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JOSEPH NEEDHAM ON CHINESE STEEL AND IRON METALLURGY

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Introduction

In May 1980, the journal *Past and Present,* published by T.H. Aston in Oxford, issued a critical review on Joseph Needham's *Science and Civilization in China.* In this review specialists from different fields – but not working personally for Needham's team – gave an appraisal of some chosen chapters of Needham's œuvre: W.J. Peterson wrote a critical piece on Needham's interpretation of Chinese scientific philosophy, especially of his concept of «philosophy of organism»; U.J. Libbrecht interpreted Needham's work on Chinese mathematics and found that it constitutes a very good «first *ad interim* synthesis»; and C. Cullen analysed Needham's chapters on Chinese astronomy, pointing out that Needham seems to have failed to detect «the theoretical sterility of Chinese astronomy», whereas his description of Chinese instrumentation is probably the best available.

Since Needham's volume on Chinese metallurgy (Vol. V, part 36) will not appear until 1987, we would like – in the line of T.H. Aston's symposium – to provide some critical remarks on a very important paper on Chinese iron and steel technology published by Needham many years ago. The echo of this paper, presented to the Newcomen Society, was tremendous at the time. An analysis of it – never done before – seems to be a necessary preview of the basic ideas and of the method of the future volume V, part 36. In time, a critical examination of said volume will be made available to the interested readers.

The available papers

Any proper evaluation of Joseph Needham's monumental work on Chinese science and technology* should, of course, include his contribution to the history of iron and steel metallurgy, although Vol. V, part 36 *(Chinese mining and metallurgy)* has not yet been published. However, we do have material on Chinese metallurgy from his pen, beginning with his famous «Second Biennial Dickinson Memorial Lecture» to the Newcomen Society in 1956 (published by Heffer & Sons Ltd. for the same society in 1964 under the title: *The Development of Iron and Steel Technology in China).*[1] We also find remarks on metallurgy in general and on iron metallurgy in particular in his other writings, for example in *Clerks and Craftsmen in China and the West,*[2] in a contribution to the *Cyril Stanley Presentation Volume,*[3] in *Celestial Lancets*[4] (on iron acupuncture needles), and, of course, frequently in *Science and Civilisation in China.* It is therefore possible today to judge and esteem his views on the development of this sector of technology in China. Although the Dickinson Lecture is rather old and certainly does not reflect the most recent state of knowledge on ancient Chinese metallurgy, it still has the special merit of being the first great synthesis in this field. At the same time, it reflects Needham's general commitment to what he calls «oecumenical science». Together with his excellent classification – the first – of the relative importance of various metallurgical processes in the Chinese iron and steel economy, these facts suffice to justify the reputation this paper has enjoyed and still enjoys (although its few shortcomings have never been submitted to a detailed analysis). A work of this kind can be achieved only by a scholar who sees his studies and research not merely as a profession but also – and essentially – as a vocation.

From a short talk with Needham during the Third International Conference on Taoist Studies in Zurich in 1979, and from longer talks with him in Cambridge in 1984, the author learnt that specialists all over the world – especially in Canada for non-iron metals, and in Denmark for iron and steel – are actively engaged in research, compilation and translation in connection with the preparation of the metallurgy volume (*SCC,* Vol. V, 36), whereas Needham's own work in this field is now very limited. Consequently, his personal contribution to the metallurgy volume will be much smaller than usual, probably being limited to giving a general view of the overall development of both Chinese and Western metallurgy throughout the ages in an adequate «Author's Note». Considering the enormous range of Needham's work today and taking due account of his advanced age, this is clearly a very logical approach. Bearing in mind that he was not a metallurgist, his contribution to the lectures to the Newcomen Society can thus be considered as the work of a master. His views certainly aroused considerable interest among metallurgists at the time. His work was quickly translated – unfortunately with too many mistakes – into French[5] and published in the *Revue d'Histoire de la Sidérurgie* in

Nancy in 1961–1962. It has also been the subject of a few – unfortunately rather uncritical – discussions in the meantime.

The discovery of China as an «Iron Culture»

In contrast to other fields such as philosophy or mathematics where a knowledge of the classical Chinese language is instrumental for understanding the Chinese contribution to world civilization, much of the information available on Chinese metallurgy was gathered in earlier times by non-sinologists who, by means of drawings, reports, and other records, adduced evidence of the achievements of the Chinese in this field. Such travellers as Rocher, Licent, Lux, Cremer, Ledebur, Hommel had, of course, the advantage of being «archéologues sans le savoir», since the relative stagnation of China after the destruction of the Song Empire by the Mongols made it possible for them to observe *in vivo* techniques already in common use in ancient times. However, empirical observations are not sufficient by themselves; reports by professional archaeologists, translation and interpretation of old texts by sinologists, analysis of artifacts, slags, crucibles and furnace walls by professional metallurgists are indispensable, if we are to obtain a complete picture of an iron culture. It is then a question of producing a synthesis of these facts – a very difficult task indeed – and no one need be astonished to find a bibliography containing more than 185 names to sustain Needham's paper of 48 printed pages.

Having said this much, let us now review some aspects of Needham's *Development of Iron and Steel Technology in Chin (DIST)* and try to identify with him the main features of what characterizes the Chinese achievements in the field of iron and steel metallurgy.

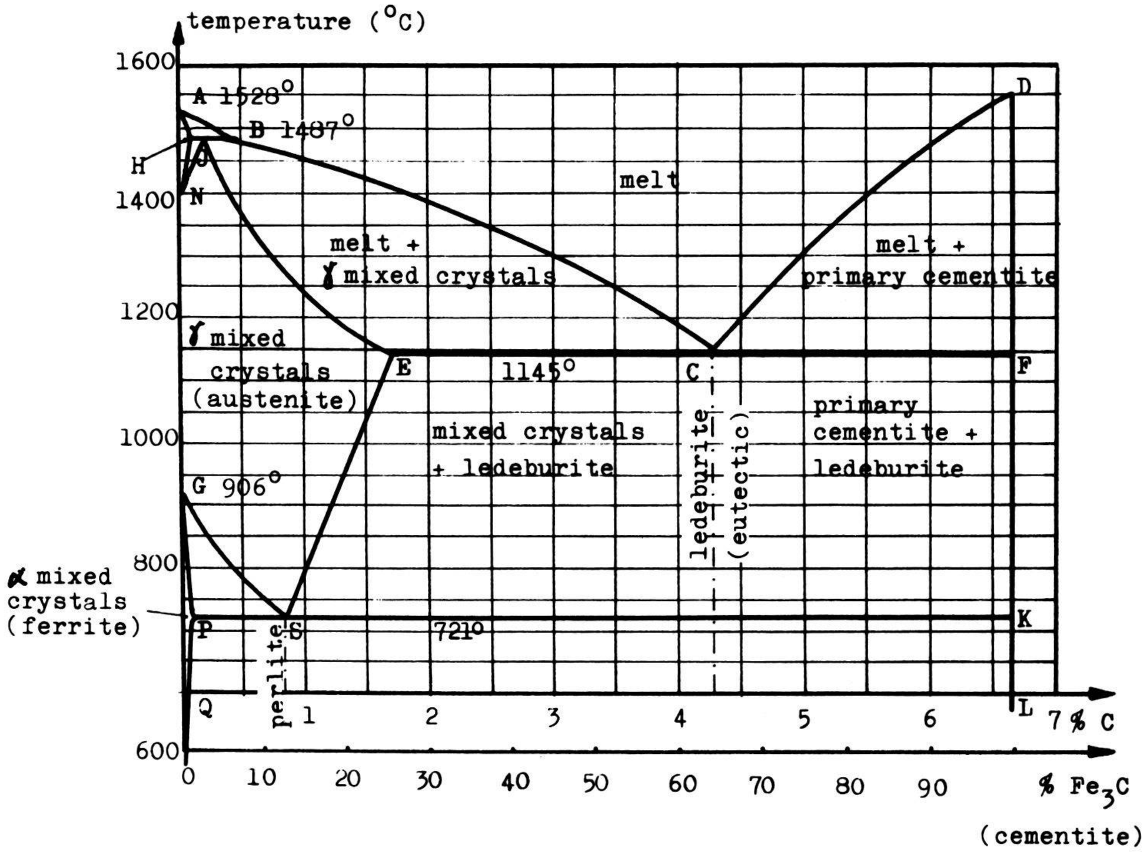
Needham's contribution

Needham's eminent position in the field of Chinese science – the fact that he is both a scientist and a sinologist – is evident at the very beginning of his paper: his knowledge of Chinese culture enabled him to place the technical problem of iron metallurgy into the correct framework of the indigenous philosophical environment of Chinese dialectical thought (here «hard/soft», similar to «yin/yang», etc.) on the one hand and of the ideographic etymological tradition of the Chinese written language on the other. Every reader of *SCC* certainly knows the fascination which the table of «Ideographic etymologies of some of the words important in scientific thinking»[6] exerts on minds interested in technical things: here we find the fascination of discovering *visible traces* (i.e. drawings) of fundamental ideas and basic artifacts of human civilisation. Similarly, in his *Development of Iron and Steel Technology in China (DIST)* Needham explains in detail almost all the ideograms pertaining to metallurgy.[7]

It is also Needham's excellent knowledge of Chinese civilisation which enables him to supplement his translations of ancient Chinese texts on metallurgy with remarks and notes on the economic developments of the relevant periods and dynasties and on the corresponding importance of iron. His remarks for instance, on the existence of production facilities on an industrial scale in China as far back as the Qin dynasty (221–209 BC), were fully confirmed by the recent discovery of huge melting and casting plants for stack casting near Wenxian.[8] Taking the paper as a whole, however, Needham's economic comments are a little disappointing since they are not developed systematically. The dramatic growth of iron production under the Song dynasty in particular does not receive the comments and explanations it surely deserves. However, it should be remembered that in 1956 Needham could not have been aware of the data obtained in the meantime from discoveries in this field. His note on the relationship between the salt and the iron industries (*DIST* p. 15) is a good remark in the right direction. However, the sentence on p. 19: «. . . of course, the total tonnage remained extremely small throughout the Middle Ages in comparison with what the epoch of heavy industries was to bring forth in due time. . .» cannot be accepted. It would have been more appropriate to look at the beginning of heavy industry in the West in the eighteenth century with which China compares favorably.[9] There is little point in comparing Chinese production in the late Middle Ages with contemporary production in the West.

The technical field

In his interpretation of the metallurgical techniques of old China, Needham encounters certain difficulties. Admittedly, he demonstrates very well the main differences between the development of the iron industry in China (where smelting of cast iron was the main process and where most of the steel and wrought iron was obtained by indirect metallurgy, i.e., by decarburization of cast iron), and that in Europe (where most of the iron was produced by direct metallurgy of lumps of spongy, slag rich iron, then forged to wrought iron for subsequent conversion into steel by cementation, and where cast iron was almost unknown until the fourteenth century). On the other hand, his explanations of the difference between these two processes run to several pages of often superfluous and sometimes even unclear comments (*DIST* pp. 9–14). An iron-carbon diagram and a text of not more than one page would have provided a much clearer explanation for both layman and specialist.



The iron-carbon diagram gives the basic chemical relationships between carbon and iron in iron and steel metallurgy. The diagram shows that carbon is absorbed by molten pure iron – at first rapidly, then more slowly as the C-content grows – to produce iron-carbide crystals Fe_3C. The upper curve ABCD of the diagram (so-called «liquidus») indicates the temperature of beginning crystallisation in function of the C content. It shows that with growing carbon content, the beginning temperature falls by almost 400 degrees, from the melting point of pure iron (1528°C) to the melting point of the eutectic containing 4.3% C (only 1145°C). This fact explains why the Chinese could smelt high-C iron («cast iron») so early in history: this was possible from the moment they were able to control furnace temperatures of 1150°–1200°C (which they had learnt early for sintering ceramics).

From 0 to 1,7% C, the composition of the mixed crystals formed following ABC is given by the curves AH and JE (so-called «solidus»). Up to this point, iron remains malleable and/or elastic (wrought iron, steel). With the C content growing over 1,7%, the metal becomes harder and brittle («pig iron») because of the growing proportion of eutectic crystals formed.

With the Fe-C diagram, any intersted layman is able to decypher easily Needham's explanations on pages 9 to 14 of *DIST* and to understand a lot of peculiarities of the iron and steel metallurgy, as well as all explanations concerning the co-fusion (or co-diffusion) process (see below).

Needham's text also contains several inaccuracies: the *puddling furnace* does not work on the basis of cast iron and scrap as stated (*DIST* p. 10); it relies on the oxidation induced by the furnace atmosphere and on the iron oxide content of the slag. This slag is obtained chiefly from iron ore and hammer scale. Needham corrects his mistake himself in a note on p. 15, where he speaks of the iron oxide used «to form a fusible oxide slag». But on the same page the similar Chinese fining process is questionably treated in the sentence: «Here decarburization is effected by stirring and adding silica. . .». It is difficult to understand how stirring alone could appreciably decarburize the molten iron – there has to be an oxidizing atmosphere. As for the addition of silica, mention should be made of its desulphurizing function and of the effect of silicon on the solubility of oxygen in iron. The acidity of the slag, the presence of manganese and the FeO-phosphorus balance are all important factors, and the simple description of a fining process consisting of a few men stirring a pool of molten iron after a little mud was thrown into it gives the reader a completely false impression of the complexity of metallurgy.

Generally speaking, Needham did not pay adequate attention to the importance of secondary factors and phenomena of metallurgy, e.g. furnace linings (refractory properties, reactions between lining and melt), reactions in the slag, elimination of phosphorus and sulphur, alloying elements, and so on. He occasionally mentions very interesting facts, for example the presence of salt, lime and vinegar(!) in the linings of Chinese smelting furnaces (*DIST* p. 16), but fails to develop the most interesting aspects of this information on *acid* furnace linings. It seems that the Chinese actually knew a great deal about the effects of linings and slags, and this aspect should be further explored. While Needham did probably not possess enough concrete data on these aspects of the problem to give clear answers, he nevertheless should have formulated the questions clearly.

We can only hope that in the near future Chinese scholars will analyse enough samples of cast iron, slag and refractory linings in all the old furnace sites accessible to archaeologists to be able to furnish additional data urgently needed in this field. Since China itself is unlikely to have either the resources or the specialists needed for this research,[10] cooperation with metallurgical and cement laboratories in the West would be commendable. Needham, who enjoys the confidence and admiration of the Chinese and whose reputation in the West is equally high, could be instrumental in organizing this kind of work with the necessary tact and efficiency. It hardly seems rational to analyse samples in China by troublesome and slow wet processes when the same work could be done in a few minutes in Western laboratories using radio-fluorescence, spectral and radio-diffractometric techniques, and especially the newly developed, very efficient ICP (Inductive Coupled Plasma) spectral analysis, which is being used with growing success in steel and cement works to analyse simultaneously up to 60 elements with a linear response on all concentrations.

The problem of «co-fusion»

One of Needham's most important discoveries in studying Chinese metallurgy was the process he called «co-fusion».[11] According to him, this process consists of melting cast iron (high carbon content) with wrought iron (low carbon content) to obtain steel by averaging the carbon contents of the two metals. But the expression «melting» already presents an initial difficulty: on page 24 of his paper, Needham writes: «. . . already the complete fusion of the metal is assumed». But which metal? Both the cast and the wrought iron? Or the cast iron alone whose melting temperature is much lower?

In his translation of the *Bei qishu* (*DIST* p. 26), Needham renders the ideogram *shao* as «baking»:[12] «The method was to bake *(shao)* the purest cast iron, piling it up with soft ingots, until after several (days and) nights, it was all turned to steel». This is certainly a description of a co-*diffusion* rather than a co-fusion process,[13] if the Chinese observer was correct. If C-rich cast iron is piled up tightly and heated in a furnace with soft iron, a CO atmosphere builds up in the furnace and the C-poor soft iron is slowly carburized, without having to melt. The chemical process taking place here is the so-called cementation, characterized by the reaction:

$$3\ Fe + 2\ CO \rightleftharpoons Fe_3C + CO_2$$

the so-called «cementation equilibrium». The «several days and nights» needed undoubtedly point to a slow gaseous phase process rather than a process in the liquid phase, which would take only a few hours. And the word *shao* itself also seems to confirm the presence of a «dry» process («roasting», «baking») without fusion. Of course, other texts like the *Bencao gangmu* (*DIST* p. 29) use other terms such as *lian,*[14] meaning «to smelt, to refine» (it is not clear why Needham translates it as «to heat») and the highly detailed description of the process by Song Yingxing (A.D. 1637) in the *Tiangong kaiwu* definitely shows (also on p. 29) that the cast iron, melts (*hua*[15]) drips and soaks (*shenlin*[16,17]), whereas the wrought iron remains unmolten but turns pasty. This also seems to indicate co-diffusion rather than co-fusion even though the cast iron liquifies. We would even go so far as to suggest that there probably were two variant processes in China: one entirely in the gaseous phase and the other partly in the molten phase, as described by Song Yingxing. Both could work very well, the process in the gaseous phase being much slower, as confirmed by the Chinese text, but in both cases it would be more accurate to speak of co-diffusion.

Needham's comparison with the *Siemens-Martin* process also seems of doubtful value. The original idea of the Siemens-Martin process is to be found in the Uchatius[18] process, where the carbon of the cast iron is oxidized away by packing it with *oxides,* in this case with iron ore. The main idea behind the Siemens-Martin metallurgical chemistry is thus the combustion of the carbon with the oxygen from the ore, and not the equalizing of the carbon content of the cast and wrought irons – although this is also practised in the form of the «scrap and cast iron method», as Needham himself states in a note on p. 26. However, this is not central to the Siemens-Martin concept.[19] The use of oxidizing gases in the S-M process should not be neglected either.

These technical points aside, Needham's historical discussion of direct decarburization in China,[20] of the influence of Indian «Wootz», and of the making of swords in China and Japan is flawless.

A final point concerning the hardening of steel: *DIST* p. 26, mentions a method of quenching steel «with the urine of five animals». In a note, and also on p. 95 of *Clerks and Craftsmen in China and the West,* Needham states that urine was used for *fast* quenching, oil for *slow* quenching. But water would quench as fast as urine. Why use urine specifically?

Could it be that Needham missed here, in the case of China, an important point which he finds worth mentioning in the case of Western metallurgy in his chapter on swords (in a note on p. 43), namely the use of nitrogen donators for hardening the superficial layer of sword steels in the European Middle Ages? Perhaps the Chinese came to the same conclusions as the German smiths, except that they used urine instead of goose dung. In quenching with urine instead of with water, they were probably able to kill two birds with one stone: quenching would harden the mass of the metal, while the local decomposition of urine to nitrogen upon contact with the glowing hot blade would ensure extra hardening of the superficial layers and of the cutting edges by nitruration. It would be very interesting to try this method out and check its efficacy. We hope that some day a metallurgist will find the time to make micro-hardness measurements and compare the superficial hardness of two samples of steel, one quenched with urine, the other with plain water.

Summary

In summarizing this review, it must be emphasized that Needham's «Second Biennial Dickinson Memorial Lecture» to the Newcomen Society in 1956 was in its time – and still is in many respects today – a remarkable «ad interim synthesis» (to use the words of U. Libbrecht in *Past and Present,* No. 87). And, like Libbrecht, the author wishes to state clearly that he also considers Joseph Needham as his «great teacher» and as the main motor of his enthusiasm for the history of Chinese science and for Chinese civilization in general.

The other texts on the subject of Chinese iron and steel technology published by Needham later (and mentioned at the beginning of this paper) have not led to any major changes in the interpretation of the Dickinson lecture – probably because all the new material he found or received was held back pending completion of the impatiently awaited volume on metallurgy (*SCC* V, part 36). As this book has not yet been printed, a few suggestions as to its composition may be permissible.

- It would be interesting to see the economic aspects of iron and steel production in China developed more coherently and completely than in the papers published so far. Economic remarks (sometimes contradictory) are scattered throughout the Dickinson lecture. The book should gather all the economic facts in a coherent chapter, which would also deal with the influence of the Chinese bureaucracy and possibly with the influence of the Mongolian conquest of China. Approximate estimates of annual iron production in the different dynasties would also be of interest.

- As for the beginning of metallurgy, the social conditions necessary to allow (a) the working of metals and (b) mining and smelting should also be dealt with in detail for the benefit of readers interested in sociology.
- The relationship between the general economy and the iron economy should be analysed in greater detail.
- As for iron metallurgy itself, the problems that cannot be solved yet for lack of data should be precisely formulated in order to provide interested sinologists and metallurgists with an efficient tool for further research.

We could thus, as C. Cullen says, follow Needham with still greater enthusiasm in his «fascinating and unending process of exploration».

Notes

* Needham, J., *Science and Civilisation in China*, 9 volumes, Cambridge (1954 and following years), here abbreviated to *SCC*.

1 Needham J., *The Development of Iron and Steel Technology in China*, Cambridge (1964), here abbreviated to *DIST*.
2 Needham J., *Clerks and Craftsmen in China and the West*, Cambridge (1970).
3 Needham J., «The Evolution of the Iron and Steel Technology in East and South East Asia».
4 Lu G.-D., Needham J., *Celestial Lancets*, Cambridge (1980).
5 Needham J., «L'évolution de la technologie du fer et de l'acier en Chine», *Revue d'Histoire de la Sidérurgie*, Nancy, (1961–62) pp. 187, 235, (1962–63) pp. 1, 62.
6 Needham J., *SCC* volume II, p. 220 et seq. (Table II).
7 However, *not all* ideograms pertaining to metallurgy – with interesting exceptions such as *tuan* (to forge) – are perfect pictograms of the conveyed ideas. This is not surprising, since the art of metallurgy is relatively young. On the contrary, the author's discovery of neolithic astronomical alignments in Dengfeng (Prov. Henan) has yielded perfect explanations for the clearly pictographic shape of many astronomical ideograms such as *tu* (K/62) whose *yin* bone form represents an astronomical monolith (also found in the ideogram *zhi* as solstice, K/413), and for the ideograms *li* as calendar calculation, *shi* as season, and *sui* as year, which all prove, with the *han* (cliff) or with the *shan* (mountain) radicals, that sun and moon positions were observed from the monoliths through a corresponding «notch» in a mountain (as clearly visible with the songmen daiyue of Dengfeng). Like many of the oldest technical ideograms, these astronomical

pictograms are real «rebuses» describing wonderfully the suggested ideas. This is very logical since star observation is one of the oldest occupations of man, and the astronomical ideograms must be counted to the oldest ones.

8 The very important industrial scale melting and casting plants for stack casting from Eastern Han times (24–220 A.D.) found in Wenxian (Province Henan) are discussed in the *Scientific American* of December 1982 by Hua Jueming under the title «The Mass Production of Iron Castings in Ancient China». Other metallurgical finds have been made in Shandong, Jiangsu and Shaanxi provinces. Although not metallurgical in nature, the discovery of the huge terracotta army of the First Emperor near Xian proves that the Chinese could work on a broad industrial scale as early as Qin times (see, for instance, *Zhongguo xin chutu wenwu* (New Archaeological Finds in China), 1 Vol., Beijing (1978).

9 See for instance Hartwell R., «Industrial Developments: the Iron and Coal Industry», in *Change in Sung China* (Problems in Asian Civilisation Series), Lexington, Mass. (1969) pp. 34–39. It should, however, be noted that Hartwell's results are not accepted by all specialists: Yoshida, for instance, does not agree with such high production figures for the Song times. Even if Hartwell's figures are too optimistic and should perhaps be reduced (what I personnally doubt), I still think that he is basically right in speaking of a «dramatic» increase of the iron production under the Song. Among many other facts, it should be remembered that apart from a doubling of the population since Tang times and apart from the necessity of constantly producing huge quantities of armaments for fighting off the military pressure from the north, Song China witnessed an amazing development of the overall economic activity. Song China, for example, built more bridges than all other dynasties together!

10 As far as I can judge from available reports, the Chinese are also neglecting the importance of slags and linings in their examination of recent finds.

11 The Chinese specialists have uncritically adopted the same word in their books and papers (see for instance the chapter on metallurgy in *Ancient China's Technology and Science*, Foreign Languages Press, Beijing (1983), pp. 399–401.

12 *Shao* 燒 ; Couvreur: «brûler, rôtir, griller»; *Hanying cidian:* «1. burn, 2. cook or bake, 3. stew, 4. roast». Couvreur F.S., *Dictionnaire classique de la langue chinoise*, Hokien-Fou (1911). Wu Jing et al., *Hanying cidian*, Beijing (1978).

13 Co-fusion? Co-diffusion? In the context of my paper, co-fusion is different from co-diffusion in the sense that co-fusion means a process taking place entirely in the liquid phase (fusion as related to melting), whereas co-diffusion means a process where at least one component is active in (or by the means of) a gaseous phase; diffusion is defined here as the intermingling by thermal agitation of the molecules of two fluids – one of them at least being gaseous – or of molecules of one fluid (CO gas) and of a heated solid (diffusion of the gas into the solid).

14 *Lian* 煉 ; Couvreur: «purifier un métal par le feu; purifier, élaborer, perfectionner»; *Hanying cidian:* «1. smelt, refine, 2. temper (a metal) with fire».

15 Hua 化 ; Couvreur: «transformer, transformation; fondre, se fondre, dissoudre, digérer»; *Hanying cidian:* «1. change, turn, transform, 2. convert, influence, 3. melt, dissolve, 4. digest, 5. burn up».

16 Shen 滲 ; Couvreur: «tomber goutte à goutte, couler, distiller, filtrer»; *Hanying cidian:* «ooze, seep».

17 Lin 淋; Couvreur: «arroser, verser de l'eau; découler, tomber goutte à goutte»; *Hanying cidian:* «pour, drench».

18 One of the men who invented the casting of cannons in iron moulds – possibly inspired by Kong Zhenlin (see note p. 6 of *DIST*); a coincidence?

19 FeC + FeO = 2 Fe + CO is not the same as:

$Fe_{high\ C} + Fe_{low\ C} = Fe_{average\ C}$

20 Let us note one point concerning the possible existence of a process similar to Bessemer's in old China (*DIST* pp. 37–40): the main initial difficulty with the direct conversion of cast iron by air blast techniques in Europe was due to the fact that a converter with acid lining would not allow for the dephosphorizing of the iron. Since most British iron ores had a high P content, almost twenty years of trying led to no satisfactory results with direct decarburizing, until Thomas invented the *basic* linings for converters. Here again it would be fascinating to know if the Chinese knew the difference between acid and basic linings, and what materials they used (silica, dolomite?). Or did they smelt only low P iron ores?