons led to the establishment in the early Ming period of a state ironworks in Zunhua, near the capital, Beijing. It produced charcoal iron at great financial and ecological cost in order to obviate the need for transportation of iron from the south. As transportation and the market economy developed in the course of the Ming, and high-quality iron and steel from the south became easily available in north China, the Zunhua ironworks became more and more of an expensive anomaly. It was finally closed in 1581, after 150 years of continuous production, and from then until the end of the dynasty the state's need for iron and steel was supplied by the open market. A brief attempt to reopen it was made in 1623 by the now-failing dynasty, without success.[12]

It is here at the end of the Ming that the chronological part of this volume ends, for Joseph Needham's plan for *Science and Civilisation in China* sets the year 1600 as its terminus. Outside the chronological narrative, Section 2, immediately below, gives an introduction to the technology and economics of iron production in China, based on detailed studies of the iron industries of four regions in recent centuries. Section 3 then goes back to the beginning and considers the first use of iron in China. Succeeding sections proceed more-or-less chronologically. It will be seen from the Section titles that in each period some single aspect has seemed to me most important, but in fact I have attempted to cover all aspects which the archaeological and textual sources make available to us. Finally Section 9 takes up a question which was dear to Joseph Needham, the debt of modern industry to the pre-modern Chinese iron industry.

[12] The story of the Zunhua ironworks is told in detail in Section 8(i) below, pp. 327–39.