THE DEVELOPMENT OF THE EARLY STEELMAKING PROCESSES - AN ESSAY IN THE HISTORY OF TECHNOLOGY

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S U M M A R Y

The history of steelmaking, prior to the work of Bessemer and Siemens, is not well documented. This study attempts to bring together the evidence for the development of the cementation and crucible processes, including information on the other means of producing steel which were of some importance in their time but were eventually rendered obsolete by the more well-known and successful methods. In addition to the historical background, a relatively simple treatment of the technology involved is used, as necessary, to underline the reasons for the various sequences of operations which were developed.

The evolution of the cementation process for the production of blister steel was largely a British matter, although its origins were Continental. Based essentially on imported high grade Swedish iron as its raw material, it held an important place in metallurgy throughout the eighteenth century and for most of the nineteenth, first as the only worth while source of British steel and, later, as the source of raw material for the crucible process.

The crucible process itself, growing from its development by Huntsman, around 1740, into the major steelmaking method in Britain, was recognised universally as the source of quality steel. It passed through various modifications until, eventually, with the bulk steelmaking processes of Bessemer and Siemens providing a basis for the rapid expansion of the industry, the crucible process took on a new role as the source of special steels, thereby ensuring the reputation of Sheffield as a centre for these materials.

The essay includes as much of the history of this technology as has been elucidated by a research which has extended over a quarter of a century. It closes with a survey of the use of the cementation and crucible processes in Europe and America.

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A C K N O W L E D G M E N T S

At the outset, the fact has to be acknowledged that, without the enthusiasm shown me by the late W. H. ("Bill") Green for the old Sheffield traditions, it is doubtful whether I would ever have become sufficiently interested to have undertaken this study and it is really to his memory that this work should be dedicated, in a sense of gratitude for all that he taught me with regard to steelmaking - both "ancient" and "modern". I also recognise that it was a discussion with Miss Mary Walton, then Local Studies Librarian in Sheffield, that provided the impetus to start serious work on the project; I well remember her telling me, "It's up to someone from the steelworks, like yourself, to get on with it before it is too late".

To list all those who have assisted me in the collection of information is an almost impossible task. So many people have been so helpful during the last quarter of a century that, in the main, I must express my gratitude to them without being specific; individually, they all know how deep that gratitude is.

There are, however, certain people without whose help my undertaking would have been much less effective or, indeed, impracticable. Foremost among these, I must make

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A major contribution to the story in these pages has been derived from the many Swedish travel journals. Most of these are held in manuscript form in Stockholm and have so far been mainly inaccessible to the English reader. They are also in Old Swedish, which makes them even more inaccessible. I have to thank Professor Rolf Adamson, of the Economic History Institute in Stockholm,

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for taking the trouble, on my behalf, to allow one of his assistants, Bengt Fagerberg, to go through a number of these documents and to indicate which folios were relevant to the history of steelmaking. Miss Karen Hullberg of Jernkontorets Bibliotek in Stockholm then kindly arranged for photocopies to be prepared of the documents in her care and, indeed, most courteously dealt with my many queries over the years; for these services I would like to record my gratitude and I trust that she is now enjoying her well earned retirement. I would also like to thank Sven Huset of the Kungliga Bibliotek in Stockholm for similar services. Above all, however, I must acknowledge a deep debt of gratitude to the late Torsten Berg. Not only was he a close friend, but he also combined the facility of deciphering the manuscripts with a knowledge of Old Swedish and, moreover, as a trained metallurgist, was capable of interpreting the technology. It is, therefore, all the more sad that he could not live to see some of the fruits of his labour incorporated in this text. He died before he had quite completed all the translation which we had agreed; it has, therefore, been my very great good fortune that Nils Bjorkenstam, who has been closely involved with the Historical Committee of Jernkontoret, offered his assistance; he and his wife,

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Barbara, have now provided the story of the setting up of a crucible works in Sweden in the early nineteenth century and for this kindness and their friendship I am very grateful.

For much of the detail on French steelmaking, I have drawn on documents kindly provided by Professor J. R. Harris, whilst for some American information I have been assisted by Professor D. S. Landes; to both these gentlemen I acknowledge my indebtedness. The details on early Chinese steelmaking are drawn from an interview which Professor Ko of Peking University granted me; his enthusiasm was phenomenal and I trust that my notes have done him justice.

Many Sheffield firms have kindly allowed me to examine such old records as have survived - and, indeed, I have managed to persuade a number of them to transfer important items to the Archive Section of the Sheffield City Libraries. To the present Archivist, Dr. David Postles, and to his predecessor, Miss R. Meredith, I offer my thanks for the many services rendered, not the least of which was drawing my attention to items which they thought were relevant to my studies, the existence of which I was unaware. Similar thanks are due to Martin Olive of the Local Studies Section of the same libraries, who has an uncanny knack of finding relevant detail in a welter of unpromising pages. To the

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librarians in many other British cities and universities, and to some abroad, I must also render thanks for similar services.

It would, I think, also be proper to single out a few individuals for their valued assistance and these must include Billy Ibberson and Richard Doncaster, both past Masters Cutler, who not only permitted access to the records of the Cutlers' Company but also, over the years, have both provided much other information, and Charles Blick, whose connections with the British Steel Corporation allowed me access to a number of records. I must not forget my good friend and neighbour, Norman L. Clay, for assistance with the index and for many interesting discussions, in which he allowed me to try out various lines of argument with him, and for setting me right on some of the quirks of the English language, particularly on the possible derivations of some of the commonly used steelmaking terms. Also included should be Jake Almond, John Harrison and Stafford Linsley from the North East, together with Dr. George Thomson from Glasgow and Keith Gale in the Midlands, who all sought out details for me in their own localities to better effect than I would have done.

If I have omitted any particular service rendered me,

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it is not from any lack of gratitude but should be put down to lapse of memory; in any case, I crave indulgence. It should be pointed out that a number of individual acknowledgments do appear at appropriate places within the text.

My tutor, David Crossley, deserves considerable credit for his patience and indulgence in dealing with someone who is probably his "oldest" student, both on the count of age and the period of time for which he has been registered. This presentation is very much the better for his suggestions and guidance.

As regards patience and indulgence, however, my long suffering wife surely deserves the prize. The chaos at home, with mountains of books, papers, prints and photocopies around her living quarters, has at times been indescribable. In addition, she has given me hours of her time in assisting with patents, account books, business correspondence, charge books and the like, in various offices, libraries and museums around the country. Despite the times when I have sensed a certain air of detached resignation, her assistance has been both efficient and invaluable, including much work on checking the various drafts and preparing the bibliography and the index.

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Sincere thanks are also offered to Mrs. K. Langstaff for her personal involvement in the typing of the thesis. To have produced such a successful result from the boxful of papers of script complete with its inserts and amendments is almost a work of art.

Finally, I acknowledge two grants provided to further the collection of information during the course of the research. The first, from the Twenty Seven Foundation, was utilised in acquiring many photocopies of manuscripts from Sweden and elsewhere; the second, kindly provided by the Directors of Firth Brown Limited, assisted with translation fees and other expenses. I would also like to thank the Council of the Historical Metallurgical Society for the offer of assistance from its Research Fund, although in the event this proved not to be necessary through the kindness of Nils Bjorkenstam and Jernkontoret.

C O N T E N T S

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The following appear in a Supplementary Volume; details of contents appear in that Volume.

P R E F A C E

It was over fifty years ago that Professor Desch stated[1]

> '..... it is rather surprising that the history of the Sheffield steel industry has not been more fully recorded and studied. We have many notes on the position and ownership of the early forges but these are not so precise as could be wished in regard to technical processes. For later centuries, the information has to be sought in scattered sources and has never been grouped as a logical whole'.

The situation has not changed, materially, since then, other than the inevitable loss of many of the sources, particularly those held by the old steelmaking firms. The number of people still alive who remember the old Sheffield methods, and to whom "blister steel", "shear steel" and, above all, "crucible steel" were everyday items, is now exceedingly small and the part played by the production of these materials in building up the prosperity of the area is almost forgotten. So much is this so that the idea that steelmaking began with Bessemer is commonly held. Reference to most of the histories of the iron and steel industry would also lead to this conclusion, since the standard texts, from Ashton, Carr and Taplin and the like, devote only a few pages to any steelmaking activities

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1 C. H. Desch, Presidential Address, 17th January 1927, Proceedings of the Sheffield Society of Engineers and Metallurgists (1927), pp.13-19.

prior to 1856. Dr. Birch, whose study covers the period from 1784 to 1879, is perhaps the most informative, but even he devotes only a relatively minor chapter to pre-Bessemer steelmaking. Most of the available accounts, moreover, have been prepared by economic and social historians who, naturally enough, have been more interested in the personalities involved, the financial aspects and the social implications, than in metallurgy. Certainly, the technology has received less attention than it merits and the impression is given, in some of these works, that it was not quite understood and that its implications on the whole conduct of operations were, therefore, not appreciated, whilst in some cases it was quite clearly misunderstood.

This particular essay differs, in that it has been drawn up by a steelmaker with over forty years experience in the Sheffield special steel industry who, early in his career, came into day to day contact with men who had been involved in crucible steelmaking and who were applying their accumulated experience to the development of new steels by new melting methods. It was soon quite evident there was much to be gained from the past which was relevant to the work in progress. It was logical, therefore, to endeavour to discover something of the history of the "Old Sheffield Methods" and it was then that the relevance of Professor Desch's comments was realised. It has thus come about that the author became involved in a search for this information; a search which has been followed, as a leisure pursuit, for over a quarter of a century, whilst being involved in the day to day production of the highest quality steel for the most critical applications by the most modern methods. This is not the paradox it might seem at first glance, since both he and the old crucible steelmaker found themselves in the same situation, lavishing care and attention on relatively small quantities of highest quality material.

The results of such a prolonged search are incorporated in the following pages. What has been retrieved covers a wider field than Sheffield; it virtually deals with the evolution of the steelmaking industry itself. There are, however, wide gaps in the retrievable knowledge at this late date and the random survival of information undoubtedly leads to some imbalance; for example, there is a clearer picture available for the mid eighteenth century operations than for the much greater activity a century later. It must be remembered also that competition between rival steelmakers would generally

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result in strict secrecy as to technical details. It was on such grounds that Huntsman refused to take out a patent and, as late as 1884, the Sheffield steelmakers declined to act as hosts to the Iron and Steel Institute - not, it was said, from any want of hospitality, but merely that Sheffield inventors had learned by bitter experience that secrecy was their only protection.

It is necessary to stress that the account here presented is, intentionally, a history of technology. Where personalities and commercial matters have appeared relevant they have been introduced; in view of the very full survey of the commercial development of the Sheffield crucible steel trade recently carried out,[1] only passing reference has been made to this particular aspect.

An attempt has been made to explain, in relatively simple terms, the underlying technological principles pertaining to steel and to steelmaking. A brief survey of the methods used to provide steel, prior to the rise of the cementation process, is included as background

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1 J. G. Timmins, The Commercial Development of the Sheffield Crucible Steel Industry, M.A. Thesis, University of Sheffield, 1976 (unpublished).

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information. The cementation process and the development and use of the crucible process provide the major part of this history. To deal with the complications in technology which arose in the second half of the nineteenth century, it has been considered necessary to discuss the evolution of alternative steelmaking methods and also the involvement in the developing field of alloy steel production. The first of these topics is taken as far as the full commercial development of the Bessemer and Open Hearth processes; their later history is too well documented elsewhere to require any further elaboration here. As far as alloy steel is concerned, the involvement of the crucible process in these innovations is indicated and its continuing importance, subsequent to the obsolescence of its original role, brought about by the rise of the bulk steelmaking processes, is demonstrated. Finally, it has been considered worth while to follow the spread of the cementation and crucible processes abroad; whilst they are, to us, the Old Sheffield Methods, they were known on the Continent as "Les Méthodes Anglaises".

Much of the information on which this study is based has been difficult to find; a fair proportion, indeed, is from foreign sources, many so far unavailable to the English reader. The domestic information also tends to be found in unusual places, many also not readily accessible. For these reasons, no apology is made for including numerous passages of contemporary records, in extenso, within the text itself. It appears to be a reasonable argument that the comments of those involved in these now obsolete processes are of more value than any discussion from a detached viewpoint could ever be. For the same reasons, what might appear to be an excessive number of appendices has also been included.

The shortcomings of this presentation are well appreciated; indeed, the author finds himself in much the same position as Nennius who, when setting down the "Historia Brittonum" in the tenth century from a wide collection of separate sources, wrote "I have made a heap of all that I have found". It is, however, put forward as a serious attempt to provide something towards the logical whole referred to by Professor Desch, and the author would hope thereby to escape the criticism made by Cramer, speaking of one of his contemporaries two and a half centuries ago, when he said :

> 'He seems to write like one who had never blackened his fingers or singed his beard in metallick exercises'.

1 INTRODUCTION

> 'Steel is a superior variety of iron; it is hard, elastic and plastic. It can be ground to a sharp edge and hold it; it is ..... ideal for objects subject to wear and tear ..... its combination of compactness and strength makes steel an excellent construction material.'
>
> D. S. Landes, 1970

I The Nature of Steel

The simplest definition of steel is probably that it

> 'is a general name for certain artificially produced varieties of iron distinguished from those known as 'iron' by certain physical properties ..... which render them suitable as material for ..... various industrial purposes.'[1]

This is a quite valid, but imperfect, categorisation of steel which is just as true today as it was one hundred and fifty years ago. The nature of the material has changed radically over this period with the widespread use in modern times of what are best described as 'alloy steels', with their deliberate additions of elements such as nickel, chromium, molybdenum, tungsten, vanadium as well as carbon to the iron, to modify the characteristics of the metal to meet modern requirements.[2] The main period covered by this particular

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1 The Shorter Oxford Dictionary (1973), p.2118

2 The development of alloy steel is followed in detail in Chapter 10.

study, however, was prior to the use of alloy steels, which only really came into commercial significance in the last quarter of the nineteenth century.

Prior to this date, steel was an alloy of iron with carbon - such materials would now be classified as 'carbon steels' - and differed only from the metal iron itself by the contained carbon. A proportion of 'combined carbon' or 'alloyed carbon', from about 0.5% to 1.5%, was all which distinguished the soft and malleable iron from

> '..... that magnificent material, steel, which can be relatively easily worked to shape and metamorphosed by a final heat treatment into a material of strength and hardness almost unsurpassed; steel's combination of availability, fabricability and final extreme or adjustable hardness set it apart from all other materials.'[1]

This comment introduces the other important attribute of steel: its capability of being hardened by quenching it into water after heating it to a 'bright red heat'.[2] This phenomenon is almost unique in metallurgy; most other metals tend to be rendered softer, rather than harder, after comparable treatment. In this way, steel may also be distinguished from iron, since the latter, in the absence of combined carbon,

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1 C. S. Smith, 'The Discovery of Carbon in Steel', Technology and Culture, vol.5, No.2 (1964), p.149.

2 Generally referring to a temperature of 900-1000°C.

furnace from, say, 900°C to 600°C, is known as 'annealing' and produces a material only a little harder than iron itself, even when the steel contains a substantial amount of carbon. A general idea of the relative effectiveness of these various heat treatments may be obtained from Figure 2, which shows also the influence of carbon on the hardness obtained; it should be understood that the curves shown here are only indicative of the general trends, since in practice a scatter band of properties would be obtained.

It will be noted from this diagram that there is no sharp-cut distinction between 'iron', which does not harden on quenching, and 'steel', which does. The dividing line must be a somewhat arbitrary one, and is normally quoted at about 0.20% to 0.25% carbon. Prior to the middle of the nineteenth century, however, the commercially available iron was wrought iron, with a maximum carbon content below 0.20% and generally considerably lower than this figure. Steel, on the other hand, was almost invariably, in this country at any rate, produced by the 'carburisation', or deliberate diffusion of carbon into the structure, of wrought iron. Steel produced in such a manner rarely contained less than 0.50% carbon and thus the distinction between iron and steel, as demonstrated by their response to quenching, was quite clear. Such a distinction, indeed, only became blurred with the introduction of the so-called 'mild steel', with 0.20% to 0.30% carbon, following from the introduction of the Bessemer process and, later, the Siemens Open Hearth process in the period from 1860 to 1880. Such a material, it should be noted, was largely used as a substitute for wrought iron; the harder steels continued to be made by the older established methods, at least for the remainder of the century, as will be demonstrated later.

Pure iron melts at the relatively high temperature of 1535°C. The steels, however, show two differences from iron in their behaviour at high temperatures. In the first place, they do not melt at a specific temperature but pass from solid to liquid and vice versa over a temperature range. This situation is demonstrated in Figure 3; it should, incidentally, be noted that this diagram strictly refers to pure iron-carbon alloys and gives temperatures which are somewhat higher than those applicable to commercially produced alloys. These generally contain small amounts of other impurities which themselves depress the melting points still further. It will be noted from this diagram that, apart from pure iron, there is another material which melts and freezes at a fixed temperature, this being the alloy with 4.3% carbon. The cast irons normally contain from 3.0% to 4.0% carbon; such alloys all start to melt at 1130°C - as indeed does any iron-carbon alloy with over 1.7% carbon - but are not completely molten until some higher temperature is reached. For example, the pure iron-carbon alloy with 3.3% carbon is completely molten at 1260°C and is a mushy mixture of liquid and crystals from 1130°C to 1260°C. All materials with less than 1.7% carbon - this group covers wrought iron, mild steel and all the carbon steels - begin to melt along the line AB and are completely molten as shown by the line AC, the former line being termed the 'solidus' and the latter the 'liquidus'. A steel with 1.50% carbon, for example, such as might be used for the production of razors, will commence to melt at 1160°C and will be completely molten at 1430°C; conversely, on solidification from the liquid, crystals will begin to form at 1430°C but the mass will not be completely solid until it has cooled to 1160°C. A coach spring steel with 0.60% carbon will likewise commence to melt at 1350°C and will be completely molten at 1500°C.

There is a further line to be considered, showing the maximum forging temperature for steel. This is related to the solidus line and is typically indicated by the line DE, lying some 100°C to 150°C below it. This obviously implies that the maximum permissible forging temperature falls with rising carbon content. On the other hand, the resistance to deformation (or the hot strength) increases as the temperature falls, as indicated in Figure 4.[1] As with properties at room temperature, an increase in strength at high temperature is also accompanied by an increased tendency to loss in ductility and thus to a difficulty in forging without rupture. It thus becomes clear that there is a maximum content above which the material is virtually unforgeable and in practical terms this must be considered to have been reached at around 1.5% to 1.7% carbon. Conversely, of course, the lowest carbon material, which in olden times was wrought iron, was eminently forgeable. At the highest temperatures, certainly up to 1350°C or even somewhat higher, pieces of wrought iron could be forge welded together under a hammer; on account of this, these high temperatures were referred to as 'welding heat'. Again, at much lower temperatures, referred to as 'dull red heat', the virtually carbon-free material was still ductile under the hammer.

II The Growth of Knowledge

The foregoing simple basic elements of ferrous metallurgy have been expressed in the light shed by countless investigations which continued from the last few years of the eighteenth century until well into the twentieth century before they were fully understood.

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1 It has been thought fit to include some alloy steels in this diagram; comments on these will follow in Chapter 10.

It is a very significant fact, however, and one which it is vital to appreciate in a study such as this, that perfectly satisfactory steel was produced, as far as can be ascertained from the records, reliably and reproducibly, well before these theoretical investigations even commenced. Such practices were based on a combination of innate genius, care, patience and close observation of trial and error methods and the painstaking repetition of detail when once a satisfactory way through had been established. This was what a later writer chose to define as 'rule of thumb';[1] it should immediately be made clear that such a term was not in any way derogatory.

The difference in characteristics between iron and steel was clearly understood by the ancients, although the reports which have come down to us are couched in terms which are generally difficult for us to interpret fully. According to Aristotle, steel was a specially purified form of iron :[2]

> 'Wrought iron itself may be cast so as to be made liquid .... and they are wont to make steel thus; for the scoria of iron subsides and is purged off the bottom and when it has often been defecated and made clean, this is steel. But this they do not often, because of the much waste and for that it loses much weight in fining'.

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1 H. Brearley, Steelmakers (London 1931), p.119.

2 As translated by M. Lister: 'The True Way of Making Steel', Phil.Trans., vol.ii (1665-1700, abridged), p.561.

Birunguccio in 1540[1] repeated that steel was nothing else than

> '..... iron well purified by means of the art and given a more perfect elemental mixture and quality by the great decoction of the fire than it had before'

but then goes on to infer that

> '..... by the attraction of some suitable substances in the things that are added to it ..... it seems almost to have been removed from its original nature'.

Plot in describing the cementation process at Kingswinford in 1686 also refers back to Aristotle, but implies that the single long-term exposure of the iron to heat in the furnace is an adequate replacement for the repeated short term treatments employed by the Greek; he again was a little suspicious that he had not learned the whole story and that some other essential ingredient went into the chests with the iron.[2] Reaumur, in 1722, considered that the iron, during cementation, absorbed some matter, which he referred to as 'sulphurs and salts', in order to take on the characteristics of

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1 V. Birunguccio, Pirotechnia (Venice 1540), transl. C. S. Smith and M. T. Gnudi (New York 1943), p.67. The whole section referring to the manufacture of steel is reproduced as Appendix A.

2 R. Plot, The Natural History of Staffordshire (Oxford 1686), p.374. The full text of the section on steelmaking can be consulted in Appendix B.

steel.[1] It was he who first seems to have pointed out that steel occupied a place between wrought iron and cast iron, referring to the latter as 'acier trop acieré'.[2] Jars, in 1765, in terms of the current theory, implied

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1 R. A. F. de Reaumur, L'Art de Convertir le Fer en Acier ... (Paris 1722), p.242. (An English translation is available by A. A. Sisco and C. S. Smith, Chicago 1956).

2 Literally 'steel made too steely' or, in this context, 'over-cemented'.

that cast iron contained a superabundance of 'phlogiston'.[1]

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1 The Phlogiston Theory was proposed by the German scientists Becher and Stahl and seems to have been fully formulated about 1723. According to them, every combustible substance was a compound of phlogiston; metallic iron is thus really iron plus phlogiston; when it burns the phlogiston escapes into the air, leaving the calx (or oxide) behind. Plants and trees, however, can absorb phlogiston from the air; thus when the calx of iron is heated with a vegetable fuel, such as charcoal or even minetal coal since they are each derived from trees, it recombines with the phlogiston and returns to its original metallic state. In modern parlance, phlogiston can be regarded as the essential reducing agent and to view carbon in all its aspects as being akin to phlogiston would have been perfectly logical. The phlogiston theory was firmly adhered to by most of the famous scientists during the second and third quarters of the eighteenth century. Eventually, however, the work of Priestley, Black, Lavoisier and others proved conclusively that there was, in fact, an increase in weight on converting a metal to its oxide of calx; this came to be referred to as 'oxidation'. Correspondingly, there was a loss in weight of the calx when it was converted to the metal, this constituting a 'reduction'. The breaking down of the oxide of mercury under heat showed this quite elegantly; moreover, the product other than the metallic mercury was found to be the gas, previously known as dephlogisticated air and henceforth to be known as oxygen. Previously ordinary air had been found to be composed of a mixture of this dephlogisticated air, which was removed during any burning operation, and a residue which had absorbed the phlogiston released during the burning; this was clearly phlogisticated air and would not support further burning - we know it as nitrogen.

By melting cast iron and blowing air through it, the phlogiston was dissipated as the metal became refined to wrought iron; if, however, it was desired to produce steel instead of wrought iron, then care had to be taken to retain sufficient phlogiston.[1]

Within twenty years of the publication of the volumes by Jars, his countrymen Vandermonde, Berthollet and Monge put out a quite remarkable paper which clearly stated that the steel produced by the cementation process was iron, reduced as far as was possible, combined with a proportion of charcoal, which itself was a form of carbon.[2] Wrought iron, on the other hand, contained virtually no carbon, whilst cast iron contained an excess of charcoal over that required for steel but still contained some dephlogisticated air (or oxygen). This is generally taken as the first real appreciation of the role of carbon in steel. It is, however, arguable that this honour belongs rightfully to Sweden and not to France.[3] The work of the Swedish

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1 G. Jars, Voyages Métallurgiques, vol.1 (Lyons 1774), pp.21-22. A translation of the relevant extract is given in Appendix C.

2 C. A. Vandermonde, C. L. Berthollet and G. Monge, 'Mémoire sur le Fer', Mem.Acad.Sci. (1786), pp.132-200.

3 This was indicated to the author by the late Torsten Berg, who referred to a history of iron and steel: S. Rinman, Forsock till Jarnets Historia (Stockholm 1782). No translation is, unfortunately, available.

chemists, and in particular Sven Rinman and Torbern Bergmann, in the development of steelmaking theory has tended to be overlooked. Bergmann in particular carried out extensive tests on cast iron, steel and wrought iron and, whilst his reports are written in terms of the then current phlogiston theory, his analyses showed the three materials to be significantly different in the amount of 'plumbago' which they contained.[1] Vandermonde and his colleagues certainly knew of this evidence; supplemented by the information from both Grignon[2] and Priestley[3] on the increase in weight on the cementation of iron

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1 T. Bergmann, Dissertatio Chemica de Analysi Ferri (Uppsala 1781). This was translated into French by Grignon in 1783 under the title Analyse du Fer and a modern English translation is to be found in C. S. Smith, Sources for the History of the Science of Steel (M.I.T. 1968). From this latter it may be learned that cast iron was found to contain 1.0% to 3.3% of plumbago, steel from 0.2% to 0.8% and wrought iron from 0.05% to 0.2% (pp. 59-60 of the original and pp.236-237 of the English translation).

2 Grignon's translation of Bergmann's work has notes and appendices; the final appendix covers the experimental work he carried out in 1780-1781 to determine the suitability of various French bar irons for conversion into steel. Having carefully measured all the iron charged, he discovered an increase in weight after cementation of almost 1.5%. Relevant passages can be found in translation in Appendix CCC.

3 Joseph Priestley states that "in contradiction to the opinion of those who make steel" he finds a gain in weight on cementation. Experiments and Observations Relating to the Various Branches of Natural Philosophy, vol.3 (London 1786), p.370.

bars, this would lead directly to the confirmation of carbon as the vital addition to iron necessary to convert it to steel.

The work of the three French savants was used as the basis of a tract which was widely circulated inside France to encourage the production of the steel so badly required during the troubled times following the Revolution in 1789[1]. The only point where modern theory diverges from their findings is in the constitution of cast iron. This was queried within the space of a few years by Dr. Joseph Black of Edinburgh who, quite rightly, found it inconceivable that oxygen and carbon would co-exist in the white hot liquid product from the blast furnace.[2]

The carbon theory was challenged from time to time, notably around the middle of the nineteenth century when serious claims were made for nitrogen as the important agent for the hardening of iron to

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1 Avis aux Ouvriers en Fer sur la Fabrication de l'Acier, published by the Committee of Public Safety, 1793. There appeared a translation of this into English in Nicholson's Journal (1799), pp.64-70 and 102-106. (See Appendix EEE).

2 Joseph Black, Lectures on the Elements of Chemistry, vol.2 (Edinburgh 1803), pp.498-499. Relevant extracts can be found in Appendix E.

produce steel. With the growth of chemical analysis as a steelworks tool, and particularly with the application of a rapid colourimetric method for the estimation of the carbon content of steel around 1860-1865, such theories were proved to have no real substance. In passing, and as an illustration of the changing scene, it is of interest to note two patents deriving from the Lucas establishment at Dronfield. A steelmaking patent taken out in 1792 is unashamedly couched in terms of phlogiston;[1] the one in 1804 refers specifically to the importance of carbon.[2] Moreover, there is a patent of 1800 which boldly sets out to use the new knowledge by proposing to make steel by melting wrought iron with charcoal;[3] as will be shown later, there were technical difficulties in such a procedure which were not to be solved for another fifty years or more, but the underlying principle was sound, as was eventually quite clearly demonstrated.

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1 British Patent No. 1915, E. Lucas, 30 October 1792.

2 British Patent No. 2767, S. Lucas, 30 May 1804.

3 British Patent No. 2447, R. F. Mushet, 13 November 1800.

III Steelmaking Methods

The subject of this study, steel, as has already been stated, was until as late as 1860 only to be differentiated from iron by its carbon content. The derivation of such simple 'carbon steels' was practicable by a number of different routes. Prior to the development of the blast furnace, the only options were :

(a) By modification of the conditions in the bloomery furnace[1] such that some carbon was retained in the bloom and in this way producing NATURAL STEEL.

(b) By heating bloomery iron in a bed of charcoal under conditions such that carbon would diffuse into the iron. In early times such a process seems to have been confined to the treatment of finished articles so as to CASE HARDEN them.

Subsequent to the availability of cast iron, and of wrought iron derived from it, the scope becomes wider :

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1 The bloomery furnace, as will be seen in Chapter 2, was the primitive means of reducing iron ore to metal. The product, 'bloomery iron', was essentially similar to 'wrought iron' in being virtually carbon-free iron but with entrained slag.

(c) By enclosing small pieces of cast iron within layers of wrought iron sheet and heating them to a bright red heat (but short of fusion), out of contact with air, this being the CHINESE PROCESS.

(d) By melting cast iron in a crucible and immersing bars of wrought iron in the melt; in this way the iron bars absorbed carbon from the cast iron and after a while could be taken out and forged to give BRESCIAN STEEL.

(e) By applying the case hardening process to layers of bar iron, interspersed with powdered charcoal in large sealed chests, BLISTER STEEL could be made by the cementation process. The blister steel could then be broken into short lengths, these made into faggots and forge welded together to give SHEAR STEEL.

(f) By melting the cast iron and burning out just sufficient of the carbon by what was essentially a modification of the finery process to produce STYRIAN STEEL (which was also known as GERMAN STEEL and, most confusingly, was also referred to as NATURAL STEEL).

(g) By using a modification of the later Puddling process and similarly burning out only sufficient carbon to produce steel, cast iron could be converted to PUDDLED STEEL.

All the routes so far described provided steel in a 'bloom' and did not involve the production of liquid steel; such a commodity, suitable for casting into ingots or for the production of steel castings, could be obtained by other means :

(h) By remelting blister steel produced by method (e) above, in crucibles to provide CRUCIBLE STEEL or CAST STEEL (or HUNTSMAN STEEL, after its inventor).

(i) By melting together in crucibles a mixture of wrought iron and cast iron, or wrought iron and charcoal, or either combination together with suitable steel scrap to provide the later modifications of CRUCIBLE STEEL.

(j) By melting together the same ingredients on the hearth of a regenerative gas fired furnace to give OPEN HEARTH STEEL or SIEMENS STEEL. A later modification also incorporated the use of iron ore to remove carbon from the melt, which could then carry extra additions of cast iron.

(k) By melting cast iron and blowing air through the liquid in a suitable vessel to oxidise the carbon down to the required level to give BESSEMER STEEL.

The above processes cover the history of steelmaking almost down to 1900; the later developments of the electric arc furnace and the high frequency induction furnace are outside the scope of this survey. It is not, in fact, intended to make more than introductory references to the Bessemer and Open Hearth processes, other than to place them in their context of the changing pattern of the usage of the older methods; the bulk steelmaking processes are, in any case, adequately covered in several standard histories of the steel industry.

All the remaining processes, however, are relevant to the main discussion. This centres on what became known on the Continent and in America as "The Sheffield Methods"[1] - the use of the cementation furnace and the crucible hole. Their relevance arises since the earlier processes formed the logical introduction to the development of the cementation process whilst the search for larger quantities of steel around the middle of the nineteenth century, which led to puddled steel and eventually to the Bessemer and Siemens processes, acted also as a stimulant to modification of the crucible steel practice and to the proliferation of melting units and the casting of large forging ingots from the contents of several hundred crucibles. Eventually the role of the crucible furnace changed, becoming the source of the special cutting tools to deal with the masses of more common steel produced by the bulk steel processes and this leads directly to the consideration of its role in the development of alloy steels.

IV Brief Chronology of Steelmaking

The above discussion has quickly scanned some three thousand years and it may be helpful to study

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1 Or "Les Procédés Anglais".

the following brief chronological table to place some of these ideas in context.

By 1200 B.C.	Steel probably being produced by the bloomery process.
By 800 B.C.	Carburising and quenching being practised in the Near East.
By 400 B.C.	Tempered tools and evidence for the "steeling" of iron from the Near East.
About 50 B.C.	Steel chariot tyres made from bloomery steel. (Found in Anglesey but not necessarily produced there).
125 A.D.	Steel made in China by "Co-fusion".
1509	Natural steel made in the Weald by fining cast iron.
1601	First record of the cementation process, in Nuremberg.
1613/1617	Cementation process patented in England.
1699	Founding of the Crowley Works at Winlaton; first written record of steelmaking in the Sheffield area; cementation process involved in each case.
c.1730	Manufacture of "Shear Steel" invented by William Bertram on Tyneside.
1742	Huntsman's early experiments on the crucible process.
1767	Shear steel first made in Sheffield.
1822	Faraday's experiments with alloy steel.

1835	Steel first made by the puddling process in Germany.
1856	Bessemer announces his invention at Cheltenham.
1863	First successful work on the Siemens Open Hearth process.
1868	"Self Hard", the first commercial alloy steel, invented by R. F. Mushet.
1879	Basic steelmaking invented by Gilchrist Thomas.
1906	The first electric arc furnace installed in Sheffield.
1913	The invention of Stainless Steel by Brearley.
1926	The first high frequency induction furnace in Sheffield.

2 STEEL PRIOR TO THE SEVENTEENTH CENTURY

> 'Somewhere, sometime in the ancient world, smiths learned to make steel deliberately rather than accept what the accident of the bloomery yielded.'
>
> D. S. Landes, 1970

I The Bloomery Process

From early times, going back into the second millennium before our era, iron was produced by the 'bloomery process'. Iron ore was heated together with charcoal in a suitable furnace; the air necessary for the combustion was provided either by natural draught or, more usually, by some form of bellows. Iron ore is essentially an oxide of iron (that is a compound of iron with oxygen) with associated minerals such as sand, clay or lime. The burning of the charcoal in the air blast produced a sufficiently high temperature and, at the same time, a supply of carbon monoxide gas, such that a series of reactions could occur which between them would lead to the production of particles of metallic iron, which would sink to the bottom of the furnace. Not all the iron oxide, however, reacted in this way since a considerable proportion combined with the extraneous minerals associated with the iron oxide. This produced a liquid slag, which also travelled down the furnace and covered the growing agglomeration of the iron particles and these, by this time, formed the 'bloom' in the furnace hearth. The process is shown in diagrammatic form in Figure 5[1] which illustrates a late form of medieval bloomery of mid-European type. Earlier furnaces were generally smaller and lower structures, but operated on a similar principle. When the process had continued for a sufficient time for a useful bloom of iron to be produced, the blast was discontinued, the furnace broken into from the base and the bloom removed, reheated and then forged under a hammer to expel the bulk of the entrained slag and to consolidate the metal. It was now 'bloomery iron'. It is important to note that the temperature in the hearth during the whole operation did not exceed 1100°C to 1200°C.

II Steel from the Bloomery

Modern experimentation has demonstrated quite clearly that steel could well have been produced in a Roman, or even an early Iron Age bloomery.[2] This leads to the conclusion

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1 This is based on an original by Professor R. Pleiner and is reproduced by his kind permission.

2 R. F. Tylecote et al, 'The Mechanism of the Bloomery Process in Shaft Furnaces", J.I.S.I., vol.209 (1971), pp.342-363; H. Straube, 'Beitrag zur Antiken Stahlerzeugung in Raume Karnten', Radex Rundschau, Heft 2 (1973), pp.480-498.

that the history of steelmaking could well stretch back over more than three millennia. The only technique for the direct production of steel from iron ore which came down to modern times, however, was that of the Catalan Forge, which used a higher proportion of charcoal to ore and a lower inclination of the tuyere (the pipe which led the air blast into the furnace), when working to produce steel, than on its more normal ironmaking campaigns.[1]

Such steel, produced direct in one operation from the smelting of the iron ore, was known originally as 'natural steel' as distinct from 'artificial steel' produced by the carburisation of the bloomery iron (or, later, the wrought iron).[2] Eventually the term 'natural steel' came to be applied to the product refined from the pig iron derived from the Central European spathic iron ores. The same material was also known variously as 'raw steel', 'German steel' or, in France, 'acier forgé'. The bloomery product had a long history and it is not an unreasonable thesis that such a steely iron was smelted

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1 H. C. Landrin, trans. A. A. Fesquet as A Treatise on Steel (Philadelphia 1868), pp.142-148. This gives a full description of the process.

2 Mathurin Jousse, 'La Fidelle Ouverture de l'Art de Serrurier' (1627), as translated by C. S. Smith in Sources for the History of the Science of Steel (Chicago 1968), pp.51-52. The appropriate passages are reproduced in Appendix F.

by a deliberate modification of the working of the bloomery furnace, relatively early in the Iron Age.

The favourable conditions for steel production in the bloomery furnace seem to have been

a a higher than normal fuel to ore ratio

b a rapid air flow in the furnace, thus preventing excessively high temperatures from being attained

c a low silica content in the ore, preventing its early removal by slagging

d a high manganese content in the ore

e a probable advantage from a low phosphorus content.[1]

It is quite clear from these findings that the furnace must have been suitably designed and the correct procedure applied such that there was a sufficiently carburising environment and the reduced iron left for a sufficiently long time in that environment. On the other hand, it is quite probable that the iron was first quite highly carburised and then subsequently slowly oxidised so that the final material was a result of two opposing reactions. This would explain to some extent the very variable nature of the product since the smith must have organised his working pattern to provide a material which had sufficient

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1 These were the findings of a symposium held in Switzerland in 1970 published as W. V. Guyan, R. Pleiner and R. Fabesova, <u>Die Versuchschmelzen und ihre Bedeuten für die Metallurgie des Eisens und dessen Geschichte</u> (Schaffhausen, 1973). The discussion which follows comes from the same source.

carbon to render it hardenable but not enough to give an unforgeable product or, much worse, one which would actually melt within the furnace.

There is an apparent paradox in that the Bronze Age should be succeeded by the Iron Age. The typical bronze of the Late Bronze Age was essentially a copper-tin alloy with something between 5% and 10% of tin. Such a material had a relatively low melting point, could readily be cast to shape, and at the same time give good, solid castings with little difficulty. It was easily forgeable at a dull red heat and could be hammered or worked when cold to give a hard, durable cutting edge. Bloomery iron, on the other hand, was a relatively soft material. There was no opportunity of casting it: it had to be forged to shape from a spongy bloom which contained much slaggy impurity and was not really capable of being cold worked to give a serviceable cutting tool. Only by incorporating a proportion of carbon into the iron could its hardness and durability be brought up to make it comparable with the conventional bronze tool.[1] This may be appreciated by reference to Figure 6 which shows the 'proof stress' or 'yield stress' values[2] for the various materials. It

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1 J. A. Charles, 'From Copper to Iron', Jour.Metals, 31 (July 1979), pp.8-13.

2 This indicates the stress under which such metals begin to yield or show permanent extension.

would appear, then, that a knowledge of steelmaking techniques, coupled with some idea of the merits of quenching and tempering, was a necessary prerequisite for the developments, both military and domestic, which took place in the Iron Age. It might well, indeed, be queried whether this particular era should not have been more correctly termed the 'Steel Age'.

Traditionally, the Hittites were the first users of 'iron' and it was reputedly on this account that their enemies found difficulties in meeting their onslaughts.[1] Indeed, it is reported that Rameses II of Egypt applied to the Hittite king, Khattusilis III, around 1270 B.C. for supplies of iron. In reply, Khattusilis is purported to have replied[2]

> 'As for the good iron you wrote about to me, good iron is not available in my seal house at Kizzuwatna. That it is a bad time for producing iron I have written. They will produce good iron but as yet they have not finished. When they have finished I shall send it to you. Today I am despatching an iron dagger blade to you.'

Unfortunately, more recent commentators seem not to agree with such an interpretation and the dominance of the Hittites by virtue of their monopoly of iron is said to be based on an unwarranted translation of this particular document.[3] On the

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1 J. Newton Friend, Iron in Antiquity (London 1926), p.164.

2 O. R. Gurney, The Hittites (London 1952), p.83. He, however , indicates the reply was to a king of Assyria: Newton Friend suggests Rameses II.

3 J. A. MacQueen, The Hittites (London 1978), p.51.

other hand, other sources point to the growing use of iron in the Hittite world in the latter half of the second millennium B.C. and of gifts of iron to the later Eighteenth Dynasty pharoahs from the Hittite kings from 1380 to 1340 B.C.[1] A comment is also made that in the reign of Rameses III, just after 1200 B.C. iron is becoming more prevalent in Egypt, the illustrations of weapons on the monuments being coloured blue as against the red colour of the bronze weapons in the normal convention.[2] Whatever the real position with regard to the Hittites, there seems no doubt that the Assyrians, who emerged as the leading nation in the Near East around 1100 B.C. and held that position for about four centuries, were an 'iron' using community. If the translation of the Hittite letter can be taken at its face value, it indicates that the production of iron was a seasonal occupation (as indeed it was in this country well into the eighteenth century) and that as soon as the next season's stock had been built up the desired order would be despatched; alternatively, it could be argued that there had been some bother which had led to a sub-standard product and that, when this had been sorted out and good material was again in stock it would be despatched. A third explanation

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1 D. H. Trump, <u>The Pre-History of the Mediterranean</u> (1980) pp.168-171.

2 T. A. Rickard, 'Iron in Antiquity', <u>J.I.S.I.</u> (1929) Pt.2, p.329.

could be, of course, that an embargo had been placed on the export of iron, for military reasons.[1]

As far as the discovery of the arts of quenching and tempering steel is concerned, there are random snatches of evidence and one opinion is that blacksmiths had mastered carburising and quenching techniques by the beginning of the seventh century B.C. if not somewhat earlier. Tempering of steel, to overcome the extreme brittleness of the quenched product whilst still preserving the advantages of increased hardness and wear resistance, was in use by the beginning of the fourth century B.C.[2]

There is, however, an Egyptian axe, dated to around 900 B.C., which exhibits a carburised edge with about 0.9% carbon, fully hardened. As the section thickens away from the cutting edge, the carbon decreases as does the severity of the quench. An examination of the structure indicates that it was edge carburised and then heated and quenched, but withdrawn from the quenching liquid before it was cold, so that the thicker portions were tempered by the residual heat whilst the edge remained hard. Such a practice is difficult to envisage as a happy chance and appears to indicate a sound appreciation of the 'art' coupled with previous experience.[3]

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1 Gurney, loc.cit., pp.83-84.

2 R. Maddin, J. D. Muhly and T. S. Wheeler, 'How the Iron Age Began', Scientific American (October 1977), p.131.

3 H. C. H. Carpenter and J. M. Robertson 'The Metallography of Some Ancient Egyptian Implements', J.I.S.I. (1930), Pt.1, pp.442-444.

The logical explanation of the displacement of bronze by 'iron' must be that the art of steelmaking had been discovered and that this art was being practised reproducibly and on a sufficient scale to meet both military and domestic needs. At the same time, such a change had an additional driving force, since it seems clear that readily accessible sources of copper ores and even supplies of bronze scrap were becoming scarce by the eighth century B.C., if not earlier.[1]

More tangible evidence for this early production of steel comes from the examination of Iron Age metal. Normal corrosion effects make the chances of survival of iron and steel artefacts from antiquity much less than those of copper and bronze items and in many cases remains are classified as 'iron' by the remaining red oxide or even by rust stains only. The random nature of any items which survive as metal is further complicated by the fact that many are those prized as possessions suitable for accompanying the deceased dignitaries on their journey to the next world. They suffer from two disadvantages from the point of view of the technological historian: they are not a typical cross section of the smith's art and, in view of their archaeological importance, are not likely to be submitted to a thorough metallurgical

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1 This was pointed out to me in a private communication from Professor R. Pleiner of Prague.

examination. This having been said, however, a surprisingly high proportion of the 'iron artefacts' which have been examined turn out to have steely characteristics. Moreover, it seems quite clear that some can also, definitely, be identified as bloomery products. This arises from the fact that the only alternative process would be the deliberate carburisation of bloomery iron, by heating it within the body of a charcoal fire for a considerable period of time. This would be somewhat akin to the later cementation process in which, under the joint influence of temperature and time, carbon from the charcoal will diffuse into the metal from the outer surface. Such a process inevitably gives rise to a gradient of carbon content, higher in the outer layers and lower in the centre of the mass. The product of the 'steel bloomery' process, on the other hand, could be expected to give a relatively uniform carbon content through the mass. Among a hoard of metal objects discovered during the last war at Llyn Cerrig Bach on Anglesey were numerous objects categorised as 'iron' but only one, a portion of a chariot tyre, was examined metallurgically.[1] This was shown to have been produced by the forge-welding together of various small blooms of steel, each of them virtually uniform in carbon content within themselves but varying somewhat from one bloom to another, with an extreme range of 0.74% to

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1 Sir Cyril Fox, A Find of the Early Iron Age from Llyn Cerrig Bach, Anglesey (Cardiff 1946), pp.11-13, 75-76.

0.96% carbon. To quote from the metallurgical report:[1]

> 'The carbon content is such as to characterise the material as steel. Although this is distinctly variable throughout the mass, there is no significant evidence of gradation through the thickness and therefore none to suggest superficial carburisation of a wrought iron bar. On the contrary, the microstructure is almost entirely pearlitic and without the fibrous nature associated with piled wrought irons.'

In a report on Iron Age artefacts from West Pomerania,[2] about one quarter of the 82 examples examined were of hard steel, with from 0.4% to 0.8% of carbon. In confirmation of the previous report, there is no evidence of secondary carburisation, the carbon content being virtually uniform within the mass. It is also of interest that the phosphorus content of the steel is lower than that in the accompanying iron items, indicating possibly that some selection of raw materials - and by inference of suitable iron ores[3] since this was a direct process - was being practised as early as

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1 It had been hoped to check this work but unfortunately the specimens have been misplaced and the photomicrographs are no longer available.

2 J. Piaskowski, 'Technologia zelata na Pomorzu Zachddnim w okresie poznolatenskim i wczesnorzymskim', Materialy Zachodniopormorskie, xviii (1972), pp.81-134. I am indebted to Mr. E. Niesielski for a partial translation of this paper.

3 'Mines of Steel' at Llantrissant are referred to by H. R. Schubert, History of the British Iron and Steel Industry (1957), p.318; likewise 'Mines d'Acier' by J. H. Hassenfratz, Siderotechnie, vol.4 (Paris 1812), p.69, para.1079.

the Roman era.

The question of phosphorus is an interesting one. Phosphorus in iron is almost as effective a hardening agent as carbon and in carbon-free materials gives very little trouble. Even with small amounts of carbon present, however, brittleness is produced, particularly at room temperatures, giving the so-called 'cold shortness'. With the level of carbon present in these Iron Age samples, a phosphorus content of 0.1% would give problems; the Anglesey sample had only 0.030%. The Polish samples varied from 0.02% to 0.07% in the main, but there were a few with 0.10% to 0.13%. On the other hand, the low carbon materials in the same collection carried from 0.2% to 1.0% phosphorus. It is of interest, however, to note that bloomery steel, relatively high in phosphorus content, was used in Sweden in the production of pattern welded swords, the steel portions being much higher than the softer iron areas in phosphorus content.[1] Comment should be made that recent experimental work in Sussex[2] has given some indication that an increase in the ratio of charcoal to ore in an experimental bloomery has produced a few pounds of 'iron' which will harden

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1 L. Thalin, 'Metallografisk undersockning av ett vendeltida praktsvärd', Fornvännen, vol.62 (1967), pp.225-260.

2 R. J. Adams, 'Bloomery Furnace Experiments', Bulletin Wealden Iron Research Group, 15 (1979), pp.11-15.

somewhat on quenching. A local area in a sample submitted for examination was found to contain 0.4% to 0.5% carbon; the phosphorus content, however, derived from the use of local Wealden ore, was of the order of 0.25%.

There were, it would seem, other factors to be taken into consideration in the production of steel from the bloomery.[1] Central European practice was based on the use of ores rich in manganese and it would appear that the slag produced with such ores was fluid at a lower temperature and was more favourable to the retention of carbon by the iron particles which went to make up the bloom. In Styria in the second and first centuries B.C. were produced quantities of hard carbon steel implements - the so-called 'ferrum Noricum' - and these were widely traded; elsewhere in Central Europe, where the ores were less favourable, only some 5% to 7% of the 'iron' implements which have survived from this period are fully hard steel.

The use of the bloomery furnace continued well into the seventeenth century in this country[2] although the blast furnace had been introduced somewhat earlier and had tended to supersede the bloomery in those locations where the demand for iron was sufficiently great.

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1 Private communication from Professor R. Pleiner of Prague.

2 D. W. Crossley and D. Ashurst, 'Excavations at Rockley Smithies, a Water Powered Bloomery of the Sixteenth and Seventeenth Centuries', Post.Med.Arch., 2 (1968), pp.10-54.

III Methods Based on Diffusion of Carbon into Iron

The diffusion of carbon into iron at temperatures below the melting point of cast iron is a time-hallowed process by which the surface layers or even deeper levels of the iron can be converted into steel, and the mechanism will be described in detail in the discussion of the cementation process.[1] It certainly was known in Roman times[2] and the bands of high carbon material which alternate with softer iron in Dark Age and early medieval patterned swords could well have been made by such a process, followed by a forge-welding technique.

During medieval times, however, it becomes clear that the underlying principle was used in the process which we now would call 'case hardening'. Here, it may be supposed that the preformed article in soft iron, a piece of armour, for instance, would be carefully heated to redness in the depths of a charcoal fire. After a period of time it would be taken out, possibly quenched or allowed to cool freely in air, re-hammered to shape where necessary, and then polished by scrubbing with fine sand and water. In this way an article could be produced which had a hard surface, resistant to penetration by arrows or swords, capable of taking a high polish and then having quite a reasonable resistance to rusting and,

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1 Please refer to Chapter 3 (pp.55-57).

2 Schubert, loc.cit., pp.54-56.

moreover, supported by a softer core which was resistant to shattering - an ideal combination of the properties of both steel and iron, in one unit.

Another application of local carburisation which was practised in ancient times was on the edges of tools. It is not always clear how this was carried out. In some cases there is a gradation in carbon content from the working tip to the back of the tool. This could have arisen from a short term 'cementation' of the whole tool, in which the thinner part would receive a more thorough penetration of carbon than the remainder; alternatively, the parts other than the working edge could well have been 'stopped-off', or prevented from carburisation, by coating them with clay or other suitable material before putting them into the charcoal fire. Some tools, on the other hand, do not show a gradual transition from high carbon to low carbon areas but give a very marked transition line, which seems to indicate that a piece of iron was forge welded to a smaller piece of bloomery steel. In such a way, the cutting edge could be of steel, backed by a more massive piece of iron to give it support. This 'steeling' of iron is reported as early as the fourth century B.C.[1] and a photomicrograph of the

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1 J. D. Muhly, T. S. Wheeler and R. Maddin, 'An Iron Adze of the Fifth-Fourth Centuries B.C. from Al Mina', Levant, ix (1977), pp.156-161.

junction area in this particular tool is reproduced in Figure 7. It is the earliest example yet found of a practice which was prevalent right through to the end of the nineteenth century, if not into the twentieth. Steel was a precious and expensive material down through the ages and many thousands of Sheffield knife blades had wrought iron tangs and chisels and plane 'irons' only had steel for their actual cutting edges.

One late medieval process for the production of steel logically comes into this discussion. In the manufacture of 'Brescian Steel' a bath of molten pig iron was prepared and bars of wrought iron were introduced and stirred round for several hours, the temperature, seemingly, having been adjusted so that the molten metal did not freeze on to the iron bars, but neither did the wrought iron melt in the bath; this seems to indicate a temperature of the region of 1300^{o}C or just over. The contemporary account given by Birunguccio is reasonably explicit.[1] Under these conditions, the molten bath would act as a source of carbon which would diffuse into the iron. There is a sample of Brescian steel in the Percy Collection which has been examined.[2] It proved to be very uniform in carbon content, with about 0.96% present, with very little

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1 The passages relating to the above process are to be found reproduced in Appendix A.

2 K. C. Barraclough and J. Kerr, 'Steel from a Hundred Years Ago', Jour.Hist.Met.Soc., vol.10, Part 2 (1976), p.75.

impurity other than entrained slag; with 0.8% oxide present it was by no means a 'clean' steel, but the amount of slag was much lower than in most wrought irons.

IV The Blast Furnace

The blast furnace had some similarity to the high shaft bloomery, but operated at a higher temperature, the hearth reaching temperatures of 1400°C or more. Under these conditions the particles of iron were formed somewhat higher in the furnace shaft. Passing down through the fluid layer of slag into the charcoal hearth, they absorbed carbon at these higher temperatures. Such addition of carbon lowered the melting point of the iron, as can be appreciated by reference to Figure 3. Under these conditions, instead of a spongy mass of relatively pure iron, a liquid alloy of iron containing from 3% to 4% of carbon collected in the hearth, covered by a layer of liquid slag of lower density. From time to time, therefore, the metal could be run out from a taphole cut in the base of the shaft wall and either cast into 'pigs' or ladled out and poured into clay moulds to provide castings. The product of the blast furnace thus became known as either 'pig iron' or 'cast iron', the two terms really being synonymous as far as the origin and composition of the material were concerned. It will be observed that this material differed from steel only as regards its higher carbon content. This excessive amount of carbon, however, rendered it extremely brittle. It could not, in fact, be forged when hot and would shatter when hammered cold.[1] It would, however, withstand relatively high compressive loads and was eventually used for heavy mechanical equipment, machine housings, bridge members and the like.

The conversion of the brittle and intractable cast iron into the more usable wrought iron had to be brought about by the removal or 'burning out' of the carbon. From the time of the introduction of the blast furnace up to the latter years of the eighteenth century, this process was generally carried out in a 'finery'. The product was then transferred to the 'chafery' for reheating and forging to the desired shape. Subsequently, the 'puddling process' replaced these earlier methods. In both cases, however, the principle was the same. The pig iron was melted in the hearth of the finery in a bed of charcoal and a blast of air was blown in. The outer parts of the iron mass would oxidise and the iron oxide formed would react with the carbon in the remainder of the iron, producing the inflammable gas, carbon monoxide. In the puddling process,

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1 Accidental high temperatures in the bloomery would also produce 'cast iron' and there is some evidence that this did occur. The isolated examples of such products from Roman times seem to have been discarded as unusable scrap. R. F. Tylecote, A History of Metallurgy (1976), p.57.

the molten cast iron became covered in an artificially produced slag, rich in iron oxide, and the same reaction occurred. Reference to Figure 3 will indicate that, with either furnace operating at around 1350°C to 1400°C, which seems to have been the case, the cast iron charged would have been completely molten. As the carbon was gradually removed, however, the mass would begin to turn 'mushy'. The working over of the metal with a rabbling iron would progressively become more difficult. Eventually a solid ball of metal, containing less than 0.5% carbon, could be collected together and, if too big to handle, could be cut roughly into workable pieces. These, brought out individually for hammering, lost still more carbon due to reaction with the slag entrained in the somewhat spongy mass; indeed, the first result of the hammering was to squirt out the bulk of this slag. The hammer at this stage would almost invariably be water powered;[1] only those iron forges erected after 1860 were likely to have had steam hammers. The final bloom of wrought iron still contained some slag, distributed in elongated stringer formation and disseminated relatively evenly through the structure. It was this which gave wrought iron some of its unique properties - its toughness and its ease of welding.

1 Such hammers can be seen at Wortley Top Forge, an ironworks in the upper valley of the River Don, some ten miles from Sheffield, currently under restoration by the South Yorkshire Trades Historical Trust.

V The 'Fining' of Cast Iron to Produce Steel

In Central Europe during the late fifteenth and the sixteenth century, shortly after the introduction of the blast furnace, there arose a number of related steelmaking procedures which gave what might be regarded as a carbon-rich wrought iron. This came into commerce under a multitude of names, among which were 'Styrian Steel', 'German Steel' or even 'Cullen Steel' (since it was exported via Cologne and the Rhine). The ores in Styria, as we have noted, had been used for centuries. These were the 'spathic' ores, generally rich in manganese.

The blast furnace product from such ores was generally known as 'spiegel eisen' from its bright crystalline fracture. This contained from 5% to 10% of manganese and on remelting in the charcoal fired finery hearth, with a blast of air blown in from bellows, this manganese would oxidise first, giving a very fluid slag. The burning out of the carbon from the metal would follow, but the high manganese slag was less violent in its attack than the normal slag rich in iron oxide. Consequently, the burning out process could be more readily controlled and the removal of carbon could be brought to a halt at the desired stage.[1] It is, of course, easy to discuss such a procedure in the light of the accepted ideas of steel-

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1 The production of steel by this procedure was discussed at length by G. Jars, Voyages Métallurgiques, Vol.I (Lyons 1774), pp.22-24, and a translation of his account may be found in Appendix D.

making chemistry; the operator in the sixteenth century had to go by his own experience and the appearance of the slag, its colour and its fluidity and the nature of the metal, whether it was liquid, pasty or solid. The pattern was much as that derived for the production of wrought iron, up to the stage of the formation of the ball of more or less solid metal in the furnace, containing around 0.5% carbon. At this stage, a measured weight of fresh cast iron, which had been heated on the furnace sill to just below its fusion point, was transferred into the furnace and worked into the solidifying ball of metal until its pastiness was restored. The furnace during this time was damped down. The metal ball was then removed from the furnace and forged - carefully, at first, to consolidate it and then more heavily to drive out the entrained slag as much as possible.

The product, if all had gone well, would be a somewhat heterogeneous mass containing higher carbon and lower carbon areas, but capable of being hardened by quenching and of taking a good cutting edge. If insufficient carbon had been removed or if too much had been added back with the cast iron addition, the material would break up on forging - it could, of course, be charged back into the finery fire and reworked to a lower carbon content. If, on the other hand, the process was taken too far, the product would be a wrought iron, which would have its uses but was not the aim of the steelmaker. It seems that the product was sorted into three groups: true steel and the two less prized categories, known in the later French practice of the same type as 'fer doux' (wrought iron) and 'fer fort', an intermediate 'steely iron', which hardened somewhat on quenching and had some value in the making of hoes, plough shares and other agricultural items. The skill of the steelmaker, however, was assessed by the proportion of 'true steel' which he managed to produce.

In view of the somewhat variable nature even of the 'true steel', it became the recognised practice to sort out the bars according to their fracture, which was, in effect, a rough measure of their carbon content. Bars with a similar fracture were then bundled into a 'faggott', which was covered with clay and heated and forge welded to give bars of more uniform texture. This still exhibited alternating bands of high and low carbon material; nevertheless, well made steel of this type was an excellent cutlery material since, after hardening and suitable tempering, the high carbon bands produced wear resistant cutting edges. At the same time, the interleaved lower carbon areas provided a measure of ductility and flexibility and reduced the tendency to brittleness which would have been present in a more uniform high carbon material.

Such a process seems to have been employed throughout Europe until at least 1860; records of its use in Sweden, Germany and France substantiate this.[1] In Austria, indeed, the process was practised well into the twentieth century.[2] There were indeed many local variants and details of the operations were modified over the years, but the basic process remained substantially the same.[3]

In this country, according to Schubert,[4] the process was probably first used by Claudius Robynson in Ashdown Forest in 1509 and by 1539 the output of this establishment was about 40 to 50 tons per annum.[5] The Earl of Shrewsbury was also producing steel, presumably in this manner, at Linton in Herefordshire, prior to 1615.[6] It is also quite

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1 Some details can be found in Chapter 12.

2 R. F. Bohler, 'Tool Steel Making in Styria', School of Mines Quarterly, vol.xxix (1908), pp.329-341.

3 For the sake of clarity, two further descriptions are given in Appendices G and H, one from Sweden in the eighteenth century and the other from Austria in the late nineteenth century.

4 Schubert, loc.cit., pp.314-320.

5 Later investigations by D. W. Crossley seem to indicate this could be based on erroneous interpretation of the records.

6 G. F. Hammersley, The History of the Iron Industry in the Forest of Dean, unpublished Ph.D. thesis, London 1972. There is still a site there known as 'The Steelworks', now agricultural land. I am given to understand by the tenant that patches of red soil and black soil are still turned up from time to time. Schubert (loc.cit., footnote, p.324) considered this as a likely site for Sir Basil Brooke's steelmaking; this is not proven.

possible that the sword makers of Shotley Bridge originally made their first steel in the same way, from pig iron smelted from the Weardale ores. They were immigrants from Germany, arriving in 1693 and presumably bringing their Continental steelmaking techniques with them. Apart from the more positive record of Henry Sidney's activities at Robertsbridge in Kent, which will be discussed shortly, these are the only indications that the European method of steelmaking was applied in this country. As will be demonstrated in the next few chapters, the practice in this country developed to a large extent on its own lines. The production of blister steel and its conversion into cast steel became known on the Continent as the 'English Methods'[1] or, even more specifically in the nineteenth century, the 'Sheffield Methods'.

The Sidney Ironworks Accounts cover, among other things, the manufacture of steel at Robertsbridge from 1566 to 1572. The steelworks accounts themselves, unfortunately, do not permit of any technological interpretation. They do, however, include a set of 'estimates' from the Glamorgan ironworks in 1568 which indicate different charges for the blast furnace depending on whether the end product was to be 'sows' for refining to wrought iron or 'plates' for refining to steel. They also indicate the significant fact

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1 'Les Procédés Anglais' of a number of French texts.

that it was thought worth while to produce the plates from the Glamorgan furnace, presumably using the good quality haematite ore, and then to transport these for 'fining' at Robertsbridge, rather than to produce them on site from the local ore.[1] The differences in charges for the two products may be summarised as follows, the quantities being expressed in 'loads', which themselves are difficult of interpretation :

	Charcoal	Ore	Marl	Limestone
'Plates'	70	40	8	2
'Sows'	60	40	5	Nil

Expert opinion has been sought on the interpretation of the effects likely to arise from the difference in these two charges. It is considered that the working of the furnace could possibly have been a little hotter with the charge for the plates, which would allow thinner castings to be made (which would in turn remelt more easily in the fining process). In addition, the metal

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1 Kent Archives, U1475 B17/3 (Historical Manuscripts Commission Ref.388). Transcribed by D. W. Crossley in Sidney Ironworks Accounts, 1541-1573 (Royal Historical Society 1975) pp.237-244. The use of the Glamorgan ore in this case is one of a number of significant coincidences which include the success of Sir Basil Brooke in this same area with the cementation process for steelmaking and the fortuitous use of Blaenavon pig iron in Bessemer's original trials, again stressing the value of low phosphorus raw materials for steelmaking. Recent experimental bloomery work in the Weald, to which allusion has already been made, has shown the particular ore used in this case, considered to be a typical Wealden ore, to have given rise to a phosphorus content in the metal of over 0.25%.

might possibly be lower in sulphur content from the likely difference in slag composition.[1] It is felt, however, that there must be some more subtle reason for the differences.[2]

VI Chinese Steel

The development of techniques for the production of steel in China followed a completely different path from that in Europe.[3] The production of steel from the bloomery cannot be dated any earlier than the beginning of the 7th century B.C. which is probably some 500 years or so later than in the Near East and in Central Europe.

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1 Private communication from Mr. H. Williamson, Retired Ironmaking Manager, Staveley Ironworks.

2 It is not unreasonable to wonder whether they are a survival from the older bloomery practice, in which a charge richer in fuel might be expected to lead to a more highly carburised product - steel. It has to be remembered that the bloomery had not at this date been completely displaced by the blast furnace.

3 This information is based on discussions with Professor T. Ko, Dean of the Faculty of Metal Physics and Vice President of the Peking University of Iron and Steel Technology. In addition, he is in charge of a team of industrial archaeologists commissioned to investigate early Chinese metallurgy. Professor Ko visited Sheffield in May 1980 and I am grateful to Mr. D. Thacker of Sheffield Polytechnic and Dr. D. Cratchley of Firth Brown Ltd. for making it possible for me to have two long conversations with him.

The use of the blast furnace, however, the logical development of the bloomery, followed within a hundred years, and a remarkable example of metallurgical skill is provided by an adze, produced in white cast iron and dated to around 500 B.C. The fascinating feature of this implement, however, is that the cutting edge has been sufficiently decarburised to produce a steel-like structure; this is quite uniform and would appear to be a deliberate intention, resulting in a hard but reasonably ductile cutting edge backed by a solid mass of cast iron. The methods of 'malleablising' cast iron castings[1] were obviously well understood at this period since agricultural implements, cast to shape and then fully malleablised, are fairly widespread during the Menchius era of the fourth century B.C. and the use of such items was commonplace during the third century B.C. This was, of course, the process rediscovered by Reaumur some two thousand years later; in China it had gone out of use about the seventh century A.D. after a thousand years of practice.

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1 This is the reverse process to cementation, whereby the article is heated to redness whilst immersed in a material, such as iron oxide, which will remove carbon from the surface layers, followed by an outward diffusion of carbon from the centre to counteract this loss. If the process is continued long enough, the mass is entirely changed from brittle cast iron to a malleable, virtually carbon free iron, still retaining its shape.

The blast furnace had become fully developed during the Han dynasty and remains have recently been found of a double installation, dating from sometime in the first two centuries A.D. The furnaces had hearths of elliptical shape, about 13 feet by 8 feet. The foundation was of a fireclay material containing a pebble aggregate almost ten feet thick. There were two 'salamanders', each of about 20 to 25 tons of grey cast iron, rolled out in front of the furnaces. One of these also contained the frozen-up tuyere pipe, which was around eighteen inches diameter. The method of blowing this particular installation has not been identified, although elsewhere water power was in use by the end of the second century A.D. The solidified charge consisted of lumpy ore with charcoal and, significantly for such a period, some limestone had been added. It has been calculated that such furnaces must have had a volume of around 500 cubic feet each and have been capable of producing from one to two tons of pig iron per day, similar to many eighteenth century British charcoal furnaces. Coal was found on the site, but seems to have been used for ancillary operations, possibly for the malleablising since the charge itself contained only charcoal. The use of coal in the blast furnace as fuel, however, was common by the tenth century, if not earlier.

As far as steel is concerned, a dagger of medium carbon steel, the structure of which showed it had been heated for some time at a dull red heat - presumably to temper it - was found in a tomb dating back to the seventh century B.C. In another tomb dating to around 500 B.C. was found a collection of ferrous material - some cast iron spheres, a bar of soft iron which, from its structure, appeared to have been produced in a bloomery, and a piece of similar structure but containing a relatively uniform higher carbon content, sufficient to classify it as steel. This not only indicates the diversity of techniques available at this time but also almost certainly proves the production of steel from the bloomery.

By the third century B.C., swords with a laminated structure, with evidence of carburisation on their edges, were being produced and a sword from a tomb of 113 B.C. is obviously forge welded, from a number of different materials, varying not only in their carbon content but also in their inclusion content. Throughout the Han dynasty (roughly the last two centuries B.C. and the first two A.D.) a number of different techniques were employed. A tomb of 80 B.C. has given knives forged from decarburised iron - of no practical use - and also thin plates in cast iron and identical ones fully decarburised. In addition, there are cast arrow heads which have been fully decarburised and then recarburised on the edges only. From the same period is a pair of 'scissors' (more like sheep shears in miniature), originally cast in one length in cast iron, partially decarburised to steel, forged to bring the cutting edges together and finally hardened and tempered to leave the bow portion suitably springy. It has been suggested that this particular technique may show some Roman influence, which was known to have existed in China in the first century A.D. Be this as it may, it represents a high level of technical skill as well as a fairly profound understanding of the behaviour of steel and cast iron.

From the same period come a number of swords made by forge-welding, folding, again forging and so on. Three such items - a sword of 77 A.D., said to be of 'fifty refinings', a knife of 'thirty refinings' dated 112 A.D. and a sword of Chinese origin, but now in Japan, dating to 185 to 189 A.D. and reputed to be of 'one hundred refinings' - have been examined. All are very uniform in carbon content across the whole section, generally carrying from 0.8% to 1.0%, and the laminated structure can only be seen by studying the inclusion pattern. As a result of this examination, the sword said to be of thirty refinings was found to contain either 31 or 32 layers. The blades in all cases are martensitic in structure at their edges, the centre containing a mixture of fine pearlite and martensite; such structures indicate that the blades have been quenched and tempered. The phosphorus contents are low, generally between 0.010% and 0.030% (although one isolated area shows 0.15%); sulphur contents are all of the order of 0.010% to 0.020%. The inclusions are entirely of a silicate nature, invariably showing some potassium present (presumably from the use of charcoal); their iron oxide content is low. The relative inclusion content is also low and very finely dispersed by the large amount of mechanical work involved in the production of the blades. It is almost certain that the steel was produced by the charcoal refining of pig iron, probably by a process not dissimilar to the Styrian process of some fifteen hundred years later.

At the same time, wrought iron was obviously being produced and there is some evidence that as early as 125 A.D.[1] bundles of strips of wrought iron were 'soaked' in liquid cast iron for some hours and eventually the whole mass was forged out to give steel. This obviously is a closely related process to the Brescian one and seems to have been referred to as a 'co-fusion' process.

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1 The work is not yet complete on these early artefacts; the earliest written evidence comes from about 550 A.D. J. Needham, The Development of Iron and Steel Technology in China (London 1958), p.27, translates the passage as follows :

> 'Chiwu Huai Wen made sabres of overnight iron - iron heated continuously for several days and nights in succession. The method was to bake the purest cast iron piling it up with the soft ingots of wrought iron until after several days and nights it was all turned to steel'.

This does not give the sense implied by Professor Ko, however.

There were several modifications to such a process and not later than 1000 A.D. a solid diffusion method was widely practised. One passage, dating from 1116 A.D., reads as follows in translation :[1]

> 'Now for making steel, they take bars of soft iron and fold them up in coils, inserting pieces of cast iron between the layers. Then they seal up the furnace with clay and heat it. Afterwards the masses are forged so that they interpenetrate one another and the product is called 'lump steel'. It is a rough steel.'

In order to check the feasibility of such a process without any fusion being involved, strips of mild steel sheet were folded up with crushed white cast iron carefully sealed within the package and heated overnight. Examination of the resulting produce showed almost complete absorption of the cast iron and the consequent provision by such means of a relatively uniform steel, although the temperature used was only 975°C.[2]

Eventually, by about 1600 A.D., a larger scale operation using partial fusion came into operation and a manuscript of 1637 may be translated as follows :[3]

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1 Needham, loc.cit., p.34.

2 Needham, loc.cit., pp.30-31. The experimental work was carried out by Dr. P. Whitaker, who kindly forwarded to me the resulting samples. I confirm entirely his findings as published in Professor Needham's report.

3 Needham, loc.cit., p.27.

> 'The method of making steel is as follows. The wrought iron is beaten into thin plates or scales as wide as a finger and rather over an inch and a half long. These are all wrapped within wrought iron sheets and tightly pressed down by cast iron pieces placed on top. The whole furnace is then covered over with mud matted with worn out straw sandals. The bottom of the pile is daubed with mud as well. Large furnace piston bellows are then set to work and when the fire has risen to a sufficient heat the cast iron comes to its transformation first, and, dripping and soaking, penetrates into the wrought iron. When the two are united with each other they are taken out and forged; afterwards they are again heated and hammered. This is many times repeated. The product is usually called 'lump steel' or 'irrigated steel'.'

It seems that in some cases complete fusion of the mixture was allowed to take place, followed by solidification in the furnace prior to forging, thus anticipating the later Western methods but omitting the ingot casting stage.[1]

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1 Professor Ko remarked on the decline in metallurgy in China subsequent to this. He also commented that the European processes were eventually transferred to China, which started up both Bessemer and Open Hearth plants towards the end of the nineteenth century. As a personal comment, I found the few steelworks which I recently visited in China to be extremely reminiscent of those I saw in Sheffield at the beginning of my steelworks career some forty years ago.

3 THE CEMENTATION PROCESS: THE TECHNICAL BACKGROUND

> 'Cementation: the process by which one solid is made to penetrate and combine with another at high temperature so as to change the properties of one of them without liquefaction taking place.'
>
> Watt's Dictionary of Chemistry

I General Principles

It has already been established that the production of steel from pig iron by controlled oxidation presents problems. It would clearly be a more practical proposition to produce wrought iron, by burning out all the carbon, and then to reintroduce a controlled amount of carbon if such a means were available. This is the basis of the so-called 'Cementation Process' in which bars of wrought iron (or bar iron) were 'converted' to 'blister steel'. This process has origins which go back to the early days of the Iron Age. As applied to a conscious conversion of relatively massive bars of iron to steel, the process spanned the period from about 1600 to 1950.

The reintroduction of carbon into relatively pure iron had been carried out in a very superficial manner for many centuries. As indicated earlier, the Romans most certainly knew how to harden the surface of armour by heating it in a bed of glowing charcoal for a few hours. Such a process would now be termed 'case hardening', the production of a hard, resistant and polishable outer surface on a more ductile core, making it proof against penetration by spears and arrows, without making it brittle at the same time. Somewhere in Central Europe in the second half of the sixteenth century, it would seem that someone had the idea of applying the same principle on a grander scale to convert relatively massive bars of iron into raw steel.

The principle behind such a method, viewed in the light of theories which developed slowly long after the process became commercially viable, is that when iron and carbon are heated together, in the absence of air, the atoms of carbon will diffuse into the iron. All such diffusion processes are both time and temperature controlled. The longer that the iron is in contact with the carburising atmosphere, the more carbon will pass into it. Similarly, the higher the temperature, the more rapidly will the carbon diffuse into the iron. There was, of course, one proviso as far as temperature was concerned: if the bars had to be taken out solid, no melting had to occur. Reference to Figure 3 will show that, should the carbon content rise to 1.7% and the temperature rise above 1130°C, some fusion would take place. In practice, the carbon content rarely, if ever, reached such values and the temperature was not exceeded except by accident. The normal aim was between

1050°C and 1100°C, or around the temperature of the full melting of copper, as one commentator put it.[1] Under such circumstances, in a period of around a week a maximum of 1.5% carbon would be reached. Indeed, examples of 'glazed bars' were being produced, the outer layers of which had commenced to melt. Even worse were the real accidents, where over-ambitious firing, or just carelessness on the part of the steelmaker, led to complete fusion of the iron - its conversion, in fact, to cast iron - with the subsequent necessity for dismantling the furnace to remove the spoilt charge and to repair the damage.

II Raw Materials

The carburising environment requires a little clarification. In the cementation process this was invariably powdered charcoal, a highly carbonaceous material, free from impurities which would impair the product. All kinds of additives were tried from time

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1 F. le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', Annales des Mines, Tome III, 4me. Serie (1843), p.616.

to time. Indeed, Reaumur[1] carried out a lengthy study and proposed varying mixtures of soot, charcoal, wood ashes and seasalt as the most effective. Later recommendations tended to become less complicated and by the nineteenth century plain charcoal, or possibly charcoal watered with a salt solution, was all that was considered to be necessary.[2] The type of wood

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1 R. A. F. de Reaumur, L'Art de Convertir le Fer en Acier (Paris 1722), pp.15-42. This information can also be found in the English translation by A. A. Sisco and C. S. Smith (Chicago 1956), pp. 28-45. A very useful summary was made by W. Lewis, The Mineral and Chemical History of Iron, Manuscript MS 3.250, Cardiff Public Library, vol.v, Folios 107, 109, 111 and 113. This unfinished work dates from 1775-1780. The summary together with Lewis's own comments can be found in Appendix I.

2 The use of salt at a later date is confirmed by K. Hoglund, 'Making Steel by Cementation at Osterbybruk', Fagersta Forum (1951), No.3, p.12. Comment should also be made that there were other carburising media. Reference has already been made in Chapter 2 to the Chinese co-fusion processes and to the Brescian process. In these the carbon of the pig iron or cast iron involved diffuses, at least in part, into the relatively carbon-free wrought iron. In addition, a gaseous atmosphere rich in carbon monoxide and relatively free from free oxygen, such as may be obtained from the imperfect combustion of any carbon rich fuel, is an effective medium at high temperatures. It is, in fact, used to this day in case hardening operations and it could be argued that the atmosphere deep in a bed of glowing charcoal, slowly being consumed, is of this very nature and that this principle was involved in the early methods for the treatment of armour. Other random cementation mixtures can be found in Appendix DD.

used for the production of charcoal varied widely. As a generality, it has been stated that birch was preferred in Sweden, beech in Central Europe and oak in England;[1] this may, of course, indicate the prevalent timber trees in each area. As will be seen from the various references given and material quoted in various appendices, there really was no fixed preference, however.

The form of the iron bars used was important. Since the diffusion process was a surface reaction, it was soon obvious that a flat rectangular bar was more suitable than a square one, giving a larger ratio of surface area per unit mass.[2] Square bars were sometimes used for special applications; there is no record of round bars ever being cemented. They would, in any case, have been more difficult both to charge and subsequently to forge. The range of sizes usually quoted varies between two and three and a half inches wide and from three eighths to three quarters of an inch thick, although bars of sections such as 6" x 2" were occasionally included and were sometimes 'double cemented', that is to say, were put through

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1 F. W. Harbord and J. W. Hall, The Metallurgy of Steel (London 1904), p.222.

2 J. H. Hassenfratz, L'Art de Traiter les Minerais de Fer (Paris 1812), 3me. Partie, p.33 (para.1052) confirms the advantage of thin flat bars for the cementation process but points out the difficulty in their subsequent forging and thus the need for some compromise. On this basis he recommends bars from 'five to eight lines' thick, which roughly corresponds to the figures quoted above.

the furnace twice, to ensure adequate carburisation.

As to the type of iron to be used, there was surprising uniformity of opinion throughout the whole of the surviving records. From the late seventeenth century onwards, it is clear that Swedish iron was favoured; moreover it soon becomes evident that certain 'marks' of Swedish iron were considered superior to all others. These, in general, were those produced from ores mined in the Dannemora district of Sweden and exported from the port of Oregrund. They were, therefore, often referred to as the Dannemora or Oregrund irons. Moreover, the stamp marks on these bars, which identified the forge which had produced them, became well known. Descriptive names, such as 'Hoop L', 'Double Bullet', 'Gridiron', 'W and Crowns' and so on, became part of the general vernacular in use in Sheffield steel-making circles.[1] By the middle of the eighteenth century, a foreign observer clearly stated that the steel produced in England was produced entirely from Swedish iron, the English and Russian materials not

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1 To clarify this statement, it has been thought fit to provide a table of the most widely used brands of Swedish iron as Appendix J whilst comments from contemporary sources on the suitability and choice of various irons for steelmaking have been reproduced in Appendices K, L and M.

having been found to have sufficient body.[1] One of the earliest text books puts the matter of iron selection reasonably simply.[2] The types of bar iron available were divided into five categories :

1 Tough and soft
2 Tough and hard
3 Cold short
4 Hot short
5 Brittle, being both hot short and cold short.

The above classification was based on the reaction of the material to bending to and fro, both cold and after heating to a red heat. Only the first two were considered as suitable for cementation; the only difference between them was the period needed for adequate carburisation to occur, the former taking a longer time. Such a categorisation could well be explained on the basis of analysis. Both the tough materials were likely to be low in sulphur and phosphorus contents; the first would be the lowest in carbon content. The Dannemora irons would generally fit the second category. The cold short material would be relatively high in phosphorus content; most of the native English irons were of this type. Hot shortness

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1 S. Schroderstierna, Dagbok Rorande Handel, Naringar och Manufakturer, Aren 1748-1751, Folio 493.

2 Hassenfratz, loc.cit., p.13 (para.1029)

would generally be due to a high sulphur content, such as was likely in coke smelted material and it should be remembered that the Swedish iron was all made using charcoal, both in the blast furnace and in the refining to bar.

The only other process consumable was the fuel used for heating the furnace. This varied according to location and availability but as far as this country was concerned it was invariably pit coal; indeed, the location of the industry seems to have been determined by the two factors of availability of coal and accessibility of supplies of Swedish iron. Abroad, the situation was sometimes different. Certainly in Sweden the furnaces were wood or charcoal fired, whilst in Germany and Austria there is evidence of the use of lignite.

III The Furnace and Its Operation

There stands at Derwentcote, near the River Derwent and some twelve miles from Newcastle upon Tyne, the only authentic complete cementation furnace in Britain. The history of this furnace will be covered in a later chapter but it seems reasonable to use this as an illustration of a typical British furnace; there were, it is true, variations in size and in design of such furnaces but the principles involved remained the same.[1] The outer structure is stone built, as can be seen from Figure 8,[2] consisting of a well buttressed rectangular working area surmounted by an inner arched vault and an outer conical chimney. Internally, as illustrated in Figures 9 and 10,[3] are two chests, made from refractory sandstone slabs, set on either side of a central flue, below which runs a long firegrate. Subsidiary flues run along the outer edges of the chests and also round the ends of the chests. These chests have internal measurements of 164 in. long x 27 in. wide x 36 in. deep and were completely enveloped by flames or hot gases when the furnace was in operation.

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1 Some of these variants will be discussed later in Chapter 6. According to A. Rees, Cyclopaedia (London 1819), article entitled 'The Tilting of Steel', not paginated,

> 'the conical form of the external building is by no means essential; any form will operate in the same manner if it is of a proper height; some are, in practice, built nearly in the shape of the small end of an egg, with a round chimney on the top'.

There is also the rectangular building with chimneys at either end as described by Broling, as shown in Appendix II, Plate 16.

2 This photograph is the copyright of the Beamish Museum and is reproduced by kind permission of Frank Atkinson, Esq.

3 These drawings derive from a survey carried out by the students of Eston Grammar School and are reproduced by kind permission of J. K. Harrison, Esq.

The fill ratio within the chests, or the proportion of the internal volume occupied by the iron, the remainder being taken up by the charcoal, seems to have varied somewhat. A summary of early evidence[1] indicated that Reaumur cemented 500 to 600 lb. of iron in a volume of 4 to 5 cubic feet, which works out to 125 lb. of iron per cubic foot or a 25.6% fill ratio. At Osterby, however, in a three chest furnace, with each chest holding 24 cubic feet, a total of 10000 lb. of iron was a standard charge, giving 140 lb. per cubic foot or 28.6%. A Newcastle furnace, on the other hand, had chests of 68 cubic feet capacity with a charge of 14000 lb. each, giving a much higher figure of 205 lb. iron per cubic foot or a 41.8% fill ratio. Le Play based his estimates on the figures he obtained during his survey of Sheffield steelmaking between 1836 and 1842 and derived a fill ratio of 36% as being typical.[2] A study made in France some thirty years later confirmed this figure[3] which therefore seems a reasonable one to

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1 Hassenfratz, loc.cit., p.29 (para. 1049).

2 Le Play, loc.cit., p.593

3 M. Boussignault, Études sur la Transformàtion de l'Acier (Paris 1875), pp.125-126. This work refers to the conversion of 27000 kg. (26.58 tons) of iron in a furnace with two chests of internal capacity of 4.9 cubic metres each (internal dimensions 14'3" x 3'3" x 3'9"). When packed each chest contained 13500 kg. (13.29 tons) of iron bars and 1750 kg. (1.72 tons) of charcoal. With densities of 7.8 (0.283 lb./cu.in.) and 0.56 (0.020 lb./cu.in.) the relative volumes occupied were 35.6% for the iron and 64.4% for the charcoal. It is also reported that some 12% of the charcoal was consumed during the cementation operation.

use for discussion of nineteenth century practice at least. On this basis, the two chests of the furnace at Derwentcote would have held about 14 tons of iron between them; as will be discussed later, it was probably rebuilt internally at some subsequent date and originally only held about 10 tons. In any case, however, it was a reasonably large furnace for the period when it was built although it would have been considered to be relatively small when it ceased work towards the end of the nineteenth century.

A description of the method of operation of a very similar furnace, situated in Newcastle upon Tyne, has survived from 1767 in one of the Swedish travel journals and it is appropriate to include it here, particularly as the details did not change appreciably with the passing of time.[1] Indeed, the film which was made of the last cementation heat in this country, in 1951, could virtually use this text as commentary :

> 'In Newcastle's steel furnace 11 tons of iron bars are charged at a time. The bars are put in through holes made in the end wall of the furnace for this purpose. They are cut to a length which is shorter than the inside measurement of the chest by 2 inches or more. All the

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1 Bengt Qvist Andersson, Anmarkingnar samlade pa Resan i England Aren 1766 och 1767, Folios 163-169. Manuscript in Jernkontorets Bibliotek, Stockholm. Translation by courtesy of the late Torsten Berg. Please also refer to Appendix N for a nineteenth century account of the furnace and the process.

bars which are too long are cut by hand; any stumps are packed in the chests in separate rows and as tightly as possible. Whilst the required quantity of bar iron is being taken out from the store and being measured according to the length of the chests, the steelmaker has an excellent chance of inspecting each bar. If he finds one of particularly good quality, he puts a special mark on it. In this way he makes as sure as possible of obtaining some steel of advantageous quality which he carefully keeps for some exacting purpose. This is virtually all the grading of the iron which takes place at the English cementation furnaces. The loose bars of the firegates are always removed before the chests are packed, not only to clean out the ashpit but also to facilitate entering the furnace, for which no other arrangements are made. When everything is in proper order, both chests may be packed in 6 hours. For this work the steelmaker only needs one helper.

In England no other material than charcoal breeze is used to pack round the bars for converting to steel. The charcoal, however, is carefully chosen. Charcoal from broadleaf trees is preferred, from softer rather than harder wood and from young rather than old wood. Oakwood charcoal is not considered particularly good; that from young beechwood is preferred. Several steelmakers have assured me, however, that juniper charcoal surpasses all other kinds in quality for this purpose. A grinding mill is employed to crush the charcoal to breeze. The ample volume of the chests in relation to the quantity of iron bars shows that the amount of charcoal is not skimped.

A layer of it a little over an inch in thickness is packed between each row of bars. The top of the chest is covered with a thicker layer of charcoal over which pure dry sand is then packed.

When the furnace has been made ready for operation as described, the fire is lit, generally towards evening, and it then takes about 15 hours for the chests to become red hot. During this time it does not require constant supervision, but afterwards one workman has to be present all the time, to tend the fire which must at all times burn briskly. The furnace is stoked from both ends and fresh coal is added as often as required. The fire is tended in the same way as any other coal fire and as soon as the coal bakes together it it broken up to give the fire new air and to give the flame much increased strength and speed. Small coal is used in the main because it is less expensive and serves just as well as the large, provided that both are of similar quality. This applies particularly here, where there is good opportunity of looking after the fire properly. At Newcastle the firing lasts for five days and nights, during which time the consumption of coal amounts to four Newcastle cauldrons (or 84 Swedish barrels)*. No trial bars are used at Newcastle to find out how the conversion of the iron into steel is proceeding. They only go by the time that has been found sufficient for the grades of iron with which they are familiar. A certain amount of attention, however, is given to the colour inside the furnace, as determined by the temperature therein, which can be observed through the trial bar holes. Trial bars may, however, be used when unknown makes of iron are being tested.

At the steel furnaces in Sheffield and Rotherham, trial bars are always used, at least inside one of the chests. Here only 8 tons of iron are converted at one time and the sizes of the chests correspond to this quantity, otherwise the same preparations for conversion are made as already described. In Birmingham, shorter bars are used, it being general to cut them in two before charging. The furnaces do not hold more than 9 tons, sometimes in three chests per furnace. In most cases the conversion then takes a day or two more than in Newcastle. In all cases it required from 6 to 10 days to cool the furnaces before the bars can be withdrawn, depending on the weather and on how soon the openings in the stack are uncovered.

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* The Swedish barrel had a capacity of 36.5 gallons.

> At Newcastle it is customary not to carry out more than 12 campaigns in the year. The chests there last from 18 to 24 campaigns, provided they are constructed in the best possible way. The furnaces in Sheffield, Rotherham and Birmingham are kept going all the year round, or as much as possible, provided there is no lack of bar iron, but this often happens and, due to such shortage, no cementation furnace was in operation at the last mentioned place during my visit and had not been for several months.
>
> The chests do not infrequently become leaky during a campaign so that the outside air gains free entry, which causes the steel in them to melt. It has happened in this way that several skeppund* have become as fluid as pig iron and have run right out of the furnace. The steelmakers are not very keen on discussing these accidents but when they occur the furnace has to be shut down and the chests subsequently repaired or replaced before a new campaign can be started.'

One feature in the above description which requires some comment is the method of charging. In later furnaces[1] openings were provided in the wall above the ends of the chests. Through these a man might enter to charge the chests. When his work was finished, they would be filled up with loose bricks and the whole area then made airtight by luting the outside with clay. After the conversion period and a day or so initial cooling, the brickwork would then be broken down

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* The Skeppund was a Swedish unit of weight; approximately 7.5 skeppund were equivalent to the English ton.

1 Recent re-examination of the furnace at Derwentcote has confirmed that the fire bars must have been removed to allow access to the chests.

to assist further cooling and eventually the workman would go in and pass out the converted bars to his assistant. The method of sealing the chest was also varied. All that was essential, of course, was the production of an impervious crust to prevent ingress of air into the chest. The above description specifies a thick layer of dry sand. The earliest reference involves the use of a lid to be set into the sand and the whole to be luted with clay.[1] Another observer in the Newcastle area about the same time insists that the sand has to be moist so that it can be firmed into a dome shape on the top of the chest.[2] Later Sheffield practice varied from this, in that the usual material as an air-tight cement was the 'wheelswarf', the wet sludge from the bottom of the cutlery grinders' troughs. This was an admixture of sandstone wheel debris together with the small particles of steel grindings. It made a very effective refractory cement, firing to a dark-coloured impervious crust. After breaking into the cooled chests to retrieve the steel,

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1 F. M. Ress, 'Zur Fruhgeschichte der Zementstahl Herstellung', Stahl und Eisen, vol.75 (1955), p.979. A translation of the appropriate passage can be found in Appendix Q.

2 G. Jars, Voyages Metallurgiques vol.1 (Lyons 1774), p.223. A translation of the appropriate passage can be found in Appendix V.

the fired material became known as 'crozzle'.[1]

IV Blister Steel

The product of the cementation furnace was 'Blister Steel', the name being a descriptive one since its surfaces were raised locally into blisters of varying sizes. Such a commodity is now virtually impossible to obtain, but a sample from the last cementation heat in 1951 was provided for examination and various illustrations relevant to this examination can be seen in Figure 11.[2] The bar itself was roughly 2½" wide and ⅝" thick; the grade of iron is not known other than it being of Swedish origin. Chemical analysis showed it to contain only 0.007% sulphur and 0.011% phosphorus. On the other hand, as was to be expected it contained numerous slag streaks, averaging about 0.8% of the total volume of the metal. The carbon content of the

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1 'Crozzle' was used extensively in the Sheffield area for topping off walls. It broke naturally into pieces with jagged edges and provided a deterrent to the would-be intruder almost as effective as barbed wire or broken bottles and, moreover, was to be had for the carting. To this day there are interesting stretches of wall with such decoration; a particularly fine one may be seen along Brightside Lane adjoining the railway marshalling yard between the Firth Brown and the River Don Works. Examination of the wall itself shows other residual material from steelmaking operations incorporated in it.

2 The sample was kindly provided by the Sheffield Trades Historical Society. For details of the examination please refer to K. C. Barraclough and J. Kerr 'Metallographic Examination of Some Archive Samples of Steel', J.I.S.I. (July 1973), pp.470-471.

section was variable, with figures of 0.97% at the outside and 0.64% on the centre line. Blisters were present, but the rusted surface made any detailed examination of the outer layers difficult.

A more detailed examination of a number of samples of blister steel was carried out at the end of the last century.[1] These bars had all been produced from one batch of a Dannemora iron branded 'Little S' which had the following chemical analysis as received :

C	Si	Mn	S	P
0.05%	0.037%	0.108%	0.006%	0.012%

Bars were then given various cementation treatments and they were subsequently examined by chemical analysis. Millings were taken from the outside 0.020" of the bars, then from the next 0.020" layer, and so on until the centre of the bar had been reached. Each separate sample was then analysed for carbon. The results from three different 'tempers' are shown in Figure 12. Also included is similar information from an 'aired' bar - one which had been hard cemented at the time when the chest began to leak, late in the heat, so that the

1 J. O. Arnold, 'The Micro-Chemistry of Cementation', J.I.S.I. (1898, Part II), pp.185-194. The micrographs attached to this paper, reproduced from hand drawn and water coloured originals by F. Ibbotson, are extremely fine and merit examination for their own worth.

carbon from the outer layers was burned out, leaving a soft skinned bar.

The term 'temper' was in general use among the cementation steelmakers. The appearance of the transverse fracture of a piece of blister steel did, in point of fact, give a reasonably precise indication of the progress of the carburisation process within the iron. Obviously any change in structure would first show itself in the outer layers. The original wrought iron gave a relatively coarse fracture; carburised areas, unless produced at temperatures bordering on the fusion point, tended to have a fine fracture. At an early stage of carburisation, therefore, there would be a thin envelope of fine crystals on the outside and a large central area of unchanged coarse crystals, the latter being referred to as 'sap'. As cementation progressed, the outer envelope would thicken and the area of sap shrink, until eventually the whole of the fracture would exhibit fine crystals. On continuing the process - and for it to proceed further it generally needed the higher temperature or a much extended time - the general crystal size of the steel would grow. It will be appreciated, therefore, that a reasonable classification into groups of rising carbon content was feasible to the experienced steelmaker. Such groupings, which eventually became essentially standard within the established Sheffield trade, were referred to as 'tempers' and were given names or numbers; a typical list would have been as follows :

Temper Number	Mean Carbon Content %	Name	Fracture Appearance
1	0.60-0.70	Spring Heat	80% sap
2	0.75-0.85	Cutlery Heat	60% sap
3	0.90-1.00	Shear Heat	40% sap
4	1.05-1.15	Double Shear Heat	20% sap
5	1.20-1.35	Steel Through Heat	Fine crystals throughout
6	1.40-1.60	Melting Heat	Coarse crystals throughout
7	1.70-2.00	Glazed Heat	Very coarse and faceted crystals

From the results of the examinations discussed earlier, it will be appreciated that the carbon variations within the bar were much greater, certainly with the softer tempers, than the figures above. It will also be noted that the tempers quoted in Figure 12 do not coincide exactly with those in the above table; separate establishments had their own interpretation of detail in this respect but the underlying idea was the same.

The names given to the various 'heats' in the main indicate their use. The blister steel as it came from the furnace was of no direct use; it was blistered and brittle and had to be hot worked and reduced in section before it could be put into service. Originally, all the hot working was by forging under a water powered hammer. Eventually, however, the softer tempers tended to be rolled. The 'Spring Heat' bars would be rolled in a mill into what were termed 'plated bars' and utilised in large part for the production of laminated carriage and wagon springs. 'Cutlery Heat', sometimes referred to as 'Country Heat' though just why is not known,[1] treated similarly would give the raw material for cutlery blades of the cheaper kinds. 'Shear Heat' and 'Double Shear Heat' were used to provide the better class cutlery and edge tools. For this, the blister steel would be broken into lengths of about eighteen inches to two feet long, eight to twelve such pieces would be packed closely in a 'faggott' and hooped together with an iron bar, heated up to a bright red heat after being sprinkled with a mixture of sand and borax, and the steel bars forge-welded together and then drawn down. This produced 'shear steel' in which the high and low carbon areas from the original blister bar would have been intermingled and blended together

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1 This may simply be a result of the term becoming garbled during the passage of time.

to a fair degree. To improve the structure even further, such bars could then be resubmitted to the faggotting and forge-welding treatment to produce 'double shear steel'.[1] Each forging operation, however, involved a further heating which, despite the precautions taken, would deplete the steel of some of its carbon, hence the rising scale of carbon content in the raw materials for the more complicated procedures. 'Steel Through Heat' had reached the approximate limit of forgeability; it had to be heated carefully and then forged very gently to consolidate it before reheating and reforging to the required size; it was, in fact, very rarely produced in the early days of the process, being used only for such items as razors and graving tools. 'Melting Heat', as the term implies, was only produced after the invention of the crucible process for use as part of the charge. It was quite often produced by taking the cemented product from one conversion and resubmitting it to a second treatment in the furnace, giving the so-called 'double converted' material sought by Huntsman and his imitators during the latter half of the eighteenth century. It was, in any case, virtually unforgeable. The final temper, 'Glazed Heat', was the product of overheating, with the surface of the bar beginning to melt. A little more time or a little

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1 Methods of treating blister steel to make it suitable for further use are described by Andersson, loc.cit., and a translation of two relevant chapters may be found in Appendices O and P.

higher temperature and the whole would have 'run' or melted together so producing liquid cast iron within the furnace chest. In the early days, glazed bars would have been unusable; in the days of crucible steel melting they could be used as part of a charge to bring up the carbon content or could be rescued by dilution with some uncarburised iron bar in the crucible.

One thing remains to be discussed; the origin of the blisters. This was a matter which gave rise to many contrary opinions over the years. An early French opinion was that it was due to the volatilisation of zinc from the metal.[1] Twenty years later another Frenchman thought it showed the escape of entrained air within the body of the iron.[2] Karsten, a little later still, commented :[3]

> 'It is very strange that these blisters resemble the blowholes produced by a gas which endeavours to disengage itself from the mass of metal, as though the movement of carbon into the iron gives rise to an elastic fluid.'

The French version of the text, from which the above is a translation, was adapted from the German by

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1 J. P. F. G. Duhamel, Encyclopaedie Méthodique: Chymie, Pharmacie et Métallurgie, vol.1 (Paris 1786), p.461.

2 Anon, Traité du Fer et de l'Acier (Paris 1804), p.268.

3 C. J. B. Karsten, trans. F. J. Ailmann; Manuel de la Métallurgie du Fer (Metz 1824), p.575 (English translation by the author).

F. J. Culman, who added his own note to the effect that he considered it possible that the blisters arose from the slag entrained in the metal and that the carbon, penetrating into the mass, decomposed the slag and produced an evolution of carbonic acid. This was basically the theory arrived at by Percy;[1] he was rather more specific and quoted the slag as being silicate of iron and that the carbon would react with it to produce carbon monoxide rather than carbonic acid. It only remains to add that it is necessary, even understanding this to be the mechanism for the production of the gas, for the gas to be produced in sufficient quantity at a specific location in the bar for this pressure to exceed the yield stress of the material. The yield stress decreases as the temperature rises. In addition, the nearer a significant amount of slag is to the surface, the more readily will the pressure of gas be able to deform the material and the easier will be the blister formation. Percy hit upon an elegant method of proving his point.[2] He

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1 J. Percy, Metallurgy: Iron and Steel (London 1864), p.772.

2 J. Percy, 'On the Cause of Blisters in Blister Steel', J.I.S.I. (1878), pp.460-463. David Mushet may well have noticed the same feature three quarters of a century earlier. In his production of cast steel (British Patent No. 2447, 17 December 1800) he refers to the possibility of increasing the carbon content of his steel by further cementation and indicates that the bars 'being taken from the furnace will be found to possess all the solidity which they formerly were possessed of as cast steel'.

asked Charles Firth, of Firth and Sons in Sheffield, to melt some bar iron in a crucible and thus remove the entrained slag. He then arranged for the resulting bar to be put through the cementation furnace; it carburised normally but did not blister. By courtesy of the Science Museum, it has been possible to examine this particular sample.[1] It was carburised to the extent of 0.84% to 1.10% carbon and exhibited not a trace of a blister. It was obviously typical Swedish iron, with low sulphur and phosphorus contents. What was more surprising, however, was the extreme freedom from non-metallic inclusion matter. If the level of cleanness exhibited by this sample, with only 0.012% total non-metallic matter, was typical of the crucible steel of the day, the reputation of Sheffield steel was indeed well founded.

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1 Barraclough and Kerr, loc.cit., pp.471-472.

4 THE CEMENTATION PROCESS: THE SEVENTEENTH CENTURY

> 'At the beginning of the eighteenth century cementation or blister steel was not unusually distinguished from older steels for either novelty or quality ..... the fame of cementation appears to have grown in large part from the production potentialities of the process.'
>
> Theodore A. Wertime, 1961

I Continental Origins

The first clear reference to the true cementation process for the production of steel appears to come from a treatise on ores and assaying published in Prague in 1574;[1] a translation of the appropriate passage reads as follows :

> 'It is possible to make good steel out of iron, without any loss, by heating it strongly and for a long while, hidden in the glow of beech charcoal.'

The view that the cementation process was an English

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1 Lazarus Ercker, translated A. G. Sisco and C. S. Smith as Treatise on Ores and Assaying (Chicago 1951), original published in Prague 1574; translation taken from edition published in Frankfurt in 1580, p.287. Professor C. S. Smith refers to G. B. Della Porta, Magiae Naturalis (Naples 1589 with an English translation of 1658) as giving the first description of cementation of iron to massive steel; 'The Discovery of Carbon in Steel' Technology and Culture, vol.5, No.2 (1964). He has kindly forwarded me a copy of the appropriate passages but I find these cover the treatment of files and armour but not material in bulk. The use of a closed pot with the metal embodied therein together with a carburising mixture is involved, however. On this account, therefore, I still contend that the Nuremberg evidence (see Appendix Q) is the first account of the cementation method for the production of raw steel and the pattern for subsequent elaboration to provide the commercial cementation process as we normally understand it.

invention[1] must now be discarded, since there is a description dating back to 1601 concerning operations in Nuremberg; this leaves little doubt, from its wealth of practical detail, that here we have a fully established working method. The inventor, Johann Nussbaum, was a native of Magdeburg; it may not be without significance that he had spent some years in Prague before returning to Germany to operate his process. The details come from a manuscript from the State Archives in Munich.[2]

The first plant for the production of steel by this method was built by Der Gesellschaft der Stahl Invention und Kunst (The Company of Steel Invention and Art). Hans Koler had advanced the money, but on 26th September 1601 he was compelled to sign an oath that he would keep the secret of everything relating to the new art, or forfeit all part in the enterprise. The company, in addition, realised its reliance on the work of Paulus Hannibal in the matter of refractory materials. They entered into an agreement with him on 9th March 1602 which stated

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1 Rhys Jenkins, 'Notes on the Early History of Steel-making in England', Trans. Newcomen Society, vol.3 (1922-3).

2 F. M. Ress, 'Zur Fruhgeschichte der Zementstahl Herstellung', Stahl und Eisen, 75, No.15 (1955), pp.978-982. A translation of the relevant passages is given in Appendix Q.

that Hannibal, being skilled in the production of refractory materials, could be compelled to go anywhere abroad, at the expense of the company. Wherever the company would wish to introduce the art of steelmaking, he would build the necessary open flame furnaces and chests.

Should Hannibal himself be prevented from travelling, he would send, as his representative, a man not only experienced in the building operations but also one whose knowledge of the necessary refractories would enable him to seek out the required clays and sands, to mix them into bricks and to fire them. Hannibal also had to undertake, both for himself and on behalf of his two sons, Johannes and Endres, on oath and by sworn document, not to inform any person whether high or low without prior knowledge of the company, as to the recognition of the suitable clays, nor to supply bricks or build chests, on pain of confiscation of all his property. In return, he would receive the sum of 300 guilders. This underlines the importance of the refractory material to the process, something which persisted throughout the period of its operation.

The company consisted of Johann Nussbaum, with Phillipp Heinrich of Aschhausen, Johann Fabricio, Johann Muller and Antonio Zeller. They entered into discussion with Phillipp Ludwig, Count of the Rhine, giving him the details of the process only after he had deposited a sum of 6,000 guilders; on 7th June 1602, a treaty was signed allowing him to use the invention for the sum already held in trust. The subsequent history of this particular episode is, unfortunately, lost but the magnitude of the sum which was paid to the inventors is an obvious indication of its professed novelty, practicability and potential. The document involved certainly provides the first description of the packing of iron bars in chests, 'stratum sub stratum' with charcoal between them, a procedure so familiar later in the literature.

The same Antonio Zeller who was a member of the Nuremberg firm has, in the past, been considered as the inventor of the process.[1] He erected a forge for Ludwig V of Hessen Darmstadt; this was at Schellenhausen on the Fulda and the work was done in conjunction with Paulus von Meth; the steel was to be produced in a closed box containing layers of iron bars and beech wood charcoal, heated to white heat for twenty-four hours with 'brown coal in a draught furnace'; the trial did not succeed. Paulus von Meth started production there in 1609 but died two years later in considerable trouble and distress. Zeller, meanwhile, proposed the setting

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1 Otto Johannsen, Geschichte des Eisens (Dusseldorf 1953), pp.238-240.

up of a furnace at Dillenburg for Count Willhelm Ludwig but does not appear to have succeeded in making steel there either. From this evidence it appears clear that Zeller was merely endeavouring to use to his own advantage the partial information he had gained in Nuremberg some years earlier.

II Early British Development

The case made by Rhys Jenkins[1] that the cementation of steel was the invention of William Ellyott and Mathias Meysey, dating to 1614, was queried some forty years ago by Brownlie[2] who found the matter unproven and referred to traditions quoted by Continental writers of the nineteenth century which implied that the source of the invention was Germany. In particular, Landrin[3] stated that :

> 'Germany (was) also the first country where it was proposed to cement iron. Thence this art came to France and was introduced at Newcastle upon Tyne long before it was known in Sheffield, the present centre of that fabrication'.

The claim on behalf of Pierre de Coudroye and Jan van Buel of Maastricht, set out in a monopoly for the manufacture of steel dated 1613, as being the inventors

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1 Rhys Jenkins, 'Notes on the Early History of Steel-making', Trans. Newcomen Soc., 1922-3, vol.iii, pp.16-27.

2 D. Brownlie, 'The History of Cementation Process', J.I.S.I., vol.71 (1930), pp.455-464.

3 A. H. Landrin, translated A. Fasquet as A Treatise on Steel (Philadelphia 1868).

of the cementation process seems to have been disposed of by Dickinson[1] who clearly shows that their method was a refining of pig iron, akin to that used in Styria.

The real point at issue appears to be whether Ellyott and Meysey were, in fact, in the same position as Antonio Zeller, in that they had heard something of the process as used in Germany and, with incorrect detail, patented it in England with somewhat negative results. The patent granted in 1614[2] indicates a method which is indubitably the cementation process :

> 'which converting of iron into steel is performed by means of reverberatories furnace with potts luted or closed to be putt therein contayning in them certayne quantities of iron with other substances, mixtures and ingredients which being in the said furnace brought to a proportion of heate doth make or convert the same iron into steele with other heates temperatures and hammering to be afterwards given to the same doth make yt good and fitt for the uses afore mentioned'.

Again it is to be noted that the 'potts' are separate entities, to be moved in or out of the furnace, and not fixed chests. The patent was specifically drawn up to call on mercantilist sentiment, making great play on the theme that such steel production would make the country independent of foreign imports. In fact,

1 H. W. Dickinson in discussion of D. Brownlie, J.I.S.I., vol.71 (1930), p.474.

2 Patent Roll No.12 James I, Part I, No.15.

England did eventually become famous for its steel made by this particular process, but this success was founded entirely on the import of Swedish or Russian iron as the raw material. It could well be that the lack of success in the initial stages, reported below, was due to the use of inferior home-produced iron; this was the very problem which dogged the French steelmakers for many years after the British had realised the value of imported iron. James I, as a result of this application, granted Ellyott and Meysey the sole rights for producing and importing steel into the country for twenty-one years. In 1617, however, they surrendered this first patent in favour of one which differed mainly in that the fuel for heating the 'potts' would now be coal instead of wood: they reported that they had :

> 'attayned unto a certayne assured means in a reverberatories furnace to convert iron into steele or to make steele of or out of iron with or by means of pitt cole, Scottish cole or other fewell not being wood which formerlie was performed by the said William Ellyottes and Matthias Meysey with wood and have broughte the same to perfeccion as upon due and stryct tryall and examynacion had of the said steele made hath appeared and doth appeare'.

It is worthy of note that Nussbaum used wood as fuel; Zeller proposed brown coal or lignite; Ellyott and Meysey originally proposed wood but later changed to coal. Brownlie at this point refers to the use of coal or other material for the cementation and it seems this is a confusion of the issue; the 1617 patent clearly refers to the use of 'cole' as 'fewell' and it must be inferred that the insistence on beech charcoal as the cementation agent is carried through from one patent to the other.

The lack of success by Ellyott and Meysey may be adjudged by the outcry of the gunsmiths, cutlers and the like who were compelled to use a steel which they found to be 'wholly unfit and unserviceable' and a plea was made that

> 'but in the interim that tryall shall be made of the said Patent accordinge to their honours order, wee and our whole familyes are like to perish utterly except wee may have the free use of forraine steele as formerly wee had for that by lamentable experyence wee daily find the insufficyency and defects of steele made within the Kingdom'.[1]

At this juncture, it is a reasonable assumption that Ellyott and Meysey called in the assistance of Sir Basil Brooke. This at the outset, at least, gave them no more success, since the document just quoted also contains a further report :

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1 State Papers Domestic, James I, vol.105, No.1, January 1618.

> 'I, William Boreham his Majesties Locksmith doe hereby declare to have made divers tryalls of Sir Basil Brookes steele and have always found yt to be false and insufficyent to make any worke fitt for his Majesties service'.

Sir Basil Brooke is known to have been involved in ironmaking in the Forest of Dean from about 1610 onwards. When he applied for a renewal of the lease of his furnaces in the Forest in 1635 he made a claim to have settled the new invention of making steel within the Realm.[1] In 1662, Brooke was posthumously described as the great steelmaker of Gloucestershire[2] and when the 'Cutlers of Halomeshire' objected to the patent granted to Charles Tooker (or Tucker) in that same year they stated that, forty years before, Sir Basil Brooke, Sir William Bower and others had made as good if not better merchantable steel and that since the Restoration George Harrison and George Arderon had done the same and at far cheaper rates than Tooker.[3] From this evidence it would seem

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1 A. Raistrick, Dynasty of Ironfounders (London 1953), p.286.

2 T. Fuller, The Worthies of England, originally published 1662. Abridged version, ed. John Freeman, 1952, p.187.

3 Rhys Jenkins, op.cit., p.24. Tooker's patent appears to have been reversed in 1666 (according to the Memoirs of John Reresby as quoted in the Sheffield and Rotherham Independent, 15th July 1875). Charles Tooker's son, Thomas, became Master Cutler in 1685; his two grandsons, Thomas and John, were both Masters Cutler (in 1713 and 1726 respectively).

reasonably clear that Ellyott and Meysey, who probably came from Gloucestershire, called in the services of Sir Basil Brooke as someone reasonably skilled in metallurgical matters; if so, it would be the reasonable thing for him to carry out trials with his own Forest of Dean iron. In this context it should be noted as significant that the Forest of Dean ore is a haematite, virtually free from phosphorus. Working with the bar iron he produced by refining his own pig iron, which at that time would be charcoal smelted, he would not be at a disadvantage with the later workers with the process who insisted on Swedish iron. This could have contributed to his success and to the failure of others working elsewhere at the same time. If this indeed were the case, it would clearly be seen that history repeated itself for Bessemer, over two hundred years later; his original trials, which were successful, were fortuitously carried out on a pig iron produced from the very same ore deposit.

The location of Sir Basil Brooke's early steelworks is not known. There is, however, a tradition of very early steelmaking at Linton, near the border of Herefordshire and within the Forest of Dean,[1] and a suggestion has been made that this could well have

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1 Rhys Jenkins, 'Industries of Herefordshire in Bygone Times', Trans. Woolhope Naturalists Field Club (1936-38), pp.71-72. (It should be noted that the reference in Schubert is an erroneous one).

been connected with Sir Basil.[1] Whilst the evidence is not convincing, there is certainly a location there still known as 'The Steel Works' and it has been reported by the present occupier that patches of both 'black soil' and 'red soil' are from time to time turned up in the local fields.[2]

Sir Basil Brooke's later activities are of some interest, even if only vaguely known. His application for the renewal of the lease in the Forest of Dean was refused and he thereupon moved to his manor of Madeley in Shropshire in 1635 or 1636. He then erected, if tradition is to be believed, both a blast furnace and a steelhouse at Coalbrookdale. The blast furnace still stands, with the initials 'B.B.' and the date

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1 H. R. Schubert, History of the British Iron and Steel Industry, p.324 footnote. A similar suggestion comes from G. F. Hammersley in his unpublished thesis on 'The History of the Iron Industry in the Forest of Dean Region', London University 1972. He quotes Sir Basil Brooke as looking for an opportunity to expand since he had acquired an interest in the Ellyott and Meysey Patent between 1614 and 1616 and he refers to his acquaintance with Gilbert, Earl of Shrewsbury, who had made steel at Linton near the Forest of Dean. He also points out that the purity of the Dean iron, which made it suitable for conversion to steel, could well have been an attraction for Sir Basil Brooke. On the other hand, he makes it clear that there is no evidence he ever made steel in or near Dean and suggests the iron could just as easily have been shipped to Coalbrookdale.

2 Based on a conversation I had with him at the site.

'1638' on the lintel. The steelhouse was reported to have been converted to other uses about 1730,[1] but there is an earlier reference.[2] In June 1645, the works at Coalbrookdale, jointly owned by Sir Basil Brooke and Francis Plowden, both of whom were Royalists, were seized by the Parliamentary forces. The Clerk to the Works, Thomas Glasbrook, gave evidence that the steelmaking complex consisted of two furnaces, one rather significantly described as 'old', a forge for the conversion of pig iron into wrought iron and a number of cottages. The stock included 9 tons of 'raw metal' at £10 per ton, 1½ tons of iron at £18 per ton, 1 ton 16 cwt of steel at £37 per ton and a quantity of charcoal. It appears that Richard Foley took over the works in 1645 and probably operated them until 1649. The reference to the 'old' furnace naturally gives rise to some speculation; the possibility that Sir Basil was making steel from Forest of Dean iron at his other site in Coalbrookdale prior to 1635 must be considered. Another problem raises its head in this connection, since the local iron at Coalbrookdale was surely too phosphoric to produce

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1 A. Raistrick, Dynasty of Ironfounders (London 1953), p.286.

2 The Compounding Papers of Sir Basil Brooke, P.R.O., SP23/105, Folios 177-230 and SP23/237, Folios 69-70 (as summarised by M. Wanklyn, Shropshire Newsletter, No.44, June 1973, pp.3-6).

good steel; since Coalbrookdale is on the River Severn, it is just possible that Swedish iron was being imported for steelmaking. On the other hand, Forest of Dean iron would be equally suitable.

Rhys Jenkins takes the story on for a further ten years or so from the initial failure of Ellyott and Meysey, mentioning the activities of Dr. Fludd, who brought over from the Continent

> 'John Rochier, a ffrenchman skillful and experte in makeing steel'

which was certified by

> 'manie cutlers, blacksmyths, locksmyths and other artificers working in steele'

to be

> 'very good, serviceable and sufficyent'.

Furthermore, Fludd undertook to

> 'make steele as good as anie is made in forraine parts and to vent the same at easier and cheaper rates than the outlandish steele'.

He asked for no prohibition of imports

> 'more than what the goodness of their stuff shall occasion'.

Sir John Suckling appears to have furthered the granting of the patent, reporting :[1]

> 'I have twice been at Lymehouse where the houses, furnaces and water mill are buylt for the making and the working of the sayd steel, it being a very faire business and likelie to prove very profitable and against it no just exception can be taken'.

On an undertaking that James I should have one third of the profits, Fludd and Rochier were granted a patent in 1620.[2] Rochier died in 1625 and in 1626 a new patent was granted to Lord Dacre, Thomas Letsome (or Ledsham) and Nicholas Page;[3] Letsome was the inventor who :

> 'hath by his industrie, long travelle and paines and at his great charge and expense founde out and attayned unto the true and perfect waie for making steele within this our realme of England which as wee are informed hath not beene heretofore founde out or putt into practice and brought to perfeccion'.

No specification, however, was attached to this particular patent so that we are not certain that this was the cementation process. In any case, Letsome is known to have been working in Ireland in 1629; Lord Dacre died in 1630 and the patent was not renewed.

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1 Fortesque Papers, cxxiv, quoted by the Sheffield and Rotherham Independent, 4th July 1878.

2 Rhys Jenkins, op.cit., p.22.

3 British Patent No. 33, 1626.

From this same period there is a report on the method of steelmaking as practised at Piedmont in 1627, which is quite definitely by the cementation process.[1] Fifteen years later there is evidence that cementation was in use in Dantzig[2] and that from there it spread to Sweden. Certainly there is a tradition of steelmaking in Dantzig, using Swedish iron, for Moxon states :

> 'I cannot learn that any steel comes from Sweden but from Dantzick comes some which is called Swedish steel'.[3]

Furthermore, it is reported in 1687 that the conversion of forged iron bar into steel by heating it in furnaces was commonly carried out in Dantzig;[4] the same source also comments that a travel report by Jean de Bedoire, dated 1804, shows that steelmaking there lasted for at least a further 150 years since he found seven or eight furnaces, all using Swedish iron, in operation.[5]

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1 Mathurin Jousse, La Fidelle Ouverture de l'art du Serrurier (1627) (translated A. G. Sisco and C. S. Smith and reprinted in Sources for the History of Steel (Chicago 1968) pp.51-52). The appropriate passages are reproduced in Appendix F.

2 Johannsen, op.cit., p.239.

3 J. Moxon, Mechanick Excercises, 3rd edition (London 1703), p.58. (Reprint, New York 1970).

4 Carl Sahlin, 'Svenskt Stahl', Med Hammare och Fachla, vol.3 (1931), p.74. (For the translation of this and all other Swedish references given below I am greatly indebted to Mr. Torsten Berg).

5 Ny Journal uti Hushallningen, 1804, p.203.

The first Swedish cementation furnace was erected in 1653 at Davidshyttan in Dalecarlia to use the local iron.

In England it is recorded in 1677[1] that :

> 'steel is made in several places as in Yorkshire, Gloucestershire, Sussex and the Wild of Kent and cetera. But the best is made around the Forrest of Dean, it breaks fiery with a somewhat course grain. But if it be well wrought and proves sound it makes good edge tools, files and punches. It will work well at the forge and takes a good heat'.

It was at about the same time that the celebrated investigator Robert Hooke learned from Sir John Hoskins that :

> 'steel was made by being calcined with dust of charcoal'.[2]

Moxon places Yorkshire first in his list but there is no firm evidence for cementation furnaces as early as this. In the argument between the local cutlers and Charles Tooker in 1662-1665, we have already noted the reference to Harrison and Arderon. It so happens that there is a reference some forty years later to a Mr. Harrison who had a steel furnace at Richmond near

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1 Moxon, op.cit., p.57.

2 R. Hooke, Diary. Edited by W. H. Robinson et al., (London 1935). Entry for Friday, November 12, 1675.

Sheffield. This furnace was used by the Fell 'Steele Trade' for the conversion of Swedish bar iron into blister steel between 1708 and 1710;[1] it is therefore possible that Harrison and Arderon were both local steelmakers. Coupled with the suggestion from Rhys Jenkins that Tooker and his partner had knowledge of the Forest of Dean operations, this gives credence to the tradition that the method was practised in the Sheffield area from around 1650.

The main centre of such steelmaking in the latter part of the seventeenth century was without doubt the area around the Severn and its tributaries. Ambrose Crowley, the father of Sir Ambrose who was to establish steelmaking in the North East, had a steelhouse in Stourbridge in 1682[2] and four years later there appeared the first factual description of the cementation operation in this country. The furnace was situated only a few miles north of Stourbridge.[3] It should be pointed out that the diagram of this furnace which has been derived elsewhere[4] has probably led to

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1 Staveley Ironworks Records, Ledger, 1706-1711, Sheffield City Libraries Local History Collection, Reference SIR 3. See Chapter 5 for details (p.120).

2 M. W. Flinn, Men of Iron (Edinburgh 1962), p.12.

3 R. Plot, The Natural History of Staffordshire (Oxford 1686), p.374. The details are reproduced in Appendix B.

4 L. Aitchison, A History of Metals (London 1960), vol.2, p.442.

an erroneous impression of its true form, as it was too closely based on later developments. This early furnace owed much to the pottery kiln in which the work used to be put around a central hearth. These furnaces are described as being 'kranzformig' - in the shape of a garland[1] - with a fire in the middle. This particular passage goes on to state that it is not known when the more usual long chests were first used; it seems that the three chests in John Heydon's furnace were arranged round three sides of the fire, with an opening on the fourth side for firing purposes. It is also not clear whether, in fact, the chests or coffins were fixed structures in which the iron bars were laid, or whether they were charged and then put into place; either interpretation of the text seems valid but, considering the loaded weight, it seems more likely that the coffins were left in situ. If this is the case, it is in contrast with all earlier description and would indicate a fairly radical change which would lead to the introduction of furnaces specifically designed for steel-making.

Plot goes on to argue that since the practices he has described earlier, for the superficial hardening of iron implements, have involved the use of peculiar salts

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1 Johannsen, op.cit., p.29.

or juices, the addition of some such agent as

> 'old shoes burnt, urin and wood soot, burnt hoofes and hornes, bay salt, sublimat and tartar, all mixt together'

along with the iron in chests, must be suspected.

Ashton's comment that 'coal' in Plot's description indicates charcoal must quite clearly be wrong.[1] With the restrictions in force over this period concerning the use of timber and with the knowledge that Ellyott and Meysey, as well as Fludd and Rochier, were at pains not to use wood :

> 'they will waste noe wood but only make it of pitt coale'

it seems self evident the fuel used for firing the chests was pit coal and not charcoal. Charcoal would, in any case, be a difficult fuel to use on normal firebars and the Swedes had to develop a special furnace to accomplish this and so overcome their shortage of pit coal, even then preferring to use billet wood as fuel.

The really significant feature of Plot's description, however, is the insistence on Spanish or Swedish iron rather than English. Rhys Jenkins mentions that some fifty years earlier certain aldermen of the City of

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1 T. S. Ashton, Iron and Steel in the Industrial Revolution, 3rd edition (Manchester 1962), p.54, Footnote 2.

London were investigating the quality of steel which could be made from Swedish iron;[1] Nevertheless, here we have the first reference to a specific grade of Swedish iron. Bullet iron is fairly confidently to be equated with 'double bullet' or 'O O' brand, the product of the Osterby forge in Sweden, which was still made up to 1941. This was one of the more sought after 'Dannemora' irons. Clearly it had begun to be recognised that some irons were more capable of producing good steel than others and it now seems certain that, as early as 1686, the process of selection had progressed to the stage where home produced iron had not only been rejected in favour of the Swedish import but also that this source was being examined as to which grades were the more reliable.[2] It is also quite understandable that, when a procedure had been shown to give the desired results, no change, however small, could be easily accepted since the 'art' was so precariously balanced and the fundamentals were completely unknown. On the other hand, it has to be remembered that Swedish iron was by no means an unusual article of commerce in this country, even in the late seventeenth century; in 1699 some 15,300 tons were imported[3]

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1 Rhys Jenkins, op.cit., p.27.

2 Further detail on these irons may be found in Appendix J.

3 K. G. Hildebrand, Fagerstabrukens Historia, vol.1, p.105.

and the annual figure remained between 10,000 and 20,000 tons over the next century. Moreover, Swedish iron was cheaper than the home product almost throughout the whole of the eighteenth century: certainly this was the case until the impact of coke smelting and puddling began to be felt at the very end of the century. In fact, the overall import of iron rose to some 50,000 tons by 1780, the balance being made up from Russian iron from about 1730, this being cheaper than either the Swedish or the English iron.[1] The imported iron was used for general applications, the forging of anchors, agricultural implements and the like, but it was not considered to be as suitable as the English iron for nailmaking. The use of Swedish iron was therefore a logical step in areas with easy access by water for its import; the rise of steelmaking around Stourbridge can thus be explained on these grounds, together with the availability of coal for firing the furnaces, wooded slopes for the provision of the wood for charcoal and, above all, the fine heat-resisting clay, used in the pottery and tilemaking industries over the centuries, and most suitable for the provision of the chests or coffins for steelmaking.

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1 House of Commons Journal, vol.23, 1737, Entry for 20 April, pp.109-117. This indicated the annual import of Swedish iron to be 14,300 tons. Ordinary grades sold at £13 per ton whilst Moscow iron sold at £11 per ton.

And did not the cementation furnaces themselves owe some derivation to the local pottery kilns? - John Heydon was making his steel in the Tile House at Bromley.

Towards the end of the century, however, there was a shift in the location of this growing industry to North East England and, specifically, to the valley of the Derwent, a tributary of the Tyne. Between 1670 and 1710 operations were commenced at Shotley Bridge, where the Hollow Sword Company operated, and at Blackhall Mill (both of which were traditionally manned by German immigrants, possibly from the Solingen area), at Derwentcote, where there still stands a stone-built furnace,[1] and within the great Crowley organisation, which will be discussed in detail shortly. The area was obviously most convenient for the import of Swedish iron, in addition to having all the remaining requirements to hand; it was, however, found necessary to import Stourbridge clay and Windsor 'loam' in small amounts.

There is, as has been indicated, some vague evidence that small scale activities in this field occurred in the Sheffield area in the latter half of

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1 M. W. Flinn, 'Industry and Technology in the Derwent Valley of Durham and Northumberland in the Eighteenth Century', Trans. Newcomen Soc., vol.29 (1953-55), pp.255-262.

the seventeenth century. These are supported by the report of Erik Odhelius, a Swedish traveller who visited this country in 1692, that the same steel was made in Sheffield by the same process as at Bromley in Staffordshire but in smaller quantities at a time, in furnaces holding from 20-30 cwt only. The report also makes it quite clear that the author was familiar with Dr. Plot's text.[1]

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1 Erik Odhelius, Bergverksrelationen (Report on Visit to England 1691-2). Manuscript in the Riksarkivet, Stockholm, Folio 174-5. The relevant passages are reproduced in translation in Appendix R.

5 THE CEMENTATION PROCESS: THE EIGHTEENTH CENTURY

> 'Steele must be made of the best Orgroond iron, all raw ends cutt off, all flawed or cracky parts layd by; if any pitch be upon the iron designed for steele it must be burnt off; if clay it must be washed or beat off; all care in the world must be taken to keep the steele iron free from rust or dirt; be sure to take care to cover the potts with such sand as shall be found best to preserve the steele from the flames; let all possible care be taken in heating the ends of the potts equal to the middle.'
>
> Winlaton Council Instruction No.41

I General Progress

The eighteenth century proves to be one of the most intriguing periods in the history of steelmaking. One of the important aspects was, of course, the discovery and elaboration of the crucible process by Benjamin Huntsman and this forms the subject of a later chapter. It has to be made quite clear, however, that without the availability of blister steel Huntsman's process could not have come into being when it did. The story of cementation is not in any way one of supersession by the crucible process in the eighteenth century. Indeed, it can be argued that Huntsman's invention increased the demand for blister steel. This remained the sole material charged to the crucibles, other than a small amount of recycled scrap, until the middle of the next century. The integrated steelworks of the mid-nineteenth century comprised a group of cementation furnaces to feed the rows of crucible holes, as many engravings of the Sheffield works indicate.[1]

The location of the industry during the eighteenth century shows some interesting features. There is no doubt that, through the first three quarters of the century, the important steelmaking centre in this country was in the North East, particularly along the valley of the Derwent, a tributary of the Tyne. Bearing in mind that the requirements for the production of blister steel were accessibility to Swedish iron, the availability of coal as fuel, the provision of charcoal and local supplies of suitable refractory sandstones, this area, with its easy water transport system, was well suited to such operations. It is also worthy of note that Sheffield, at the beginning of the eighteenth century, was virtually reliant on pack horse transport as far as Bawtry. Matters improved later with the bringing of canal transport facilities, first to Rotherham by 1734 and then to Tinsley by 1751, and the amelioration of the roads brought about by the Turnpike Acts from 1757 onwards. That there were steelmaking operations in the Sheffield area from the beginning of the century is not to be denied, as there were in the Birmingham area, at least as early as the 1730s, but the cutlers of Sheffield and the 'toy-makers' of Birmingham

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1 A number of these engravings are reproduced in the author's book Sheffield Steel (Buxton 1976, reprinted 1980).

were major customers of the so-called Newcastle steel trade throughout most of the century.

It is during this period that the first information can be found in business records which have survived from the Sheffield area; such survivals are of necessity of a random nature, but the quirks of fate have provided three sources which, in certain isolated areas, overlap and corroborate each other. Moreover, this is the period when foreign travel diaries throw a considerable light on operations at diverse points. It is, indeed, fair comment that a more complete picture can be drawn during the middle years of this century than at any time in the previous or succeeding hundred years.

In the discussion which follows, it has been thought that a regional approach will make for greater clarity. In order to place matters in perspective, however, it should be pointed out that in 1737 it was reported that about 1000 tons of Swedish iron were converted into steel in the whole country, and that the Birmingham area was responsible for some 220 tons of this.[1] The production of the three operators in the Sheffield area at this date would not have totalled more than 150 tons; operations in the Stourbridge area, around Bristol and in the London area probably accounted for a further 100 tons or so, leaving about 500 tons or so from the North East. Certainly it was the North East which drew the foreign travellers until about 1770.

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1 House of Commons Journal, 1737, p.854

II Steelmaking in the North East

Ambrose Crowley, the son of the Ambrose Crowley who had his steelhouse at Stourbridge in 1682, left his family home in 1685 to set up a nailmaking factory in Sunderland. He used a number of foreign workers, who seem to have caused considerable friction with the local populace, and sometime shortly after 1690 he moved inland, to Winlaton, set on a hill above the river Derwent, six miles from Newcastle. In 1699, wishing to expand his activities, he secured the river valley site below, at Winlaton Mill.[1] Here in 1700 he built a cementation furnace, to be followed in 1701 by a second one. Some indication of the operations can be gained from two 'Council Minutes'[2] which give detail of the technique and the scale. There is here clear confirmation that certain grades of steel iron had already been selected as being preferable. The care with which the iron was to be selected for steel production gives the obvious impression that experience was being called upon. In addition, from the length of the bars, the reference to 'potts' being taken as

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1 M. W. Flinn, Men of Iron (Edinburgh 1962), pp.39-42.

2 Crowley Council Book, Minutes 39 (4th November 1701) and 41 (12th December 1701). Manuscript held by the Northumberland Record Office, Gosforth. These will be found reproduced in full in Appendices S and T.

evidence of a double chest furnace, and the weight of the charge quoted, internal measurements of the order of 108" x 27" x 24" can be calculated for the chests. This assumes that the ratio of iron to charcoal was of the same order as in later days. Such a furnace would be about two thirds the size of the furnace still extant at Derwentcote. The works were extended still further in 1707 by the acquisition of a site at Swalwell, down river from Winlaton Mill and near the confluence of the Derwent with the Tyne. By 1729 there were two steel furnaces at Swalwell;[1] it seems that these probably replaced those at Winlaton Mill. The last firm evidence of any steel-making there comes from 1725 when one furnace is said to have been working.[2] By 1750 there was a furnace at Teams[3] as well as the two at Swalwell. In 1753 it was reported that 400 tons of steel iron was used per year at Swalwell alone. The steelmaker in charge was paid twelve shillings a week, with a bonus of sixpence per ton of steel made.[4] Robsahm visited Swalwell in 1761;

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1 S. Schroderstierna, Dagbok rorande Handel, Naringar och Manufakturer Aren 1748-1751, Folios 314-315, seems to suggest that there were two furnaces still operating at Winlaton Mill in 1749 but there is some confusion in the text and he could well have been referring to Swalwell. This manuscript is in the Kungliga Bibliotek, Stockholm.

2 H. Kalmeter, Relationer on de Engelska Bergyerken, 1725, Folio 10. Manuscript in the Riksarkivet, Stockholm.

3 Flinn, loc.cit., p.186.

4 R. R. Angerstein, Resa genom England 1753-1755, Vol.2, Folio 203. Manuscript held by Jernkontoret, Stockholm.

his report seems to indicate only one furnace on the site.[1] Jars was at Swalwell some four years later; he refers to furnaces.[2] From the sizes of chests he gives, a calculated conversion weight per heat would be just under ten tons. He quotes heat weights of 10½ to 12½ tons and this could indicate that the figures quoted earlier[3] for a higher iron ratio in the Newcastle area have some substance; on the other hand, Jars does stress that his measurements were taken by eye. Andersson reported that the furnace chimneys were heavily stayed, some forty feet to the top, but with a final short cylindrical portion.[4] By this date, the Crowley organisation[5], of which steelmaking had been but a relatively small part, was beginning to decline; direct Crowley involvement ceased in 1782 when the firm became

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1 L. Robsahm, Dagbok over en Resa i England, 1761, Folios 20-23. Manuscript in the Kungliga Bibliotek, Stockholm. A translation of his account is to be found in Appendix U.

2 G. Jars, Voyages Métallurgiques, vol.1 (Lyons 1774), pp.221-226. A translation of this account is to be found in Appendix V.

3 J. H. Hassenfratz, L'Art de Traiter les Minerais de Fer (Paris 1812), 3me. Partie, p.29 (para. 1029) quoted in Chapter 3 (pp.61-2).

4 Bengt Qvist Andersson, Anmarkningar samlade pa Resan i England Aren 1766 och 1767, Folios 154-155. Manuscript in Jernkontorets Bibliotek, Stockholm.

5 The reader interested in the history of an early business venture should consult Professor Flinn's comprehensive survey of the whole Crowley organisation as set out in his book Men of Iron, to which reference has already been made.

Crowley, Millington and Company and, whilst their operations carried on until the third quarter of the next century, the great days when Swalwell was a magnet to visitors from all over Europe were over.

There were other steelmaking activities in the same area and the various locations can be identified in Figure 13. Indeed, the earliest steelmaking activity in the area quite probably did not involve the cementation process. German immigrants settling near Shotley Bridge, further up the Derwent, in about 1686, established what came to be known as the 'Hollow Sword Blade Company'.[1] Tradition has it that they made their own steel in the early days. The Weardale ores found to the south west of the Derwent Valley are somewhat unique in this country, being brown haematites, rich in manganese, and not greatly dissimilar from the Carinthian ores. From

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1 Rhys Jenkins, 'The Hollow Sword Blade Company', Trans. Newcomen Society, vol.15 (1934-1935), pp.186-187. Angerstein visited Shotley Bridge in 1753 and found the company run by a Mr. Blenkinsop of Newcastle (loc.cit., Folios 236-237). The arrogance and laziness of the original colony, which had numbered about 30, had led to shrinkage of activity and there were now only eight workmen, only partially occupied in the making of sword blades and spending the rest of their time making scythes and other agricultural implements. The remarkably small amount of steel they used came from Blackhall Mill. The sword blades were forged between shaped top tools and anvils with grooves, so as to provide the profile required on the first drawing down. They were subsequently dry ground, using stones which had been profiled by running them against iron tools. They were then varnished and patterns were then cut into the varnish before placing them in water containing oil of vitriol and Spanish Green to etch them. The finished blades apparently sold for 18s. the dozen.

the pig iron smelted from such ores it would have been possible to produce 'natural steel' by the Continental method and it should be noted that there was a blast furnace operating on these ores at Allensford, nearby, from about 1670. If such was the basis of the tradition, the situation lasted only for a few years. In 1703, the Hollow Sword Blade Company was being supplied with cementation steel by Hayford, who was known to be operating in South Yorkshire at this time and was also active in the North East, with operations at Allensford in 1713[1] and at Blackhall Mill in the 1720s.[2]

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1 R. Hetherington and S. M. Linsley, 'Excavation of a Charcoal Fired Blast Furnace at Allensford', Historical Metallurgy Society, News Letter No.4 (September 1977). I am informed by S. M. Linsley that the date of Hayford's activity at Allensford, quoted as 1733 in the above article, is in error and should read 1713.

2 H. Kalmeter, Dagbok ofver en 1718-1726 Foretagen Resa, Folios 349-350, gives a description of steel-making at Blackhall Mill. A translation can be found in Appendix W.
The whole question of the supply of steel to the Hollow Sword Blade Company by Hayford comes from E. Hughes, North Country Life in the Eighteenth Century (Oxford 1952), p.60. He suggests that the steel was bought by each German on his own account from Dan Hayford's forge at Roamley near Pontefract in bars at 5d. per pound. As far as I can make out there is no such place. S. M. Linsley has kindly checked the Cotesworth manuscripts in Gateshead and finds a badly damaged letter, reference SM/2/502, from Dan Hayford at 'Steel Forge', requesting a reply direct to him at Roamley 'per Bawtry post' with no reference to Pontefract. The deciphering of 'Roamley' leaves something to the imagination. In the Staveley Ironworks' records (Sheffield City Libraries, S.I.R.3) there is a reference to a letter to Dennis Hayford which I deciphered as 'at Bramley' but this again is not very clear.

As far as cementation steelmaking activities in the North East were concerned, it is quite possible that the operations at Winlaton Mill were not the earliest. William (or Wilhelm) Bertram, a steelmaker from Remscheid in Germany, seems to have been shipwrecked and stranded on the north Durham coast in 1693; a few years later he is reported to be in charge of steel-making at a furnace in Newcastle, possible also owned by Hayford. There is evidence to suggest that this was on the north bank of the Tyne in the region known as the Close.[1] Angerstein left a sketch of this area, which is reproduced in Figure 14. Bertram had mean-while transferred to Blackhall Mill, up the Derwent Valley, where there was another cementation furnace and it would seem the Newcastle and Blackhall Mill furnaces were of the same size.[2] This latter furnace was definitely owned by Hayford in 1720, with William Bertram as steelmaker. Again, Angerstein left a drawing of the furnace, which can be seen in Figure 15.

William Bertram is quoted as having pioneered the production of 'German Steel' by forging blister steel. He produced five kinds, the hardest being 'Double Spur

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1 Angerstein, loc.cit., vol.2, Folios 190-191.

2 Angerstein, loc.cit., vol.2, Folios 234-235, 238-239. He refers to the location as 'Blachermille'.

and Double Star'. Progressively getting softer, the other grades were 'Double Spur and Single Star', 'Double Spur',[1] 'Double Shear' and 'Single Shear'.[2] Angerstein is quite definite that the 'Shear Steel' mark - a stamp showing crossed shear blades - was Bertram's own mark; thus it comes as no surprise to learn that the making of shear steel was introduced into Sheffield by a workman from Blackhall Mill in 1767.[3] The process was developed by building up a knowledge of how to segregate the blister steel into batches of similar hardness, presumably by examination of the fracture, using selected grades of iron. Suitable bars would then be faggotted and forge welded. Bertram had built up a reputation for quality in this way; since he was a German, it seems to have been accepted that he had produced the true German steel - this presumably is where the later confusion between German steel and shear steel arose. In any case, it

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1 T. S. Ashton, An Eighteenth Century Industrialist (Manchester 1939), p.48, quotes Isaac Cookson and Co. as selling 'double spur steel' at £60 per ton in 1799. The Cooksons at that time seem to have owned Blackhall Mill, Derwentcote and the Newcastle furnaces, as will be pointed out later.

2 This information is, in the main, supported by W. Lewis, The Mineral and Chemical History of Iron, vol.iv, Folios 225 and 227. This manuscript dates from about 1775-1780 and is in the Cardiff Public Library, MS3.250. The relevant passages are reproduced as Appendix X.

3 J. S. Jeans, Steel: Its History, Manufacture, Properties and Uses (London 1880), p.14. This states that Thomas Eltringham left Blackhall Mill in 1767 to make shear steel for Thomas Boulsover in Sheffield.

seems that Bertram made a good living from his craftsmanship. He had trained other workers to make this special steel; these he had paid £7.10s. per ton of product, the normal straight forging of blister steel only earning 12s. per ton. In addition, he had provided them with a house and free coal and had paid them 5s. per day when there was no water, or when the hammer was under repair - good treatment indeed in those days. Nevertheless, three of his workmen had left him to work for competitors in the area. William Bertram had died around 1740. In 1753 Angerstein found his son in charge at Blackhall Mill; he was doing the special forging himself until such time as his son would be old enough. At this time some thirty tons of 'German steel' were made in the year with a further hundred tons or so of blister steel drawn down into simple bars.

As to the steelmaking itself, Angerstein indicates a furnace built from dressed sandstone, with a wide conical chimney. The long central flue had on either side a sandstone chest measuring 11 feet long x 22 inches wide x 32 inches deep internally. Bars of iron were packed into the chests with birch charcoal; oak charcoal would have been preferred but was difficult to obtain. The final cover was four inches of fine sand, well packed down. The charge for each heat was ten tons. Firing lasted about six days, but the cooling down period lasted fourteen days, and longer in summer. The charcoal cost 4s.6d. per load of 10 bushels.[1] The steelmakers were paid 9s. per week. The Oregrund iron used cost £21 per ton. The cost of cementation was about £1 per ton and the steel as it came from the furnace would sell for £26; the profit on the normal twelve conversions per year was therefore of the order of £500.

The furnace at Newcastle was let to a Mr. Hall prior to 1753. He had by that time acquired a second furnace of a similar size; the text is not clear but it implies this was on the same site. The chest sizes quoted here are the same as at Blackhall Mill, having dimensions of 132" x 32" x 22", each chest holding five tons of iron (ten tons per furnace). The charcoal used was from juniper or alder (which seem to be unusual choices). Firing lasted from five to six days and used £2 worth of coal, which was 12 fothers or four cauldrons. The two workers each received 7s.6d. per week. The furnaces between them consumed about 150 tons annually of Dannemora iron, costing £21 per ton.[2]

Fifteen years later, the steel from Newcastle and Blackhall Mill was still holding the reputation of being the best in England, consequent on the care taken in

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1 Such a load can be calculated to have been about 140 lb. in weight.

2 Angerstein, <u>loc.cit.</u>, vol.2, Folios 190-191.

selecting the iron for conversion and its subsequent processing. The furnaces were said to have chests 127 inches long, made from sandstone. The flues and vaults were in Stourbridge bricks and the rest of the structure was in dressed stone, in contrast to the brick-built Swalwell furnaces. The furnace chimneys were 28 to 30 feet high with a top diameter of about 3 feet.[1]

The sole survivor of this group, namely the furnace at Derwentcote, has not yet been discussed. The date of its foundation is not known with certainty. Alderman Reed had a forge at Derwentcote in 1719, but there is no record of steelmaking on the site at this time.[2] There is no doubt of its existence there in 1753, at the time of Angerstein's visit, since he left both a description and sketches as reproduced in Figure 16.[3] He indicated that it belonged to a Mr(s). Hodgson. The forge itself had one hammer and two hearths, making about 150 tons of bar iron a year from American and English pig irons. In addition, there was the steel furnace with its own hammer. The structure remains essentially as depicted by Angerstein, apart from the

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1 Andersson, loc.cit., Folios 151-152.

2 H. Kalmeter, Relationer on de Engelska Bergverken, 1725, Folio 11.

3 Angerstein, loc.cit., vol.2, Folios 246-247.

present buttresses. He stated it to be similar to the furnace at Blackhall Mill, taking charges of 10 to 11 tons of Oregrund per heat. The two workers received 8s.2d. for every ton of steel produced; the output was just over 100 tons per annum. The main restriction on production was stated to be the lack of sufficient Oregrund iron of suitable quality at a reasonable price. The hammerman at the steelworks had been a trainee with old Bertram[1] and still made a few tons of German steel a year, but in the main the blister steel was drawn down into simple bars for despatch to London.

The capacity of the furnace given by Angerstein is at variance with what the present structure might have been expected to produce since the existing size of chest would have been capable of holding at least 7 tons each side. The absence of buttresses in the Angerstein drawings has already been noticed and it could well be that, sometime late in the eighteenth or early in the nineteenth century, the internal walls would be thinned to allow the insertion of larger chests and the walls then buttressed, to give extra support. Certainly the structure seems to show the

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1 In passing, it might be noted that Angerstein also found other former Bertram employees making German steel for the Crowleys at Teams (Folio 202). Good quality iron was cemented, the blister steel drawn down, recemented and faggotted, drawn down, again recemented and faggotted, finally being made into bars of rectangular section about four feet long. It was all charcoal heated and sold eventually at 10d. per pound.

buttresses as a later addition rather than integral with the main building.

Robsahm's account of steelmaking at Swalwell[1] reports on the activities of Mr. Hodgson of the Close, Newcastle, who appears to have acted as Robsahm's host for some of the time he was in the North East. Hodgson had a foundry and 'some steel furnaces in Newcastle'. Eight years previously, Angerstein had associated Derwentcote furnace with the name of Hodgson. Robsahm clearly states that Hodgson's mark on his 'German steel' was the cloth shear mark, which had been Bertram's stamp from Blackhall Mill somewhat earlier. It is tempting to assume, therefore, that Hodgson had gathered together all the steelmaking facilities outside the Crowley organisation and that this combination passed from him to the Cookson family, probably before the end of the century, in view of their sale of 'double spur steel' already noted. Certainly Derwentcote and Blackhall Mill were being worked by the Cooksons in 1810[2] and Blackhall Mill and the Newcastle furnaces were in their care in 1811.[3]

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1 Robsahm, loc.cit., Folio 23. For details see Appendix U.

2 J. Bailey, General View of the Agriculture of the County of Durham (London 1810), p.288

3 E. Mackenzie, A Historical and Descriptive View of the County of Northumberland, vol.1 (Newcastle 1811), p.165.

III Early Sheffield Steelmaking: The Fell 'Steele Trade'.

Hidden among the records of the 'Iron Trade' carried on in South Yorkshire and North Derbyshire by John Fell I, his son John Fell II and their partners during the last few years of the seventeenth and most of the eighteenth century, are details of a 'Steele Trade'.[1] This was, indeed, a very minor part of the activities of the Fell partnerships, which were mainly involved with the running of the blast furnace at Chapeltown and the operations of the iron forges at Wadsley, Attercliffe, Roche Abbey and

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1 These records are collectively known at the 'Staveley Ironworks Records' since they were held by that company before being transferred to the Archives of the Sheffield City Libraries. The ledgers in question are numbered S.I.R. 1 to 11 with dates as set out below. Some complementary information is also to be found in the account books, classified as S.I.R. 12 to 25, which between them cover the same period.

S.I.R. 1	1691-1699	S.I.R.2	1699-1703	S.I.R.3	1706-1711
4	1711-1716	5	1716-1722	6	1722-1729
7	1729-1736	8	1736-1744	9	1744-1751
10	1751-1758	11	1758-1765		

It will be noted that the volume covering the period 1703-1706 has been lost; fortunately, something can be gleaned from the corresponding account books S.I.R.13 and 14. Specific reference to particular parts of these volumes is rendered difficult by either absence of pagination or repeated pagination within a volume, quarter by quarter or half year by half year. Moreover, the lengths of the 'quarters' are somewhat elastic although the accounting year in total always corresponds to start of July to end of June. Precise references, other than to volume, have not therefore been attempted.

Staveley.[1] By a careful search, however, it is possible to find a continuous series of accounts dealing with steel production and sales from 1699 to 1765 and the abstracted details are summarised in Table I.

The activities of Dennis Hayford in the North East have already been discussed; in the present context it is interesting to find him as partner in the 'Steele Trade' with John Fell I. The full list of partnerships runs as follows :

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1 The Fell partnerships, in fact, complemented the other great ironmaking group, the Spencer Stanhope partnerships, based on Cannon Hall, west of Barnsley. Between them, they worked the ironstone found along the outcrop of the Tankersley coal seam from just south of Leeds right down into Derbyshire. Using local wood for charcoal and water power for blowing, between them they operated some nine charcoal blast furnaces and refined the pig iron in a dozen forges. Some idea of their operations can be obtained by consulting A. Raistrick and E. Allen, 'The South Yorkshire Ironmasters, 1690-1750' Economic History Review, vol.ix (1938-1939), pp. 168-185.

1699-1724	John Fell I and Dennis Hayford; equal shares.
1724-1727	John Fell II and Dennis Hayford; equal shares.
1727-1735	John Fell II, seven shares; Millington Hayford, six shares; Arthur Speight, three shares.
1735-1738	John Fell II, six shares; Millington Hayford, six shares; Arthur Speight, three shares; Gamaliel Milner, one share.
1738-1743	John Fell II, six shares; Millington Hayford, six shares; Josiah Clay, three shares; Gamaliel Milner, one share.
1743-1748	John Fell II, five shares; Josiah Clay, two shares; Gamaliel Milner, one share.
1748-1762	John Fell II, five shares; Josiah Clay, two shares; Executors of Gamaliel Milner, one share.
1762-1765	Madam Fell, nine shares; Josiah Clay, four shares; Executors of Gamaliel Milner, two shares; Richard Swallow, one share.

The dominance of the Fell family is obvious, the more so when it is appreciated that Gamaliel Milner was brother-in-law to John Fell II and Richard Swallow his adopted son. Millington Hayford was the son of Dennis Hayford. Arthur Speight and Josiah Clay, however, are not known to have had other than business connections.

In the early years of involvement with steel, its procurement appears to have been delegated to a certain Field Sylvester. Originally he obtained this from cementation steel makers in the area, providing his own iron and selling the steel to the partnership. In 1701, for instance, two deliveries of steel, of 64 cwt. and of 57 cwt.,[1] brought him payments of £64.9.0. and £60.0.0. respectively. The material was described as 'blistered steele' or alternatively 'ruff steele'.[2] Some was further drawn down under a hammer to 'ffagott' or bar steel; small quantities were drawn down even further into 'gadd steele', the small section bar required by the cutlers. Such forging was, at least in part, carried out at Attercliffe Forge, which was run by the main partnership in which John Fell was involved. In June 1706, for example, the 'Steele Trade' was charged £1.2.6. for[3]

> 'coales, rent of ye forge and the drawings of 30 hundredweights of steele'.

The steelmaking facilities which can be identified were at Richmond, Ballifield and Darnall, all villages to the south east of Sheffield, and at Rotherham. In 1708, there is an entry for the carrying of 15 cwt. of steel from Richmond; the following year a more specific one, the significance of which has already been noted:[4]

> 'charges on Danks iron for use at Mr. Harrison's ffurnace at Richmond'.

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1 It could well be that these weights represent the contents of the furnace operated entirely for the benefit of Field Sylvester.

2 S.I.R. 2

3 S.I.R. 3

4 S.I.R. 3

In 1710 Field Sylvester was paid £1.10.0. being

> 'one quarter of two years rent of Mr. Roper's steele ffurnace'

and also

> '£10.11.3. for one quarter of Mr. Stanyford's ffurnace at Rotherham and ye tools'.

The same year there is an item covering

> 'Danks iron for ye ffurnace at Ballyfield'.[1]

As fortune would have it, light can be shed on all these from other sources. There is an indenture dated 23rd September 1709[2] in which Dysney Staniforth granted to Field Sylvester for the sum of £37.12.6.

> 'all that steele ffurnace with smithy and tenting belonging thereto situate in Rotherham in or near the beast market there'.

This would not appear to have been a sound purchase as far as steelmaking was concerned, since on 1st January 1717 there is a transfer[3]

> 'for fforty ffour pounds all that barn as the same is now builded near the beast market in Rotherham on which lately stood a building commonly known as the ancient steele ffurnace'.

The tradition of earlier steelmaking in this area certainly runs strongly and the inclination to see

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1 S.I.R. 3

2 Sheffield City Libraries, Wheat Collection No. 1966.

3 Sheffield City Libraries, MD 401.

links here with the activities of Charles Tooker is most plausible, however speculative it may be. Mr. Roper's furnace seems to have been used by Field Sylvester until at least 1713, when there is a payment covering a quarter of the rent and repairs.[1] The next connection is as late as 1737 when payment of £49.12.6. is made to cover a quarter part of a steel furnace bought from Mr. Steer.[2] This transaction is documented elsewhere[3] and the preamble states that

> 'George Roper of Richmond did on or about 15th January 1734 demise to George Steer all that ffurnace with smithy and tenting house thereto adjoining situate at Darnall for fifteen years at a rent of £5'

and the property is then indicated as being transferred in 1736 to Samuel Shore the younger (one half), John Fell (one quarter) and Mrs. Elizabeth Parkin (one quarter). There is, however, one slight confusion; all references to operations on this site in the ledgers are stated as being at the Attercliffe Furnace; this is a small point, however, since the parish was Attercliffe-cum-Darnall. Entries for the Attercliffe Furnace operations occur all the way through from 1737 to 1765; there is a rental charge on this furnace of £12 per annum from 1755 onwards, after the expiry of the previous agreement, but there is no indication to

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1 S.I.R. 4

2 S.I.R. 8

3 Sheffield City Libraries, Tibbitts Collection No. 699.

whom such payments were made. Entries for operations at Ballyfield or Ballifield Furnace, on the other hand, continue from 1710 to 1765. This furnace was rented from the Stacyes or Stacies of Ballifield Hall, initially at a figure of £3 per annum, later increased to £5.5.0. per annum. On the Fairbank plan of Ballifield Hall, drawn in 1795[1], whilst no furnace is shown, the area immediately south of the hall is marked 'Steelhouse Close', so its location would seem to be fairly precisely known.

There have been two mentions so far of 'Danks' iron for steelmaking. This term is generally taken to imply the Swedish (or Russian) iron which was shipped through the port of Dantzig, but it came to be used as an indication of Swedish iron. The entries for 'Danks iron' or 'steele iron' soon become more specific and individual brands of Dannemora begin to appear in the accounts.[2] The first mention of 'Hoop L' comes as early as 1701. By 1720, however, there has been a display in these account books of all the major Dannemora stamps, either by reproduction of the symbol or by name, such as 'Double Bullet', 'C and Crown', 'Steinbuck', 'W and Crowns', 'Gridiron' and 'GL'. There is no evidence that any iron other than Swedish was used in their

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1 Sheffield City Libraries, Fairbank Collection HAN23L.

2 For details of such irons please refer to Appendix J.

steelmaking operations, in any of these records. This is significant, since the partnerships were producing their own iron, locally and in quantity. Quite obviously it was considered unsuitable for steelmaking. The main supplier of Swedish iron to the partnership was the merchant house of Sykes in Hull; this was to be the continuing pattern in the Sheffield steel trade until the 1850s.[1] Other names such as Thornton, Victorin, Stallard, Boulton and Mould, presumably all merchants but not known apart from these records, occur fairly frequently. It is also to be observed that both Shore and Parkin, who have been mentioned already as local steelmakers, supplied small quantities of iron from time to time.[2] The size of bar is rarely mentioned; on occasion there is a special mention of square bars.[3] The iron came from London or, more rarely, from Hull. In 1717 to 1718, the carriage charge by ship from London to Stockwith on the Trent was 4s.6d. per ton. At Stockwith it was transferred to river craft for carriage to the inland port of Bawtry, on the River Idle; this cost 2s.6d. per ton.

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1 The situation with regard to supplies of Swedish steelmaking iron in about 1860 is discussed by L. E. Gruner and C. Lan, <u>L'État Present de la Metallurgie du Fer en Angleterre</u> (Paris 1862), pp.789-790. A translation appears as Appendix Y.

2 It would appear that the still current custom of the Sheffield steelmakers helping each other out when in difficulties, even though competition may be fierce, had its older precedents.

3 S.I.R. 4.

The overland carriage from Bawtry to Ballifield added a further 15s.0d. per ton. These figures equate approximately to ¼d, 3d and 9d per ton-mile.[1]

It has been noted that Field Sylvester originally operated as a steel supplier, purchasing his own iron and arranging for its conversion. From 1711, it is clear that the partners themselves were purchasing the iron and that Sylvester was being paid only for its conversion, at a rate of £2 per ton, as far as can be ascertained. This situation lasted until his death, which occurred either late in 1717 or early in 1718. At this time the stock at the furnace, the tools, grate bars, 'potts'[2], supplies of building stone, beam scales and weights were all valued and the amount paid in full to his widow.

Prior to the discovery of the above evidence, the earliest documentation concerning cementation steel production in Sheffield was thought to date to 1709. This takes the form of an agreement dated 1st April of that year between Samuel Shore

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1 S.I.R. 5. In 1724 there was a direct shipment of Hoop L iron from Amsterdam to Stockwith at a shipping charge, including duty and dues, of 48s. per ton (S.I.R. 6).

2 These were the sandstone chests for cementation (or sandstone slabs for building them).

> 'who was the owner of several steel furnaces'

and the steelmaker, Henry Ball.[1] It was agreed that

> 'the said Samuel should employ the said Henry and no one else for a space of seven years and so often as he should have occasion to make steel and should for every making of steel, or heat as it is by the workmen called, pay the said Henry ten shillings, which was above the customary price'.

Henry Ball, on his part,

> 'would not assist in making steel for anyone else during the term of seven years under a penalty of £50'.

It seems that the agreement was subsequently modified to allow Henry Ball to work, in addition, for a group of file cutters. It is reasonably certain that cementation is involved here in view of the term 'heat' being used. Ten years later it was reported that

> 'George Steer first began to lay iron in the furnace to make steel'.

This, without doubt, was the cementation process in operation.[2]

In 1720, Alstromer confirmed that there were two steel furnaces in the town of Sheffield, He identified one as being run by Shore; the other, however, he

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1 This agreement was reprinted in the Sheffield and Rotherham Independent, 6th January 1876. The whereabouts of the original is not now known.

2 G. I. H. Lloyd, The Cutlery Trades (London 1913), p.74, quotes T. A. Ward, Diary, p.237, for this information.

reported as belonging to a Mr. Perkins. He also quoted two other furnaces at a distance of two or three miles from the town; their locations and owners were not specified, but they were said to convert about six tons in one heat.[1]

Considering the evidence available, Alstromer definitely confirms Shore as a Sheffield steelmaker; his other reference could be to Parkin, rather than Perkins.[2] Of the furnaces outside the town, the Ballifield and the Attercliffe/Darnall furnaces would fit the geography. The former was definitely connected with the Fell partnership whilst Steer was known to be connected later with the Darnall furnace, although it was owned at the time of Alstromer's report by George Roper.[3]

In 1737, however, when Thomas Oughtibridge drew his 'Prospect of Sheffield' for the Cutlers' Company,

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1 J. Alstromer, Resa i England, 1720, Folio 117. Manuscript in Kunglika Biblioteket, Stockholm.

2 Parkin supplied steel iron to Fell in 1714 (S.I.R. 4); a Mrs. Parkin took a quarter share of the Darnall furnace in 1736 (Sheffield City Libraries, Tibbitts Collection No. 699).

3 The manuscript quoted in Reference 2 transfers a steel furnace at Darnall from George Roper to George Steer, who later lets it to John Fell, Samuel Shore Junior and Mrs. Elizabeth Parkin.

he made specific reference in his key to 'The Steel Furnaces', and depicted two buildings with conical superstructures and short final cylindrical chimneys, with the obvious inference that there were still only two cementation furnaces in the town at this later date (Figure 17).

The conclusion which can be drawn from this discussion is that there was an increasing interest in steel production in the Sheffield area in the early years of the eighteenth century. It would, however, seem doubtful whether this production was sufficient to provide for all local needs since, as has been pointed out earlier, 'Newcastle steel' was being sent both to Sheffield and Birmingham as late as the third quarter of the century.

Field Sylvester died just prior to Alstromer's visit to Sheffield and subsequently Fell and Hayford appear to have installed John Twig[1] together with John Twig Junior as steelmakers, and the direct employment of someone skilled in the art was probably the operating pattern through to 1765. The Twigs were in charge during the early 1730s and probably beyond. Unfortunately, for about twenty years from 1735 direct references to payments on steelmaking activities become blurred into block entries 'as per

1 The reporting of the name varies between John Twig to Jno. Twigg and all combinations.

Steele Book'. This latter, which would have been a most interesting document in the present context, does not appear to have survived. When details again become available, in 1753, the steelmaker is John Makin[1] and the records suggest he was in charge until the accounts end in 1765.

The sales by the Fell partnership were mainly of the raw blister steel or 'ruff steele', with smaller proportions of the forged products 'ffagott steele' and 'gadd steele'. The selling prices were, in the main, related to the cost of the iron. The carriage costs were generally of the order of £1 per ton and the conversion charge was around £1.10.0. to £2 per ton; the selling of blister steel at a margin of around £5 to £6 per ton over the cost of the raw iron, which was the usual pattern, thus yielded a profit of up to £3 per ton. Faggot steel usually sold at £2.10.0. more per ton than the blister steel. Considering the forging cost and the loss in yield involved, this was not unreasonable.

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1 John Makin (or Jonathon Mekin) seems to have been a man of considerable accomplishment. As will be seen later, he was involved with the Cutlers' Company enterprise and, whilst he did not sever his connection with the Fell partnership, being active on their behalf through to 1765, also worked for the Cutlers' Company from 1763 to 1772. He then set up on his own account since he appears in 1774 as 'Mason and Steelburner' at Attercliffe (J. Sketchley, Sheffield Directory (Bristol 1774), p.42). The term 'steelburner' is an unusual one, implying blister steel maker; interestingly, it has the same connotation as 'Brannstal', the Swedish term for blister steel.

Similarly, gadd steel called for an extra premium of £2 per ton. Reference to Table I will show that gadd steel was replaced by 'slitt steele' from 1741 onwards. This slitting was carried out in a mill at Attercliffe Forge.[1] The proportion of forged steel in the total sales varied considerably in the earlier years; it never seems to have been more than about 25% and was more generally between 5% and 15%. After 1751, when the production of faggot steel was discontinued, just over 5% of the sales, which averaged something over 80 tons per annum, were of slit steel bars; the remainder were unforged blister steel.

A study of the overall sales pattern indicates three periods. Under Field Sylvester, from 1699 to 1718, the maximum capability was around 30 tons per annum. From 1718 to 1743 the corresponding figure is around 70 tons per annum, and from 1743 to 1765 about 110 tons per annum. This could either indicate an increase in the number of furnaces employed or an increase in capacity of furnaces by rebuilding, or a combination of both. There are several references to repairs, purchases of stone and the like, but these seem to be regular

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1 There is, for instance, a charge for the slitting of 126 cwt. of steel between February 1748 and June 1750 at a rate equivalent to £1.5.0. per ton (S.I.R. 9). The change from forging to slitting is intriguing and whilst the arrangements at Attercliffe Forge at this time are not known, it is just possible that the change was due to the setting up of slitting facilities there at this time.

occurrences and no individual list of items seems particularly noteworthy. Some such item could, of course, be hidden in the references to the 'Steele Book'. Consideration of Table I, however, shows three years when the cost per ton is inexplicably high - 1712-1713, 1739-1740 and 1760-61. The first two cases mentioned also show a marked drop in sales compared with the years on either side; in the third case, there is a drop in sales the following year. This could be taken to indicate extra capital expense coupled with a lack of production due to the carrying out of substantial alterations. It has been assumed from the wording in the ledgers that there was only one furnace on each of the Ballifield and Attercliffe sites and there is no real evidence to the contrary. The building of a second furnace at Ballifield in 1739-1740 might, however, explain the above evidence and also the fact that there is a marked change in the profit margin pattern from the late 1730s onwards. From 1706 to 1737 profits range from 10% to 30% with a mean of 18% whilst afterwards they are only 4% to 17% with a mean of about 10%.

Selling prices and costs show variations, but the most obvious feature is the marked rise in costs from 1717 to 1720, when the price of bar iron rose dramatically.[1] This was due to an embargo on trade with Sweden, imposed on account of the pro-Jacobite sympathies of the Swedish Government. Iron became difficult to obtain, mainly being re-exported to this country from Holland. This occurred at a time when the Fell 'Steele Trade' was growing significantly and it is rather surprising that they managed to obtain the supplies they needed. The Crowley organisation in the North East most certainly suffered from shortages of Swedish iron at this time;[2] the quantities which John Fell required would, of course, have been much less in total weight. At the same time, it would seem that the local trade was willing to pay the enhanced prices for the steel. It seems that it could well have been a seller's market for some years after the return to more normal iron prices, which could explain the very handsome profits made for the next few years.

Most of the sales, as far as can be made out, were to local customers. The names in the early years are not generally familiar ones in subsequent Sheffield steel and cutlery circles. Names such as Kenyon,

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1 The prices of 'Hoop L' bar iron from Sweden, given in the ledgers, have been collected together in a table, which also contains later prices, for the sake of completeness, as far as is possible. This may be found in Appendix ZZ.

2 Flinn, <u>loc.cit.</u>, p.67.

Spencer and Huntsman himself[1], however, do appear in the accounts in later years.

IV A Later Eighteenth Century Sheffield Enterprise: The Cutlers' Company

The Sheffield scene as regards cementation steelmaking is, unlike that in the North East, hardly mentioned by the many foreign visitors to this country. Apart from the two short references by Odhelius and Alstromer relating to the early years, which have already been mentioned, the only Swedish visitor to comment was Andersson and he contented himself by commenting that the furnaces in Rotherham and Sheffield were designed in the same manner as those at Newcastle, but were smaller and that the resultant steel was not deemed to reach the same standards as that from Newcastle and Blackhall Mill.[2] There is nothing from Schroderstierna; Angerstein is definitely known to have visited the Sheffield area but the pages of his journal reporting on this are missing. Robsahm was chiefly interested in the crucible process, as will be seen in Chapter 7; he did, however, leave some comments on local cementation steelmaking which will be discussed shortly.

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1 Details of Huntsman's transactions with the Fell partnership can be found in Chapter 7 (pp.224-226).

2 Andersson, loc.cit., vol.3, Folios 149-150.

The most extensive report in the third quarter of the century by a foreign visitor comes from Gabriel Jars.[1] In the main, however, his conclusions are similar to those of Andersson.

It so happens, however, that a further set of accounts has survived from this period which provides evidence of cementation steelmaking. The records of the Company of Cutlers in Hallamshire contain a day-book and a ledger[2] relating to a steelmaking enterprise operated under the Cutlers' Company control between 1759 and 1772, the expressed aim being:[3]

> 'that the steel shall be disposed of amongst members of the Corporation equally and impartially at the rate or price directed which rate or price shall if possible be something below the common market and yet to bring a gain to the Company something more than equal to answer the expenses of the Trust and the Interest of the Capital Stock or Fund appropriate or set apart to that end.'

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1 G. Jars, Voyages Métallurgiques, vol.1 (Lyons 1774), pp. 256-258. A translation of the relevant passages can be found in Appendix Z.

2 Volumes 47 and 48 in the Archives of the Company of Cutlers in Hallamshire. I was privileged to examine these records in detail by courtesy of W. G. Ibberson, Esq., a Past Master Cutler, and of R. T. Doncaster, Esq., who was Master Cutler at the time. An earlier report on these records prepared by me appears in a volume published by the Cutlers' Company in 1972 entitled Extracts from the Records of the Cutlers' Company, and reprinted in Bulletin of the Historical Metallurgy Group, vol.6 (1973), Part 2, pp.24-30. The discussion here incorporates some later findings but also omits some of the detailed figures; the interested reader is therefore referred to the original paper for these.

3 Extract from the minutes of a meeting of the Master, Warden and Searchers of the Cutlers' Company, held at the Cutlers' Hall, Sheffield, on 26th February 1763.

Operations commenced during the summer of 1759 by:[1]

'taking a cementation furnace in Scotland Street.'

The first heat was 'carried out'[2] in November 1759. For the period up to August 1763 the operations were under the control of Mr. Joseph Ibberson, Master Cutler for 1759-1760. From the accounts it is clear that he employed John Morton as his stonemason. Initially, John Marshall was his steelmaker;[3] from June 1760 to September 1763 the payments for 'heats', however, are made to John Smith and 'Brother'.

The iron used was Swedish throughout, the major grades being 'Hoop L', 'double bullet' and 'GL', their cost, delivered British port, being £21 to £22 per ton. Some cheaper grades, 'CDG' at around £20 per ton and 'AOK' at £19 per ton, were also used. The material was all supplied either through Samuel Wordsworth or Joseph Sykes, some of the earlier supplies coming through London, by sea to Hull at 3s.9d. per ton, thence from Hull to Tinsley by canal at

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1 R. E. Leader, History of the Cutlers' Company (Sheffield 1905), pp.174-175.

2 'Carrying out' refers to the operation of removing the converted blister steel from the furnace and thus the successful conclusion of a heat. It invariably is accompanied by the granting of ale to the workmen.

3 Presumably the same John Marshall who was producing cementation and crucible steel at Millsands some fourteen years later.

10s. 0d. per ton, the final road transport from the canal wharf at Tinsley to the furnace at Scotland Street in Sheffield costing 2d.6d. per ton.[1]

Full details of the individual iron shipments are not preserved, but the road transport charges indicate receipt of 138^{2}/3 tons during the period of Ibberson's stewardship. Some 10¼ tons of this was unused and this tallies with sales of 128 tons 8 cwt. and 1 ton 4 cwt. of steel in stock.[2]

In the first fifteen months of operation, some seventeen entries appear for 'steele carrying out'. The accounts for the remainder of the period are, unfortunately, not as detailed but, since steel sales are reasonably constant, it is reasonable to assume that this was the established tempo of working. Some repairs were undertaken, including the replacement of two chests, which could have led to the loss of two or

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1 These figures work out at ^{1}/3d, 3d and 10d per ton-mile, virtually identical for sea, canal and road transport with those forty years earlier. It should be noted, however, that the canal journey was now much longer and the road journey much shorter, to the benefit of the steelmaker.

2 The stock in hand in October 1762 is given as follows, the prices per ton having been calculated by the author :

			Per ton
	t c q lb	£. s.d.	£. s.d.
Steel at the Furnace	1. 0.0.10.	24.17.6.	24.15.0.
Slit Steel	4.2. 0.	6. 1.6.	27. 0.0.
O O Iron	1.13.3. 4.	36.14.9.	21.15.0.
AOK Iron	8.11.0. 4.	168. 0.9.	19.13.0.

three heats, leading to the suggestion that about 34 heats were required to produce 129 tons 12 cwt. of steel. This indicates the furnace capacity, from both chests,[1] to be around 3¾ tons, which is confirmed by a rough note on the flyleaf of Volume 48 which states :

'Steel in furnace, 25.10.62, T3.16 cwt. 3 q. 4 lb'.

Taking these figures into consideration, the likely internal dimensions of the chests would have been 6 to 7 feet long and some such section as 21 inches x 24 inches.[2] Obviously, by Newcastle or Blackhall Mill standards, this was a small furnace; this confirms the comments of Jars and Andersson.

At this point, however, it is of interest to turn to the report given by Robsahm.[3] On 11th July 1761 he reports a visit to a steel furnace in the town of Sheffield itself[4] which was on the same site as three crucible melting furnaces belonging to Mr. Smith. It is important to note, in connection with the Cutlers' Company enterprise, that the furnace utilised was an

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1 The accounts cover 'a paire of pottes' at the time of the furnace repair in 1761.

2 Using the formula quoted by Le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', Annales des Mines, 4me. Serie, Tome III (1843), pp.593-594.

3 L. Robsahm, loc.cit., Folios 84-85.

4 He had previously been visiting Huntsman, 'two miles outside the town'; his report on this aspect of steel-making is discussed in full in Chapter 7 (pp. 226-229).

existing one - it was 'taken', according to Leader - and that Ibberson's steelmaker from June 1760, and therefore at the time of Robsahm's visit, was John Smith, assisted by his brother. Robsahm refers to a sketch he made of this furnace; unfortunately this has been lost, but he goes on to describe it as follows :

> 'In the morning I went to see the steel furnace which was not in operation at the time. I was allowed to look at the inside and for this purpose required a candle which the steelmaster obtained for me. I found the inside of the furnace was designed as indicated in the attached sketch in which aa is the height and width of the chests, b an opening between the chests through which the flame sweeps up, cccc are holes for the flames to pass below and beside the chests, e is the vault that surrounds the chests on both the long and the short sides, ff are holes through which flame and smoke leave the furnace proper and of which there are six spread around the vault, d is the iron grate upon which the coal is placed, g is another vault where the smoke and flame collect in order to be brought out through the chimney stack h, i is an opening with a wooden door allowing access to the vault e for repairs. The length of the blister steel bars permitted me to conclude that the furnace is 9 feet square internally, the height and width of the chests aa is 2 feet, the flues cccc of which there are six along the length of the chest were 8 inches square and the supporting walls for the chests 9 inches thick. The outside plan of the furnaces was 16 feet square.'

Robsahm further discusses the crucible furnaces and then continues his comments on cementation steelmaking:

> 'The same day, after dinner, I again went to the place where I saw the crucible steel furnaces in the morning ... and I was shown another small cementation furnace with only one chest in which only two tons of iron could be converted at any

> one time. It was built in the same way as already described with a vault above the chest from which the smoke and flame was drawn out through a chimney built of masonry at the centre of the vault. The iron that was going to be converted was of the stamp 'AOK' with the figure 'VII' stamped at the middle of the bars. This make of iron was said to have been good previously, when it did not have the stamp 'VII' but the bars were not now considered to be the most suitable kind.'

The coincidences here, of operations by a Mr. Smith, of a double chest furnace, of the appropriate size, and of the use of AOK iron, must amount to a reasonable assumption that here there is an independent reference to the operations of the Cutlers' Company, particularly as the association with crucible steelmaking on the site is later shown in the account books.

There is also a further piece of corroborative evidence for this same period in that a note book of Matthias Spencer indicates steel purchases from Mr. Ibberson and the entries check, with slight discrepancies, with those in the Account Book of the

Cutlers' Company.[1]

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1 This note book was kindly loaned by Spencer, Clark and Company through the courtesy of Mrs. Lipson; it has subsequently been lodged with the Archive Division of the Sheffield City Libraries at my suggestion. It is a general memorandum book, with varying completeness of entry. Used pages from other accounts are somewhat randomly filled up with later additions and the back end of the book has payment accounts for servants and other employees, of a domestic nature. The comparative entries referred to above can be illustrated by those for 1761:

Spencer Note Book			Archive Volume 48		
18 March	5.2.0 @ 27/-	6.15.0	18 March	5.0. 4	6.16. 0
22 April	10.0.9 @ 27/-	13.12.2	22 April	10.0. 9	13. 7. 2
20 May	10.0.1 @ 27/-	13.10.3	20 May	10.0. 1	13.10. 3
16 June	1.0.8 @ 27/-	1. 9.0	17 June	1.0. 8	1. 8.11
	No entry		22 July	5.0.10	6.17. 3
	No entry		19 August	9.0. 4	12. 3.11

The iron accounts indicate that the AOK iron came from Samuel Wordsworth and the deliveries in August 1761 and in January 1762 are clearly indicated as being 'AOK VII'.[1] CDG and GL grades were supplied by Joseph Sykes. The accounts are not complete, giving between them some 17 tons less than that actually received by Ibberson and there is no 'double bullet' included, although it appears in the remaining stock at the end of the period. There is, however, a further fly-leaf note that 15 tons of this iron was ordered from Mr. Sykes on 17th December 1761; its price is not quoted, but it is credited at £21.15.0d. per ton in the stock balance.

It was towards the end of the period of management by Joseph Ibberson that the meeting took place at which the underlying principle, quoted above, was reiterated.[2]

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1 The addition of the symbol 'VII' to the AOK stamp calls for some comment. The AOK stamp was owned by Gysinge Forge and their forging rights were increased in 1761 from 1800 skeppund to 2800 skeppund per annum (from 240 to 373 tons per annum). Gysinge Forge had always drawn its pig iron from the seventh Mine Inspection Territory in Dannemora but for some reason it only thought fit to advertise this by adding the stamp 'VII' to its bars after its reorganisation in 1761. (I am indebted to Mr. Bo Molander of Stockholm for this information). It is clear from Robsahm's report that the Sheffield steelmakers considered that the increase in output had been accompanied by a deterioration in standards.

2 The full text of the minutes may be found as an appendix to the author's article in Bulletin Historical Metallurgy Group, vol.6 (1973), Part 2, pp.29-30.

One of the decisions made on that occasion was that, in future, the management should be in the hands of the current Master Cutler. Ibberson therefore relinquished the post at the end of October 1762, having shown a profit of £212.6.11d. over a period of about 3¾ years. He was succeeded by George Greaves, whose accounts cover November 1762 to August 1763. The records under him are by no means as detailed but he returned a profit of £71.8.0d., a similar return on an annual basis as his predecessor. One change in policy can be discerned during this period, in that some iron was taken in as 'free issue' for one or more clients and converted into steel as a service, the so-called practice of 'hire-conversion'. For this a charge of 50s. 0d. per ton was made, which would appear to have been quite profitable.[1] Over the ten month period some 27 tons 16 cwt. of steel was produced for sale, from purchased iron, and 6 tons 7 cwt. was hire-converted. As far as can be ascertained, there were nine heats produced, which would confirm the scale of operation under Ibberson.

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1 Information on operating costs turns up randomly throughout the extant records and it has been thought useful to attempt to gather them together and present them in a separate section (see Chapter 6 V). As a guide here, however, it will be shown shortly that within five years the same work was being carried out by the Master Cutler, for 30s. per ton, and a very reasonable profit was being made.

John Morton was still employed as mason under Greaves and there was extensive repair work at the beginning of the period. There is an intriguing entry for 17th August 1763 covering work done by Morton at 'Milnsands Furniss'. There is no known connection of the Cutlers' Company with this site.[1] In addition, the ledger records a payment in June 1763 to Jno. Makins for two plans in connection with the 'New Furnace', whilst Morton received £10 on 'the new furnace account'.

The confusion becomes even deeper in the next phase, under the new Master Cutler, Joseph Hancock, from August 1763 to September 1764. From August to November 1763 some fifteen tons of steel was sold; likewise

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1 Milnsands (or Millsands) Furnace when first anything is known about it was a crucible melting furnace operated by a certain John Marshall; this was either in the late 1760s or the early 1770s. Comment has already been made that the same Marshall could well have been the first steelmaker for Joseph Ibberson. Why the Cutlers' Company should finance any work there is a mystery, unless possibly they were at this stage considering the venture into crucible steel making and were investigating Millsands as a convenient site. Even more plausible would be that the crucible furnace was actually at Millsands and that when the Cutlers' Company ceased their operations in 1768 or 1769 the premises were taken over by Marshall. This, of course, is pure speculation. R. E. Leader, loc.cit., p.174 gives a footnote to the effect that a new furnace was erected on land leased to the company by Matthew Lambert for 800 years, at a ground rent of £1.2.0½d. He goes on to imply that this establishment gave its name to 'Furnace Hill' with the adjoining 'Lambert Croft'. He also states that the cost of liquor at the stone laying was £1.16.0d. On what authority he made these statements is not clear; as far as I can make out it does not appear in the two volumes specifically relating to this particular enterprise.

there are payments for 'ale at steele drawing' in October and November, indicating two cementation heats; payments are still being made to Mr. Smith. These payments are, however, in a section marked 'Old Steel Furnace'. Thereafter there are no further cementation heats during the following ten months; there are no further sales until April 1764 and the steel then is said to be from Darnall. The 'New Steel Furnace' accounts are quite a different matter and will be discussed in their proper context in Chapter 7, since this was quite clearly a crucible melting furnace; it would seem that operations on this project were started on 6th July 1764. The list of stock which passed from Joseph Hancock to his successor, Samuel Bates, on 1st October 1764 is worth recording :

Steel now remaining in the steel furnace at Scotland[1]	68.1. 4.
L Steel from Darnall	7.3. 3.
Raw ends	2.1.27.
AOK iron and ditto misconverted	13.2.24.
L , GL and O O Iron at Darnall	118.3.12.
To Cast Steel	3.3. 7.
Scraps	5.0.21.

Several inferences can be drawn from this information. In the first instance, the scale of operation in the old cementation furnace is as previously, as deduced from the weight of steel remaining in the furnace. That it was remaining in the furnace, and seems to have done so

1 This obviously refers to the furnace in Scotland Street.

for some time, rather indicates that something had gone wrong, which could only be rectified with difficulty. Meanwhile, there were customers to be supplied. Since hire conversion had been entered into, what was more natural than to do this in reverse. Moreover, with Jonathon Makin involved on behalf of the Cutlers' Company, in connection with the new furnace, what was more natural for him to suggest than that his colleagues at Darnall should work temporarily for the Cutlers' Company. This would explain the entries for 'steel from Darnall' both in the Sales Ledger and the stock return and also the stock of iron at Darnall. It would seem that about 12½ tons of steel was obtained from Darnall.[1] The cast steel and scraps, of course, belong to the 'New Furnace' operations. In view of all this confusion, it is not surprising to discover that the overall operations made a loss of some £38 under Joseph Hancock.

Under Samuel Bates, from October 1764 to September 1765, operations on crucible steel melting continued, but on a very small scale. The cementation furnace carries charges for repairs and for payment of

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1 On the assumption that no major modifications to this furnace had been made over the years this could have been the product of two heats; it will be remembered that Alstromer found that the furnaces outside the town converted six tons at a time.

rent, but there is no mention as to the identity of the landlord. There is also an odd item recording the payment of a guinea on 20th April 1765 to a Mr. Samuel Bullas for encroachment on his land in building the furnace. Rather significantly, such tally as can be made from the stock lists at the start and finish of this year, together with steel sales and iron receipts, indicates the production of 11 tons of steel. There are, however, only two heats recorded, both incidentally with Jno. Makin as steelmaker.[1] This quite clearly points to an enlargement of the chests within the furnace and this may have involved more or less a rebuild, which could explain the need for the appeasement of Mr. Bullas.

Joseph Bower's year saw the production of 18½ tons of steel; Makin was paid for four heats, which confirms a higher weight per heat than the original, but gives a lower figure than the previous year. Some crucible activity continued but the most significant feature in the accounts is the purchase of a ton or so of iron - presumably for steelmaking trials since it appears alongside the iron from Mr. Sykes - 'from Mr. Swallow'. Richard Swallow had largely inherited the Fell empire

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1 He was, of course, still acting as steelmaker to the Fell partnership at this time.

and was running Attercliffe Forge at this time. If it can be assumed that this was local iron, then it is the first time that a record of such a trial has been noted. It should also be noted that a similar size purchase is recorded the following year; in this case the supplier is Mrs. Fell. These are two isolated examples. The accounts for the two years of Samuel Bates and Joseph Bower are not clear as to what is carried forward; it seems as though there could have been a profit of about £7 for the two years together.

The next master, William Birks, took over in October 1766 but remained in charge for three years despite the previous agreement. There are no further entries with regard to cast steel. On the other hand, there is evidence of a major building campaign in late 1767 and early 1768. Accounts in the Day Book commencing 20th February 1768 are headed 'New Steel Furnace'. In addition, there are earlier entries for stone, lime and slate, together with payments to Jno. Makin totalling £70.13.0d. between December 1767 and February 1768 for his work as a mason. This expenditure required the injection of new capital and some £100 was provided. The ordinary profits over this period were £56, which really showed a loss, therefore, of £44. The steel produced in this three year period for sale by the Company was 975 cwt. In addition, hire conversion to the extent of some

380 cwt. is recorded. The overall production from the furnace was thus around 68 tons. There were seven heats on the 'old' furnace and four on the 'new' one; assuming 4½ tons in the first case, as for the previous year, this implies a capacity of around 7½ tons for the new furnace. As will be seen, this is consistent with evidence from the last period of Cutlers' Company management. The sales ledger for this period shows purchases by Benjamin Huntsman and by Boulsover and Company, the latter also supplying iron for hire conversion. In addition, sales to Matthias Spencer in the ledger are confirmed in his own note book, on two occasions, as being 'bought of Mr. Birks'.

The final period, from 1769 to 1772, was supervised by Thomas Beely, who was immediate Past Master at the time of his taking over. He apparently closed the cast steel operations, by sale of the ingot moulds, late in 1769; unfortunately the records do not specify to whom. Under Beely there were 34 heats on the cementation furnace. There were sales of only 24¾ tons of steel. More important, there was hire conversion of almost ten times this amount, mainly for one customer, Messrs. Watson, Raynor and Taylor, who took 191 tons whilst other customers took 64½ tons. The total conversion, therefore, was 260½ tons, giving a mean weight per cementation heat of 7 tons 13 cwt. The records also include a list of the weights supplied to Watson, Raynor and Taylor which vary between 6¼ tons and 8¾ tons and actually average 7 tons 13 cwt.[1] Thomas Beely took over £57 worth of stock; he eventually handed over £344.15.7½d. plus bad debts for about £50.[2]

Jonathon Makin worked as steelmaker and mason for Birks and Beely, with the exception of the 26th to 28th heats under the latter; for the period Christmas 1771 to February 1772, steelmaking appears to have been supervised by one Thomas Bradley. With regard to sales of steel, Matthias Spencer was a fairly regular customer, with transactions in 1763, 1765, to 1767 and 1769; the items in this last year appear in the Spencer note book as 'Taken at the Corporation' and there are corresponding, but slightly differing, entries in the Sales Ledger. Other customers of the 'Corporation' were John Cockshutt, Benjamin Huntsman, Thomas Boulsover and John Kenyon. Matthias Spencer, according to the ledger, also used the hire conversion service on three occasions between 1770 and 1772, supplying a total of one and a half tons of iron; there is, however, no mention of this in the note book.

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1 This excludes one item of only 2½ tons, which would appear to have been a split heat.

2 Of these, only Mr. Boulsover is recorded as having made a subsequent payment; this was £2.10.0d. in this case.

Other customers for this service, apart from Watson, Raynor and Taylor, were Boulsover and Company (27 tons), Broadbent (22½ tons), Price Hepponstall (8½ tons) and Cooke (5 tons). The charges per ton were from 30s. to 40s. The charges to Boulsover were noticeably higher than for other customers and it is probable that, since he was engaged in crucible steel melting at this time, he would require steel which was more completely carburised. This, in turn, would entail the metal remaining longer in the furnace and this would explain the higher cost.

This, as far as the Cutlers' Company were concerned, was the termination of their direct involvement in steel-making. In October 1772 they leased the furnace to Watson, Raynor and Taylor at £20 per annum and eventually sold it to Peter Cadman and James Camm for £200 in 1784.[1]

Previous assessment of this enterprise has implied that it was a failure.[2] If the assessments made here of

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1 Peter Cadman was an active proponent of the extension of the Don Navigation into Sheffield around 1800; the Dunn Survey (Sheffield City Libraries) which was carried out about that time to estimate the amount of traffic likely quoted Peter Cadman as using 150 tons of Swedish iron a year. Whether he was still using the same furnace is not clear. Certainly by 1824 Peter Cadman and Company were making steel in the Wicker and their premises were taken over by Henry Unwin in 1841. (J. G. Timmins, The Commercial Development of the Sheffield Crucible Steel Industry, unpublished thesis, Sheffield University (1976), pp.155, 170).

2 Leader, loc.cit., p.175, states '... but it was of no use. In August 1772 the Company resolved to give up the steel furnace.'.

the profit or loss at each stage are correct, however, noting that interest charges and rents are included in the expenses and remembering that the furnace was eventually let and then sold, it could be argued that the venture produced an average of forty tons of steel per annum over a period of fourteen years, and made a slight overall profit.[1] In addition, it investigated cast steel manufacture, albeit somewhat unsuccessfully; had this not been included the exercise would have been quite profitable. Ibberson and Greaves, with the original furnace, were notably successful, with a profit margin of £1.15.0d. per ton; Beely, with the larger furnace, managed almost double the annual output but with a profit margin of only £1.2.0d. per ton. Those who came in between were harassed with furnace rebuilding problems, together with the diversion of the cast steel trials, and never produced sufficient heats per annum to make out.

V Other Sheffield Cementation Activities

The discussion which has gone before has hinted at a growing activity in the Sheffield area but the records

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1 This surely was the original aim. The minute of 1763 simply asked for 'a gain to the Company something more than equal to answer the expense of the trust'.

are scattered and lost, with only odd snippets of information to be gleaned. Confusion arises both from the growing integration of cementation steelmaking with crucible melting and also from the tendency to use specialised facilities on a hire working basis. Thus, the fact that Thomas Boulsover employed Thomas Eltringham, late of Blackhall Mill, to make shear steel for him does not necessarily imply that he himself produced blister steel in his own cementation furnace. He certainly purchased blister steel elsewhere and had his iron hire converted to blister steel, as has already been noted. He also produced crucible steel[1] for which he would have required blister steel. There is, however, no convincing evidence that he had his own cementation furnaces. On the other hand, it would seem fairly certain that at least one of the two cementation furnaces which are known to have stood at the 1772 Huntsman works site until 1899[2] was an integral part of the original works. Huntsman, however, in all the eighteenth century Directories is recorded as a 'Steel Refiner' only.[3]. The only establishment consistently denoted as 'Converter and Refiner' is that of John

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1 J. Sketchley, <u>Sheffield Directory</u> (Bristol 1774), p.20.

2 A copy of a photograph is included in R. A. Hadfield, <u>Faraday and His Metallurgical Researches</u> (London 1931), facing p.59. One of these furnaces will be seen to have a stone-built lower half.

3 Namely the 1774, 1787 and 1797 issues.

Marshall at Millsands.[1] William Parker appears in the 1774 Directory as a 'manufacturer of iron and steel'; there is, however, evidence that Matthias Spencer purchased blister steel from him in 1761, 1768 and 1769.[2] Spencer also purchased blister steel from Mr. Shore in 1761 and 1762 [3] and from Swallow and Company in 1772.[4] He also used the Walker concern at Masbrough as a source of blister steel between 1771 and 1775.[5]

The story of the Walkers is an interesting one, apart from their traditional involvement in the stealing of

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1 This, in fact, is the case right through until the Marshalls abandoned operations about 1830.

2 In 1768 the purchase was 'Steel Dubbel Bullots'; on June 14th 1769 he purchased a ton and a half of 'Hope Ell Steell'. Thus did the Swedish Forge stamp marks pass into the Sheffield vernacular!

3 The entries are variously Mr. Shore, Messrs. Shore and Roberts or Mr. Shore and Company. One entry in 1761 is for 29 ends of steel to be converted a second time.

4 Richard Swallow is known to have been operating as a cast steel maker at Oakes Green about this time. He would presumably have required a supply of blister steel and, having been involved in the Fell partnerships, should have understood the art. There is, however, no other evidence of a cementation furnace operating in the Attercliffe area at this time. Swallow appears as an unclassified 'Steel manufacturer' in both the 1787 and 1797 Directories.

5 Matthias Spencer had cause to find fault with a consignment of 'F Steell' which he returned for replacement in December 1775; the reason is not stated.

Huntsman's secret, which will be discussed later. They became famous as the largest iron founders in the North of England but also, like the previous Fell partnerships, ran a steel trade. This eventually included crucible melting as well as cementation but, as far as the latter is concerned, commenced with the erection of a furnace at Masbrough in 1748.[1] A second furnace was erected alongside in 1771 and still another in 1776. This furnace is specifically stated to be 'outside of brick' which rather implies that the earlier ones were of stone. A fourth furnace was added in 1785 and still another in 1787. The Walker enterprise, ironworks and steel trade alike, ran into financial difficulties in the post-Napoleonic period and the steel making activities were abandoned in 1829. At the time of the erection of their first cementation furnace, the Walkers were also in business at Grenoside in association with the Tingles. It would seem that some antagonism developed between the partners and the Walkers withdrew from the area, around 1751. There is a surviving tradition that the Tingles carried on with steelmaking on the Grenoside premises until half way through the nineteenth century and it is said that a cementation furnace was standing in the area known as the 'Cupola' into the present century.[2] Another

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1 A. H. John (Ed.), The Walker Family (London 1951) gives details from the Minute Books of the Foundry Company and the comments given here derive from that source.

2 Private communication from James Beevor, Esq.

area of cementation activity could well have been Wortley, where Cockshutt is known to have worked blister steel[1] and where the remains of a furnace structure bearing some resemblance to the single chest furnace depicted by Jars have recently been uncovered.[2]

The 1787 Directory[3] lists eight firms who were only 'Converters'; significantly, only one of them, John Kenyon,[4] seems to have survived to be included in any later Directory. The 1797 Directory[5] lists sixteen steelmakers; surprisingly enough, an independent witness stated that this same year there were sixteen firms making blister steel in Sheffield and several of them were then melting it in crucibles.[6] Most of the Directory entries, however, are classified as 'Refiners', that is crucible steel melters, with no mention of them also being 'Converters'.

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1 W. Lewis, loc.cit., vol.iv, p.225. The steel made by Cockshutt was not of such a high repute as Crowley's according to H. R. Schubert, History of the British Iron and Steel Industry (London 1957), p.329.

2 K. C. Barraclough, 'Wortley Top Forge: The Possibility of Early Steel Production', Journal Historical Metallurgy Society, vol.11, No.2 (1977), pp.82-92.

3 Gales and Martin, A Directory of Sheffield (Sheffield 1787).

4 John Kenyon was purchasing blister steel from the Fell partnership in the 1750s.

5 J. Robinson, A Directory of Sheffield (Sheffield 1797).

6 G. Broling, Anteckningar under en Resa in England Aren 1797, 1798 och 1799 (Stockholm 1812), vol.2, p.138.

All this evidence of activity, however, gives no indication of scale of operation. As to furnace size, the use of relatively small single chest furnaces in the Sheffield area is mentioned by Robsahm in 1761[1] and by Jars, who visited the town in 1765 or 1766;[2] it is also confirmed by Lewis, writing about 1775[3] and by Hatchett in 1796.[4] Hatchett, indeed, described such a furnace, capable of converting about six tons at a time, at a Sheffield steelworks, presumably that at Millsands :

> 'belonging to a Mr. Marshall ... The bars are of various sizes and are about 12 feet long. They are placed horizontally in the chest so as not to touch each other on a stratum of powdered charcoal and between each layer of bars a stratum of charcoal is placed and when the chest is thus filled the whole is covered with sand to prevent the combustion of the charcoal. The aperture by which the people entered to arrange the iron is then well closed up and then the fire is kindled (the Fuel is pit coal) and the Red Heat is kept up e.g. from Sunday evening till Saturday following. There is a small aperture in the side by which a bar may be occasionally taken out and also the degree of heat seen. This forms Blistered Bar Steel (N.B. here about 6 tons are made in each furnace. The blisters are hollow). To form what is called German Steel the Blistered Bar Steel is forged under hammers and reduced even occasionally (as for watchmakers etc.) to the size of one eight of an inch square'.

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1 Robsahm, loc.cit., Folio 85.

2 Jars, loc.cit., vol.i, pp.256-257.

3 Lewis, loc.cit., vol.iv, Folio 204. This furnace had a chest 15 feet long and 4 feet wide, measured externally, and held six tons.

4 A. Raistrick (Ed.), The Hatchett Diary (Truro 1968), pp.69-77.

The following day he went on to Rotherham: and having visited the ironworks at the Walker establishment he reported :

> 'In another quarter we went to see the Steel Works belonging to Mr. Booth, a partner with Messrs. Walkers. These works are very considerable. The Furnaces in which the Iron is converted into steel are many but in general they work two at a time - each of these contain about 8 tons of Iron Bars 10 feet in length - these furnaces have two chests (those at Sheffield had but one) and the flame passes up the middle between them. The other parts of the operation are the same as at Sheffield.'

Since Walker and Booth were known to have five cementation furnaces at this time, it seems strange that they should only work two at a time unless, of course, this was a period of bad trade. It would appear, however, that they had a capability of converting some 500 tons or so of iron per annum.

The only other indication of production levels in the area comes from the survey carried out in 1802[1] when proposals to extend the canal from Tinsley to the centre of Sheffield were being seriously considered. This document gives estimates of the amount of various commodities which would be likely to be conveyed by the extension, including the supplies of iron. The details quoted are as follows :

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1 Sheffield City Libraries, Dunn Papers, Document MD 1740-21.

	Tons per annum
Jonathon Marshall	800
John Kenyon	160
Walker and Wilde	500
Mount Taylor	250
Love and Spear	50
Eyre Hall	150
Young and Co.	150
Cadman and Son	150
Barley and Oates	150
Swallow	75
Huntsman	75
Hawksleys	150
Knattons	150
Abm. Hawley, Hoyland	140
Mr. Stringer of Bowling	100
TOTAL	3050

Of these users, Marshall, Kenyon, Walker and Wilde, Love and Spear, Eyre and Hall, Younge and Whitlock, Swallow and Huntsman were all Sheffield steelmakers, according to the 1797 Directory; to them can most certainly be added Peter Cadman and Son, who were running the old Cutlers' Company furnace. Between them they account for 2110 tons of iron. Of the remainder some 100 tons would have been destined for transfer out of the area; could this imply there was steelmaking at the Bowling Ironworks? According to the 1797 Directory there were three factors in the town operating as Taylor, Parkin and Company (of High Street), Oates, Colley and Wigham (of Hollis Street) and Thomas Knatton and Sons (of Paradise Square). It could well be that these three supplied the seven listed steelmakers whose names do not occur in the list of direct iron purchasers. This only leaves Hawksleys and Hawley, Hoyland, to be accounted for. The only Hawksley who can be identified is a File maker and merchant in West Bar Green, not known to have any steelmaking facilities. He could, of course, have purchased iron for hire conversion somewhere in the town or have been a factor for steel-iron. There was a John Hoyland with either two or three cementation furnaces in Peacroft in 1810 (see Chapter 6) and the Abm. Hawley, Hoyland item could refer to his activities. It has also to be remembered that the requirements of Walker and Booth at Masbrough, probably the largest producers in the area, are not included in this list since their iron would be off-loaded at Rotherham. The two surprising figures in this list are the requirements estimated for Jonathon Marshall at Millsands and for the Walker and Wilde partnership operating in the Wicker. Marshall's cast steel was certainly well known in Europe[1] where it was surpassed in esteem only by Huntsman's steel. Although he had been operating continuously as a steel producer for over thirty years, and his concern was eventually to grow into the massive Vickers complex, to find him using some ten times as much iron as Huntsman at this time is hard to believe, particularly as there is evidence elsewhere[2] that the scale of operation at the Huntsman works

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1 See Section 7 V for further details (pp.254-5).

2 The iron intake for the Huntsman works was around 50 tons in 1805 according to a surviving ledger covering the period 1787 to 1806. Sheffield City Libraries, LD 1612.

was of the order indicated by the survey. There is, on the other hand, a drawing of the Millsands Works dating from 1830 which shows four cementation furnaces integrated into a building complex around a courtyard.[1] If these furnaces had been there in 1802 and had a capacity of twelve tons each, they could have consumed 800 tons of iron in the year; on the other hand, such an establishment must surely have been commented on by one or other of the visitors to the town. The other, probably more surprising, total is that for Walker and his associates; they were known to be operating a cementation furnace in the Wicker and possibly another in Castle Green[2] in the early 1800s, but these would not utilise the total estimated.

Given that these estimates were produced to make out the best possible case for the extension of the canal, they could be considered as being somewhat inflated. Nevertheless, one is led to the opinion that, including the Walker and Booth output, steel production by the cementation furnaces in the Sheffield and Rotherham area at this time must have exceeded 2000 tons per annum. This, it should be noted, is about a fifteen-fold increase in just over sixty years. Such a growth is sufficient to permit the claim to be made

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1 This appears as the frontispiece to J. D. Scott, <u>Vickers - A History</u> (London 1962).

2 Timmins, <u>loc.cit.</u>, p.64.

that here was the centre of the growing steel industry, the North East having surrendered the leadership by the end of the eighteenth century.

VI Cementation Elsewhere in Britain

Birmingham and the area to the south west, and particularly the Stour Valley, was probably the second most important steelmaking region of the country in the first half of the century. The earliest specific information comes from a Swedish travel report of 1720. On the occasion of his visit to 'Brommicham', Alstromer reported three or four furnaces for the making of steel. For this purpose about 200 tons of Oregrund iron was used in the year, William Kettle using 150 tons of this. The iron stamps seen were L which had the strongest body and O O which was good, but not for sword blades since they broke on being quenched. Other grades were X, GL and 'W and Crown'.[1] Another Swedish traveller in 1725 reported the presence of quite a few furnaces in and around Birmingham.[2] In Stourbridge he found two furnaces of the two chest type, one with chests seven feet long and a total charge of three

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1 Alstromer, loc.cit., Folio 134, entry for 5 March 1720. The reference to 'Brommicham' is intriguing in its similarity to 'Brummagem'.

2 Kalmeter, loc.cit., Folio 111.

tons, and one with eight feet chests capable of converting four tons, but there was one being built with three chests and two firegrates.[1]

A 'Prospect of Birmingham' dating from 1731[2] shows three 'Steelhouses' with domed tops and central chimneys; two of these were, appropriately enough, in Steelhouse Lane and were run by Kettle.[3] The other furnace was owned by a Mr. Carlesse. In 1737 it was stated that 220 tons of Swedish iron were converted into steel annually in Birmingham.[4] The iron used was 'Swedish Oregrunds' of which two sorts were imported :[5]

> 'The first is generally made into steel and is the fittest for it of all the irons yet discovered and sold at Bewdley at £17.10s. sometimes £18 per ton; the second which has not enough body to make steel sold at £14.10s. per ton.'

If the three furnaces of which we have knowledge were the sum total, then they should have had a mean capacity of around five tons each.

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1 Kalmeter, loc.cit., Folio 113. A translation of the relevant passages from this account may be found as Appendix AA.

2 This 'East Prospect of Birmingham' is reproduced in R. K. Dent, Old and New Birmingham (Birmingham 1880). It is by one Westley and published either in 1730 or 1731.

3 Dent, loc.cit., pp.66-67 refers to Kettle's two steel houses as being the first in Birmingham for converting iron into steel, erected about the beginning of the eighteenth century in White Hall but later known as Steelhouse Lane. Carlesse's steel house was at the junction of Stafford Street and Coleshill Street.

4 House of Commons Journal, 1737, p.854.

5 House of Commons Journal, 1737, p.853.

The next report indicates that there were two furnaces of five tons each at the only steelworks in Birmingham and that this was owned by a Mr. Willemoth.[1] Four years later, however, there were two furnaces belonging to a Mr. Kittel operating on Oregrund iron.[2] The same report describes a steelworks at 'Snowshill' in Birmingham which, in addition to a two chest furnace, had one with three chests, taking an overall charge of seven tons. Firing continued for seven days and nights, consuming a total of 16 tons of coal. The workers were each paid nine to ten shillings a week. The iron used was exclusively Oregrund, imported via Bristol and costing £22 per ton. Boulton's works were in this area of Birmingham and it is known that he had a very similar furnace to the one just described in 1770.[3] This was a three chest furnace with a capacity of eight tons. The chests were 36 inches deep and 18 inches wide; on the usual basis of calculation they must have been about 8 feet long. Only Swedish iron was used and the firing occupied six days. The three chest furnace was regarded in 1768 as the typical Birmingham and Stourbridge type; it had an

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1 Schroderstierna, loc.cit., Folios 202-202A. A translation can be found in Appendix BB.

2 Angerstein, loc.cit., vol.I, Folios 384-385.

3 Letter from Robert Erskine to R. Atkinson dated 11th October 1770. The original is in the Library of the New Jersey Historical Society, Newark, U.S.A. The text of the letter may be found in Appendix CC.

internal vault sloping up on all four sides to a central chimney flue, with a conical stack or 'roundhouse' superimposed. The lengths of the chests were said to be typically 7 feet 6 inches long.[1]

Angerstein also visited another cementation furnace site outside Birmingham which he called 'Braidwaters', which seems to have been Broadwaters, near Kidderminster.[2] Here there were two cementation furnaces, but their sizes are not given. The furnaces were used alternately, one being heated up whilst the other was cooling. Oregrund iron of the best marks was used, costing £23 per ton. The conversion cost was £2.10s. per ton. The raw blister steel sold at £28 per ton but after forging to bar it fetched £32 to £33 per ton. It is also commented that only oak charcoal was used.[3]

The same report remarked that building operations were in hand to make the furnace up to the same capacity and dimensions as commonly used in London. There obviously was some activity on steelmaking in London,

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1 Andersson, loc.cit., Folios 155-156.

2 I am informed, in a private communication from Mr. W. K. V. Gale, that this is most likely Broadwaters, known as an old established ironworking site near Kidderminster. It was not previously known that there had been any steelmaking activity on the site.

3 Angerstein, loc.cit., vol.I, Folios 366-367.

but none of the travel diaries or any other contemporary record give any positive information. Ambrose Crowley, writing to Winlaton with regard to steel manufacture at the end of 1700, commented thus:[1]

> 'The furnaces about London: the bars are not above one inch square, 7 foot long, 18 inches broad above the seeges. The seeges stand in at least 3 inches and are the breadth of a brick or a brick edgeways above the barrs, the furnace 18 inches high above the seeges. A man in half a day putteth in fresh seeges, the vents are from 5 to 6 inch square and at the mouth of the furnace.'

In the middle of the century comes the report just quoted; from the end of the century there is the description of an unusual pattern of furnace.[2] This is, as far as the central block is concerned, a conventional two chest structure with a superimposed vault. Instead of having the cone and central chimney, however, the roof is flat with two square chimneys set centrally on the outside long walls. The comment follows that such a furnace was seen in London, at a big factory making carriage springs; the furnace was capable of converting about three and a half tons of iron at one time. No other evidence relating to cementation steel manufacture in London is known.

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1 Crowley Council Book, Minute 3 (5th November 1700).

2 Broling, loc.cit., vol.3, pp.143-145.

There is some evidence for steel converting in the Bristol area. Mention of a furnace at Keynsham, between Bristol and Bath, is made in 1725.[1] A later visitor commented further on this establishment :[2]

> 'At the end of Keynsham, right next the brassworks, lies a steelworks with furnaces and one hammer for forging. The steel here is made from Oregrund iron or other Swedish iron, although Spanish, Russian and even English iron has been used from time to time. The proprietor also converts iron for the merchants of Bristol on a hire basis. For the conversion of iron into steel he charges £2 per ton; forging costs a further £1 per ton.'

The same report goes on to comment on Bristol itself :[3]

> 'In the neighbourhood of Bristol steel is made from Swedish iron and is called blister steel. It is also made into a kind of German steel which is considered very good. The steel made from Oregrund iron is sold without forging, just as it comes from the furnaces at £28 to £30 per ton; the German steel made in this country costs £50 to £60 per ton. Large shipments of steel come into Bristol as well from Holland. This steel is made at Remscheid and each particular grade of steel is used for a different purpose. I went to the weighbridge to inspect all the different kinds of iron I could find, especially the American. Most of it was forged to bars one inch square and was generally red short; some bars were cold short. The Russian iron was similar, although some stamps were quite cold short, but most of it was good, ductile material made, as I was told, in Siberia. There was no Spanish iron and it was said that little or none had arrived since the last war. Likewise, there

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1 Kalmeter, loc.cit., Folio 296.

2 Angerstein, loc.cit., Folio 367.

3 Angerstein, loc.cit., Folio 368.

> was no English iron in evidence. Gothenburg iron sells at £16 per ton, Stockholm iron at £17 per ton and Oregrund iron at £19 per ton.'

It has always seemed illogical that the fine haematite ores of Cumberland, smelted with charcoal, should not have been capable of providing bar iron, equal in quality to the Swedish iron, and therefore capable of conversion to steel. Such thoughts obviously persuaded the Sheffield firm of Read and Company to set up a cementation steelworks at Cleator in 1794. A drawing showing a group of six cementation furnaces at this site still survives[1] although it has to be noted that, for reasons not divulged, the operations were closed down in 1799. There is a further vague reference to a spade forge, with cementation steel-making clearly described, at Halton, near Lancaster.[2]

Over the border, comment must be made of the activities of the Cadell family, who took over the Cramond Iron Works from the Carron Company in 1770. By 1773 it is reported :[3]

> 'we have since added to these works a furnace for converting barr iron into steel and a forge for drawing it into different purposes.'

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1 J. C. Caine, Cleator and Cleator Moor (Kendal 1916), pp.216-217. It appears that the illustrations vary from one copy to another; the drawing of the cementation furnaces appeared only in the second copy of the book I consulted.

2 Lancaster Gazette, 20th November 1824.

3 Letter from William Cadell to Sir William Forbes, 1773, quoted by P. Cadell, The Iron Mills at Cramond (Edinburgh 1973), p.9.

This was to be described later as :[1]

> 'the first steel works in Scotland.'

In 1797 the capital employed was of the order of £30,000, the works consisting of two steel furnaces, three forges and two slitting mills making blistered, square and faggott steel as well as German steel, together with rod iron, rolled iron, boiler and pan plates as well as spades and nails.[2] The report continues :

> 'The iron used at Cramond Works comes chiefly from Russia and Sweden, upwards of a thousand tons being imported from the Baltic yearly. The average cost per ton, including customs at 56s. and freight from 8s. to 15s., is £17 for Russian and £18.10s. for Swedish iron; but a very fine kind of the latter, the produce of the famous mine at Dannemora in Upland, called Oeregrund's iron, from the port whence it is shipped, comes to £24 per ton. This sort is used solely for making steel. These different kinds of iron are 50 per cent dearer than they were in 1780.'

There are records of 100 tons of iron being received in 1778

> 'for steel, hoops and rods, mostly Russian, but 30 tons from Gothenburg.'

whilst in 1796 there were some 218 tons

> 'Swedish and Old Sable, for steel, hoops and plate.'

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1 H. Hamilton, The Industrial Revolution in Scotland (London 1966), p.165.

2 J. Sinclair, The Old Statistical Account of Scotland (Edinburgh 1799), pp.212-213.

These figures are supplemented by a reference to Swedenstierna's journal in 1802 indicating the making of

> 'some hundreds of skippunds of steel in two furnaces from Russian and Swedish iron.'

This information in total[1] indicates a production of something rather less than 100 tons per annum. How long steelmaking survived at Cramond is not clear. A description in 1855 does not mention steel and the 1851 census at Cramond does not include any steel-makers. Charles Probert, steelmaker, aged 63, appears in the 1841 census, however. It could well be, therefore, that when the company was restructured in 1847 the steelmaking activities were discontinued.[2]

Other evidence for early cementation steelmaking in Scotland, however, has survived. Advertisements of the 'Dalnotter Iron and Steel Works' appeared in the Glasgow Journal in 1770, 1773 and 1774.[3] The

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1 Taken from Cadell, loc.cit., pp.69, 19. There are, incidentally, approximately 7.5 skippunds to the ton.

2 Private communication from Dr. G. Thompson.

3 G. Thomson, 'The Dalnotter Iron Company', The Scottish Historical Review, vol.xxxv (1956), No.119, pp.10-20.

earliest of these indicates the availability of

> 'Blistered, German and English square steel of the best quality.'

It is, however, uncertain as to the origin of such steel. The works were founded by three Glasgow merchants, together with a George Hudson and a James King who had been

> 'for a short time engaged in steel making near Newcastle.'

The agreement setting up the company in 1769 clearly states that the production of steel so far had been in Newcastle

> 'for want of proper accommodation in Scotland'

but that the partners were committed to carry on

> 'the said manufactory at their works in Dalnoter whenever and as soon as they shall judge it expedient.'

Moreover, George Hudson was to instruct

> 'any person or persons the Company shall nominate and appoint in the art and busyness of converting iron into steele and to conceal no art, branch or mistery of the said busyness from the person or persons so to be named and to do the utmost in his power to make the said person or persons expert and qualified therein.'

Whether this was ever done and whether steel furnaces were erected at Dunotter, however, is not known. Russian iron was imported in 1785, but this was not necessarily for steelmaking. The works was partly closed in 1807, due to the taking over of land for the cutting of the Forth-Clyde canal. The remainder was sold in 1813 and a cotton mill erected on the site.

In the same area, the Faskine Iron Works was set up in 1794 at Calderbank, near Airdrie. There is no mention of steelmaking at that time but the works was taken over in 1805 by the Monkland Steel Company, which had commenced steelmaking shortly before, almost in the shadow of Glasgow Cathedral. Very soon the new owners were making up to 100 tons of steel per annum by the cementation process and were producing files. They gradually abandoned steelmaking, however, concentrating on iron production; certainly it had gone by 1842.[1]

Such, then, was the pattern of steel production by the cementation process in the various parts of Britain in the eighteenth century. The use of the process was also growing outside Britain; comparable operations in Europe and elsewhere will be studied in a later chapter.[2]

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1 Private communication from Dr. G. Thomson.

2 Please refer to Chapter 12.

6 THE CEMENTATION PROCESS: THE NINETEENTH CENTURY ONWARDS

'Ce n'est pas assez de savoir les principes;
il faut savoir manipuler.'

(Dictionaire de Trevoux,
early 19th century)[1]

I Introduction

It has already been established that, by the end of the eighteenth century, the cementation process, with some two hundred years of operation already behind it, was the major primary source of steel in Britain. To be sure, increasing quantities of its product, blister steel, were being melted and refined in crucibles to produce a superior material. This circumstance, however, only increased the importance of the process; its growth, for a further fifty years or more, was to be a vital factor in the expanding steel industry. By 1800, the procedure was fully established. Swedish bar iron, supplemented by smaller quantities of the essentially similar premier grades of

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1 'It is not enough to know the principles; it is necessary to know how to make it work' would be a rough translation of the quotation. Paradoxically, the British seem to have known how to make it work without knowing the principles; the French, having discovered the theory, appeared to have stayed blindly with it and failed to make the method work, until they learned from the English. This aspect will be dealt with in a later chapter.

Russian iron, was virtually the only raw material considered; indeed, for the very finest steel, only a handful of the Dannemora forges in Sweden were considered capable of providing a good enough iron, and the steelmakers were prepared to pay premium prices for this quality. The preferred carburising medium in which the iron was to be packed was nothing more than powdered charcoal. Although many and varied, and sometimes almost unmentionable, mixtures were suggested from time to time,[1] plain crushed charcoal performed quite effectively. That this should be so was now understandable since within the past few years it had been recognised that carbon, the essential ingredient of charcoal, was fully responsible for the difference in properties between iron and steel or, more to the point, for the difference between the iron, when it went into the cementation furnace, and the blister steel, into which it was converted during its sojourn in that furnace. The universal covering for the tops of the chests after they had been charged with iron bars and charcoal was sand; whether this should be applied moist or not seems to have been open to argument.[2]

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1 As a matter of interest, a variety of these suggestions are collected together in Appendix DD.

2 The introduction of the use of 'wheelswarf', well known in Sheffield in later times, is of unknown date. The earliest reference appears to be in Rees' Cyclopaedia in 1819 (see Appendix N). More specific is the mention in British Patent No. 8930, taken out in the name of Henry Browne :

> 'I then cover the whole close down with loam, sand or swarf from a cutler's grinding mill, or other suitable substance to exclude the air, spread over the pot to the thickness of five or six inches.'.

The design of the furnace had shown regional variations during the eighteenth century and there had been major shifts in the location of the main industry. By 1800, however, Sheffield was rapidly becoming the main centre of British steelmaking and the two-chest furnace, with a superimposed conical chimney, was established as the predominant pattern, but with a change to a brick rather than a stone built structure. To meet the growing demand for steel, the story is one of increase in size of individual furnaces and of a proliferation in numbers. Whilst there have survived a few drawings of cementation furnaces prior to 1800, from then onwards they become more frequent, culminating in the text book illustrations, from Percy onwards, in the last half of the century. Considering such drawings in isolation, however, it is difficult to appreciate the variation in size between the earlier and later furnaces. With this in mind, a collection has been made of most of the available illustrations and this has been redrawn to a standard scale.[1] These, as might be expected, are mainly of furnaces in the neighbourhood of Sheffield, but the series also includes some foreign examples, as can be seen from Figures 18, 19 and 20 and their accompanying key. As far as is known, the largest furnaces ever built would convert up to 40 tons of iron in one heat, implying up to 20 tons

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1 Figures 18 and 19 as reproduced here are to the same scale; Figure 20 has, unfortunately, been reduced a little further in reproduction. There is, however, a scale attached to each drawing.

of iron charged to each chest. Such furnaces, ten in number, were erected by John Brown and Company in Sheffield in 1857.[1] It should be reported, however, that the sole surviving complete (or virtually complete) furnace in Sheffield, the Daniel Doncaster No.5 Furnace at Hoyle Street, is only marginally smaller. The fullest report of the process, as practised in Sheffield in its heyday, is that of Professor le Play,[2] who was at pains to express doubts as to the value of such large furnaces, maintaining that a unit with a total capacity of from 15 to 20 tons was ideal, both for economy of working and the reproducibility of the product. There is, however, a somewhat earlier description of a cementation furnace, and the method of its operation, which is so detailed as to merit reproduction in full.[3]

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1 Thos. Firth and John Brown Ltd., 100 Years of Steel, printed privately, Sheffield 1937, p.33.

2 F. le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', Annales des Mines, 4me. Serie, Tome III (1843), p.592. A complete translation of the part of this report dealing with the cementation process, prepared by the author, may be found in Bulletin Historical Metallurgy Group, vol.7, part 1 (1973), pp.7-22.

3 A. Rees, Cyclopaedia (London 1819). Not paginated. Surprisingly, this information is included under the heading 'Tilting of Steel'; it can be found reproduced as Appendix N.

II Developments in the Sheffield Area

The development of Sheffield as a steelmaking centre was closely linked to improvements in the transport facilities in the area. The problems in the early part of the eighteenth century have already been touched on in discussing the provision of bar iron to the Fell 'Steele Trade'.[1] The first improvement was the making of the River Don navigable as far as Rotherham in 1734 and further to Tinsley in 1751. This was followed by the improvements of the roads under the Turnpike Acts, from 1758 onwards. There was considerable interest on a number of occasions in schemes to extend the canal further, but it was only in 1819 that the centre of the town was to have a canal basin. The major factor in establishing the supremacy of Sheffield as a steelmaking centre, however, was the penetration of the railway system into this difficult terrain. A direct line to London was not to prove possible for many years, but a branch line, to connect Sheffield with the North Midland Railway at Rotherham, was built in 1838. This left Sheffield by the valley of the Don, the only level land in the area, which at that date was open fields and marshland, virtually untouched by industry. Within twenty years this terrain was destined to be covered by the major steelworks, whose names became synonymous with Sheffield quality.

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1 See Chapter 5 (pp.124-125).

Prior to this expansion, however, steelmaking activities were mainly in the town itself, as can be demonstrated by reference to any of the local Directories up to 1840. As to the growth of cementation steelmaking itself, and indeed its involvement in the crucible steel melting activities, there is no consistent record. Some random detail appears from time to time. In 1810[1] Mitchell and Company operated two cementation furnaces in Norfolk Street; Coldwell and Company had two in Gibraltar Street and Brittain and Company 'a house and two furnaces' in Carver Street. It may also be assessed from the rate charges that William Ibbotson of Bridge Street, Weldon and Company of Castle Hill and John Hoyland in Peacroft also had two furnaces each, although Hoyland may well have had three. Jonathon Marshall at Millsands had at least two cementation furnaces in addition to his crucible steel melting holes. The Walker establishment at Masbrough, however, with its five furnaces still operating, as far as can be ascertained, must have been the largest producer in the area.

Information on the erection of new furnaces in Sheffield and Attercliffe between 1821 and 1836 has been collected.[2] Together with further random items of information, this leads to the conclusion that at least

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1 This information is derived from the rate books and is taken from J. G. Timmins, The Commercial Development of the Sheffield Crucible Steel Industry, M.A. Thesis (Sheffield 1976), p.42.

2 Timmins, loc.cit., p.264.

thirty furnaces started operations during this period. A contemporary account indicates that there were 56 cementation furnaces operating in 1835 in the Sheffield area[1] and it is of interest to attempt to account for this total from the evidence available.

Naylor and Sanderson were producing steel in West Street from 1819; by 1837, when the firm was known as Sanderson Brothers, they had five cementation furnaces.[2] Jonathon Marshall had given up steelmaking in 1829 and the Millsands premises had been taken over by Naylor and Company, who were operating four cementation furnaces in the early thirties.[3] By 1836, Daniel Doncaster in Copper Street had built four cementation furnaces.[4] Wilson and Hawksworth in Arundel Lane, Walker, Eaton and Company in the Wicker and Marshes and Shepherd in Blast Lane all were operating four furnaces each.[5] William Ibbotson was still in business and presumably still operated two

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1 G. P. Porter (ed. Hirst), The Progress of the Nation, (Revised Edition, London 1910), p.241. The information probably came from W. Vickers (see below).

2 G. B. Callan, 'Four Hundred Years of Steel', Sanderson Kayser Magazine, vol.2, No.4 (1969-1970), pp.2-15.

3 J. D. Scott, Vickers - A History (London 1962) has a frontispiece which illustrates this, showing quite clearly the four cementation cones.

4 Notes from J. H. Barker in the Doncaster Archives. These were consulted by kind permission of R. T. Doncaster, Esq.

5 Timmins, loc.cit., pp.56-57. He also confirms the information in the previous two references from rate book evidence.

furnaces, as in 1810; Huntsman had two furnaces, and the two furnaces, the remains of which have recently been discovered at Bower Spring, were built by Turtons in 1828.[1] Taking into consideration the above information together with the additional detail from the 1821 to 1836 survey, there are still a number not accounted for. The 1837 Directory,[2] however, is reasonably precise in its categorisation of steelmakers into 'converters' and 'refiners'; if the names of the 'converters' extra to those listed elsewhere are each considered to have a single furnace, the tally comes to 59 furnaces as against the 56 quoted in 1835. This latter is the first of a series of figures for cementation furnace activity stretching over almost thirty years, which may be listed as follows :

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1 These were two furnaces in Russell Street, the remains of which were exposed when some sheds were demolished at the rear of Gibraltar Street. The remains have been preserved by courtesy of Messrs. Brook Shaw Ltd., on whose property they stand. I am informed by Martin Olive of Sheffield City Libraries that the furnaces were erected in 1828 by Thos. Turton and were used by them until 1860 when they were taken over by Moss and Gamble, being last used about 1930.

2 W. White, History and General Directory of Sheffield (Sheffield 1837).

Year	Number of Cementation Furnaces	Estimated Annual Output of Blister Steel (tons)
1835[1]		12,000
1835[2]	56	
1837[3]		18,000
1842[3]	97	16,250
1843[4]		21,400
1846[5]	105	26,250
1851[6]	145	35,000
1853[5]	160	40,000
1856[7]	206	51,500
1863[7]	205	78,270

The significance of these various figures will be considered in detail in a later chapter, together with the similar evidence on crucible steel manufacture. Suffice it

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1 W. Vickers, Minutes of Evidence, Lords Committee on the Sheffield to Rotherham Railway, 1835, p.11.

2 Porter, loc.cit., p.41.

3 Le Play, loc.cit., p.621, p.687.

4 E. G. Dannielsson, Anteckningar om Norra Amerikas Fri Staters (Stockholm 1845), pp.32-33.

5 C. F. Waern, Om Jerntillverkningen och Jernhandeln (Stockholm 1853-54), pp.49-50.

6 The Great Exhibition, Reports of the Juries (London 1851), p.10.

7 J. Hunter (ed. Gatty), The History and Topography of the Parish of Sheffield (Sheffield 1869), p.214, p.216.

to say here that they corroborate the two factors already indicated, namely the growth in numbers of the furnaces and also the general increase in furnace capacity.[1] As will also be noticed, the middle years of the century saw the major growth. At the time of the 1851 London Exhibition, Naylor, Vickers and Company, at Millsands, had eight cementation furnaces producing 2300 tons of steel per annum.[2] By 1852, Turton and Matthews at the Sheaf Works had eleven furnaces, William Jessop and Sons had ten furnaces, as had Sanderson Brothers,[3] whilst Daniel Doncaster could well have been operating eight furnaces.[4]

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1 Some indication of the increase in size may also be obtained from the rate charges. For example, two furnaces at Millsands in 1842 were rated at £20 whilst two furnaces at Sheaf Works in 1845 were rated at £35.5.0d. (Timmins, loc.cit., p.62). The figures here indicate 167 tons per furnace per annum in 1842, 241 tons in 1851 and 381 tons in 1863. The remaining figures are all so close to 250 tons per furnace that it seems this was the basis of estimation.

2 1851 Jurors, loc.cit., p.10.

3 Sheffield Independent, 2nd October 1852.

4 This is the conclusion reached by Timmins, loc.cit., p.61. Assuming that the Copper Street furnaces were still operating at this time - there were four of them - notes, in the Doncaster Archives, left by Mr. J. H. Barker would suggest that there were a further five furnaces built at Doncaster Street between 1835 and 1848. It is the last of this group, and the largest, which still survives and it is this furnace which was the last to be used. The above notes also imply that Doncasters found need for extra capacity, early this century. The six furnaces at the Philadelphia Works (in the Don valley before it reaches the centre of the town) were built by Butcher in 1854 and, subsequently, were owned by Bury and Company, from whom Doncasters hired them about 1904. The furnaces were of about 25 tons capacity and were worked by Doncasters until 1924 or 1925. They similarly hired the three Leadmill Road furnaces from Brittain and Company for a period, finally closing these down in 1923.

Fifteen years later, Jessops had no less than fourteen furnaces at their Brightside Works in addition to ten at Park Works; the total number of furnaces at Sheaf Works was fourteen, with capacities of 23 tons each,[1] whilst in the works adjoining the railway, John Brown had eighteen furnaces,[2] Thos. Firth had eleven and Charles Cammell had eight.

There was a significant change beginning to make itself felt in the old Sheffield steelmaking traditions at this time, however. William Jessop installed a further two furnaces at Brightside in 1867, as did Beardshaws in Attercliffe in the same year; Brown, Bayley and Dixon installed a bank of six furnaces in Attercliffe in 1874.[3] These, nevertheless, appear to have been the final additions to the ranks of cementation furnaces in the area. In addition, it must be pointed out that the major new crucible melting shop of the area, the River Don Works, to which Naylor, Vickers and Company moved from Millsands in 1863, was not provided with any cementation furnaces; the same applied to the Toledo Works, set up at Neepsend by J. H. Andrew and Company in 1872. The first of these works had the enormous output capacity of 15,000 tons

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1 S. Jordan, Revue de l'Industrie du Fer en 1867, vol.4 (Paris 1871), p.301.

2 Jordon, loc.cit., p.303.

3 Timmins, loc.cit., pp.197-198.

of crucible steel per annum, whilst the other was over a third as large, between them probably accounting for about a fifth of the total Sheffield output of these materials. Prior to this time, the 'integrated steelworks' had comprised a group of cementation furnaces with associated crucible melting holes, as seen in old engravings in advertisements and on letter heads from 1830 to 1860. Now the cementation furnaces were no longer an essential part in an increasing number of cases. When extensive new melting facilities were installed at the Darnall Works of Sanderson Brothers, in the early 1870s, there was no addition to the cementation capacity. Similarly, both Seebohm and Dieckstahl and Huntsman and Company moved to new melting shops just before the end of the century, and abandoned their cementation furnaces in the process.

There were good reasons for this. Over most of the period from 1830 to 1860 it can be deduced that between 50% and 75% of the blister steel produced was melted down in crucibles, the proportion probably rising as time went on.[1] The remainder was either rolled to spring bars or forged to give either Single Shear Steel or Double Shear Steel (the older term for these being

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1 According to le Play (loc.cit., p.639), some 52% was treated in this way in 1842; in 1862 (Reports of the Jurors to the 1862 Exhibition, Class 32, p.2) the proportion was 66%.

German steel). From about 1860 onwards, however, particularly with the growing need for more and more steel, it became increasingly unacceptable, both from the point of view of economics and from the time involved, to put the iron through the lengthy cementation process. Apart from the highest class of material, it was found perfectly adequate to melt Swedish bar iron, with a suitable proportion of Swedish cast iron, directly in the crucible. The implications of such a change in technology will be discussed later in the context of crucible steel making. Suffice it to state here that such a change was facilitated by a reversal of official government policy in Sweden, in 1855, which thereafter permitted the direct export of Swedish cast iron. This then came in ever increasing quantity to the Sheffield area. It may be argued that it was the new availability of such a material, with its low sulphur and phosphorus contents, which persuaded men like John Brown and Charles Cammell to commence the production of puddled steel in Sheffield. Certainly, within five years of the release of Swedish cast iron, John Brown was selling 'melting base', which seems to have been produced by the puddling of such iron, to his fellow Sheffield steelmakers, at £13 to £14 per ton; reasonable quality blister steel at this time would have cost at least twice this figure.

The figure given for the estimated production in 1862 in the above table could well, therefore, represent the peak value, to be followed by a slow decline. This was to be accelerated by the introduction of the Open Hearth furnaces for the production of forging ingots by Firths, Browns, Vickers and Cammells in the 1880s. As an example, it may be noted that an illustration of the John Brown works in 1903 does not show a single cementation furnace, whereas the eighteen furnaces operating in 1867 must have had a joint capability of around 10,000 tons of blister steel per annum.[1] There were those, however, who still considered that only by melting blister steel could the optimum properties and that essential, but rather indefinable, characteristic known as 'body' be assured[2] and one of the authors of this type of statement was certainly continuing to practise what he preached, since William Jessop was still operating eight cementation furnaces in 1913.[3] Thomas Firth and Sons, in their 1901 catalogue, also publicised the fact that they were still making blister steel although the illustrations indicate that the number of furnaces had been reduced to three. In 1924 to 1930

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1 John Brown and Company, Atlas Works (Sheffield 1924), p.16 and p.20.

2 H. Seebohm, On the Manufacture of Cast Steel, printed privately (Sheffield 1869), p.ii; W. Jessop and Sons, Visit to a Sheffield Steel Works (Sheffield 1913), p.6.

3 Jessop, loc.cit., p.7.

it is known that Huntsman and Company who, as mentioned above, had abandoned their cementation furnaces in 1898, were purchasing blister steel from Thos. Sorby and Sons, R. G. Holland and Company and Daniel Doncaster.[1] Daniel Doncaster and Company continued to produce blister steel throughout the Second World War years and when their No.5 furnace was damaged in the bombing of Sheffield in November 1940, the top was rebuilt with a damper device which acted as a blackout screen during air raid alerts. This accounts for its atypical appearance to this day, shown in Figure 21. Details of a quotation for a set of 'pot stones' for the rebuilding of the two chests in this furnace, given only a month prior to the aid raid damage, have survived.[2] The operations on this site continued to the end of 1951 and, as far as can be ascertained, this finally closed the chapter on the production of blister steel.

III Operations in the North East

In view of the earlier importance of cementation steel production in the North East, it is appropriate to

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1 Sheffield City Libraries, Huntsman Stock Book, LD 1618.

2 Doncaster Archives. The quotation is reproduced as Appendix EE. Calculated in the normal way, each chest would have been capable of holding just over 20 tons of iron, whilst the furnace capacity (both chests) is usually quoted as 38 tons.

examine the later history of the early furnaces; such evidence as can be deduced is extremely sketchy.

Since Derwentcote furnace has survived, it would have been appropriate to have a full history; very little is known, however. Early in the nineteenth century it was worked by the Cookson family, who were known to be in charge in 1810[1] and were still working it in 1863, six crucible furnaces having been added to the site by this time.[2] By 1876 the works had been taken over by Charles Winter.[3] N. C. Cookson[4] reported that, when he closed down their operations on the site just prior to this, there were only a handful of men, all between sixty and seventy years of age, but he added that

> 'the steel they made was of extraordinary excellence'.

Charles Winter is still listed as holding the works in 1894.[5] Lord Gort, whose family seems to have owned the

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1 J. Bailey, General View of the Agriculture of the County of Durham (London 1810), p.288.

2 T. Spencer, 'On the Manufacture of Steel in the Northern District', The Industrial Resources of the Tyne, Wear and Tees (London 1864), p.768.

3 R. Slater, Royal National Commercial Directory (Durham 1877), p.261, p.265.

4 Victoria County History, Durham, vol.2 (London 1907), p.290, footnote 90.

5 F. Whellan, History of the County Palatinate of Durham (London 1894), p.1267.

land, later expressed the opinion that the site had been abandoned by the end of the century.[1] Now, apart from the cementation furnace half way up the hill, the other parts of the works are just an unrecognisable collection of heaps of decayed masonry.

Blackhall Mill was also worked by the Cooksons in 1810 to 1811.[2] Thereafter, there is only negative evidence. Its omission from the 1863 list[3] merely indicates that it had gone out of operation at some date in the interim. An old postcard, dated 1913, shows it to have been essentially similar to the Derwentcote furnace, but without the buttresses. It was demolished in 1916 to make room for the schoolhouse.[4]

The Newcastle furnace likewise was run by the Cooksons in 1811.[5] In 1851, T. Cookson and Company are listed as steelmakers in the Close and also at Forth Banks.[6] The latter was the location shown by Angerstein in his sketch of a hundred years earlier. In 1853,

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1 J. K. Harrison, 'Derwentcote Steel Furnace', Bulletin Industrial Archaeology Society of North East, No.9 (July 1969), p.14.

2 Bailey, loc.cit., p.288; E. Mackenzie, A Historical and Descriptive View of the County of Northumberland, vol.1 (Newcastle 1811), p.165.

3 Spencer, loc.cit., p.768.

4 Private communication from Dr. Stafford Linsley.

5 Mackenzie, loc.cit., p.165.

6 Ward's North of England Directory, 1851, p.373.

however, they are only listed as ironfounders at South Street.[1] They are not included in the 1863 list as steelmakers other than at Derwentcote. It can only be concluded that the furnace at Newcastle was abandoned between 1851 and 1853; perhaps Blackhall Mill was also closed at the same period.

The later history of the Crowley works is not much more accessible. Crucible steel manufacture was first carried on as a commercial venture by Crowley, Millington and Company at Swalwell in 1810.[2] It seems that Winlaton was abandoned in 1816 but Swalwell is reported to have been quite busy in 1834 and it was sold as a going concern to a Mr. Laycock in the 1850s. The new owner goes down in history as having consigned the records of one hundred and fifty years' operations to the furnaces.[3] In 1863 the works were taken over by Pow and Faucus and were listed in that year as comprising two cementation furnaces and six crucible furnaces. In 1876 Ridley and Company took possession of Swalwell and by 1893 had considerably expanded steelmaking operations. A description of the works at that date quotes a 'gas furnace' along with foundry working;[4] on the other hand, the detail of the

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1 Ward's North of England Directory, 1853, p.384.

2 Spencer, loc.cit., p.765.

3 M. W. Flinn, Men of Iron (Edinburgh 1962), pp.91-93.

4 Anon, A Descriptive Account of Newcastle Illustrated (Brighton, not dated but around 1895), Article on Ridley and Company. The 'gas furnace' might have been an open hearth furnace; alternatively, it could have been a gas fired crucible furnace.

making of crucibles, and an accent on tool steel manufacture, indicates a flourishing business on the Sheffield pattern although there is no mention of cementation furnaces at this time. Like others elsewhere, they could already have gone out of use. The article giving this detail, however, appears curiously ill-informed in that it refers quite categorically to Ridley and Company as being the first to introduce steelmaking to this area. The old Crowley works at Teams provide something of a mystery. They appear to have been taken over by Morrison, Mossman and Company in 1812,[1] yet were still rated as being owned by Crowley, Millington and Company in 1860. Nevertheless, they were not included in the sale to Pow and Faucus in 1863. By 1865 the Low Forge was being used as a pulp mill and the High Forge was incorporated into the farm property of William Burdon.[2]

There was, however, a fairly substantial new development in the North East in the nineteenth century. John Spencer, originally an apprentice in Sheffield and subsequently having worked for Crowley, Millington and Company, set himself up as a filemaker in Newcastle in 1810. He made his files in Fighting Cocks Yard at Bigg Market and had a warehouse in White Horse Yard, Groat Market.[3] In 1822 he moved to Newburn on Tyne and adapted

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1 (J. Hodgson), A Picture of Newcastle upon Tyne (Newcastle 1812), p.285.

2 F. W. D. Manders, A History of Gateshead (Gateshead 1973), p.65.

3 Most of this information comes from John Spencer and Sons Ltd., Centenary of John Spencer and Sons Limited, 1810-1910 (Newcastle 1910).

the old water driven cornmill for file grinding. Sometime between 1830 and 1845 he erected a cementation furnace and crucible holes. Spencer himself had the idea of calling his establishment 'New Sheffield' but it always seems to have been known as the Newburn Steel Works. His activities expanded, the firm becoming John Spencer and Company in 1853, forge hammers and a rolling mill having been installed, but still dependent on water power.[1] By this time there were two cementation furnaces, a further four being built within the next five years. By 1863, it was clear that this was the major steel producing establishment in the North East.[2] Of the 300 people employed on steel-making and of the 3000 tons of steel made annually in the area,[3] Newburn accounted for at least two thirds. There had been a ninefold increase in turnover for steel in the area since 1838, when only 70 to 80 people had been employed; such was the impact of the new Newburn works.

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1 Spencer was also one of the pioneers in the making of castings in crucible steel and his activities in this field rivalled those of Naylor, Vickers and Company at Millsands in Sheffield.

2 Spencer, loc.cit., pp.766-767.

3 There would have been nine cementation furnaces in operation in the area at this time. Six of these were the relatively new ones at Newburn. The others were the one at Derwentcote and two at Swalwell. The old furnaces were originally only of about ten tons capacity, whilst several of those at Newburn were twice this. There is, however, some evidence that one of the Swalwell furnaces had been enlarged (see Appendix U).

An inventory of the Newburn works in 1868 has survived.[1] It lists a cast steel melting shop and crucible house built in 1853, six converting furnaces, a foundry and moulding shed, a forge built in 1852, two rolling mills (one water powered and one steam driven, the latter only recently built), a smiths' shop with ten hearths, recently extended, a file cutting shop and a joinery shop. There was also a coal store with four coke ovens. Offices, a storehouse, a steel warehouse and a dwelling house are included, together with a 'new building', 300 feet by 60 feet, to accommodate lathes, buffer shops, finishing shops and an engine house. Across the burn, it was indicated there was 'considerable room' for depositing rubbish. This was obviously a prosperous and expanding business. From the point of view of cementation steelmaking, however, there is one slight confusion. An inventory of 1856[2] lists

> 'two large cones of brick for making steel'

whilst the 1868 one covers

> 'six converting furnaces, the oldest built in 1845 and the last in 1861, of stone held together strongly with iron bands'.

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1 Northumberland Record Office, ZAN/BELL/70/09.

2 Northumberland Record Office, ZAN/BELL/70/11.

Other steelmaking methods eventually came to Newburn[1] but the cementation process remained of importance in the 'Old Works' since by 1895 the number of furnaces had increased to eight.[2] These must have been among the latest to be built in this country. Four had been demolished, however, by 1910.[3] In the post war depression the 'New Works' at Newburn, with its battery of open hearth furnaces, the plate mill and the forge, was closed down, leaving only the 'Old Works' producing tool steel and tools in 1927. How long they survived is not clear, but the cementation furnaces there had been demolished by 1950.[4]

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1 Two 7 ton Siemens Open Hearth furnaces were built in 1872 and a third, of 25 tons, had been added by the time the firm became a limited liability company in 1888. There were plans at that time for the installation of a further five furnaces of 30 tons each. The Newcastle Daily Journal, 24th August 1888, gives a description of the whole works. By 1910 there were 12 Open Hearth furnaces, of 10 to 45 tons capacity, making 1500 tons of steel a week, with facilities for producing plate and forgings for the ship-building industry.

2 Newcastle Illustrated, loc.cit. Article on John Spencer and Sons, Limited.

3 John Spencer Centenary Booklet, loc.cit.

4 The only evidence remaining on the site is a retaining wall containing fire-reddened and slagged pieces of sandstone, firebricks with evidence of heat attack and odd pieces of 'crozzle' embedded in it, situated in an area where the furnaces are indicated on the plan attached to the 1868 inventory.

IV Activities Elsewhere in Britain

Outside Sheffield and the North East, information on cementation steelmaking in the nineteenth century is even more difficult to find. A general statement dating from 1843[1] may be translated as follows :

> 'Many steelworks are established near to London and on the coal basins of South Staffordshire, Somersetshire and Lancashire. These deliver about 4000 tons of raw cemented steel a year. The average production in England can thus be evaluated at a very approximate figure of 20,250 tons per annum'.

Where such furnaces were, in the main, is not known. As far as London is concerned, there is a complete blank and the same applies to Lancashire. The only known activity in Yorkshire outside the Sheffield-Rotherham area was at Kirkstall Forge near Leeds, where a single furnace was built about 1805[2] and seems to have been on the side of the Leeds to Liverpool canal.[3] One wonders, however, from the reference to iron destined for Bowling, included in the Sheffield Canal survey,[4] whether the same could have occurred in Bradford. As far as Somerset is

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1 Le Play, loc.cit., p.687.

2 R. Butler, The History of Kirkstall Forge (York 1954), p.89.

3 H. M. Butler, A Kirkstall Forge Romance (Leeds 1939). The drawing is reproduced as the frontispiece. I am grateful to Professor J. Nutting for bringing this to my attention.

4 Sheffield City Libraries, Dunn Papers, Document MD 1740-21.

concerned, there is an unconfirmed report of a cementation furnace at Mells.[1] Only in the Black Country is there any substantial evidence; even so, this only highlights one particular site where there is a chance survival of records. This area, of course, was much more important for its puddling furnaces and its wrought iron production.

The works of William Hunt and Sons 'of the Brades' appear on an old plan of 1798 as being specifically a steel-works.[2] According to a later description they were[3]

> '... the oldest steel manufacturers in Staffordshire. This is a very old and highly respectable concern and the article turned out is of excellent quality. They have seven puddling furnaces and three mills with extensive converting conveniences on the old Sheffield plan. Cast, shear, blister and all other kinds of steel are made here of the highest quality, quality, not quantity, being the great object of the proprietors. The works will be found on the left of the Dudley road near to the town of Oldbury'.

Some papers in connection with the works have been preserved.[4] These include a plan of the works in 1820 and drawings and plans of the works in 1874, the latter showing a fairly run-down state of affairs. The view of

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1 Private communication from John Cornwell, Esq. The excavations at the edge tool factory at Mells, owned by the Fussells, are revealing a number of furnace structures, one of which could have been a cementation furnace.

2 Private communication from W. K. V. Gale, Esq.,

3 S. Griffiths (ed. Gale), Guide to the Iron Trade of Great Britain (1873) (Newton Abbot 1967), p.71.

4 Birmingham City Libraries, Lee Crowder Papers Nos. 915 to 931.

the cementation furnaces at this date can be seen in Figure 22. The valuation of the estate given in a co-partnership deed, dated 19th September 1825, between Henry Hunt, Thomas Yate Hunt and Samuel Hunt

> 'in the business of Steel Manufacturers and Coal Masters at the Brades in the County of Stafford'

indicates the survival of the eighteenth century mixed economy :[1]

Mansion House and Farming Buildings	£15,000
Steelworks including Engines and Machinery	£10,000
Dwelling Houses for Workmen	£1,600
Colliery Erections including Mine Engine, Whimseys and other Apparatus	£8,400
Boats, Tools, Bricks, Ore, Sand, etc.	£1,000
Fixed Value	£36,000
Book Debts, Stock in Trade, Farming Stock and other property of a variable nature	£14,000
	£50,000

The steelworks was leased in 1860 to George Adkins, Francis Adkins, Henry Tate and Charles Rickards;[2] at this time there were four cementation furnaces in operation. A further lease was negotiated in 1870[3] in favour of Charles Rickards, Caleb Adkins and Francis Adkins covering five

1 Birmingham City Libraries, Lee Crowder Papers No. 915.

2 Ibid, No. 922.

3 Ibid, No. 931.

cementation furnaces, a steel casting house with twelve pots, rooms for the making and drying of crucibles, an auger maker's shop, a scythe forge and a coke store. The works was sold in 1880 to George Caleb Adkins and George Heaton, the remainder of the estate being sold in 1889. There is an inventory of 1868[1] which gives some details of the cementation furnaces :

> 'One large 40 Tons Converting furnace with outside cone 26 feet diameter and say 50 feet high with two pots 12 feet long, 3 feet wide and 4 feet deep. Firebrick linings to flues, chimneys and arches and firegrates underneath with plates, binders and underground chambers and approaches. Two other Converting Furnaces about 24 feet diameter with two pots in each as last. Two smaller Converting Furnaces about 25 feet diameter at the bottom on ground level 45 feet high with ashpit 5 feet deep but without underground cellars. Two converting pots in each say 12 feet long, 2 feet 8 inches wide, 3 feet 3 inches deep with firegrates, plates, lintels and firebrick linings, flues, chimneys and arches. The pots in one of the furnaces are out of repair'.

The sizes of chest quoted indicate that the larger furnace, stated to be of 40 ton capacity, would only take around 22 tons per heat, whilst the smaller ones would have had a capacity of 15 tons. With normal working, however, an output of some 1000 to 1500 tons of blister steel per annum should have been possible.

There is some other evidence for the making of blister steel in the Black Country :[2]

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1 Birmingham City Libraries, Lee Crowder Papers No.930.

2 Griffiths, loc.cit., p.161.

> 'The Darlaston Steel Company ... convert steel on a large scale on the cementation process. All kinds of steel are made here and the brands are well known and appreciated in the market'.

No further details are given. The most intriguing information in the volume from which the above quotation was taken, however, appears in the advertisement section, which identifies Isaac Jenks of Wolverhampton as manufacturers of blister steel and cast steel. Moreover, there are woodcut illustrations of the Minerva Works and the Beaver Works owned by Jenks. These show a number of conical structures, strapped with circular bands at regular intervals and resting on circular bases. There are two groups of these, one of six[1] and one of three, at the Minerva Works, and one pair at the Beaver Works. It is very likely that these were examples of the locally derived type of cementation furnace which was described many years later in the reminiscences of an old iron maker :[2]

> 'A circular excavation of about 25 feet diameter, about 7 feet deep, had a brick wall built all round it. The furnace was built inside this enclosure, and was about 18 feet in diameter and 30 feet high, of a circular dome shape, with an opening at the top for a chimney or a stack. The space between the outer wall and the furnace

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1 Adjacent to this major group is a building with a rectangular chimney which could well be the crucible melting shop. If this is correct, it would appear that the latter operations were on a relatively small scale.

2 M. Millard, 'Old Methods of Ironmaking', Journal Staffordshire Iron and Steel Institute, vol.xxvii, (1911-12), pp.189-191. The drawing of the furnace is reproduced in Fig.19. (Ref. No. 22).

> proper was covered over and approached by steps and was called the cellar. (Similar furnaces externally may be seen at the glassworks of Stourbridge). Four firegrates were placed in the furnace at the level of the cellar, thus obviating the effects of stormy winds and weather and ensuring a steady draught for the fires; the form of the grates was a medium between the ordinary boiler and furnace grates. There was a flue across the centre of the furnace about one foot wide covered over with cramped bricks, with an opening near the centre to allow the escape of smoke and flame; the other grates had an opening to the left and the right for the same purpose. There was thus formed two 'beds' or 'muffles', each about 3 feet wide and 14 or 15 feet long, the height generally being about 4 feet'.

The description later refers to doorways in the sides of the furnaces, at just above ground level, fitted with iron doors to allow the taking in and the removal of the iron bars. The cementation medium was small wood charcoal; the cover to the chests was finely sifted, soft loamy sand. The weight of iron charged per 'muffle' is given as 8 to 10 tons, which fits in with the dimensions quoted. Rather surprisingly, however, it appears that the temperature was limited to 'a dull red colour' which obviously would give a slower diffusion of carbon than was common in Sheffield, with its higher temperatures, and cementation times of 10 to 14 days were the norm. Conversely, with less heat in the furnace structure, cooling periods were only 4 to 6 days. There was, in fact, another unusual feature connected with these furnaces; they from time to time operated on charges largely consisting of locally produced 'puddled steel', something which will require discussion in a later chapter.

V Production Costs

Some information as to the operating costs of the cementation process may be found by diligent search through the records; as may be expected, it is of a somewhat random nature and comes from the second half of the eighteenth century and the nineteenth century. The collected information is summarised in Table II and the detail on which this table is based may be found in Appendix FF.

As may be expected, with evidence drawn from records over such a period of time, from numerous sources and with no consistent accounting system, there are wide variations in costs. The main comments which may be made are as follows :

(1) As expected, from the almost constant ratio of charcoal to iron in the chests, the cost of charcoal per ton of steel is reasonably constant, tending to rise somewhat during the nineteenth century, presumably indicating a rise in the cost of charcoal once it ceased to be a major metallurgical fuel.

(2) Labour costs, with the exception of the early operations by the Cutlers' Company and the Birmingham furnace, are relatively consistent. In the case of the former furnace, the scale of operations was small and, in comparison with later operations, it would be relatively overmanned. The Birmingham furnace, as noted below, was hardly a typical example.

(3) The large variation in fuel costs requires some explanation. There are three figures which are out of line. There is no clear explanation for the Blackhall Mill figure; it just seems to be too low. The Birmingham information relates to one of the three-chest furnaces with two firing flues. This design, on the face of things, should have been more efficient but it was peculiar to this area which later adopted the more usual 'Sheffield Type' with two chests. If the Birmingham 'cauldron' of coal contained the normal 16 cwt., then the coal consumption was about 3.2 tons per ton of steel as against figures of 0.75 (Le Play), 0.60 (Gruner and Lan) and 0.82 to 1.21 (Marsh Brothers) found elsewhere. The final abnormal figure comes from Sweden and it must be remembered that this refers to a charcoal fired furnace, essentially different from all the others.

(4) The wide variation in miscellaneous charges clearly indicates that certain accounts contained items ignored elsewhere.

(5) It must be remembered that these items are isolated references and that there were likely to be variations of a significant nature within one plant from one year to the next, as is demonstrated by the Marsh Brothers information.

Within this context, the figures charged for 'hire conversion' within the trade become of relevance. Thus the Cutlers' Company in 1769-1772 charged between 30/0d and 40/0d per ton,[1] whilst conversion charges of 28/0d to 32/0d were current from 1848 to 1859.[2] Thus an actual conversion cost of around £1 per ton or just over would give the converter a reasonable return for his trouble and this, indeed, is the level indicated by most

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1 Company of Cutlers in Hallamshire Archives, vol.48.

2 Sheffield City Libraries, Brittain Accounts, LD 266.

of the evidence. A twentieth century indication comes from Doncasters, with a note dated 1904 quoting conversion costs of 16/0d to 17/0d per ton and a hire converting charge of 22/0d. per ton.[1]

VI Retrospect

The life span of the cementation process can be shown to have been at least 350 years, from the early report of 1601 to the last heat on the Daniel Doncaster No.5 furnace in 1951. Over the final hundred years it was waning in importance, but for the previous one hundred and fifty it reigned supreme in this country as the source of steel. Before Bessemer and Siemens revolutionised steelmaking, from 1856 onwards, the raw material for the only rival steelmaking method, Huntsman's crucible process, was blister steel from the cementation furnace. The remaining blister steel was either rolled or forged to produce springs, edge tools and cutlery. Britain went its own way, relying on imported primary material, in the form of Swedish bar iron, in which it cornered the market. The Continent, on the other hand, relied on the older refining methods, using its own pig iron to

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1 Doncaster Archives. Communication from J. Barker to B. Doncaster, 1953.

produce natural steel. In 1842, the amounts of blister steel and natural steel produced in Europe were roughly equal, with Britain producing over 80% of the blister steel, the bulk of this within a few miles of the centre of Sheffield.[1]

There are other aspects which have not so far been discussed. It will have become clear throughout this chapter that it is extremely difficult to disentangle the cementation and crucible processes during this period. The discussion of levels of production will therefore form the subject of a separate section when the final development of the crucible process has been fully discussed.[2] Likewise, the use of these two procedures, which came to be referred to abroad as the 'Sheffield methods', will be considered jointly as far as their developments outside this country are concerned.[3]

The remaining evidence for the cementation process is pitifully small. The Doncaster No.5 furnace, with its partially modified superstructure, is still preserved within the premises of the B.S.C. Laboratories at Hoyle Street in Sheffield. Recently revealed, by the removal

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1 Le Play, loc.cit., p.692. He points out that the Sheffield figures which he quotes represent an under-utilisation of capacity, suggesting that working on a fully extended basis could possibly have produced about 32500 tons of blister steel in the year.

2 Please refer to Chapter 11 (pp.512-516).

3 See Chapter 12.

of other buildings, is a partially demolished furnace in Bower Spring in Sheffield; this has now been scheduled and it is of some considerable interest because its condition allows the internal structure of such a furnace to be seen and appreciated. That priceless relic in the North East, the furnace at Derwentcote which is now about two hundred and fifty years old, where the steel made over a century ago was of that 'extraordinary excellence', still stands. Almost complete, it is good to know that plans are now in hand for its restoration and for the clearing of the area around it.

A reasonable amount of 'crozzle' still survives, mainly as a coping to walls in the industrial East End of Sheffield. There is also the film of the last operations in the Doncaster No.5 furnace in 1951, although the few available copies of this are becoming rather worse for wear. There are even one or two samples of blister steel still surviving from this last heat although they are now very difficult to locate. It is also now virtually impossible to purchase a genuine shear steel carving knife other than as an antique. It will always be a tragedy that some means of preserving the group of six furnaces at Holmes (Figure 23) could not have been worked out.

7 THE EARLY DEVELOPMENT OF THE CRUCIBLE PROCESS

> 'Huntsman's patient efforts, at last rewarded with success, entitle him to an elevated niche among the heroes of industry; the invention of cast steel was second in importance to no previous event in the world's history unless it may have been the invention of printing'.
>
> An anonymous American, quoted by Sir Robert A. Hadfield.

I The Work of Benjamin Huntsman

Benjamin Huntsman, born of Quaker parents, probably of Dutch extraction, at Epworth in Lincolnshire in 1704, took up the profession of clockmaker in Doncaster in 1725.[1] He was a practical man and busied himself in making his own tools and clock parts and he found that the steel which was available, particularly for his springs and pendulums, was far from ideal. It was, of course, derived from blister steel and was not uniform in structure throughout its section; although an excellent material for cutlery blades, its shortcomings as a spring material, particularly for precision clockmaking, can be appreciated. It seems that that practical man, Huntsman, with the activities of the brassfounders as a guide, considered that he could make a

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1 For further biographical details on Benjamin Huntsman, the reader could consult Benjamin Huntsman, 1704-1776, an information booklet published by the Sheffield City Libraries and containing the text of a lecture given by the author at the Cutlers' Hall, Sheffield, on 21st June 1976, the 200th anniversary of the death of Benjamin Huntsman.

more uniform material from his steel if only he could remelt it. This was a revolutionary idea - no steel had, so far, been taken to such temperatures. According to contemporary theory, it never had had an opportunity for its constituent atoms to intermix. There were, of course, considerable problems involved. The temperature needed for the fusion of steel was much higher than that needed for brass. This required not only a furnace which would sustain such a temperature for a considerable time but also a suitable container, or crucible, which would withstand such a temperature and also withstand the possible attack of the metal on it during the fusion period. He was, in a sense, born at the right time. Only thirty years earlier Abraham Darby had demonstrated that coke could be used as a metallurgical fuel in his blast furnace at Coalbrookdale. Using a deep bed of incandescent coke and a suitable draught it was now possible to maintain a high temperature for a longer period than had obtained from the use of charcoal, hitherto the universally utilised fuel in metalworking. About the same time, also, the value of Stourbridge clay had been demonstrated in glass-making; there was, indeed, a glass works operating in the area at Catcliffe about the time Huntsman started his experiments. The clay used for the glassmaking pots was, in fact, Bolsterstone clay, not dissimilar from the Stourbridge clay.[1]

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1 Huntsman seems to have had continual trouble with the material for his crucibles but there seems no doubt that the experience of the glass makers had some lessons for him.

It is always presumed that Huntsman commenced his steel melting trials whilst he was still at Doncaster and that he moved to Handsworth to be near the source of steel, fuel and clay in 1742. Be this as it may, what is clear is that his cottage at Handsworth, of which a water colour painting and an old photograph survive, had a small extension. When the property was demolished in 1933, flue marks were quite clearly observed in this outhouse[1] and it must be presumed that it was here that the experimental work was carried out in deep secrecy. Meanwhile, Huntsman continued with his work as a clockmaker[2] and it was only by 1751 that he felt he could set himself up as a steelmaker and move to premises which he designed himself in Worksop Road in Attercliffe.[3]

He moved once more, to premises later to be known as 'Huntsman's Row', but there is confusion as to the date of the transfer. It is generally suggested that it happened in 1770[4] and that the

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1 W. S. Patrickson, in discussion reported in <u>Trans. Newcomen Soc.</u>, vol.xxiv, p.46.

2 He took on a further apprentice clockmaker in 1743.

3 The firm run by his descendents as B. Huntsman Limited always quoted 'Established 1751' on its stationery.

4 Anon., <u>L'Invention de l'Acier Fondu par Benjamin Huntsman</u>, published privately in Paris about 1890 by Marchand, Bignon, Ammer et Cie, p.13.

building with the date '1772'[1] on the gable end nearby was his residence for his last few years. These later works were occupied by his descendents until 1899, when the operations were transferred to a new works in Coleridge Road; only the Huntsman's Gardens School, built near the works in 1884, perpetuates his name in this area today. *

The earliest written record of Huntsman as a steel melter appears in the archives of the Cutlers' Company, where there is an entry in 1750 :[2]

> 'By expenses at Jacob Roberts's request about
> Huntsman's, the steel founder's ... 4s'

There is, most tantalisingly, no further information on the matter. This was obviously about the time that

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1 This building is now the Britannia Inn in Worksop Road. The figures are allegedly in Huntsman's steel. This tradition is quoted by G. R. Vine, The Story of Old Attercliffe (Sheffield 1936), p.295. The Fairbank Survey of 1819 (held by Sheffield City Libraries) shows this property to be owned by Ann Hancock and not by Francis Huntsman, who owned much of the nearby property. In one of the earlier Fairbank sketchbooks (Field Book 25, p.38, 11th August 1763 - also held by Sheffield City Libraries) there is property adjoining Attercliffe Green (which could have been on the Worksop Road) containing buildings erected by Benjamin Huntsman; amendments in a different ink, presumed to have been made in 1781, show the furnace on this site then to have been occupied by Thomas Gunning; the 1819 survey indicates it to have been held by Charles Hancock, brother of Ann Hancock mentioned above. The 1819 survey also indicates a house, a pleasure garden, ten workmen's houses (in Huntsman's yard) , a steel furnace and a warehouse together with other property in the area occupied by Francis Huntsman, the grandson of Benjamin. The Ordnance Surveys of 1854 and 1893 both show this Huntsman property virtually unchanged (except for the shape of the ornamental beds in the garden).

2 R. E. Leader, History of the Cutlers' Company (London 1905), vol.1, p.174.

* Although this statement was correct when this was written, by the time this thesis is handed in, this building also will have been demolished.

Huntsman was beginning to feel sufficiently confident to set up commercial operations. The Company, indeed, did investigate the process, but that was some fourteen years later and hardly seems to have been under the auspices of the inventor.[1]

It seems that his steelmaking prospered.[2] There are no surviving account books from Benjamin Huntsman's time; the correspondence between him and Matthew Boulton, however, is still available.[3] Their association seems to have begun prior to 1757 in view of a letter from Boulton which instructs Huntsman as follows :[4]

> 'When you have any steel of a proper size and quality you may send it, but should be glad to have it a little tougher than the last which our workmen complain makes a good deal of waste'.

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1 K. C. Barraclough, 'An Eighteenth Century Steelmaking Enterprise: The Company of Cutlers in Hallamshire, 1759-1772', Bulletin Historical Metallurgy Group, No. 6:2 (1973), pp.26-28.

2 The London Chronicle, 14th July 1761, thought fit to report on 'the recent invention of Huntsman's crucible steel' and considered it ideal for sinking dies 'which produce excellent pieces'. There is no contemporary record of a comparable nature from Sheffield, however.

3 These papers are now in the Archives Division of the Birmingham City Libraries. References below refer to the Birmingham catalogue. Photocopies of a number of them relating to steel supplies may also be consulted in the Sheffield City Libraries.

4 Letter, 19th January 1757, Box H3, No.231. The closing paragraph reads as follows : 'I hope thy philosophick spirit still laboureth within thee and may it soon bring forth fruit useful to mankind but more particularly so to thy selfe'.

As early as 1764 Boulton wrote :[1]

> '... we should be glad to know if you can make us a pair of rolls about 7 Inches and ¼ long and ye diameter about half the length for the rolling of silver and copper. Such a pair we would be glad of ... You may also send us one Hund^{d}. W^{t} of fine refined steel rolled exactly one tenth of an Inch thick and likewise a Barr sufficiently large to forge into some fine dyes'.

Less than three months later, he was concerned to hear that Huntsman had been ill, repeated the request for the rolls and also requested :[2]

> '... one Hundred of Refined Tilted Steel which we want to draw into fine wire and therefore must be good and tilted small'.

In 1774, Boulton forwarded samples of hammers and 'dyes', asking Huntsman to produce six dozen of each.[3] From some of Boulton's letters it would seem that Benjamin Huntsman late in 1775 was attempting to persuade Boulton to give him the whole of his steel business, as indeed did his son a year later, after his father's death;[4] Boulton's reply was the same in each case, to the effect that if further trials proved the continuing excellence of the steel he would be willing to consider it. At the same time, Boulton was a little critical about Huntsman's prices.

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1 Letter from M. Boulton to B. Huntsman, 9th August 1764, Letter Book B, p.8.

2 Ditto, 26th November 1764, Letter Book B, p.33.

3 Ditto, 2nd July 1774, Letter Book G, p.54.

4 Ditto, 28th December 1775, Letter Book G, p.496; letter from M. Boulton to W. Huntsman, 7th December 1776, Letter Book G, p.767.

In 1774, he indicated that, whilst Huntsman was charging 10d. per pound for his steel sheet, he could obtain as much as he wanted at 7½d. per pound

> 'from other people in your neighbourhood'.[1]

Early in 1776 the competitor's price had fallen :[2]

> 'Now if you wish to sell ten times the quantity of steel you have ever sold you may easily do so by conforming to your neighbour's price of 7d. per pound rolled. This I give you as a friendly hint not from any wish of our own to reduce the price. For our very fine steel buttons we shall buy your steel be the price what it will, but the great consumption is in the common cheap steel buttons. We have some button makers that order 2 or 3 Tons at a time'.

The use of such quantities of steel in button making at this time is fascinating. It is made even more so in the light of some slightly later information which shows quite clearly that the value of Huntsman's steel was that it did not give rise to blistered surfaces on the finished product. It seem that the technique employed by the button makers was to decarburise the steel sheet completely, to form what was essentially a pure iron - wrought iron, as it were, but divested of its slag streaks - into the required shapes, to cut the desired patterns into the soft iron and then to

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1 Letter from M. Boulton to B. Huntsman, 24th June 1774, Letter Book G, p.41.

2 Ditto, 25th January 1776, Letter Book G, p.517.

recarburise, harden and polish.[1] The value of crucible steel in such an application was obviously determined on a practical basis almost a century before the cause of blistering during the cementation process was properly elucidated.[2] The connection of the Huntsmans with the button makers of Birmingham is of further interest in that William Huntsman was a partner of Robert Asline in the production of buttons in Sheffield in 1774.[3] In response to a request from

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1 T. Gill, 'On Fine and Delicate Steel Work', Gill's Technological and Microscopical Repository (London, 1830), vol.6, pp.275-288. I am indebted to R. D. Rawlings of the Royal School of Mines for this information.

2 J. Percy, 'On the Cause of the Blisters in Blister Steel', J.I.S.I. (1878, Pt.II), pp.460-463.

3 J. Sketchley, Sheffield Directory (Bristol, 1774), p.37. The list of 'Sundry Manufacturers of Steel' on p.20 only gives Thos. Boulsover, Benjamin Huntsman and John Marshall as makers of cast steel; on the other hand, John Love is indicated as 'Draper, Cast Steel Refiner and Factor' in the alphabetical section on p.37. The association of Asline with the Huntsman family went back at least to 1761 since Huntsman and Asline were purveyors of steel to Thos. Patten and Company of Cheadle at 84s. per cwt. in that year (Patten Account Book, 1761-1765, currently held by Thomas Boulton and Company of Froghall); a similar entry in 1763 involves Huntsman and Company, who also figure in the 1774 Directory. Gales and Martin, A Directory of Sheffield (Sheffield, 1787) again list Huntsman and Asline among the 'refiners' (that is to say, cast steel manufacturers, as contrasted with 'converters' or blister steel makers). Other refiners are Hague and Parkin, William Houlden, Love and Spear, John Marshall, Townrow Burdekin and Tingle and John Walker. In addition, although not specifically listed as cast steel makers or refiners, it is arguable that the following should be included: John Harrison, Richard Swallow, Walker Booth and Crawshaw and Younge Sharrow and Whitelock.

William Huntsman late in 1776 Boulton replied :[1]

> 'We shall be very glad to serve you in buttons on as cheap terms as our other friends. We will send you our patt^{n}. cards if you'll acquaint us whether you want solid Gilt and plated or comm^{n}. g^{t}. and pt^{d}. on box or bone buttons'.

Buttons were, however, only part of the steel market and it is obvious from this correspondence that the real value of cast steel lay in materials for tooling, dies, hammers and, above all, for rolls, which called forth all the skills of the steelmakers' art :[2]

> 'We should esteem it as a fav^{r}. if you would without delay make us a pair of rolls for the purpose of rolling burnished Gilt Foil which foil is from ½ an Inch to 2½ Inches broad. I therefore think the Rolls should be 2½ broad upon the face at least and not rounded as those are for the flatting of wire. We have 3 rolling mills that go by water and therefore as we have these conveniences we shall avail ourselves of them and not work the rolls by hand as the gold wire drawers do. Our frames are adapted for and our Rolls are of the size of the Drawing A but as you probably can't make 'em so broad upon the face as 5 inches we must submit to have them narrower although we should prefer A 5 Inch to B 2½ Inch and therefore submit the breadth to your convenience but should be glad that our present frames may serve. We presume your greatest difficulty will be to harden them free from cracks and when polished to be free from clouds and soft places. If you have no conveniency for dressing them when hardened we have such as will lap them fine and perfectly true. We suppose you may

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1 Letter from M. Boulton to W. Huntsman, 7th December 1776, Letter Book G, p.767.

2 Letter from M. Boulton to B. Huntsman, 25th January 1776, Letter Book G, p.517.

> venter to make 3 Rolls for if you get 2 good out of 3 you will have good luck and if they should all 3 be good we will take 'em'.

How Huntsman could conceivably provide such a roll from the small ingot he was able to produce is not clear; nor is the outcome of this enquiry. Certainly almost a year later Boulton is still enquiring when they will be delivered.[1]

II Local Competition

Huntsman did not patent his process; such a move would probably have worked to his disadvantage in any case. He was, of course, dependent on others to supply his crucible materials, his ingot moulds and his blister steel and, let it be made clear, to forge his ingots. That he would have inquisitive observers would be obvious; the fact that he was working in premises attached to his residence, however, should have provided him with reasonable security. The story of the beggar approaching the warmth of the furnace room on a cold winter night and seeking shelter from the storm is well known. Having been allowed to enter, he feigned sleep but, through half closed eyes, observed the whole process and departed with the secrets the next morning.[2]

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1 Letter from M. Boulton to W. Huntsman, 7th December 1776, Letter Book G, p.767.

2 Anon, The Useful Metals and Their Alloys (London, 1857), pp.348-349.

It is a plausible and colourful story; considering the difficulties experienced by Huntsman with his crucible materials, the provision of the required temperature for a sufficient period and the importance of the selection of the raw material, the 'beggar' would have to have been very skilled in the art and extremely observant even to have been able to put in hand any meaningful experimental work after such slight acquaintance with the operations, let alone copy the process. The 'industrial spy' concerned in this alleged deception is generally identified as Samuel Walker, who was involved in the local iron trade. He was known to have built a steelhouse at Masbrough in 1748; this was presumably a cementation furnace for the production of blister steel. In 1750, however, he was reported to have built

> 'a house and furnace for refining steel at Grennoside'.[1]

It is possible that this was his attempt to copy Huntsman; if tradition is to be believed, this espionage must have occurred at the Handsworth premises. It does, however, under those circumstances seem rather strange that there should have been a group of workmen there at night or that Huntsman himself, living in the

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1 A. H. John (Ed.), The Walker Family: Extracts from the Minute Books (London, 1951), p.3.

adjoining house, should not have been personally aware of what was happening. The Walkers departed from Grenoside shortly afterwards for the much more accessible Lower Don Valley and their next recorded activity in the steelmaking field was in 1771, at Masbrough again. This appears to indicate that their early attempts were abortive. The picture is confused, however, in that their premises at Grenoside were taken over by Benjamin Tingle, who had been a partner with the Walkers. Local tradition in the Grenoside area, outside the town boundary and thus largely ignored by the Sheffield historians, is that Benjamin Huntsman's secret was stolen from him, only two or three years after he had made it a commercial possibility, by a joint conspiracy between Samuel Walker and Benjamin Tingle. The two conspirators had what was referred to as 'a terrible flare up' shortly afterwards and Walker left the area, leaving Tingle in charge of both the premises and the secret. What truth there is in this tradition will probably never be known but there certainly were Tingles making crucible steel at Grenoside in the latter part of the eighteenth century and right through to 1863.[1]

Other attempts were soon made to copy Huntsman's process. The trials made by the Cutlers' Company

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1 Private communication from J. Beevor, local historian.

have already been mentioned; these took place between 1764 and 1768 and were clearly unsuccessful. Further afield there was a failure in the Newcastle area about 1765,[1] although a furnace in the Birmingham area, possibly worked by Matthew Boulton himself, is described in 1770.[2] In Sheffield itself John Love and Thomas Manson set up a business

'for the running and casting of steel'[3]

near West Bar in 1765 or 1766. Manson was replaced by Spear in 1769.[4] John Marshall was casting steel at Millsands by 1774 and his name (variously corrupted to 'Marschall' or even to 'Martial') became almost as famous as Huntsman's on the Continent in the early years of the

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1 G. Jars, Voyages Métallurgiques (Lyons, 1774), vol.1, p.227.

2 Letter from Robert Erskine to R. Atkinson, 11th October 1770. Original in the Library of the New Jersey Historical Society, Newark, N.J., U.S.A. During the 1760s, Benjamin Huntsman was invited to set up a works in Birmingham and he apparently considered this seriously; on learning that part of the agreement would be that he should instruct six others in the finer points of his process, he indignantly refused and returned to Sheffield (S. Smiles, Industrial Biography: Iron Workers and Tool Makers (London, 1863), pp.106-107.

3 Agreement between the partners (Tibbits Collection, Manuscript 200, Sheffield City Libraries). This document has an omission in the final word in the year, but is in the sixth year of George III; M. Walton, Sheffield, Its Story and Its Achievements, 3rd ed. (Sheffield 1962), p.179, is thus in error when she quotes the date as 1760, although this is a valid interpretation on reading the first line of the document.

4 The firm eventually became Spear and Jackson and has survived to the present day.

nineteenth century. John Marshall died in 1793 and was followed by his nephew, Jonathon Marshall.[1] He gave up the Millsands Works in 1829 and was succeeded by Naylor and Sanderson (later Naylor, Vickers and Company) who moved from there to the River Don Works in 1863. In 1776 the Sanderson Brothers set up crucible steelmaking at Wadsley Bridge, whilst Richard Swallow, having taken over the Attercliffe Forge in the same year, started similar operations at Oakes Green nearby.[2]

Some interesting sidelights on the early days of competition with Benjamin Huntsman can be found in a contemporary notebook.[3] Matthias Spencer was a filemaker - he was supplying files made from cast steel as early as 1765. The notebook records his purchase of an 'ingate'[4] of cast

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1 Walton, loc.cit., p.179.

2 G. B. Callan, '400 Years of Iron and Steel', Sanderson Kayser Magazine, 2:4 (1969-70), p.7.

3 A notebook of Matthias Spencer, filemaker. This has details of steelmaking transactions at one end and domestic accounts at the other. It was previously in the possession of Spencer, Clark and Company and I was kindly allowed to study it by courtesy of their publicity officer, Mrs. Lipson. Following my suggestion, it is now lodged with the Archives Division of Sheffield City Libraries.

4 The notebook is notable for its variations in spelling of certain terms. This particular spelling, however, is consistent throughout and it is worthy of note that the term 'gate' is given to the orifice through which the molten metal is poured into a casting. An 'in-gate' would seem to be a reasonable description of the metal from a relatively long parallel mould; it could indicate the derivation of the word 'ingot', which seems to be obscure.

steel weighing as much as 20 pounds in 1763. For this he paid 6d. per pound (£56 per ton). In 1768 he purchased an ingot of 17 pounds, at the same price, from one Samuel Jubb, whose name is not otherwise known. In 1770, he became associated with 'Jon. Marshel' - presumably John Marshall - from whom he purchased ingots, again at 6d. per pound, the ingots weighing, on average, 21 pounds. The ingots were forwarded to a Mr. Smith for tilting, the forging charges being 4s. 6d. the hundredweight; it is not stated how far they were forged down, but presumably this was to sizes for conversion into files. Then, at the end of 1771, there is a significant entry :

> 'Sent to John Marshalls the weight of scraps 10 stone to put half a stone to it to make seven ingates'.

This type of transaction was repeated several times up to 1774, the ingot weight involved being between 19 and 22 pounds. There are no indications of cost for these transactions, however. Meanwhile, in 1773, an 'ingate' of 21¼ pounds was purchased from one Joseph Mellor. At the end of 1774, Spencer seems to have ceased his transactions with Marshall; until 1778 he was sending his scrap to John Love and Company. Thereafter, until the entries cease in 1786 the name is changed to Love and Spear. Throughout this period, the ingots vary in weight between 21 and 25 pounds; the charges were originally 4d. per pound for hire conversion of Spencer's scrap, the figure being reduced to 3½d. for the last few years.

This evidence is valuable in that it shows the growth in ingot size over this period; it will be shown below that Huntsman produced ingots of only 13 pounds in 1761. It also indicates that others were involved in the cast steel trade and that scrap steel was being recycled as an addition to blister steel in the crucible charges. The extent of this usage is not clear. It would, however, be wrong to infer that, because Spencer received back in ingots the same weight as he forwarded in scrap, the utilisation of 100% scrap charges was current. Circumstantial evidence would imply that steel melters would purchase back scrap from their customers and incorporate this along with blister steel in their crucibles.

III Foreign Visitors

The first visitor to the Huntsman works to leave a report was the Swedish engineer, Ludwig Robsahm.[1] He arrived in Sheffield on 1st July 1761 and made his way to

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1 J. L. Robsahm, Dagbok over en Resa i England, 1761, manuscript in Kungliga Bibliotek, Stockholm. The comments given below are from a translation of the relevant passages (Folios 58, 68-70 and 84-86) provided by the late Torsten Berg.

the premises of Osborne and Gunning, merchants with steel furnaces.[1] They showed him over various works during the next two days. On 3rd July, Mr. Watson, landlord of the George Inn, took him to see Mr. Huntsman, two miles outside the town. Here he saw the whole works, but Huntsman refused to let him see how the crucibles were made

'not even if we had offered him fifty pounds'.

Robsahm did, however, see the finished crucibles, reporting them to be about eighteen inches high and holding about three quarters of a gallon,[2] somewhat wider at the top than at the bottom. In the large workshop with a brick floor there were nine square openings along one side, each about eighteen inches wide. The crucibles were placed in these holes and the openings closed with lids. When Robsahm visited the works there were no crucibles in the holes because steel had been cast the day before. Since the room below the casting floor was completely dark, he was unable to see how the firegrates were designed, or how deep the holes were. The moulds for casting the steel were made of cast iron and split longitudinally into two halves; the internal space was two inches octagonal and the length

1 Thomas Gunning probably took over Huntsman's original works when he moved to the Huntsman's Garden area; he certainly was in possession of the site in 1781. (Fairbank Plan, Ref. SheD 71S and Field Book 25, Sheffield City Libraries).

2 This seems rather a high estimate; the liquid steel would only occupy a quarter of this volume.

approximately eighteen inches.[1]

In an adjacent workshop was a mill for breaking down the clay, consisting of a horizontal stone below and a vertical stone running on top of it, pulled round by a horse. This also was not in operation when he saw it, but he understood from other sources that the mill was used for grinding down pots or crucibles, used by goldsmiths and other founders. Huntsman imported these from Holland. Robsahm felt sure that they were made of some kind of black lead or graphite and that the crushed material was then blended with Stourbridge clay; such a mixture, he thought, was probably what Huntsman used to make his crucibles, the whole secret being to make crucibles which would withstand the hot fire necessary for the melting of steel.

He reported that Huntsman did not use full bars of blister steel but purchased the short bar ends cut off after cementation, as likely to be faulty for normal processing by rolling or forging. Robsahm saw a large number of such pieces in a shed. Huntsman himself informed him that the time required for a melt was from three to four hours, after which time the pots were lifted out from the holes and the steel poured into the moulds.

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1 Assuming the mould was filled to within two inches of the top, this would have provided an ingot of around 13 pounds in weight.

He implied that, with three assistants, he was producing about eight tons of steel per annum; with more workers, if he cared to hire them, he could produce as much as twelve tons.[1]

The next day he visited Huntsman's son, who lived in Sheffield. In addition to being a partner in his father's business, he owned a works where all kinds of buttons were made from 'White Metal'. As he was not at the works, Robsahm subsequently invited him and his wife to supper, during which meal he constantly tried to bring round the conversation to steelmaking topics. He learned that the types of iron which were suitable for steelmaking showed a white fracture with shining grains when broken cold, but at the same time were tough and ductile. On the other hand, good quality steel could never be made from poor quality iron. With regard to crucibles, all he was told was that they could do with a few tons of the earth from which the Dutch crucibles were made. Robsahm considered this as a clear indication that they were compelled to use the Dutch crucibles and to grind them down in default of suitable raw materials. This he considered to be a most expensive procedure. Huntsman himself later claimed that the mineral from which the Dutch crucibles were made was not black lead, but Robsahm was not convinced.

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1 These figures, assuming about a 75% yield of good material after forging the ingot, would imply using each hole twice daily for either two days or three days a week, or once a day for four or five days a week.

Some comments should be made at this point. In the first place, since the description of the furnace layout is different from the later description available in 1772, it is quite clearly the Attercliffe Green works that Robsahm visited. The purchasing of used crucibles from Holland can be traced into the early years of the nineteenth century.[1] Moreover, there is a report from this period which states that the English steelmakers preferred the 'black crucibles' from Ypse in Germany to any others.[2] It is probable that Ypse was in fact Ybbs, on the Danube, between Vienna and Linz; here, just north of the Danube, in the area around Persenbeug, black lead or graphite had been mined for centuries and crucibles were certainly being made there in 1817.[3] Finally, the same report confirms that the crucible steelmakers in England purchased the cropped ends from the blister bars at an advantageous price.[4] This particular point has ample confirmation. It is reported by Andersson after his visit to Sheffield in 1767.[5] More tangible evidence can be gleaned from the records of the Fell 'Steele Trade'.[6] Here Benjamin

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1 B. Huntsman and Company, Ledger 1787-1806. Sheffield City Libraries, LD 1612.

2 F. Hassenfratz, L'Art de Traiter les Minerais de Fer (Paris, 1812), 3me. Partie, p.85 (this work is sometimes referred to as Siderotechnie).

3 Private communication from Miss M. C. P. Scholte, Erasmus University, Rotterdam.

4 Hassenfratz, loc.cit., p.96.

5 Bengt Qvist Andersson, Anmarkningar samlade pa Resan i England aren 1766 och 1767, manuscript in Jernkontorets Bibliotek, Stockholm, Folio 173.

6 Staveley Ironworks Records, Sheffield City Libraries, SIR 9, 10 and 11.

Huntsman appears as a customer first in 1748, when he purchased 127 lb. of 'olde steele' for £1. 1s. In the following June he took a further 11 cwt. of similar material for £11, at a time when blister steel was normally selling at 25s. per cwt. This was when he was still working at Handsworth. Between 1751 and 1755 he took just over two tons of 'double converted steele' or 'twice put in', that is, more highly carburised than usual, capable of giving a harder steel when remelted in his crucibles. From 1757 to 1765, when these ledgers cease, Huntsman was a regular customer, with an account of his own, rather than being lumped in with 'sundry small items', as previously. His purchases over this period, in hundredweights, may be tabulated as follows :

Year	Raw Ends	Loose	Loose Double Converted	Sound	Sound Double Converted	TOTAL
1757-58	18½	6	10	1	6	41½
1758-59	14½	16	12½	17½	6½	69½
1759-60	19¾	36½		5		61¼
1760-61	5½	47¾				53¼
1761-62	26¾	29		16¼		72
1762-63		53¾		1		54¾
1763-64	20	68¾		5		93¾
1764-65	16	38¾	22¼	117		194
Price per cwt.	13s./ 14s.	23s.	23s./ 24s.	30s.	32s.	Mean 22s.9d.

'Loose' steel would appear to have been open grained and somewhat defective material, probably excessively blistered and thus difficult to forge to a good quality product. This use by Huntsman of a 'sub-standard' material, judged as normal blister steel, but perfectly satisfactory as a re-melting base for his crucible steel, saved him some 25% on what he would have paid for sound steel over this period, a not inconsiderable economy of over £200. It is also noteworthy that only a few odd pounds of 'raw ends' were sold to other customers over this period. A few years later, Huntsman is also buying 'raw ends' and cheaper steel from the Cutlers' Company.[1] At a time when the normal price of blister steel was 28s. 6d. per cwt., the relevant entries are as follows :

23.3.67	4 cwt. 2 qr. 0 lb.		@ 18s.0d.	£ 4. 1. 0d.
10.2.68	1 T. 5 cwt. 0 qr. 0 lb.		@ 23s.0d.	£28.15. 0d.
	3 cwt. 2 qr. 0 lb.	Raw Ends	@ 18s.0d.	£ 2. 5. 6d.

Now, however, he had competition. Messrs. Kenyon purchased 11 cwt. of raw ends @ 14s. 0d. in June 1766[2] and Boulsover and Company purchased 2 cwt. of raw ends @ 13s. and 26 cwt. of cheap steel @ 23s. in 1769.[3]

There is one further item of interest in the Robsahm report: a description of a steelmelting shop owned by a Mr. Smith, situated within the town of Sheffield. It also had both a single chest and a double chest cementation

1 Company of Cutlers in Hallamshire Archives, vol.48, Folios 83 and 85.

2 Ibid, Folio 76.

3 Ibid, Folio 89.

furnace on the same premises. Robsahm reports that there was a bank of three crucible melting holes, eighteen inches square and two feet deep. At the bottom were grates with deep pits below for ash and to create a good draught. The crucibles were made entirely from Stourbridge clay; they were about one foot high and nine inches in diameter and capable of holding about 20 lb. of steel. They were placed on the grates and charged with broken blister steel; lids were then placed on top to prevent fuel getting into them. The opening of the furnace hole was then closed by a cover made of four thin bricks in a frame of iron :

> 'after the holes had been filled with coal, placed around and on top of the crucibles, the coal having been previously burned to a slag, which here they call 'coak'.'

The fire was then lit and heating proceeded for six hours, during which time more 'coak' had to be added. The steel was eventually ready for teeming into the moulds, specially made from cast iron for the purpose. The crucibles were lifted out by a long pair of tongs which could grip them around the whole of their girth.

The cementation operations on these premises, together with the possibility of the Mr. Smith being the steelmaker employed by the Cutlers' Company, have already been discussed.[1] The coincidence becomes stronger, however, when it is found

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1 See Chapter 5 (pp.137-139).

that the Cutlers' Company records between 1764 and 1769 have references to crucible steel melting under their auspices and that the ingot weights quoted are 19 to 20 lb., as in the Robsahm report. The 'New Steel Furnace', brought into action under Joseph Hancock,[1] was obviously a crucible furnace since there are references to two 'pott' moulds, four 'furnish' covers, a 'trading' trough, clay scuttles, 'coak' baskets, steel scraps purchased, four pairs of cast iron ingots (presumably moulds) and so on. At the end of this year the stock covered 3 cwt. 3 qr. 7 lb. of cast steel, together with 5 cwt. steel scraps and 2 cwt. of 'raw ends'. Steel scraps and clay feature in the accounts under Samuel Bates (1764-65) and under Joseph Bower (1765-66) and it is during his period of stewardship that 'ingots run steel' were sold.[2] Later operations are on a very small scale and the moulds were sold in 1769. In passing, it may be commented that the melting shop described by Robsahm had three holes; this establishment had four pairs of moulds and four furnace covers.

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1 During the period August 1763 to September 1764.

2 The Company of Cutlers in Hallamshire Archives, vol.48, Folio 77, has the following entry:

2nd August 1766	1 ingot run steel to Geo. Hanson	19½ lb. @ 6d.	9s.9d.
	Ditto Jno. Green		9s.9d.
	Ditto Jno. Barlow		9s.9d.

Whether these included spares and whether the two shops were the same is a matter for conjecture, but the coincidences are intriguing.

The next visitor to Sheffield who left a record of crucible steelmaking was the Frenchman, Gabriel Jars, who came in 1765.[1] He does not specifically mention a visit to Huntsman but reports as follows :

> 'Blister steel can be made more perfect by the following operation. They usually use the scrap pieces arising in the steelworks. They have furnaces of fire-clay similar to those for melting brass, but much smaller, which receive the air they need from an underground passage. At the mouth, which is square and at ground level, there is a hole through the wall which rises to the base of a chimney. These furnaces only hold one large crucible, nine to ten inches high and six to seven inches in diameter. The steel is put into the crucible, with a flux which is kept secret, and the crucible placed on a round brick placed on the grate. Coal, converted to coke, is placed around the crucible and fills the furnace; the fire is lit and the upper opening of the furnace is completely closed with a lid made of bricks bound in an iron frame. The flame goes through the chimney flue. The crucible is five hours in the furnace before the steel is perfectly melted. There are square or octagonal moulds, made in two pieces in cast iron, put one against the other, and the steel is poured in at the one end. I have seen the ingots of cast steel and they look like pig iron. The steel is drawn down under the hammer, as is done with blister steel, but it has to be heated less strongly and treated with more care because of the risk of it cracking. The object of the whole operation is to bring together closely all the constituent parts of the steel so that there are none of the roaks present of the kind found in German steel and which, it is considered, cannot be prevented except by melting the steel. This type of steel is not in general use; it is only employed for those items

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1 Jars, loc.cit., pp.257-258. Translation by the author.

> requiring a fine polish. The very best razors are made from it, some penknives, the best steel chains, the springs of watches and small watchmakers' files'.

Bengt Qvist Andersson, another Swede, is known to have been in Sheffield in 1767 and to have visited Huntsman. He left no comment at all on his visit and his official report never even mentions crucible steel. On his return to Sweden, however, he set up a crucible steelworks at Ersta, near Stockholm, and this must surely be the earliest foreign crucible shop. A set of drawings of this Swedish establishment has survived showing two rows of three furnace holes each[1] and this is reproduced in Figure 24. It should be observed that Andersson can only have seen three or four such establishments, all of them in Sheffield; these drawings, therefore, are of supreme value in depicting what could have been a contemporary Sheffield crucible melting shop.

The final visitor in this group was another Swedish engineer, Erik Geisler.[2] Again there is no specific mention of the Huntsman works. He visited a shop with ten melting holes, with a chimney stack at each end of the building serving three holes each, and a central stack

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1 C. Sahlin, 'De Svenska Degelstalsverken', Med Hammare och Fackla, vol.IV (1932). Inset between pp.42-43.

2 T. Althin, 'Erik Geisler och hans Utlandska Resa, 1772-1773', Med Hammare och Fackla, vol.XXVI (1971), pp.32-33. Translation provided by the late Torsten Berg.

serving four holes. There is an old pen and ink sketch of the Huntsman works, supposedly dated to 1787,[1] and also a later engraving from the company's letterhead, both of which show transverse chimney stacks, as can be seen from Figure 25.[2] Whether the sketch given by Geisler, which it must be admitted has suffered both from age and in reproduction, can be interpreted to show such a chimney arrangement is a matter for subjective judgement; if so, it might well represent the Huntsman shop of 1772. In any case, since the description is of interest, the drawing is reproduced as Figure 26 and the relevant commentary runs as follows ;

> 'A is the fireplace which is located below ground and provided with a brick vault. There are ten air holes, a, 13 to 14 inches square and 60 inches high. The grate bars of the fireplace are at b and on them is placed a disc of fire-clay d on which stands a round clay crucible c. The disc and the crucible are made of the same kind of clay which comes from Staffordshire. The latter looks like an ordinary brass founder's crucible and is six inches wide and about twelve inches high inside. The furnace hole is as wide where the crucible stands as it is down below

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1 Held by Sheffield City Libraries and reproduced with their permission.

2 The representation from the letterhead of around 1850 will be seen to have four transverse rectangular chimney stacks on the crucible melting shop. Suspicion as to the correctness of this representation must be aroused in comparison with the earlier drawing, when it is realised that the number of cementation furnaces has also proliferated; this does not seem to be other than artist's licence, since old photographs and the Ordnance Survey both agree as to there having been only two cementation furnaces on this site.

and when the crucible has been charged it is covered with a lid of clay e which is larger than the disc and it is then placed on the grate with an ordinary bent pair of tongs. Around it are placed burnt pieces of pit coal. It requires three and a half or sometimes four hours to melt the steel at a very great heat, which often converts the lower part of the crucible to slag and glass. The flame goes directly through the opening f to the upper space which has the same width and here the draught can be regulated by means of the hinged doors i which can be closed. The flue g branches off to the chimney just below the floor. At h there are openings to the outside of the buildings and at k stairs between the floors. It was not possible to find out much about the charge in the crucibles. I was only shown the ordinary steel that had been broken into pieces according to the width of the bar, generally one to one and a half inches. The bars had been converted from Swedish L iron in special separate furnaces, not working now. With this steel are mixed separate diverse small pieces of steel that are collected and purchased from smiths and workers in the town. According to the workers at the crucible furnaces some flux is added to the charge but this is kept a secret. It was possible to see that a used crucible which had broken had a whitish to yellow and rough glass coating, bottom and sides. When the crucible has been removed from the furnace the molten metal is poured into octagonal moulds of iron as required. The ingots are subsequently drawn down under the steel hammer. The moulds used were a good two inches wide and consequently a length of 6* inches requires a fairly high level of steel in the crucible; so far as could be judged from the appearance of the crucible, it had been filled to about three quarters of its height. The Oregrund iron used was said to cost £27 to £30 per ton'.

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* There is something wrong here. In comparison with other evidence, it is suggested that this figure should probably read 16 rather than 6. A calculation on the volume quoted suggests that a figure of around 18 to 20 would be reasonable.

If this was indeed the new Huntsman works, its productive capacity would appear only to have been some 50% or so greater than the earlier one. We do know, however, that the iron intake in 1805 was of the order of 50 tons per annum which, with a reasonable scrap intake, gave at least an eightfold increase over the situation in 1761.[1]

As for the market, there is evidence both from Jars and from Boulton that crucible steel was only used for special applications. It also has been noted that its worth was well appreciated for such purposes on the Continent almost before it made its mark in Sheffield. When the account books begin to shed more light, Benjamin Huntsman had been dead for over ten years but there is no reason to think that the situation had changed dramatically. Looking through these early records, it is clear that fair quantities were still going to France and also to Switzerland. Home customers included tool makers and cutlers in Sheffield. Peter Stubs of Warrington bought steel for his files; steel wire was sold to a number of firms, particularly to Millwards of Redditch for making needles. Thomas Patten of Cheadle was still a customer. The trade in steel, however, was clearly a two-way business; we find there were sales to other Sheffield steel suppliers as well as purchases of steel from them, from time to time. The methods of payment are

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1 B. Huntsman and Company, Ledger, 1787-1806. Sheffield City Libraries, LD 1612.

interesting. It may be in services rendered, such as rolling or slitting; it may be in finished goods, such as planes, scythes or saws; it may be in scrap or raw material supplies, or items classed as 'goods', or even bales of cloth, supplies of rum or lottery tickets! On contra account, the goods - saws, silver spoons, coffee pots - could well be sold to customers along with fresh supplies of steel.

The correspondence between Matthew Boulton and the Huntsman concern still continued beyond the end of the century and is the most important contemporary evidence available. In 1781 William Huntsman wrote :[1]

> 'I am now at liberty and beginning my steel manufactory again. I have improved my rolled steel and steel for toys so that it will not rust so soon as that made by other steel-makers. The price is £4.4. per hundred'.

Again, in 1788, he was offering his steel, at the same price, remarking in addition :[2]

> 'Each piece of steel will be marked B. HUNTSMAN. My mark hath been often counterfeited and inferior sold for mine until the workmen begin to find out the fraud'.

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1 Boulton and Watt Papers, Birmingham City Libraries. Letter from William Huntsman to Matthew Boulton, 11th September 1781, Box H3, No.243. This letter implies Huntsman had been in some sort of trouble, the details of which are not known.

2 Ditto, 4th May 1788, Box H3, No.244.

A major exchange of correspondence commenced in 1789; in April Boulton wrote :[1]

> 'I am about to undertake the striking of some millions of copper pieces which will require a hard blow in hardened steel dies. I have tryed various kinds of steel but am not satisfyed with any of them. I am of the opinion that the best cast steel you are capable of makeing will answer the best ... It must be the best you can possibly make without any regard to price or expence that being a trifling object in comparison to the quality of the steel ... The steel I have hitherto tryed either cracks in the hardening or breaks afterwards in the striking or is so soft as to sink in the middle and become hollow both which extremes I wish to avoid'.

Within a month he had his reply :[2]

> 'I have sent you 12 pairs of dies. The steel I send you will be sound and bear a great force being of a good body'.

In August, he replied to another request :[3]

> 'I will send you 10 pair of dies to pattern sent, together with some steel for tools'.

All was not well, however :[4]

> 'I gave you an exact sketch for the size of the dies and the manner in which the steel should be forged. None of the dies sent are finished in that manner but are nearly twice

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1 Letter from Matthew Boulton to William Huntsman, 24th April 1789, Letter Book L, p.112.

2 Letter from William Huntsman to Matthew Boulton, 22nd May 1789, Box H3, No.233.

3 Letter from William Huntsman to Matthew Boulton, 2nd August 1789, Box H3, No.235.

4 Letter from Matthew Boulton to William Huntsman, 23rd January 1790, Letter Book Q, p.26.

> the size and weight. Therefore they are not fit for my use. I desire you will send me no more dies. But send me 4 cwt. of best steel such as you think will serve my purpose as I mean to have them forged under my own eye ... You will know better than me which is the most proper'.

There was still a problem and Boulton showed himself appreciative of the practical aspects of the matter :[1]

> 'I must beg of you to take the very best marks of Swedes iron to make the Steel and that you will cast it into short thick square bars suppose 4 Inches square and then forge it down into bars about 2¼ by 1½ which we will cut into proper size pieces. I prefer casting thick bars in order that it may take more forging for the more it is forged the better is the steel ... Please to send one hundred weight as soon as possible'.

As steel was still being ordered late in 1791, it seems that other things were now going reasonably well as regards quality[2] but there were other problems, as William Huntsman reported :[3]

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1 Letter from Matthew Boulton to William Huntsman, 21st May 1790, Letter Book Q, p.51.

2 Ditto, 19th November 1802, Box H3, No.242. This letter commences 'Some years ago you supply'd me with cast steel forged to the size of 2¼ by 1½ for the purpose of making coining dies which proved very good.' It goes on to complain of the very variable quality of the last consignment. It should be noted that this complaint comes during the first phase of the Napoleonic Wars when the supply of Swedish iron to this country was running short and complaints of the quality of Sheffield steel were numerous. See T. S. Ashton, <u>An Eighteenth Century Industrialist</u> (Manchester, 1939), pp.46-50.

3 Letter from William Huntsman to Matthew Boulton, 29th September 1791, Box H3, No.238.

> 'Have received your order for one ton of my fine cast steel. I am afraid the great want of water at the mill will be a hindrance unless rain comes'.

This business continued at least until 1802 when Boulton was complaining of the quality of recent deliveries of steel, indicating that his mint was almost at a standstill for want of dies.[1] These exchanges between the foremost steelmaker of his time and his famous engineering customer serve to show how they both contributed to the development of the technology which put Britain ahead in the Industrial Revolution. When Huntsman had improved his practice so as to provide the larger bar that Boulton desired, Boulton compared the two methods of producing his dies. One was by cutting up flat bars and engraving his impression into the flat surface; the other by cutting up a piece of smaller section bar, flattening it by forging so as to obtain the larger surface area and then engraving the flattened end of the bar. In other words, he was comparing a longitudinal section with a transverse section across the grain. The results were in favour of the former method;[2] such a method

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1 Letter from Matthew Boulton to William Huntsman, 19th November 1802, Box H3, No.242, quoted previously.

2 Letter from Matthew Boulton to William Huntsman, 6th July 1797, Box H3, No.241. This is of such technical interest as to merit quotation in full and the detail can be found in Appendix GG. T. Ashton, Iron and Steel in the Industrial Revolution (Manchester, 1924), p.59, states Huntsman received payment in coin minted in his own steel dies. On 14th August 1798, no less than £100 was sent in penny pieces. This has not been found in the records, however, despite a diligent search.

of avoiding cutting through the central segregated area of a forging was adopted and became standard practice for at least a century.

IV Gustav Broling and the Crucible Process

Gustav Broling was one of the last of the long line of Swedish visitors who examined closely the metallurgical industry in this country in the eighteenth century. He was commissioned by the 'Bruks Societeten' in Stockholm to study steelmaking and visited England between 1797 and 1799. His report is, quite untypically, published in printed form in three volumes together with an atlas of plates.[1] Quite

1 G. Broling, Anteckningar under en Resa i England aren 1797, 1798 och 1799 (Stockholm, 3 vols: vol.1, 1808; vol.2, 1812; vol.3, 1817 - with plates). Gustav Broling, born 1766, died 1838, was President of the Swedish Academy of Science in 1803 and Master of the Mint in 1833. He had a commission from the Brukssocieteten to study the making of cast steel, steel wire and surgical instrument manufacture and to study forges and foundries in this country from 1797 to 1799. He apparently spent the first year studying the language; he himself commented that 'without properly knowing the language it would have been impossible to understand all the new techniques'. His setting up of a steelworks only came in 1808 in response to the offer of an award by Jernkontoret for a Swedish factory making cast steel of the equivalent of Huntsman's quality. Broling was a great innovator, installing the first steam engine to be made in Sweden. In addition to his steelworks, he established a surgical instrument factory, one for producing lacquered sheet ironware and still another for preparing quinine from cinchona bark. His printed report, the third part of which interests us here, was awarded a prize by the Swedish Academy for its elegant style of writing. It is worthy of note that the illustrations were engraved 'in the English style' by his nephew Carl Abraham Broling, manager of the

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clearly, he was a man of culture, as well as a technologist, and he reported at length on his discussions with leading men of the day in London, in the arts, science and industry, on the progress of agriculture and on his visits to country houses: in South Yorkshire he considered Wentworth Woodhouse to be rather splendid.

From the technological point of view, he was intensely interested in the crucible process. On his experiences in Sheffield he had a considerable amount to say. He reported that, whilst the population of Sheffield was less than 30,000, there were at least 40,000 souls in the immediate area involved in the making, forging or handling of steel or steel products,[1] there being specifically sixteen makers of blister steel, several of whom had crucible melting shops.[2] He went on to say :[3]

> 'The purifying of blister steel by remelting it in crucibles, the manufacture of cast steel in other words, has certainly been the main reason for the great renown which English steel has received. Through this process the steel is given not only great homogeneity through the advantage of being uniform throughout; during the melting process it is also

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(continued from previous page)
printing office of the Bank of Sweden and the originator of the modern Swedish banknote. (The above notes were kindly provided by Nils Bjorkenstam, quoting from Svenskt Biografiskt Lexikon).

1 Broling, loc.cit., vol.2, p.137.

2 Broling, loc.cit., vol.2, p.138.

3 Broling, loc.cit., vol.2, pp.145-146.

> separated from all the foreign substances which may have become admixed with it during the forging of the iron bar. This gives it the property of being able to receive a completely perfect polish, which is so attractive to the eye and convinces the buyer that the goods have been made of the best materials since such a faultless surface could not possibly be obtained on any type of steel which had not been melted'.

During his visit he obviously called at the Huntsman establishment. His comments on his meeting are intriguing :[1]

> 'The most renowned of all the cast steel manufacturers in England was Mr. William Huntsman, whose works is located at Attercliffe about a couple of miles outside Sheffield. He was a Quaker and was then already quite old and seemed to be a basically honest and well intentioned man, but at the same time something of an eccentric and he would have been a first class subject for the author of 'Tristram Shandy'. Just the same, he had a quite admirable streak of national pride as a genuine Englishman. Over his glass of grog, he, quite openly and without any false modesty, declared that he gave England preference over all countries in the world, but that he had been given very favourable offers from both Russia and America, had he wished to go. In a tone worthy of a patriot, he declared 'I know what I owe my country and I would despise myself if I robbed it of anything simply for my own benefit'. Not without pleasure did the old man listen to my well deserved praise of his own renown. 'Yes, it is true', he answered, 'but I will honestly tell you how this renown has been created. In my youth, I spent several years, at much expense, in trying all types of iron from the whole of Europe. I found three Swedish stamps to be the best and since then, during nearly half a century, I have not used any others. This is the reason why my product always has been uniformly good and, although I sell my cast steel at a slightly higher price than anyone else, the demand for it has never been lacking'. The old man is now dead, but there is no doubt that his famous brand, both now and in the future, will be just as good as it has been in the past'.

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1 Broling, loc.cit., vol.2, pp.148-149.

Despite this eulogy on William Huntsman,[1] Broling thought fit to mention the tradition that his father, Benjamin Huntsman, was not the real inventor of the crucible process. According to the account he published[2] one Waller, a goldsmith, attempted to produce steel rolls for use in his own trade and, having discovered a satisfactory steel melting process, tried to sell it, first in Birmingham and then in Sheffield. In the latter town the secret was wormed out of him and he was sent back to London with a mere pittance for his pains. The evidence, such as it was, was sorted out in the nineteenth century by such eminent people as Professor le Play, Dr. John

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1 This was written in 1812 about a meeting some fifteen years earlier. At the time of the interview, William Huntsman would have been about 65 years old. He died in 1809. There is a little confusion, however, in that William Huntsman took over control only in 1776. Certainly the overall picture was correct but the experiences of both Benjamin and William are together presented as those of the younger man.

2 Broling, loc.cit., vol.3, pp.5-6. The confusion may have arisen from an invitation given to Benjamin Huntsman by the Royal Society to put evidence of his process before them with a view to his being awarded a Fellowship; it seems that he had discussions with Lord Macclesfield, but, in true Quaker fashion, declined the personal honour. This information is alleged to have been passed by one of those present to his friend Waller and thus the information came back full circle to Sheffield. If, indeed, those said to be more skilled in the art who cajoled the secrets out of Waller were Tingle and his partner, Walker, this would explain matters without any need for the picturesque fable concerning the shivering beggar. The interested reader should refer to John, loc.cit. (Foreword, p.iii) and also R. A. Mott 'The Sheffield Crucible Steel Industry and Its Founder', J.I.S.I. (1965), p.236.

Percy[1] and Sir Robert Hadfield,[2] all of whom were convinced of the rightful claims of Benjamin Huntsman. The Broling report, however, found its way into 'The Times' as late as 1864 and drew forth a rebuttal from another Benjamin Huntsman, great grandson of the inventor.[3]

In addition to his visit to the Huntsman works, it is known that Broling visited the Walker and Booth establishments at Masbrough. They were arguably the largest steel producers in the area at this time. It is also a reasonable assumption that the representation of a crucible shop 'near Sheffield' which he included in his volume of plates[4] is the Masbrough shop, particularly as it does not have the layout of the Huntsman shop as indicated by the evidence already given.

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1 J. Percy, Metallurgy: Iron and Steel (London, 1864), p.830. The story seems to have been first reported in H. Horne, Essays Concerning Iron and Steel (London, 1773), pp.165-169. Percy considers Horne to have published 'a singular and no doubt erroneous statement'.

2 R. A. Hadfield, 'The Early History of Crucible Steel', J.I.S.I. (1894, Pt.II), p.228.

3 Benjamin Huntsman II, letter to The Times, dated 30th December 1864. This is given in extenso in Appendix HH.

4 The two plates in question are Plates 1 and 2 of Broling's report and are reproduced in their appropriate position in Appendix II. C. Sahlin, Med Hammare och Fackla, IV (1932), pp.54-55, reproduces both these plates with an indication that they were probably representations of the Huntsman Works in Attercliffe; this does not agree with my interpretation of the evidence.

What is much more important is that Broling, on his return to Sweden, established a crucible steelworks, based on what he had studied in Sheffield. His report covers the setting up of this works and its operation, together with copious comments on practice elsewhere, and in the main this refers to Sheffield practice. It is thus the earliest first hand account with any real detail on the crucible process and, in the absence of any comparable contemporary local information, must be considered as the most valuable evidence of the type of operation involved in the Sheffield area at the end of the eighteenth century, at a time when a standard pattern of operation was beginning to be established. The size of shop set up in Stockholm, indeed, is surprisingly similar to that at the Abbeydale Hamlet, which would appear to be of similar date.[1] In view of its importance, it has been arranged for the whole of the information which the report contains relative to steelmaking to be made available for the first time in the English language.[2] The report will be found to cover the

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1 The Abbeydale Hamlet is now preserved as an industrial museum as a result of the campaign initiated by the Sheffield Trades Historical Society and carried to completion by the Council for the Conservation of Sheffield Antiquities. It contains a five hole crucible shop of somewhat indefinite date from 1786 to 1829, thus roughly contemporary to the Broling enterprise.

2 The few earlier pages of this document were translated for me some years ago by Paul Widgren and I am indebted to him for whetting my appetite. As he was unable to complete the exercise, I applied to my good friend Torsten Berg for assistance but this was denied me by his untimely death. I am therefore deeply indebted to Nils Bjorkenstam who, in collaboration with Jernkontoret in Stockholm, has kindly carried out the task for me. The text is reproduced here by their kind permission.

building of the works, a description of the furnaces and a discussion of the requirements with respect to crucibles, tools, fuels, fluxes and the steel for remelting. Subsequently, the manufacture of the crucibles is given in detailed treatment and comments on the production of coke and the use of cementation furnaces complete the story. The translation is presented in extenso, complete with the relevant plates, as Appendix II.[1]

A few comments are necessary.

The melting shop which he installed, as already mentioned, would not have appeared out of place in any of the smaller establishments in the Sheffield of that time. There are some differences of detail compared with what we in retrospect consider to be standard, such as the handles on the furnace covers (Plate 6) and, possibly, the cluttering up of the melting floor with ancillary pieces of equipment (Plate 4), but it is not far removed from twentieth century survivals in this country.

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1 The references to Plates and Page Numbers in the discussion below refer to the original and are given in the translation in the Appendix.

The moulding of the crucibles shows some differences, mainly in the omission of the treading of the clay.[1] The plug and flask technique (pp.86-92 and Plate 7) here received its first mention in connection with the crucible steel trade; it does, however, seem then to have continued relatively unchanged for well over a century, at least in the smaller establishments. There is, however, one major difference in this earliest description, in that the point is made that no clay must exude from the top joint between the plug and the flask but that the constraint put upon it by hammering against a tight seal will consolidate the clay (p.87). Later Sheffield practice, using the well trodden clay, was to allow a small quantity to overfill the top gap between flask and plug. This was then cut off cleanly with a strickle. Furthermore, no inward forming of the top of the crucible was reported from Sweden; the use of the 'Bonnet' for this purpose could well have been a later development in Sheffield. The insistence on the value of the Stourbridge clay (p.81), taken together with the more than likely use of graphite crucibles by Huntsman and possibly some other Sheffield steelmakers, presents difficulties. It does seem that

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1 It is also to be noted that the treading of the clay is not mentioned by le Play. It seems inconceivable that as late as 1843 this practice was not to be remarked on by a visitor to Sheffield, in view of the known widespread use of the practice over the next hundred years.

most foreign commentators, including Jars and le Play, follow the same line as Broling; so much so that one almost suspects a deliberate propaganda campaign to the effect that the success of the Sheffield steelmakers was almost entirely due to their use of the famous Stourbridge clay.[1]

The tools used by Broling in the main could well have been expected in an early twentieth century environment. There are some exceptions. The charging shovel shown by Broling is, without doubt, an elegant method of solving the problem (p.37, Plate 6); later practice, however, seems to have ignored it by substituting an enlarged version of the charging funnel. The placing of a ball of paper in the neck of the funnel (p.38) is an example of one of those simple but effective procedures which rarely get reported, akin to the modern practice of tying up the leaves of the bottom charge bucket with a piece of rope, which burns through when the device is lowered over the hot furnace shell and gently deposits the charge in the furnace. Elegance, however, seems to have gone a little too far with the coke basket (p.38) which seems more appropriate to the manager's living room; the wicker

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1 The lack of a clay similar to that of Stourbridge is commented on frequently by would-be foreign imitators of Huntsman, as will be indicated in Chapter 12. It is a reasonable conclusion that its lack led to the widespread use of graphite crucibles both on the Continent and in America. See pp.580-1, pp.612-3 and p.631.

coke basket of the Sheffield pattern has something to recommend it.[1] The tongs, rakes and pokers (Plate 6) are all quite familiar and examples can be seen at Abbeydale today. The ingot moulds shown indicate that the practice did not change overmuch. The screw device for clamping the two halves of the moulds was, indeed, used in some places at a much later date; accidental spillage of liquid metal on the screw thread could[2] cause problems in unscrewing, however, and wedges were surer in this respect.

The comparison between coke and charcoal as a fuel (pp.46-47) was, of course, a very valid one for the Swedish steelmaker. He was used to using charcoal; on the other hand, all his coal had to be imported. This made coal and coke very unfamiliar and also very expensive commodities.

The comments on fluxes (pp.48-50) are also of more than passing interest since this was the period at which considerable 'mystique' had been generated on this particular topic, most visitors to Sheffield going away with the impression that the flux was an essential

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1 Not only does it appear more manageable, but also I am given to understand that, reared at an angle on a pile of coke, it served admirably as a reclining seat for the weary 'odd job man'.

2 I personally remember the problems with small test moulds fastened in this way, when the contents had to be quenched as soon as solid; we eventually resorted to wedges and had no further trouble.

ingredient. Again, as with Stourbridge clay, one senses some sort of propaganda. It should be pointed out that Broling's reasoning on this point was very sound, even to his conclusion that it really was the quality of the blister steel which made all the difference between Huntsman's steel and the others.

The melting process follows in the way one would anticipate, but the small details are of considerable interest, being a first-hand account. The addition of a second part of the charge after a primary melt down (p.56), using the charging funnel, is a feature not previously met. It can be appreciated that, in this way, the level of molten metal in the crucible can be increased - there was usually a considerable space above the metal since the charge occupied much more room. This in its turn allows a smaller, and therefore probably more robust, crucible to be used. The insistence on the mould being perfectly vertical for teeming (p.60) is, of course, at variance with later Sheffield practice in which the mould was always set at a slight angle to accommodate the natural line of pour over the crucible lip. On the other hand, with a smaller crucible and a lighter load, and with two men doing the pouring together, the conditions were different. It is worthy of note that the mould walls were deliberately coated with soot, albeit by a rather different method from the more usual Sheffield 'reeking' procedure with burning tar.

The capping of the steel with moist sand and an iron plug (p.65) to prevent it from rising on solidification seems rather crude to the modern steelmaker. There is no doubt, however, that the chilling action so induced would freeze the top crust and prevent any marked gas reaction.[1] It has to be remembered that remedies for this particular problem were being sought long after this report was written and the proposal by Broling has more sense in it than many of the devices tried later.

The deliberate lowering of the charge weight for the second and third melts during the day (p.67) is quite clearly something which dates back to the full development of the process. The 'fettling' of the furnace, however, in Sweden differed from Sheffield practice (pp.68-69). Here again, local availability is involved. Ground ganister was the natural thing to use; in Sweden they only had refractory bricks. The comments on the production of coke, again, are of peculiarly Swedish interest (pp.95-101); that Broling was reasonably well informed, however, comes out in his references to Lord Dundonald and by-product recovery.

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1 The practice of 'plating' ingots, that is putting an iron plate on the top of the metal in the mould after casting, was certainly used in the production of rimming steel as late as 1950. The use of "stoppers" to be inserted in the tops of moulds is covered in British Patent No. 546 (1867) in the name of A. L. Holley.

From the point of view of this survey, however, one of the most intriguing features of the whole report is the almost casual reference to Mushet and the incorporation of charcoal with a bar iron charge (p.69); this patent was issued in Britain after Broling had returned to Sweden. The remainder of the paragraph, however, is nothing less than astonishing. It refers to the combination of pig iron and bar iron as the charge for the crucible, making up the carbon where necessary with charcoal. When it is realised that this was not done in Sheffield, as far as is known, for almost forty years after Broling wrote this, and that it had to wait for the relaxation of the Swedish regulations to permit export of Swedish pig iron before becoming more or less standard practice in Sheffield, the cause of the astonishment will be clear. A search for a further paper on this subject by Broling has so far proved fruitless. It would, indeed, be a most interesting document if it were, in fact, ever produced. It goes without saying that Sweden, with its supplies of charcoal pig iron and the charcoal refined bar iron produced from them, all low in sulphur and phosphorus, was the ideal place for such a process to succeed.

The final comment must be concerning the type of cementation furnace which Broling describes (pp.142-147, Plate 16); he, indeed, appears to consider this as reasonably typical and quite clearly states that furnaces of the same type, but with four chimneys, can be found in

Yorkshire. He never mentions the conical chimney, which has always been considered archetypal. This obviously implies that there were local variants which were not recorded.

Reading the Broling report, with its first-hand knowledge of steelmaking, backed by information gathered in this country and a wide experience of the metallurgy of his own times, leads inevitably to the conclusion that this is an invaluable addition to our understanding of the period when Huntsman's invention had reached full commercial status and his products had proved their worth throughout Europe. No other contemporary record with anything like as much detail appears to be extant and it provides a backcloth against which the further development of the process, to be followed in the next chapter, may be set.

V The Importance of Huntsman and His Invention

It is no exaggeration to claim that Benjamin Huntsman laid the foundation on which all ingot-making steelmaking processes are based; the steel produced in his crucibles was referred to as 'cast-steel' since no previously made steel ever had been cast - at least in the Western world and on a reproducible commercial scale - and he produced the first ingots of steel.

It is also no exaggeration to state that he was responsible for Sheffield becoming the quality steel producing centre of the world. All steel required for any onerous application throughout the nineteenth century, and well into the twentieth, was made by his process and the bulk of it in Sheffield, where the skills built up in this tradition still persist. There are no firm statistics and the growth of production was slow, but it is not unreasonable to suggest that, over the two hundred year period for which the process was used, something over five million tons of such steel was produced in the Sheffield area, with a not dissimilar total from elsewhere, mainly from America, Germany and France. When Benjamin Huntsman commenced his first essays with the method, shortly before 1740, it is doubtful whether more than 200 tons of steel was made per annum in the Sheffield area. The major requirements, as we have seen, were obtained from the Newcastle area. A hundred years later, Sheffield produced one hundred times this figure and this represented some 40% of the total European production.[1]

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1 F. le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', <u>Annales des Mines</u>, 4me. Serie, Tome III (1843), p.687. This gives the total of steel produced in Britain as 20,250 tons, some 400 tons being produced outside Sheffield; six years before, the figure for Sheffield alone had been of the order of 18,000 tons, but he points out that at the later date there was idle capacity due to lack of orders.

Within the next twenty years the figure again quadrupled[1] and the peak output of 1873 could well have been half as much again. This was the heyday of the Huntsman process; thereafter the Sheffield trade became more diversified, but it is significant that the crucibles provided the special steel needed for at least a further fifty years.

It is noteworthy, however, that despite the immense significance of the invention of crucible steel on the whole future history of steelmaking and, indeed, on the course of the Industrial Revolution, those abroad seem to have been more acutely aware of the importance of Huntsman's activities than those around him.[2] Foreign visitors undertook long journeys to visit him; the French used his steel, appreciating its special qualities, and produced superior cutlery which not only found a ready market in France but also soon appeared in England. The Sheffield cutlers, who had erstwhile virtually ignored the new material, finding it too difficult to forge compared with their normal shear steel, realised the competition.

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1 J. Hunter (Ed. Gatty), The History and Topography of the Parish of Sheffield in the County of York (Sheffield, 1869), p.216. This gives the overall production of steel in Sheffield for 1862 and quotes a figure of 78,270 tons.

2 The original version of the above work, usually referred to as 'Hunter's Hallamshire', published in 1819, does not even mention Benjamin Huntsman, let alone his important contribution to the growing Sheffield steel industry at that date.

Thereupon, they lobbied Sir George Savile to use his influence in Governmental circles to prohibit the export of Huntsman's steel to France. Having looked into the circumstances, however, he refused to become involved and thereafter its local use spread.[1]

As to the fame of cast steel on the Continent, there are several sources which could be quoted but one from Switzerland in 1778 spreaks for them all :[2]

> 'The cast steel of England is, without contradiction, the most beautiful steel in commerce; it is the hardest, the most compact and the most homogeneous; one can recognise it at a glance
>
> 1. because if a bar is fractured in the unquenched condition its grain is as fine as that of other steels in the quenched condition;
>
> 2. the bars are so well forged and finished that they were for a long time thought to be rolled;

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1 Smiles, loc.cit., pp.106-107.

2 J. J. Perret, 'Mémoire sur l'Acier', Mémoires de la Société Établie a Genève pour l'Encouragement des Arts et de l'Agriculture (1778), pp.10-11, p.25. The references to Huthmant and Martial are clearly corruptions of Huntsman and Marshall. The latter's rise to fame as a cast steel maker was clearly a rapid one; the earliest reference to him in this capacity seems to be in 1771. Perret also comments on blister steel :

> 'Blister steel holds second place; it is clearly a cemented steel and is made in Newcastle .... and sells at 12 sols per pound.'

The translation of these passages is the work of the author.

3. the bars are around three feet in length; those from Huthmant have the two ends cut as though they have been passed through a draw plate but the Martial bars are simply broken. The steel sells at 28 to 30 sols per pound. Huthmant and Martial are the owners of the works making cast steel in England.

It has to be observed that these Englishmen have guarded well their secrets with regard to the production of cast steel .... I suspect that it gets its good quality in the crucible .... but I do not know the means used to melt it .... Cast steel should be placed, according to my way of thinking, in a class of its own .... Many forgers believe that cast steel is unforgeable but they are in error. Care and attention will master it ....'

Benjamin Huntsman's son, William, carried on his father's precepts well, as will have been realised from Broling's comments, and it was he who in 1792 received the testimonial from Fourness and Ashworth, Engineers to the Prince of Wales, which opened as follows :[1]

'In justice to Mr. Huntsman, who makes the best cast steel in this, or perhaps in any other, country, we wish to present Society at large with the following brief character of it, which, as persons who have for several years been in the practice of using it, we shall at all times be ready to confirm. We have made trials of different kinds of cast steel but never met with any that would abide the same execution as Huntsman's'.

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1 Fourness and Ashworth, A Report on Huntsman's Cast Steel, printed privately and issued in both English and French versions, 28th March 1792. The full English text is reproduced as Appendix JJ.

It was only to be expected that, just as Huntsman had his competitors in Sheffield, efforts would be made abroad to produce this attractive new form of steel. As will be made clear later[1] J. C. Fischer made satisfactory cast steel in Switzerland as early as 1804; Alfred Krupp did the same in Germany some ten years later. France had to import a Birmingham man, trained in Sheffield, one James Jackson, to establish the method near St. Étienne after the peace of 1815. The earliest crucible steelmaking in America was during the 1830s. Nevertheless, there was still a good market for English steel, and Huntsman and Company had to make arrangements with their agent in Paris for all genuine Huntsman bars to pass through the one depot and receive a counter stamp from the agent so as to combat the growing practice of counterfeiting the famous Huntsman stamp.[2]

Le Play was obviously convinced of the superiority of the value of such a stamp :[3]

> 'The purchaser of this article, who pays a higher price for it than for other sorts, is not merely acting in a spirit of blind routine but is

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1 The spread of the crucible process abroad is discussed in detail in Chapter 12.

2 Anon, L'Invention de l'Acier Fondu par Benjamin Huntsman, published privately in Paris about 1890 by Marchand, Bignon, Ammer et Cie., p.15.

3 F. le Play, 'Sur la Fabrication et le Commerce des Fers a Acier dans le Nord de l'Europe', Annales des Mines, 4me. Serie, Tome ix (1846), p.266.

> paying a logical and well deserved homage to all the material and moral qualities of which the true Huntsman mark has been the guarantee for a century'.

There was, however, more to it than this. Huntsman's process not only established his and his family's reputation; it established a reputation for the quality of steel from Sheffield. The obituary of his grandson, Francis Huntsman, states this well :[1]

> 'Mr. Huntsman was a member of a family of whom Sheffield has just cause to be proud, for it is to the invention of cast steel by Mr. Huntsman's grandfather, Benjamin Huntsman, that the town owes its present position'.

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1 The Times, 27th February 1879.

8 THE CRUCIBLE PROCESS: THE THEORETICAL BACKGROUND AND LATER DEVELOPMENTS

'A furnace at work smells of wet clay, creosote oil, burning sulphur, tar, sweat, beer and bacca. It has doors and windows, but no window panes, and what are technically called sky-lights, which have more to do with letting out reek than letting in daylight. As there is ample ventilation the work is not unhealthy but a man needs to be strong to stand up to it with enjoyment'.

Harry Brearley: the opening paragraph of 'Steel Makers'

I The Coke Fired Furnace

The melting of steel as envisaged by Huntsman was, quite clearly, an extension of the established technique of the brassfounders for the production of liquid metal to pour into moulds for the making of castings. There were the fundamental difficulties inherent in the difference in melting point between the two metals, however; steel melting requires temperatures some 500°C higher than that of brass.

As pointed out elsewhere,[1] the development of coke as a metallurgical fuel was a necessary prerequisite for such an operation, since only with a deep bed of such a fuel, with a plentiful air supply, could the necessary temperature be maintained for a sufficient period to enable steel to be

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1 R. A. Mott, 'The Sheffield Crucible Steel Industry', J.I.S.I., vol.203 (1965), pp.231-232.

melted in a crucible. Even from the earliest drawings which have survived, for example those of the furnace set up near Stockholm in 1769 shown in Figure 24,[1] the necessity of a large cellar below the furnace chamber and a tall chimney, to provide adequate amounts of air and a strong draught, is quite clearly demonstrated. This pattern of coke fired furnace survived, with some increase in scale but otherwise with only minor modification, for a further two hundred years.[2] Basically, the furnace chamber or 'hole', as it came to be called, was originally square in cross section, made in refractory sandstone blocks carefully cemented together with the minimum of good quality fireclay. The base was provided with two iron runners across which loose furnace bars could be placed, access to these being from the ashpit below in the cellar. The top of the furnace was closed with a cover, usually an iron frame filled with fitted firebricks and provided with an iron handle. At the back of the furnace chamber a flue led from near the top of the wall to the chimney. A later modification was to take a connection from this flue to an opening at the ashpit level; by placing a piece of paper over the mouth of this auxiliary channel the draught went through the furnace bars but, by taking it away, the air could be diverted from the furnace. This made it more comfortable

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1 See also p.230 and p.528.

2 There were, however, alternative methods of firing the furnace introduced in some works in the latter part of the nineteenth century, as will be discussed later. See pp.335-344 and p.641.

when the cover had to be removed for attention to the coke level or examination of the contents of the crucible during the progress of the melt.

The method of operation of the fully developed furnace will be described later; suffice it here to say that blister steel, broken into fairly small pieces, was charged to a preheated crucible placed in the furnace 'hole', a lid placed on the crucible and the contents melted slowly by means of the heat generated by the burning coke which surrounded it, prior to the crucible being withdrawn and the contents poured into a cast iron mould to produce an ingot of steel.

The original square shaped melting holes accommodated only one crucible each. By 1842, however, the normal Sheffield pattern would appear to have involved a rectangular or an oval hole capable of taking two crucibles.[1] Indeed, as early as 1793, the point was made that a multiple crucible furnace hole should be more economical although it was stressed that this still had to be

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1 F. le Play, 'Mémoire sur la Fabrication de l'Acier en Yorkshire', Annales des Mines, 4me. Serie, Tome III (1843), p.640.

demonstrated.[1] Experimentation with still larger holes, even though they were, in practice, found to be more economical in both fuel and labour, was discontinued in England and the two-crucible hole prevailed in all the major Sheffield coke-fired installations. Larger holes, however, found favour in France.[2] The drawbacks seem to

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1 French National Archives, F14.4485, Rapport sur la Fabrication d'Acier Fondu du Citoyen le Normand. The date is 15th May 1793 and the report is signed by the well known metallurgist Hassenfratz, later to be the author of one of the earliest comprehensive texts on iron and steel production. I am indebted to Professor J. R. Harris for bringing this interesting evidence to my attention. My translation of the parts of the document relating to steelmaking is reproduced in full in Appendix KK.

2 L. E. Gruner and C. Lan, L'État Present de la Métallurgie du Fer en Angleterre (Paris, 1862), pp.748-753. Sizes of hole are quoted as 16" square for single crucible furnaces, 18" x 22" for double crucible holes and 22" x 24" for holes to contain four crucibles. The coke consumption is quoted per ton of steel at 5-6 tons, 3-4 tons and 1.8-2.5 tons respectively, with, however, a 25% increase in crucible cost for the four crucible hole. Total costs for the three types of operation in France, including labour and maintenance, are given as follows :

Single furnaces	203 to 250 francs per 1000 kg.
Double furnaces	161 to 195 francs per 1000 kg.
Quadruple furnaces	128 to 175 francs per 1000 kg.

It is pointed out, however, that the risk of loss of metal in the quadruple furnace was higher by about 2-3% and that, whilst this still showed economy with cheap puddled material, worth 400 francs per 1000 kg., with best quality cemented iron at 800-1000 francs per 1000 kg. in the crucibles, the loss involved could well outweigh any fuel economy.

have been the lack of uniformity in heating and the greater wear on the crucibles, coupled with a more arduous task for the melter due to the concentration of heat.

The lining of the furnace is a matter which was very adequately discussed in a contemporary report :[1]

> 'The most refractory of bricks cannot withstand the excessive temperatures which must be developed in the steel furnace. To make the walls of these furnaces, one employs a sandstone, called 'gannister', very close textured, breaking with a very fine sugary splintery grain, formed of pure quartz and, on account of this, highly refractory. It enters into the construction of the furnace in two forms. The sandstone, by reason of its hardness, being used with good effect for the metalling of most of the roads leading to Sheffield, one collects with great care the dust and mud which results from the wear of the causeway; these powdery materials, composed essentially of quartz sand mixed with traces of animal matter and the fine coal dust which impregnates the ground in all the manufacturing districts of Great Britain, are as refractory as the sandstone itself and are economical to use since they do not require any labour for cutting and erecting masonry. To make anew the walls of a furnace after having taken out the damaged parts, it suffices to pack the lightly moistened refractory material into the eleven inch space between the fixed furnace wall and a central wooden core* with which one can produce exactly the shape and position which the hole must have. Unfortunately for the steel melters, one uses here and there for the metalling of the roads certain fusible materials, the admixture of which completely destroys the quality of the dust; thus, in 1842, I saw used, along part

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1 Le Play, <u>loc.cit.</u>, pp.641-642.

* This was generally known as a 'former' and was of rectangular section with rounded corners, with the vertical sides slightly tapered, the section being somewhat larger at the top than at the base. A large hook was fixed centrally in the top face to facilitate its withdrawal after the ramming operations around it were complete.

> of the road from Sheffield to Attercliffe, in the midst of the region where the melting shops abound, the blast furnace slag from Sheffield Park. Being unable to obtain completely refractory dust all the time, the manufacturers of cast steel are often obliged to use the stone itself. In such case, the wall in contact with the fuel is made with the cut stone to a thickness of about 4½ inches; the space between this and the fixed wall may then be filled with dust of a mediocre quality'.

It is worth adding, in this context, that within ten years of this report being published, ganister was being ground and admixed with a small quantity of clay and horse droppings by Joseph Bramall of Oughtibridge. This he sold to the steelmakers, who referred to is as 'muck' or 'muckite', presumably harking back to its original origin as road scrapings.[1]

II The Crucible

The crucible obviously was a vital part of the equipment. It had to withstand temperatures of 1500-1600°C

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1 Bramall liked to refer to his material as 'pulverised sand' but it would seem that his customers were not impressed by his efforts to raise the status of his product and still called it 'muck'. Bramall's success, however, persuaded others to follow suit and in 1855 William Hollis began similar operations, to be followed in 1861 by Russell and Young, all in the Oughtibridge area. I am indebted to A. Nicholson of the Steetley Refractory Company for this information. It is also worth noting that John Brown and Company, about this time, worked the ganister on Hoodlands Farm in the Stocksbridge area, this operation being managed by Joel Bramall (quoted by J. Kenworthy in his unpublished history of Stocksbridge, Sheffield City Libraries, MD 3336-4).

for periods of four to five hours. At the same time, it must not be unduly eroded or attacked by the steel, or by any small quantity of slag which formed upon the surface of the steel and it must retain sufficient strength to sustain the lifting out process and subsequent use as a pouring vessel.

The earliest known discussion on the requirements for crucibles appears in a report on the production of cast steel in France in the early days of the Revolution. This document is important as an indication of the serious attempts made to surmount the difficulties caused in France after the prohibition of importation of English cast steel.[1] The recommendations are worthy of full quotation :

> 'Four qualities are required in steelmaking crucibles:
>
> 1. to be highly infusible;
> 2. to have sufficient thickness to resist the weight of the steel;
> 3. to withstand the initial firing without breaking;
> 4. to be able to be returned to the fire after pouring the steel so as to serve for several consecutive heats.
>
> The composition of crucibles as used in the

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1 French National Archives, F^{14}.4485, <u>loc.cit.</u>

> glassworks fulfils the first requirement* whilst the thickening up of the walls meets the second. It is necessary, however, on heating up to take particular care; the least lack of attention and a fire pushed too quickly or applied unevenly often suffices to crack them. The crucibles used by the copper founders have the same defective tendencies; since it is possible to warm them up without breakage and then make them serve a great number of operations, it makes one think that the same could come about with the crucibles for steelmaking produced from the composition used in the glassworks, except that there will have to be even greater care taken because of their greater thickness'.

It has already been noted in the last chapter that Huntsman probably used crucibles containing plumbago or graphite, the balance most likely being local clay from Bolsterstone[1] or Stourbridge clay.[2] Such a mixture would produce a dark coloured crucible, which seems to have been referred to as a 'blue pot' or even a 'blew pot'.[3] In contrast, a 'white pot' was produced from

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* It has already been explained that these crucibles are produced from specially selected clays, which are pure mixtures of silica and alumina, free from lime and magnesia, which only occur at five or six places in France. It has also been made clear that the raw clay is compounded with a third or even a half of its own weight of the same clay, previously fired and crushed, which assists in meeting his third requirement.

1 Mott, loc.cit., p.242.

2 L. Robsahm, Dagbok over en Resa i England, 1761, Folios 68-69. An account of the clay workings at Stourbridge from a slightly earlier date can be found in Appendix LL. Reference to Stourbridge clay is also made by Broling, as given in translation in Appendix II.

3 Cutlers' Company Archives, Sheffield, Volume 47, Accounts for 'New Furnace', 1763-64.

clay mixtures; a patent taken out in 1762 covering the provision of 'white crucibles or melting pots' gives the following instructions :[1]

> 'Take Sturbridge clay and Dorsetshire clay, calcined; mix then with Woolwich sand and water; to be trodden with the feet and then burned'.

Clay pots, made on the steelworks premises, using a private recipe for the clay mix formula, became the rule in Sheffield. One report[2] suggests that the proportions of the various clays used by nine different steelworks in the Sheffield area early this century were covered by the following ranges :

China Clay	10-35%
Derby Clay	15-45%
Stourbridge Clay	20-45%
Stannington Clay	0-30%
Coke Breeze or Grog	5-16%

These figures are in general agreement with some notes entitled :

> 'Mixtures for clay pots as used at the Technical School'.[3]

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1 British Patent No. 762, William White, 25th January 1762.

2 H. Brearley, <u>Steel Makers</u> (London, 1935), p.25.

3 This information is to be found at the back of a Furnace Charge Book from Samuel Peace and Sons of Wellmeadow Steel Works, Allen Street, Sheffield. It covers operations from 1895 to 1898. I am indebted to Geoffrey H. Peace, Esq. for permission to study this most interesting document.

These date from about 1895 and are as follows :

	No.1	No.2	No.3	No.4
Stourbridge Clay	45%	40%	21%	Nil
Derby Clay	21%	17%	39%	20%
Stannington Clay	21%	17%	15%	30%
China White Clay	10%	20%	20%	35%
Coke Dust	3%	6%	6%	15%

Of these, No.1 is said to have been useful for research work, Nos.2 and 3 for ordinary works practice and No.4 for castings, being very strong and tough; in addition, it is pointed out that the high coke dust content will throw a lot of carbon into the melt, whilst the white clay has a tendency to give an increment in silicon content. These particular details must have received wide circulation since they are repeated, with minor differences, in a text book issued in 1905.[1] Here, however, No.1 is indicated as being eminently suitable for the melting of high speed steel, whilst No.3 composition is modified to contain 35% Derby clay, 21% China clay and 9% coke dust. The same four compositions are repeated, but with minor modifications, elsewhere,[2] but with additions of two other mixtures

'largely used in Sheffield'

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1 P. Longmuir, Practical Metallurgy: Iron and Steel (London, 1905), p.17, pp.171-172.

2 A. B. Searle, Refractory Materials; Their Manufacture and Uses (London, 1940), p.601.

made up from the following ingredients :

	E	F
Stourbridge clay	47%	Nil
Derby clay	Nil	40%
Stannington clay	47%	28%
Clay or plumbago	Nil	4%
Grog	6%	28%

The writer in this case is at pains to point out :

> '.... it must be clearly understood that each maker works according to his own ideas and alters his recipes whenever there appears any advantage in doing so'.

In addition, it is made clear that the use of such 'white crucibles' or clay pots was confined almost entirely to this country and that graphite crucibles were universally used in both Germany and America. Le Play gives a typical mixture for use in Sheffield 1842, giving the following requirements for a single crucible :[1]

Stourbridge clay, dry and powdered	11 lb.	8 oz.	(= 47.9%)
Stannington clay, dry and powdered	11 lb.	8 oz.	(= 47.9%)
Fragments of old pots, powdered		14 oz.	(= 3.7%)
Powdered coke		2 oz.	(= 0.5%)

Mushet also gave full instructions for the preparation of

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1 Le Play, loc.cit., pp.644-650. The full desciption, in the author's translation, is to be found in Appendix MM.

the raw materials required for such crucibles.[1]

Further afield, the crucibles used in 1878 at the Small Arms Factory at Kama, 560 miles from Nijni Novgorod, were made from the following mixture :[2]

Clay (unspecified)	14 lb.
Old potsherds	14 lb.
Siberian graphite	4 lb.
English graphite	1 lb.
Anthracite	6 lb.

These were reputed to last not more than two melts each, some 30% failing after only one melt.

More interesting, however, are recipes which have survived from William Jessop and Sons of Brightside Works.[3] A document of 22nd August 1899 gives details of three batches :

	72 pots	96 pots	50 pots
Derby clay	10.1. 4.	13.2.24.	7.0.16.
Common clay	4.2. 0.	6.0. 0.	3.0. 0.
White clay	5.0.16.	6.3.12.	3.2. 8.
Coke dust	1.1. 4.	1.2.24.	3.16.
	21.0.24.	28.1. 4.	14.2.12.

1 British Patent No.213, R. F. Mushet, 28th July 1861. The relevant details are reproduced in full in Appendix NN.

2 Anon, Iron (1878), vol.xi, p.583.

3 I am indebted to L. A. Keen, Esq., for providing me with photocopies of these documents. I understand that both the 'Common Clay' and 'Woodwards Clay' were most probably Stannington Clay.

These figures work out to give the following approximate percentages :

Derby clay	49%
Common clay	21%
White clay	24%
Coke dust	6%

It will be noted also that whilst Le Play indicates a crucible weight of 24 lb. and the Russian figures give 41 lb., these Jessop crucibles were about 33 lb. each in weight. At this time the weight of steel per crucible was of the order of 70 lb.

A further document from the same source gives the recipe for specially strong pots to be used in the melting of high speed steel in their gas fired furnaces;[1] this is dated 18th December 1906 and provided 44 pots, each weighing 30 lb. each :

5 cwt. White clay	=	41.7%
5 cwt. Woodwards clay	=	41.7%
1 cwt. Coke dust	=	8.3%
1 cwt. Ground Pot Lids	=	8.3%

Brearley commented further on the make up of the clay mix.[2] He pointed out that washing of the China clay to remove the gritty impurities and, in particular, the iron

1 The use of gas fired furnaces will be discussed later (p.335ff).

2 Brearley, loc.cit., pp.26-31.

pyrites, was essential, since these, if not removed, decomposed on heating, starting small cracks which caused the surface to 'spall' (or break away in local areas) or, alternatively, would give local fusion and thus a tendency for holes to form in the walls. Derby clay was favoured since it readily absorbed water and became plastic with a minimum of effort :[1]

> '.... it is therefore easy to tread and always figures largely in the mixture when the percentage of each clay is left to the pot-maker'.

Stourbridge clay was said to be 'stronger' than the other clays and contained a proportion of free sand

> '.... which is at once apparent by grinding a sample between the teeth'.

The use of 'grog', or crushed burned clay, permitted more even drying of the pot, as well as giving it greater 'green strength' - that is after moulding. It also reduced the contraction on drying which, with pure clays, could give rise to cracking. It had, however, to be carefully prepared; not too strongly burned, since then it would not adhere to the clay, but sufficiently hard burned so as not to crush to powder. It should also be angular in character.[2] The alternative use of coke breeze, generally

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1 This comment is confirmed by a note in the Wellmeadow Charge Book.

2 According to Searle (loc.cit., p.601) the grog should be passed through a 40 mesh sieve and all the fine particles rejected.

the case in Sheffield, served the same purpose and also reduced the fusibility as long as it was enclosed within the clay. When it burned away, it left the walls porous and somewhat soft to the tongs, but since the pot at steelmaking temperatures was not impermeable to gases, it was argued that coke had an advantage in protecting the metal from some oxidation.

The mixed clay ingredients were sometimes just moistened and covered with wet sacking and then left overnight; otherwise they would be mixed dry next morning in the treading trough and sufficient water added and mixed in, as though one was making a stiff mortar. The next procedure was to tread the clay mixture with bare feet for four or five hours to homogenise it and to drive out air bubbles; when trodden into a thin layer, it was again heaped up and trodden out again and so on until it assumed a strong dough-like consistency. Weighed lumps, each sufficient to produce one crucible, would then be individually balled up and then moulded, using a plug and flask. This method has a long history. It was certainly in use in Sheffield late in the eighteenth century[1] and was demonstrated at the Abbeydale Hamlet only a few years ago by an old potmaker.[2] The

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1 G. Broling, Anteckningar under en Resa i England 1797-1799, vol.3 (Stockholm, 1812), Plate 7, shows this quite clearly (see Appendix II).

2 At a demonstration at Abbeydale Hamlet in 1975, George Goodwin, the last of the potmakers from B. Huntsman and Co., trod the clay and moulded crucibles. He was then turned eighty but had worked until about eight years earlier. He has since died and the technique died with him.

moulding operation consisted of throwing the cylindrical shaped rough piece of clay into a cast iron 'flask', whose internal shape was that of the finished crucible exterior, except that the top continued the gentle outward contour. The base of the flask had a large central circular hole and was fitted with a loose iron plate with a small central hole. The flask itself was supported on a stout ring base. Into the mass of clay was pushed the 'plug', the exterior shape of which was generally that of the final interior of the crucible. The plug also had a central iron spike which fitted the hole in the base plate of the flask; the upper end of this spike terminated in a stout metal boss to allow it to be driven home with the aid of a mallet. The whole plug, indeed, could be of cast iron, as may be seen at Abbeydale; the bulk of the surviving evidence, however, suggests that it was more usually of lignum vitae[1] with the iron insert. The movement of the plug in the flask served to drive the clay up the annular gap between flask and plug, the inside of the flask and the outside of the plug having been previously lubricated with 'pot oil' - a thick

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1 The use of lignum vitae is confirmed by Broling (see Appendix II), by le Play (loc.cit., p.649) who describes a plug

> 'made from a hard and heavy wood, coming from the tropical regions, run through with an axletree of iron',

and in the Wellmeadow Charge Book.

creosote. Properly carried out, this would just give a slight oozing of surplus clay above the rim of the flask and this would be cut off cleanly by means of a 'strickle', The plug was then lifted clear, the flask lifted up and its base placed upon a 'tree' - a square block of iron set firmly in the floor - which supported the crucible on the iron plate from the base of the flask. This allowed the flask itself to slide downwards, leaving the crucible to be carefully lifted off, using two specially shaped pieces of sheet iron, and placed on a thick wooden board which would eventually accommodate four or six 'green' crucibles. Finally, a 'bonnet' - a short truncated cone of sheet metal - would be pushed down on to the top of the crucible, with a rotating movement, to turn in the top and give it the conventional shape. The boards with their crucibles would then be set aside for two or three days to dry, prior to being placed on the racks in rows over the melting holes for as many weeks. From here they would be taken, as required, the night before they were to go into the furnaces, and placed in a small coke fired stove,[1] usually at one end of the melting shop,

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1 This process was usually known as 'annealing' and the stove is variously described as an 'annealing stove', a 'nealing stove' or a 'nailing fire'.

where they would be brought up to a good red heat over a period of twelve hours or so, ready for transfer to the furnaces themselves. There was, of course, some weight loss during the drying out and one case is quoted of crucibles weighing 29 lb. as moulded, 25 lb. after drying and 21 lb. after 'annealing' as charged to the crucible furnace.[1]

This procedure was the general practice in virtually all the crucible melting shops in Sheffield, until well into the second half of the nineteenth century. It survived as long as crucible melting in many of the smaller shops. In the larger establishments, however, it was thought fit to mechanise the moulding process by the installation of screw presses; other features, however, remained the same. Pictorial evidence of such an operation survives from William Jessop and Sons.[2] The earliest written evidence, however, comes from the River Don Works in 1867, where it was reported that all crucibles were formed wholly by machinery at the rate of 1000 per day and were dried slowly over a period of thirty days, so as to drive off all moisture. The drying house for these crucibles was a separate building, large enough to contain the 30,000 pots, in two sizes suitable for 60 lb. or 100 lb. melts, each crucible

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1 Longmuir, loc.cit., p.172.

2 Wm. Jessop and Sons, Visit to a Sheffield Steelworks (Sheffield, 1913), p.18. This photograph probably dates from late in the nineteenth century. Such a device was also installed at Osterby in Sweden in the 1870s (p.531).

being used three times only and then discarded.[1]

The other change, however, was that graphite crucibles came into more general use in certain cases. As mentioned above, this had always been the type of crucible utilised in Germany and America; they seemed to have difficulties in operating satisfactorily with clay pots. Admittedly, a clay pot would not travel[2] (this explains why the domestic manufacture of such items was the invariable rule) and would only stand three successive melts, whilst a prefabricated graphite pot had adequate strength to withstand all normal transport hazards and would last ten to twelve melts. The clay pots, nevertheless, were cheaper overall and had other advantages. In the first place, the erosion of the crucible by the metal, although more severe with clay, did not contaminate the melt with carbon, which was the case with a graphite pot; moreover, the carbon increment in this case was unpredictable, being more marked with a new crucible than with a partly used one. Secondly, the graphite pot was a better conductor of heat than the clay one; this certainly gave faster melting, but when withdrawn from the furnace the heat was conducted more quickly away from the metal, particularly when pouring in a thin stream over the crucible lip. Graphite crucibles were only used in Sheffield,

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1 Anon, 'Report on the River Don Steelworks', Engineering, 25th October 1867, pp.383-385.

2 But see Appendix JJJ for limited use of "imported" clay crucibles.

therefore, for steels which were higher in carbon (these, in general, also had lower melting points) such as the harder carbon tool steels and, later, the alloy tool steels such as 'Self Hard' and their twentieth century counterparts, the 'High Speed' steels.[1] It seems that graphite or 'plumbago' crucibles for steelmaking were first made available commercially between 1870 and 1880[2] although melts could well have been made experimentally in the ordinary plumbago crucibles designed for melting non-ferrous metals, which were certainly available prior to 1856. An advertisement from the Morgan Crucible Company in 1883 advertises the 'standard steel crucible' whilst a 'Special High Bulge Sheffield Pattern' was still being made about 1930. Various mixes were used for plumbago crucibles. A standard one in this country seems to have been equal volumes of Stourbridge clay, China clay and grog blended together and then admixed with up to 40% to 50% of its total volume of flake graphite. A German mixture is quoted as 36 measures of fireclay, 23 of coarse grog, 23 of powdered coke and 18 of graphite. Normally, such crucibles were press moulded, allowed to dry and then 'soft burned' at about 750°C. In such a condition they were stable and durable enough to withstand trans-

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1 The development of these alloy steels and the part played by the crucible process forms the subject of Chapter 10.

2 Private communication from D. W. Brown, Esq., of Morganite Modmor Ltd.

port. When required for use they would be 'annealed' in the usual way, prior to being charged hot to the melting furnace.[1]

It seems there was also a compromise between clay and plumbago since Morgans produced a clay lined plumbago crucible[2] from about 1915 onwards as being suitable for the melting of stainless steels and other low carbon materials.

There were, of course, two other pieces of clayware required for use in conjunction with the crucible. The first was a 'stand', a cylindrical block or cheese, slightly larger in diameter than the base of the crucible.[3] This was placed on the clean firebars, prior to putting in the hot crucible; with both in place, a handful of Belgian sand was thrown in and, under the action of the fierce heat, this fritted the two together and filled the hole in the crucible base left by the spike of the plug during moulding. The other piece was the crucible lid, slightly larger than the top of the crucible, with a flat base and a domed top, being about an inch thick at the edge and two inches thick at the centre.[4] Both

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1 Searle, loc.cit., pp.601-602, p.618.

2 This was their pattern D384 (private communication from D. W. Brown, Esq.). See also Appendix JJJ and p.641.

3 According to the Wellmeadow Charge Book, this weighed about 4 lb. as moulded.

4 This item weighed about 5 lb. as moulded.

these were moulded from cheaper clays,[1] usually trodden and shaped by the 'cellar lad', the most junior member of the team, as part of his training.

Before leaving the subject of crucibles, it should be pointed out that there was a limit to the growth in size which could be accommodated, in a process where a man had to lift the crucible from a hole below ground level. In the ultimate, as far as can be ascertained and with the single exception of the use of 100 lb. charges at River Don Works, this gave a molten metal weight of around 70 lb. This, together with a crucible weighing 25 lb. or so, and a sturdy pair of tongs of at least the same weight, implied the lifting of over a hundredweight; a mansize job, without the complication of the intense heat. The growth in size of crucible charge can be traced from a number of sources and provides the following information :

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1 The Wellmeadow Charge Book gives the following costs for 1895:

Derby clay	28/6d. per ton
White clay	40/0d. per ton
Stourbridge clay	30/6d. per ton
Stannington clay	22/6d. per ton
Stand clay	10/0d. per ton
Fireclay for lids	15/0d. per ton
Ground ganister (for furnace lining)	12/6d. per ton

1761[1]	Huntsman	13 lb.
1766[2]	Cutlers' Company	19½ lb.
1771[3]	Ersta, Stockholm	10 lb.
1771-74[4]	John Marshall	19-22 lb.
1777-86[4]	Love and Spear	21-25 lb.
1808[3]	Eskilstuna, Sweden	10-12 lb.
1815[5]	Birmingham	20 lb.
1818[6]	St. Étienne, France	33 lb.
1818[7]	Sheffield	28-30 lb.
1831[8]	Sheffield	30-40 lb.
1859[3]	Viksmanshyttan	33-36 lb.
1864[9]	Sheffield	50 lb.
1867[10]	River Don Works	60-100 lb.
1870[3]	Soderfors	50 lb.
1878[11]	Sheffield	70 lb.
1895-98[12]	Wellmeadow Works	45-56 lb.

1 Robsahm, loc.cit., Folio 69.

2 Cutlers' Company Archives, vol.48, Folio 77.

3 C. Sahlin, 'De Svenska Degelstalsverken', Med Hammare och Fackla, vol.IV (1932), p.44, p.66, p.81, p.127.

4 Matthias Spencer Notebook.

5 J. C. Fischer, Tagebucher (Zurich, 1951), p.109.

6 James Jackson et Ses Fils, (private publication, Paris, 1893), p.177.

7 Morning Star (Sheffield, 1818), p.7.

8 D. Lardner, The Cabinet Cyclopaedia, vol.1 (London, 1831), p.236.

9 J. Percy, Metallurgy, Iron and Steel (London, 1864), p.835.

10 'River Don Works', Engineering, 25th October 1867, pp.383-384.

11 J. S. Jeans, Steel, Its History .... (London, 1880), p.88.

12 Wellmeadow Steelworks Charge Book.

It should be remarked in this context that crucibles containing 100-160 lb. were used in Pittsburgh in 1913 - but with mechanical lifting devices.[1] These figures are all part of the story of the development of the process and certain important aspects still require elaboration. The main stream of growth in this country, and in Sheffield in particular, is clearly shown, but there are comments which need to be made. For instance, the use of the 100 lb. charges at the River Don works was something of a special case, connected with a special adaptation of the process for the production of large castings and ingots, and the major works were content with a 60 lb. or possibly a 70 lb. charge. The smaller Sheffield works, however - those in the old town rather than those in the newly developed East End - tended to use smaller charges, as evidenced by the Wellmeadow works, and there were still smaller scale operations even at this late date. In addition, the developments abroad tended to lag behind in scale, as will be made quite clear in a later chapter.

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1 J. H. Hall, 'The Manufacture of Crucible Steel', Iron Trades Review, 3rd April 1913, p.797.

III Coke

The question of fuel for the melting furnaces remained uncomplicated until after the middle of the nineteenth century - it was invariably coke as far as operations in this country were concerned. Indeed, the availability of coking coals could well be argued as one of the major factors in the location of the crucible steel trade. Indeed, as le Play stated in his preamble to the report on steelmaking in South Yorkshire :[1]

> 'The terrain is formed of one vast coalfield, one of the richest in England, from which the coal, obtained at a low cost from mines of shallow depth, is eminently suited to the many facets of the manufacture and working of steel'.

The coke, nevertheless, had to be suitably prepared. Experiments carried out to simulate the conditions in a crucible furnace, with a twelve inch bed of incandescent fuel, have shown that charcoal would give around 1425°C, which would be insufficient for steelmelting, whilst coke made from lumps of Barnsley hard coal would give 1530°C - barely sufficient. Beehive coke, however, gave a temperature of 1600°C and it is stated that the latter fuel was that used for the crucible process after about 1805.[2]

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1 Le Play, loc.cit., p.589.

2 Mott, loc.cit., p.231 and footnote. Mott also quotes a report from Hunter to the effect that in 1846 the cast steel furnaces in the 78 Sheffield works of that type consumed the coke prepared from some 188,486 tons of coal.

Furthermore, the coke required had to be hard and firm, capable of withstanding a fair amount of crushing and free from fines. The matter of coke was discussed at some length by le Play :[1]

> 'The coke used in most steel melting shops is heavy, very hard, composed of a perfectly vitrified matrix but riddled with cavities, most microscopic, of which the largest scarcely exceeds one twentyfifth of an inch in diameter. The pieces are, however, furrowed here and there by large fissures. The mean (relative) density varies on account of these fissures between 0.75 and 0.92. Submitted to incineration, the coke leaves a clayey residue which does not effervesce on treatment with acid and which is scarcely coloured with oxide of iron. The assay of a coke reputed to be of very good quality for steelmaking has given me the following figures :

Fixed carbon	83.7%
Volatile combustibles	3.9%
Moisture	1.5%
Clayey cinders, very refractory	10.9%

> Before being used the coke is broken by the coke basket filler* into pieces whose volume varies from about 4 cubic inches to 12 cubic inches. The dust and small debris produced during this breaking and that which remains on the shop floor are used either in the melting furnaces whilst lighting up or between two melts in the same campaign or in the stove where the preliminary heating up of the crucibles is carried out'.

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1 Le Play, loc.cit., pp.652-653.

* Usually referred to in Sheffield parlance as 'coaky'. The other members of the team were the potmaker, the cellar lad, the two pullers out, the teemer (who was the 'boss-man' or 'cod'), an odd job man and an ingot cleaner.

Some of the dust was, of course, also used in the crucible clay mix.

After about 1865, however, the coke fired furnace was not the only one used for crucible steelmaking and gas fired furnaces, on the Siemens regenerative pattern, began to be used in some works. Their use spread, but never completely displaced the old 'Huntsman type' furnace. This matter will, however, be discussed later among the other modifications to the process.

IV The Steelmaking Procedure

The operating procedure in the coke fired furnace, particularly in the smaller works in Sheffield, fully developed by about 1800, remained virtually unchanged until the crucible process was displaced in the years between the two wars. It is, therefore, eminently appropriate that a description of the process given by a practical steelmaker in the early years of this century should be given in extenso.[1] It can be taken as typical of Sheffield steelmaking at any time between 1820 and 1920.

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1 D. Flather, 'Crucible Steel; Its Manufacture and Treatment', Proc. Staffs. Iron and Steel Institute (1901-02), pp.58-60. This very good description of the traditional process is little known, being printed in an unexpected context.

'The night before starting the furnaces, a complete set of pots is taken from the drying shelves and placed in the annealing furnace and raised to a full red heat. The material for the charges must also be weighed out and placed in scoops or baskets for the first round. The material, of course, varies according to the requirements. Usually a certain proportion is used, containing perhaps 1½% carbon, together with sufficient bar iron to reduce the average of carbon to the required amount. To the quantity required for each pot must be weighed off a sufficient quantity of fluxing material.*

On starting work for the day** the furnaces are lighted, first with coal and then, after putting in the crucibles which are covered with their lids, the hole is filled with coke and the draught urged until a full white heat is obtained. The hole is then uncovered, the pot lids are moved to one side and a wrought iron funnel is lowered into the mouth of each pot in turn and the charge of blister steel, etc., carefully placed into the crucible. The lids are replaced, the furnaces filled up with coke and the covers replaced. From this point on, the operation depends entirely on the skill of the melter who must go round all the holes regularly and watch the process of melting, now urging, now holding back the heat, and so working the holes that the charges shall all be ready in turn for drawing and casting.*** The operation of melting may occupy from three to five hours and during this time much has to be done in preparing for the next round. As a rule, three rounds or heats are got out of each furnace each day. While the first round is being melted, the charges for the second round must be weighed up, also the ingot moulds have to be prepared to receive the melting charges. As the steel and the fluxes used in the process react, to a

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* It is significant that the nature of the flux is not revealed; this was part of the 'mystique'. It could well be that no flux was added!

** This would be at 6.0 a.m. at the latest. The first operation would be the cleaning of the fire bars and the putting down on these bars of the fireclay stands to support the crucible.

*** This would involve the refilling of the holes with coke, at least on two occasions during the round.

considerable extent, on the crucible, in such a manner as to weaken it at the point which is at the level of the molten steel, it is necessary for this level to be lowered at each successive heating. Thus, if 60 lb. of steel be melted in the first round, about 54 lb. only is taken at the second round and 48 lb. at the third and after working three rounds the pots are destroyed as being unfit for further use.* The steel is not ready for casting until it has been in the molten state for some considerable time or until, as the expression used by the melters says, 'it is killed'. Steel which has not been killed teems 'fiery', that is to say it gives off a profusion of little sparks and appears to boil in the pot, while the ingot, when cold, will be full of honeycombs. If the steel be too hot it will show the same fault, while if it be kept in the fire too long it will be very rotten and brittle. Should a piece of coke fall into the crucible it will result in the steel being spoilt by the sulphur present in the coke.

When the melter judges the steel to be ready for casting, or 'teeming' as we say, each pot in turn is seized by a pair of tongs and pulled up to floor level and lifted alongside the trough in which the ingot moulds are placed. The lid is removed and the crucible gripped about the middle by another pair of tongs. On the surface floats the flux and this is rapidly skimmed off. The crucible is then lifted, by hand of course, and its contents carefully poured into the ingot mould. This, as you will understand, is a very delicate and difficult operation and only the most reliable men can be employed for this purpose. As each crucible is emptied of its contents, the lid is replaced and the crucible returned quickly to the furnace and covered with coke until once more it reaches the proper heat to receive the next charge'.

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* There is also evidence that a similar procedure applied even with plumbago crucibles in American practice, it being quoted that successive charges may well be 85 lb., 80 lb., 78 lb., 75 lb., 72 lb., etc. (H. M. Howe, Metallurgy of Steel (New York, 1891), p.298). It should also be noted that, in addition to the attack on the crucible, the actual physical size changed due to shrinkage on heating, so that the capacity was reduced for subsequent melts.

The pulling and teeming process was such a skilled job and gave such an aura of prestige to those marvellous men whose everyday task it was that it is difficult to refrain from enlarging on it, again quoting one who was familiar with the operations :[1]

> 'It goes without saying that a man who can lift a pot containing sixty pounds of molten steel with a pair of heavy tongs from a furnace below ground level at a dazzling white heat is no weakling. I say 'lift', but the pot is not lifted; to call the men 'lifters' instead of 'pullers out' would be insulting. The actual pulling out is like Macbeth's job; 'when 'tis done, then 'twere well it were done quickly'. Once in Sweden I saw a pot, a large pot, of molten steel lifted from a below-ground furnace with an arrangement of chains and pulleys - an outrage of the sentiments. It is an advantage to the puller out to be tall and strong but neither quality in excelsis is essential; a smaller man may learn the knack of it, though he can hardly hope to appear so graceful as his larger brother who has the knack. At steel melting heat the pot is not 'as hard as a brick'; if it were, it would crush or crack in the grip of the double claw-like tongs used by the puller out. The pot is soft and in a degree yielding; it could be hit with a hammer and deformed without cracking. It needs to have these properties to serve its purpose. The feeling of 'give' gives him confidence to straighten his back and with an unbroken pull and swing to set the pot on the floorplates. His ends of the tongs are held together by his hands only; he might use a ring to hold them together but by doing so his sense of feeling would disappear and the contact between him and the pot would be less intimate'.

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1 Brearley, loc.cit., pp.67-68. This fascinating book has been out of print for so long that I make no apology for making extensive quotations from it. The author had spent the best years of his life in close proximity to the processes and the people he described.

He goes on to say that the job was obviously a dangerous one, particularly when dealing with leaky pots; much was risked to save the molten steel and many a puller out got a 'sup of steel' inside his clog! When he talks of teemers he comments :[1]

> 'The teemer is the autocrat of the furnace gang and the best paid man of the lot, but he does not make the mistake of supposing that when it comes to making good steel he is the only man that matters .... As he has been a puller out in his time, the teemer is generally big and strong, but as he is no longer young, he may be rather fat and generally has a ruddy face. The colour of his face may be due to a combination of good health, the scorching heat of fire and the stimulation of alcoholic drink ....
>
> As soon as the puller out has swung the pot of molten steel up to the ingot mould, one of the odd men, or the cellar lad if he is lucky, inserts a slim rod with a blob of metal on it the size of an orange, and mops off the floating layer of slag; he should pick up the slag without allowing any part of his mop to touch the liquid steel. During this interlude, the teemer has been holding the pot with his bowed tongs, which grip it generally about midway, but specifically where he is likely to be most satisfied when the loaded tongs are balanced on his knee. Having mopped off the slag, the molten steel is visible. What there is to see distinguishing one pot of steel from another the novice cannot tell. But the teemer can. If ever so few sparks should rise from the surface, the old melter would grunt and mutter some doubt about the steel being killed; his successor is less worried; he just drops a 'pill' into the pot - an aluminium pill - and is confident that the ingot will be a sound one.* The teemer grumbles if he considers the molten steel to be on the cold side, as that limits his

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1 Brearley, loc.cit., pp.69-78.

* The background to such treatment will be explained later in this chapter.

choice of moment and manner of teeming; to hurry molten steel into the ingot mould for fear it will not get there at all is considered a disgrace. He minds less if the steel in the pot is too hot to cast, as he can wait, and with his eye on the surface of the molten metal he waits for the right moment. Watch him teem; and if the physical grace of the bulky man and the play of colour around the pot do not enchant you, try and realise what it is he is trying to do. From the bowed ends of the tongs which grip the pot, long shanks pass over the knee of the crouching teemer and extend as far as his left arm can comfortably reach. With the leverage of the long shanks operated by one hand and a steadying lift exerted by the other, the pot is balanced on the teemer's knee at the moment his good judgement decides is the right moment for casting. The metal flows over the lip of the pot, which has been curved inwards to an appropriate angle, passes down the mould and, from first to last, at whatever speed it may be delivered, does not make contact with the side of the mould. No lady, handling a delicate china cup, ever sipped tea with a greater niceness than the knowing melter delivers the glistening stream of molten steel into the soot-lined mould* ....

When arranged for casting, the moulds rest, in turn, in a square box let into the floor and partly filled with sand. The sand is used to adjust the height the top of the mould stands above floor level. But the mould does not stand vertically; it slopes towards the falling stream of metal at an angle decided in the teemer's mind by his acquaintance with the extent to which the top of the pot is turned in and the way the steel will fall over its lip. Unless these trifles are considered, no amount of skill could deliver the

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* The moulds were made in two halves, split longitudinally, with dovetailed edges. To prepare them, the halves were laid, inside faces downwards, across two rails supported a foot or so from the floor. A pan with burning tar would then be placed below them and moved from time to time so as to ensure a uniform coating of soot on the parts which were later to receive the molten steel. This served as some protection to the cast iron but also contributed to the smooth flow of the metal as it rose in the mould, giving an improvement to the surface of the ingot. I can well remember an old melter who boasted that his ingots had skins like Morocco leather. The process of soot-coating the moulds was known as 'reeking'.

> steel into a mould without catching the sides; and a 'catched' ingot is, of all faults, the most obvious sign of negligence or incompetence. As the split moulds are held together by top and bottom rings and wedges, and the rings are of a uniform size, it is a simple matter to fix the bottom ring higher or lower and, by bringing this bottom ring hard up against the wall of the teeming box, to adjust the slope of the mould to the teemer's liking ....
>
> By the time the teemer has got rid of his rags* the moulds will have been laid across a horizontal rack and the ingots will be at least partly visible. The old teemer, still mopping his face with a 'sweat rag',** will eye them over and have this one or that one chalked, in the spirit of an enthusiastic gardener eyeing his blooms ....
>
> In taking my leave of the teemer, I doff my cap to him for the noiseless and apparently effortless contribution he has made to the Art of steelmaking'.

As has already been said, the pots by then had been returned to the furnace, heated up and again 'steeled' or charged up, the space around the crucible filled up again with coke and the next round set on its way.

> 'By this time, the puller out, more than any man in the gang, is soaked with sweat from top to toe. By all accounts, this is the time when a couple of pints of beer will fill most tastily a long felt want and, when the men had the freedom of the works gates, one could tell by the goings and comings, but particularly by the goings, how the operations stood'.

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* 'Rags' referred to the multiple layers of sacking tied round the legs and thighs of the teemer and the puller out; these were well saturated with water (or 'doused') before either of them submitted themselves to the heat of the crucible.

** The 'sweat rag' was a piece of towelling, normally worn round the neck. Whilst pulling out or teeming, the ends would be held in the teeth to prevent the inhalation of any noxious fumes. Sweat rags, incidentally, are still universally used in the Sheffield melting shops.

With this final quotation[1] a fair impression of the operation of Huntsman's process, using the type of furnace he designed but on a somewhat larger scale, has been obtained.

V The Size of Ingot

In the early days of the process and, indeed, for the general case right through to the twentieth century, one crucible charge provided one ingot, so that ingot weights gradually increased from Huntsman's early 13 lb. one to almost 70 lb. by about 1870. It seems that Huntsman used a 2 inch octagonal mould.[2] Octagonal, square and rectangular moulds are illustrated early in the eighteenth century,[3] but, in general, for ordinary purposes, a square ingot seems to have been the most favoured, sizes of 2½", 3" or 3½" being most usual, according to the weight available, the ingots being from about 18" to 30" long.[4] There is, however, evidence of 'doubling up', that is pouring the contents of one crucible into another

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1 Brearley, loc.cit., p.62.

2 T. Althin, 'Eric Geisler och hans Utlandska Resa, 1772-1773', Med Hammare och Fackla, vol.XXVI (1971), pp.32-33.

3 Broling, loc.cit., Plate VI (reproduced in Appendix II).

4 After crucible steel melting had been superseded by the high frequency process, I well remember the use of 3½" square ingots for special alloy steels, whilst most of the high speed steel was made in 4" ingots in Sheffield at least up to 1960 and still is in some of the smaller works.

before teeming, particularly when ingots of rectangular section, such as 7" x 3", were required to produce sheet for saws or even for pen nibs.[1] The doubling up not only provided the extra weight required but also mixed the contents of the two pots, giving a uniform composition of the metal throughout. Records also exist of from three to five melts being poured together to produce ingots of up to 200 lb. in weight in tool steels.[2]

Within the larger works, however, much more complicated operations were carried out. As it so happened, the earliest example of multiple pouring on a large scale in this country refers to the production of a casting rather than an ingot. This was at the Millsands works of Naylor, Vickers and Company in 1860.[3] The casting involved was a steel bell, destined for the Fire Station in San Francisco; its finished weight was 5824 lb. and required the contents of 105 crucibles for its production. Such multiple pouring operations had been carried out previously, since ingots of weights from 1000 lb. to 6000 lb. were shown at the various exhibitions from 1849 to 1853. Krupp's works in Essen was amongst the leaders

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1 Evidence for this comes in the form of a photograph kindly provided by Vessey and Company, dating from about 1950.

2 Wellmeadow Works Charge Book.

3 Illustrated London News, 7th January 1860, p.12. The casting was perfectly sound, stood 5'3" high and had a diameter of 6'2" at the mouth.

of this type of production[1] but the Sheffield firms also cast large ingots fairly frequently. Naylor, Vickers and Company, after their removal from Millsands to the River Don Works, could cast a 25 ton ingot, using 576 crucibles, in 1866.[2] Thomas Firth and Sons cast an ingot of 20 tons, requiring the contents of 628 crucibles in 1874[3] and there is a drawing, reproduced as Figure 27, depicting a similar operation at the same works a year later, witnessed on this occasion by the Prince of Wales.[4]

It is clear from the illustrations that the Sheffield method was to use a refractory lined tundish set in the floor, with its central nozzle located over the mouth of the ingot mould set in a pit below. It should be made clear that, once the metal has begun to flow through this nozzle, a constant stream must be kept flowing until the casting operation is finished; otherwise, any interruption in the casting would cause a 'cold shut' or wrinkling of the ingot surface which would cause blemishes or even tearing of the surface of the article forged from the ingot. There was, therefore, little margin for error in

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1 A quite detailed account can be found in the section dealing with German steelmaking. (See pp.579-586).

2 'River Don Steelworks', Engineering, 25th October 1867, pp. 383-384. According to Sheffield and Its Neighbourhood (Sheffield, 1889), p.132, such an ingot was forged to produce a marine shaft for the steamer 'Wisconsin' in 1866.

3 Sheffield and Rotherham Independent, 28th April 1874. The account is reproduced in extenso in Appendix OO.

4 Illustrated London News, 28th August 1875, p.193.

the provision of a constant succession of men with their pots full of steel, at the right temperature, in the central casting area.

In the period up to about 1865, there was no alternative to crucible steel for the production of large masses of steel, using a technique which to us, over a century later, seems incredible in its concentration of labour and the precision of timing required. For the next fifteen years there were other sources of metal in bulk but they were mistrusted on the grounds of quality. The Bessemer process, indeed, was never seriously considered for the production of forgings, but by the early 1880s the Acid Open Hearth process was found to be acceptable as providing the required standard of quality, and large crucible steel ingots were no longer produced in Sheffield. Not so in the Krupp Works in Germany, however, where, as will be shown later, the casting of large ingots from regimented armies of crucible melters continued, at least to the end of the century if not beyond.

VI The Chemistry of the Process

The underlying chemistry of the crucible process seems to have received little attention and the only evidence of any systematic work comes from Central Europe. An abstract of a doctoral thesis submitted to the University of Berlin reports works trials with three types of crucible, the charge consisting of a mixture of puddled iron with some 5-8% spiegeleisen.[1] The results are tabulated in Table III. Further evidence from the use of clay crucibles with an admixture of 15% graphite at Duisburg may also be quoted as set out in Table IV.[2] Some information on Sheffield crucible practice around the beginning of this century indicates a loss of carbon of around 0.10%, a silicon increment of about 0.05%, a manganese loss of 0.15% to 0.25% depending on the original level, a sulphur increment of 0.010% to 0.015% and no change in the phosphorus level, all this being relevant to melting in clay crucibles.[3] As would be expected, Brearley has some appropriate comment :[4]

> '.... there was an extra fire given to the molten steel, known as a 'killing fire' ... if it was omitted when melting blister bar or bar iron, the ingots would probably contain blow holes .... there was an air of mystery about the killing fire .... the furnace was urged to its utmost heat consistent with the stability of the pots themselves .... the pot itself had something

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1 A. Brand, 'Einige Beitrage zur Kenntnis der Vorgange bei Stahlschmelzprozessen in Tiegeln', Berg und Hutten Zeitung, vol.xliv (1885), pp.105-107, pp.117-121.

2 F. C. G. Muller, 'Untersuchingen uber den Tiegelstahlprozess', Stahl und Eisen, vol.6, No.11 (November 1886), pp.695-704.

3 Private communication from the late W. H. Green, Esq., crucible steelmaker, 1905-1928, later manager of the High Frequency Melting Shop, Firth Brown Ltd.

4 Brearley, loc.cit., pp.64-66.

> to do with the killing operation; it was easier to kill steel in some pots than in others. It was believed that China clay did not help but coke dust and Derby clay helped a great deal; and when one tries to sort out these notions in terms of analytical chemistry, it turns out that the pot most favourable to the killing of the steel is also the pot from whose sides silicon can readily be reduced into the molten steel. This may not be the complete story but it is an intelligible part of it and explains why some people doubted the genuineness of crucible steel unless it contained a certain amount of silicon; and it explains why Continental steels, made in graphite pots, contained more silicon than similar steels made in clay pots in Sheffield'.

A German explanation from the end of the nineteenth century is largely confirmatory.[1] It referred (as we should now consider erroneously, since it is clear to modern steelmakers that the gas involved was carbon monoxide) to :

> '.... the tendency of the steel to take up hydrogen and nitrogen which, whilst solidifying, it subsequently evolves in the form of bubbles. This will make it useless for tools and most other purposes. Only after many failures and much experience were the rules established which must be followed in order to make sure that the castings from crucibles will be homogeneous and free from blow holes. At the same time it was learned that crucibles of different compositions which had been differently treated would act on the steel differently and that Sheffield methods were not always applicable in Continental steelworks. Only recently has scientific research thrown some light on these dark problems. It has been found that by the natural action of the wall of the crucible on molten steel that part of the silicon is reduced so that all cast

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1 F. G. Muller, Krupp's Steel Works (London, 1898), pp.38-39.

> steel contains about one quarter per cent of silicon. On the other hand, it has been proved that a small amount of silicon prevents release of the occluded gases. This binding of the gases does not, of course, occur if the steel is cast as soon as melted but in order to take up the silicon it must remain one or two hours longer in the furnace at a high degree of heat. In this way the beneficial effect of what the English call 'killing' finds its scientific explanation'.

Consideration of the available evidence indicates that conditions within the crucible changed during the course of the melt. The initial period was 'oxidising', whilst the final stages were 'reducing'. The original Huntsman process was, quite simply, the remelting of blister steel and this technique, with slight modifications, has already been shown to have continued for at least a century and a half.[1] Blister steel, having been produced from what was nothing more or less than wrought iron, albeit one with high purity and desirably low contents of both sulphur and phosphorus, still contained the entrained slag from the refining process to which the Swedish pig iron had been subjected. The iron

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1 It should be remembered that, for the first fifty years of this period, the role of carbon was not understood and that blister steel was the only form of steel commonly known in the Sheffield area. It was, therefore, the obvious and only raw material for use as the charge in such a process, apart from the small amounts of scrap steel which were available from time to time and which were increasingly used as partial supplements to blister steel for this purpose. The continued use of blister steel in the last half of the nineteenth century, however, can only be looked upon as sheer conservatism; the Sheffield steelmaker would have argued that it was a matter of fitness for purpose, established by custom and practice.

used could also be badly scaled, or it might well be rusty from its sea voyage. The slag, together with the rust or the scale or both, would introduce oxygen into the crucible; in addition, additions of oxide of manganese, along with the charge, were fairly commonplace. In the initial stages of the melt these oxidised materials would react with the crucible wall to form at least a glaze, if not an actual separation of liquid slag, floating on top of the melt. In the Sheffield process, using a clay crucible or 'white pot', it was to be expected that this slag would eventually begin to react with the carbon, silicon and manganese present in the steel, and thus lower the levels present to a greater or lesser degree. In the presence of the large amount of aluminosilicate from the clay, these reactions would be complex but can probably be best illustrated by considering them as being motivated by the presence of free oxide of iron at this stage. This would lead to oxidation of carbon, the reaction product escaping in gaseous form, and also of silicon and manganese, whose oxides would go to make up the slag. All this would be accompanied by an overall reduction of the amount of iron oxide present and, therefore, a move to somewhat less oxidising conditions.[1] If, however, the metal were to

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1 The sequence of reactions may be expressed as follows :

$$C + FeO = Fe + CO \text{ (gas)}$$
$$Mn + FeO = Fe + MnO$$
$$Si + 2FeO = 2Fe + SiO_2$$

followed by

$$2MnO + SiO_2 = Mn_2SiO_4 \text{ (slag)}$$

In addition, some iron oxide would attack the silica in the crucible :

$$2FeO + SiO_2 = Fe_2SiO_4 \text{ (slag)}$$

be poured into an ingot mould at this stage, there would still be sufficient free iron oxide present for the production of gaseous carbon monoxide on solidification. The ingots would then be honeycombed with 'blowholes' caused by this gas escaping from the metal. That this did happen in practice is convincingly demonstrated by the discovery some years ago of several such pieces of ingot material buried on the site of the old Huntsman Attercliffe Works.[1] The analysis of one of these specimens is given as :

Carbon	1.12%
Silicon	0.04%
Manganese	0.03%
Sulphur	0.011%
Phosphorus	0.014%

This analysis, very significantly, shows an extremely low silicon content; it had not been 'killed by fire'. Note, however, the low sulphur and phosphorus contents which indicate the use of a high grade iron, probably of Swedish origin. In modern parlance, such a metal was in need of 'deoxidation'; this is really a misnomer, the actual removal of oxygen being incidental. if occurring at all. What was really needed was the

1 '200 Years of Steelmaking', British Steelmaker, March 1942. This article was issued also as a reprint and a photograph of the honeycombed ingot together with this analysis appears on p.4 of that reprint.

fixing of the oxygen present in such a form that it would not react with the carbon during the solidification. 'Killing with fire' essentially did this since, if the conditions became sufficiently reducing, by removal of iron oxide and other easily reactable oxides with carbon, an increase in temperature would then cause reaction of carbon with silica, to bring about a return of silicon to the metal.[1] With sufficient silicon in the metal, any iron oxide which tended to form, after withdrawal of the crucible and during the solidification period in the ingot mould, would react with the silicon present, rather than with the carbon. The product of this reaction was silica, which was solid and which could not give rise to blowholes. Reaction of this silica with carbon, although it occurred at the higher temperature of the killing fire, was less likely at the lower temperature and in any case the reaction rate was slow - the killing fire took at least an hour whilst the ingot, once cast, would be solid in a few minutes. Hence an ingot free from blowholes was produced.

The rules for 'killing' or 'deoxidation' changed

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1 The reaction involved is

$$2C + SiO_2 = Si + 2CO \text{ (gas)}$$

The rate of reaction is low, requiring a considerable time for it to make its effect; it occurs more readily at high temperatures.

over the years. The principle remained the same. Since silicon produced the desired effect, it was obvious that the addition of silicon metal or, more conveniently, of ferrosilicon (one of the so-called 'ferroalloys' produced as aids to the steelmaker and consisting in this case of an alloy of 45% or so of silicon, the remainder being essentially metallic iron) to the crucible, near the end of the melt, would obviate the need for the long 'killing fire' - when, of course, the role of silicon was understood. Aluminium, however, was found to be even more effective than silicon and as little as one quarter to half an ounce of aluminium - often in the form of an 'aluminium pill' - would quieten most pots of crucible steel. The addition of aluminium to crucible steel was generally frowned on in the trade in Sheffield but, as Brearley stated :[1]

> 'Whether the steel is killed by an extra fire at superheat, as it used to be, or whether it gets its quietus from a pill is supposed to be all the same. I am not sure; the newer method is much cheaper than the older and that kind of pill has been known to affect steel manufacturers' decisions'.

Such treatment, however, was the foundation of the Mitis process[2] for making steel castings, using a ferroaluminium

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1 Brearley, <u>loc.cit.</u>, p.72.

2 See pp.532-533 for details of this process. See also British Patent No. 8269, 1885, taken out by T. Nordenfelt as agent for the inventor of the process, C. C. Wittenstrom.

containing 8% aluminium and adding from 0.05% to 0.10% aluminium to the metal as soon as it was clear melted and hot enough for casting.

The role played by manganese in crucible melting was a complex one. In a clay crucible, any manganese present in the metallic form in the charge was subject to a marked degree of oxidation during the melting period; subsequently, it remained largely unaffected. Indeed, the conditions which favour a return of silicon to the metal could well reintroduce some manganese at the same time. Any manganese oxide added, however, was merely an oxidising agent and would produce slag, tend to aggravate the erosion of the crucible and oxidise some further carbon.

In crucibles containing carbon, however, the situation was rather different. Erosion of the crucible caused the release of some carbon, which speeded up the absorption of the oxygen present. Eventually, any excess carbon would be absorbed by the metal, the amount of the carbon increment being dependent on the amount of carbon in the crucible mix, the degree of erosion and the time of exposure in the crucible. Moreover, there was a much more rapid rise in the silicon content; so much so that a killing fire was not generally applied or needed. The situation with regard to manganese, however, was unexpected under these conditions, in that there appears to have been a continual loss during the process, which can only be explained by attack on the crucible, the manganese releasing silicon to the metal.[1]

VII Physics and Nostrums

The deliberate addition of manganese to steel is generally associated with the name of Josiah Heath. He took out a patent in 1839 in which he proposed adding a 'carburet of manganese', prepared by the reduction of a mixture of oxide of manganese and carbonaceous matter at a high temperature and then adding some of this

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1 It is likely that a reaction of the type

$$2Mn + 2SiO_2 = Mn_2SiO_4 + Si$$

was responsible, although it is not clear why this should occur in the presence of excess carbon. It is known, however, that a slag rich in manganese oxide is less active an oxidising medium than the corresponding iron silicate. The slag in the last of the trials listed in Table IV, using crucibles containing 15% of graphite, was analysed and the results, with their low iron oxide content (2.30%) and high manganese oxide content (18.45%), the balance being 35.85% alumina and 41.24% silica, indicate the above reasoning to be plausible. A very similar analysis for the slag found on teeming a melt from a graphite crucible (44.4% SiO_2, 1.08% FeO, 24.04% MnO and 28.8% Al_2O_3) is given by A. Ledebur, Handbuch der Eisenhuttenkunde (Berlin, 1884) p.856. An interesting commentary on what has just been discussed with regard to the chemistry of the process will be found later, when steelmaking in Austria is discussed. (See pp.595-596 and Appendix GGG).

preparation, which undoubtedly would contain metallic manganese, to the charge in the crucible.[1] It was elsewhere generally claimed that this allowed cheaper native iron to be used for the steelmaking process instead of the higher priced Swedish irons.[2] It is as well to examine this matter fairly closely. The effect of manganese metal could be twofold; it could help to sweep out the slaggy matter entrained in the iron and it could also help to neutralise the detrimental effect of higher than normal sulphur contents in the iron, thereby making the material more readily forgeable from the ingot. The cheaper native irons, however, were also relatively high in phosphorus content and in no way would manganese help in combating the brittleness induced by this unwanted impurity. It would, however, be quite effective in producing a reasonable steel from the cheaper grades of Swedish iron, some of which sold at a price little more than half of that of the top Dannemora grades.

According to the usual story, Heath later patented the moulding of the oxide with tar and the baking of this mixture into cakes, thus obviating the costly high temperature treatment, but no trace of such a patent can be found.

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1 British Patent No. 8021, J. M. Heath, 5th October 1839.

2 Percy, loc.cit., pp.840-841.

In any case, such a mixture would not contain the essential metallic manganese and would be ineffective in either of the mechanisms quoted above. On the contrary, it is likely that it would disintegrate in the crucible, possibly raising the carbon content of the metal a little but, more importantly, the free manganese oxide would erode the crucible quite badly, particularly since the mixture was added towards the end of the melt when the temperature was high. Henry Unwin, who had been Heath's agent, began supplying the oxide-tar mixture to the Sheffield steelmakers and seems to have made a fortune out of it, whereas Heath, who challenged Unwin in the courts, died in poverty whilst the litigation was still in progress. Brearley's comments are again worthy of quotation :[1]

> 'In the train of the Heath persecution came superstition and avoidable loss, which lived on the back of the tool trade for half a century. Heath's real discovery was ignored in favour of the use of black oxide of manganese; and the trade deluded itself into believing that the black oxide of manganese, known as 'physic', was potent for good whereas it was not even the shadow of the substance of Heath's discovery. Up to 1900, hardly anyone dared to make crucible steel without adding an ounce or two of black oxide of manganese to the pot; and its main effect was this - along the wash line where the slag floated on the molten steel, the black oxide of manganese was drastically corrosive and frequently ate holes through the pot's side and wasted molten steel through the grate bars into the cellars. A heap of 'runnings', representing thousands of tons of wasted steel, would be a fit memorial to the greed of the steel manufacturers who disputed Heath's claim and for his knowledge substituted their ignorance'.

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1 Brearley, loc.cit., pp.21-22.

There is much truth in this but also some exaggeration, since the use of metallic manganese, in the form of 'spiegeleisen',[1] as a standard addition to crucible charges, seems to have had widespread currency from about 1870 onwards.[2] The addition of manganese in metallic form to steel was fostered by Mushet, who made what he referred to as a 'triple compound of iron, carbon and manganese'[3] which would appear to have been similar to spiegeleisen.

Whilst discussing manganese and the evidence from patents,

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1 'Spiegeleisen' was the manganese-rich cast iron produced in Central Europe from the spathic iron ores; the metal contained about 10% manganese in the average case.

2 There is a document in the Doncaster Archives which advertises made up crucible charges which were available from the firm in 1880 and each 50 lb. lot contained 1 lb. of spiegeleisen. There is a statement to the effect that this is included 'for the purpose of neutralising the sulphur, every part of which requires 7 parts of manganese to neutralise it'. This refers to the fact that, in the absence of manganese, the metal contains iron sulphide which tends to form films on the crystal boundaries and leads to rupture on forging. In the presence of sufficient manganese, the iron sulphide is replaced by manganese sulphide, which tends to form in globules which are relatively harmless. (See Figure 34).

3 British Patent No. 3125, R. F. Mushet, 19th December 1857. Mushet continued to patent this type of treatment in various applications and also in conjunction with other elements such as titanium, chromium and tungsten. His mixtures were, in fact, early forms of what later became known as ferroalloys.

there is one example which illustrates the sort of wrong thinking which was generated about the time of the Heath-Unwin affair and at the same time acts as a warning that the patent literature should be used with considerable care. A mixture ;

> 'an oxide of manganese, forty two pounds, of plumbago, eight pounds, of wood charcoal, fourteen pounds, and of salt petre, two pounds'

added in the proportion of two to three pounds to every thirty pounds of steel, would seem to have been very likely to provide quite a spectacular firework display.[1]

Brearley, it will be remembered, referred to the black oxide of manganese as a 'physic'. It might also have been referred to as a 'nostrum'. These terms were used for any non-metallic addition to the crucible melt, with the obvious intention of curing some ailment in the metal. There was always some scepticism as to whether these additions had any real effect and among these sceptics was certainly H. M. Howe, who wrote :[2]

> '.... a little ferromanganese or spiegeleisen is usually added to prevent blowholes and promote forgeableness; about a struck tea-spoonful of oxide of manganese to form a thin slag (it also increases the absorption of silicon and carbon); and often physics, not

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1 British Patent No. 10204, C. Low, 25th November 1844.

2 H. M. Howe, <u>Metallurgy of Steel</u> (New York, 1892), p.308.

> to say nostrums, such as salt (to thin the slag), ferrocyanide of potassium (it should promote carburisation), sal ammoniac and so on. Without direct experimental evidence we cannot tell whether these physics have any valuable action or whether, as one strongly suspects, they are mere ginger-bread pills. The crucible steel maker is very secretive about his mixtures; it is doubtful whether we would be much wiser than now if he told us frankly all he certainly knew about them'.

It seems, however, that others were more serious, taking out patents to cover additions for which plausible reasons were given. Brooman[1] used 2 pounds of sal ammoniac and 1 pound of prussiate of potash to every 100 pounds of bar iron, it being implied that the nitrogen improved the hardness of the steel.[2] Pauvert seems to have represented French ideas:[3] he used a very complicated mixture :

4 parts by weight of dry carbonate of soda
4 parts dry carbonate of potash
3 parts wood ashes
2 parts borax
3 parts oxide of manganese
4 parts of charcoal or soot or lampblack

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1 British Patent No. 359, R. A. Brooman, 22nd July 1856.

2 The prussiate of potash may have been potassium cyanide but is more likely to have been potassium ferrocyanide. A later patent of French origin, taken out by C. Cowper (British Patent No. 2165, 7th September 1860) clearly states the use of yellow or red prussiate of potash, which are potassium ferrocyanide and potassium ferricyanide respectively. This was the period when nitrogen as an addition to steel was in fashion and some opinions were expressed that it was more important than carbon; it was a passing craze.

3 British Patent No. 610, C. Pauvert, 1st September 1857.

at the rate of 5-6% of the weight of the iron charged. He went on to explain the various reactions supposed to occur, which only adds to the general confusion; it becomes clear, however, that the main aim was the cleansing out of the slaggy impurities and the more effective absorption of carbon. Thomas[1] used a mixture of chloride of sodium, prussiate of potash and bichromate of potash, this improving the hardness of the steel. The use of perchloride of iron with 'muriate' of soda or potash, together with sufficient charcoal, is claimed to enhance the absorption of charcoal by wrought iron in the crucible.[2] One further example, however, would seem to have had more substance, since it covered the separation of 'silex' and other siliceous matters from the steel, by using some form of 'fluoric acid', ground fluorspar or 'fluate of lime' being preferred, on account of the fluxing action of the lime.[3] This principle is in use to this day in all the basic steelmaking processes.

The list of these 'nostrums' cannot be closed, however, without reference to what must really be the

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1 British Patent No. 2039, G. C. Thomas, 3rd September 1856.

2 British Patent No. 2390, J. and D. F. Bower, 3rd October 1860. 'Perchloride of iron' was ferric chloride; it seems odd that reference in the same sentence should be made to 'muriates', since these were also chlorides.

3 British Patent No. 685, J. J. O. Taylor, 19th March 1861.

prize one amongst them.[1] This covered the melting of scrap and malleable iron in crucibles :

> '.... with borax, carbonate of cadmium, the nut of the horse chestnut ground to meal, the tartar argols of commerce and charcoal of wood. .... Should a hard steel be required, for each hundredweight of metal the juice of four white onions is also added'.

VIII Modifications to the Crucible Charge

So far it has been assumed that the charge to the crucible was mainly blister steel; the developed process by about 1800 used small amounts of available scrap but in the main the charge came from the cementation furnace. This was, of course, the period when the true role of carbon in steel was elucidated and it was not long before the logical thought of producing steel by melting bar iron

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1 British Patent No. 2870, F. Prange, 7th November 1865. This puts me in mind of the occasion when I witnessed the shop manager carefully surveying the contents of a crucible that was ready for teeming, pulling out a small brown paper packet from his pocket, throwing it in and prodding the surface of the metal with an iron rod; he then gave instructions for the contents to be teemed. I asked him later what was in the packet. 'Well, lad, the last ingot was porous. What do you usually take for flatulence?'. 'Bicarbonate?', I queried. 'Good guess, lad', he said as he walked away. I never knew whether he was pulling my leg or not, but that ingot was certainly sound. (I suspect that it was another of those aluminium pills, in actual fact).

in a crucible with charcoal was proposed; the idea was, indeed, patented by David Mushet :[1]

> '.... cast steel may be made by taking any convenient quality of malleable iron, according to the size of the furnace and crucible or crucibles to be employed and introducing it into the crucible or crucibles along with a proper proportion of charcoal, charcoal dust, pit coal, pit coal dust, black lead or plumbago or of any substance containing the coally or carbonaceous principle .... For this process not only bar iron may be employed but also what is commonly called scraps or waste iron ....'

It must surely have been an error to use pit coal or pit coal dust.[2] Otherwise, in theory at any rate, such a process should have been workable. There is evidence that Mushet supplied steel from the Calder Ironworks in 1802, presumably made by this process, to Peter Stubs, who seems to have found it soft and returned it.[3] The problem with such a method was that it would require a temperature of between 50° and 100°C in excess of that usually sufficient to melt the blister steel charge; the bar iron would not melt below about 1500°C. Although there was probably carbon in actual contact with the iron, as has been demonstrated in an earlier chapter the very slow rate of diffusion of such

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1 British Patent No. 2447, D. Mushet, 13th November 1800.

2 The sulphur so introduced would have been highly detrimental; in the standard crucible melting practice, should a piece of coke accidentally enter the crucible, the melt was considered as ruined and discarded. It was said that it would 'stare' during teeming and would not forge or roll satisfactorily and that it would be 'rotten'.

3 T. S. Ashton, <u>An Eighteenth Century Industrialist</u> (Manchester, 1939), p.50.

carbon into the iron would mean that such a mechanism would have no opportunity of lowering the melting point in the three or four hours in which the crucible was in the furnace. That such a procedure was not, as far as can be ascertained, put into general use until after the advent of the gas fired furnace rather confirms the difficulties of maintaining the necessary temperatures in the normal coke fired furnace without excessive damage to the structure.

The next proposed alteration to the charge was a more practical one, again aimed at obviating the need for carburising the iron in the long and tedious cementation process. This was originated by a Sheffield steelmaker, part of whose 'Improvements in the Manufacture of Cast Steel' reads as follows :[1]

> 'In order to make cast steel on the improved plan, the ordinary furnaces and crucibles, heats and moulds may be used but instead of melting in these crucibles broken pieces of the bar steel commonly called blister steel, as heretofore, I melt the following ingredients together in the following proportions. Of ordinary wrought iron borings or turnings or scraps: 100 lb; of black oxide of manganese: 2 lb. 3 oz; of cast iron turnings or borings or other such very small particles of cast iron: 28 lb. .... It is evident the foregoing proportions may be susceptible of some slight variation .... If turnings are used, they should be pounded into small pieces before they are put into the crucible'.

This, in contrast with Mushet's earlier patent, covers a real improvement since the cast iron, as well as providing the

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1 British Patent No. 8206, Wm. Vickers, 26th August 1839.

carbon necessary for the melt of steel, begins to melt at a much lower temperature (around 1150-1200°C) and, as the temperature gradually rises, the wrought iron would be absorbed, giving a fluid melt at the minimum temperature.[1] Here again, however, there were problems which retarded the proper development of such a process - in this case a lack of suitable raw material. The Sheffield steelmaker, with his tradition of using high quality Swedish bar iron, had to find a comparable cast iron, as regards its low sulphur and phosphorus contents, and such a material was not readily available. To have used the local pig iron would have been unthinkable. Furness pig or Blaenavon pig would have been suitable, but he was not to know. At this time, it must be remembered, there was no chemical analysis to guide the steelmaker, only 'rule of thumb' trials which could be expensive should they produce unforgeable ingots and, more importantly, damaging to the reputation if unsatisfactory material went out to a customer. It would have been considered reasonable to

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1 It should be noted that there is a vague anonymous reference to such a process much earlier, in a comment on a hearsay report of the English steelworks using only grey cast iron to which they add, as necessary, either lightly cemented steel, to give it hardness, or bar iron to give it body (Journal des Mines, No.151, July 1809, footnote, p.10). In addition, there is the reference made by Broling (loc.cit., pp.69-70) to the melting together of pig iron and bar iron, on which comment has already been made. Please refer to p.250 and to Appendix II.

use Swedish pig iron, but that was not available since by edict of the Swedish government the export of pig iron was prohibited. It was obviously economically correct to refine the pig iron to bar iron in Sweden and so produce the extra profit, and quite a handsome one at that, for the Swedish economy. Indeed, up to 1846, the regulations operated by the central organisation in Stockholm, Jernkontoret, limited strictly the output of each bar iron forge. Subsequently, they were allowed to increase their production, subject to prior intimation of their intentions. The demand for iron was growing rapidly at this time, however, and the supply of charcoal in Sweden was soon to become the limiting factor. Thus, on 19th December 1855, by royal decree, the export of such pig iron as could not be refined was permitted, to be followed two years later by withdrawal of the similar ban on the export of Swedish iron ore. The release of Swedish pig iron was a most significant occurrence as far as the Sheffield steelmaker was concerned and, quite clearly, the Vickers process could now be implemented on a reasonable basis.[1] By 1862, imports of Swedish pig iron into Hull were 7816 tons in the year and figures from 1863 to 1869 ran at the level of 4000 to 6000 tons per annum.[2] The official statistical report from

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1 The availability of Swedish pig iron in this country was also significant for the growth of the production of puddled steel in this country, a matter which will be discussed later. (See Chapter 9).

2 Private communication from Miss Karen Hullberg, late of Jernkontoret, Stockholm.

Sweden in 1862 comments that :[1]

> 'When it is taken into consideration that Britain produces 3,712,390 tons of pig iron in the year at 50s. to 70s. per ton but is still willing to purchase Swedish pig iron at £6 to £7 per ton, this difference can only be accepted as indicating a superior usefulness of the Swedish make for special purposes'.

Total imports of Swedish pig iron into this country averaged about 10,000 tons per annum from 1862 to 1864 and had reached 20,000 tons by 1870. Not all this was necessarily used in crucible melting. Some was undoubtedly refined by puddling, but a good deal of this could well have found its way into crucibles. Some was probably used in Bessemer steelmaking, following the lead given in Sweden.[2] It may be significant that the amount coming into Hull in 1862 and 1863 represented about 70% of the total import, whilst by 1867 to 1869 it had fallen to 35%.

What is significant, however, is that the River Don Works, started in 1863 and destined to be the largest crucible steel works in the world, was built without any cementation furnaces. In its original design, it was to have had 384 double crucible holes.[3] It seems, however,

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1 Bidrag till Sveriges Officiele Statistik, 1862. Translation by courtesy of the late Torsten Berg.

2 Per Carlberg, 'Early Industrial Production of Bessemer Steel at Edsken", J.I.S.I. (July 1958), pp.201-204.

3 S. Jordan, Revue de l'Industrie du Fer (Paris, 1871), vol.4, pp.297-300.

that only three quarters of this capacity was installed as conventional coke fired furnaces;[1] the remainder of the capacity was eventually provided by the installation of gas fired Siemens type furnaces, capable of melting in up to 216 crucibles at any one time. In view of the association of the Vickers family with the River Don Works and the 1839 patent, it had previously been considered that the melting together of Swedish bar iron and Swedish pig iron was employed at the River Don Works. The article quoted[1] is quite specific, however, in that Swedish bar iron was melted with charcoal. As pointed out earlier, such a process was more onerous both on the furnace and on the crucible due to the higher temperature required; this is substantiated by the use of a more refractory crucible with a deliberate plumbago or graphite addition, as well as the move on a large scale to the Siemens gas fired furnaces which were capable of operating for longer periods at higher temperatures than the conventional furnaces, a matter which will be discussed later.

Elsewhere in Sheffield, however, it is clear that Swedish bar iron and Swedish pig iron were combined in

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1 'River Don Works', Engineering, 25th October 1867, pp.383-385. It is possible that 336 holes were installed with coke firing and that 48 of these were subsequently demolished to make room for the bank of gas fired furnaces. See also J. Hackney, 'The Manufacture of Steel', Proc.Inst.Civil Engineers, vol.xlii (1874-5), Appendix C, p.61, where information from Mr. E. Reynolds of Messrs. Vickers, Sons and Company is quoted. (See Appendix PP).

crucible charges, thus vindicating the Vickers patent[1] and giving a perfectly viable procedure. This eliminated the need for prior carburisation and, whereas the 'integrated steelworks' in Sheffield from 1825 to 1855 or so had been a combination of cementation furnaces with crucible melting facilities - and many examples appear as woodcuts on letterheads or advertisements - the use of the cementation furnace, as a source of raw material for the crucible process, declined from about 1860 onwards.

On the subject of crucible steel charges, much has been made of the statement made by Henry Bessemer in 1880 that the crucible steelmakers of Sheffield at that time used 50 to 60 tons of Bessemer scrap per week.[2] A similar comment, to the effect that some of the difficulties of the steel trade arose from the use of inferior Bessemer steel for tool and cutlery making, was made a few years later.[3] Obviously, only random records have

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1 It is difficult to understand why patents which deal with almost precisely the same procedure were later allowed. Gentle Brown of Swinton (British Patent No.205, 23rd July 1856) melted 7 to 12 lb. of pig iron with a balance of bar iron to give a 42 lb. ingot whilst John Henry Johnson (British Patent No.874, 5th April 1860) also melted together pig metal and wrought iron together with oxide of manganese and sal ammoniac. Such patents, however, are indicative of the current trends at the time.

2 H. Bessemer, On the Manufacture and Uses of Steel, a lecture given at the Hall of the Company of Cutlers in London, 1st December 1880. The text was published in the 'Ironmonger' of 4th December 1880; the copy I was able to consult was reprinted as a private publication, unpaginated.

3 S. Uttley, Evidence to the Royal Commission on Depression (London 1886), p.238.

survived to throw any light on this matter but, strangely enough, in the main these do not substantiate any major deviation from the policy of using Swedish iron.

The earliest evidence is contradictory. Alexander Galloway commented in 1824 that French bar iron was not as good as our iron or Swedish iron for steelmaking.[1] He went on to state

> 'Many people in this country entertain the notion that good steel cannot be made from English iron; this is a very incorrect notion. Twenty three years ago when I began business I used nothing but Swedish iron. I now use in bar iron perhaps 100 to 150 tons per year and I have never bought in the last fifteen years one ounce of foreign iron'.

Mr. P. Ewart, asked whether he agreed with the evidence of Mr. Galloway, said he did not.[2]

> 'I have been a good deal concerned with the making of steel. I have built mills and forges and I have seen many attempts for upwards of thirty years to make good steel from English iron and they all have failed ... The best iron we have is made from charcoal but there is no good steel except from Swedish iron ... We want the best steel for tools to make the machinery. Next to Swedish iron for making steel I have understood that some of the Russian iron makes steel of good next quality'.

In 1835, William Vickers reported that Sheffield was then producing 12,000 tons of steel per annum from 10,000

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1 First Report of the Select Committee on Artisans and Machinery (London, 1824), p.21.

2 Fourth Report of the Select Committee on Artisans and Machinery (London, 1825), pp.253-254.

tons of Swedish or Russian iron, 1,000 tons of English iron, only used for the manufacture of springs, and 1,000 tons of steel and iron scrap.[1] Le Play, a few years later, indicated that some 2,650 tons of home produced material was used in Sheffield steelmaking, being some 13% of the total; he did not differentiate between English iron and scrap intake.[2] Waern quoted Gustav Ekman as having stated that the amount of home produced iron used in Sheffield steelmaking had gone up by 1845 to 3,000 tons, whilst Waern himself computed that the figure in 1853 had risen to 7,200 tons, or 18% of the total raw material.[3] Waern was at this time endeavouring to persuade his government to allow additional production of Swedish bar iron to meet the rising demand and could, therefore, be expected to make as large an estimate of the competition as possible. He went to the length of praising the English iron as regards its 'density';[4] he did, however, make it clear that there were no official figures and that he was assessing the amount used by deducting the known re-exports of steel-iron from the total

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1 G. R. Porter, The Progress of the Nation, (ed. Hurst), (London, 1912), pp.240-241.

2 Le Play, loc.cit., pp.604-605, p.687.

3 C. F. Waern, 'Om Jerntillverkningen och Jernhandeln', Riksdag Bilaga, 1853-54, pp.49-50.

4 H. Scrivenor, History of the Iron Trade, (London, 1854), p.155, translates this as 'closeness'. I am informed that the Swedish is better rendered as 'density'. Scrivenor does not translate the last sentence in this paragraph referring to the English iron, which reads: 'No wonder the Swedish manufacturer is worried'.

known import from Russia and Scandinavia and assuming that the remaining raw material used in British steelmaking was home produced iron.

All this was at the time when the use of the Heath patent for adding manganese to steel melts was supposedly making the use of home produced iron practicable for the production of steel; this is supported by no less an authority than Dr. Percy.[1] Nevertheless it must be made clear that the addition of manganese would only modify the ills caused by the presence of sulphur in the iron, rendering it less red short and, therefore, possibly rendering it forgeable whereas, without the manganese, it might not be. The main trouble with the English bar iron, however, was that it generally contained substantial amounts of phosphorus, which would render the steel brittle or 'cold short', particularly if the carbon content was at all high. It is just conceivable that the lower carbon materials for springs, as mentioned by Porter, with about 0.5 to 0.6% carbon, might be serviceable with a maximum of 0.1% phosphorus present. For edge tools and the like, however, it is almost inconceivable that English iron, except possibly that from the Forest of Dean or the North West, could be used as a satisfactory substitute for the Scandinavian or Russian irons.

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1 J. Percy, Metallurgy: Iron and Steel (London, 1864), p.840.

The local evidence, meagre though it is, appears to confirm this line of reasoning. From the Tyzack records, it can be seen that quantities of local iron were purchased but it is clear that they were used in toolmaking - for welding to steel and generally referred to as 'skelp iron' - from the Milton Iron Company or from Low Moor.[1] It has to be added that small quantities of 'bar steel', presumably blister bar, were also purchased from both Low Moor and Bowling, names which also figure in Le Play's list. On the other hand, of the purchases over the period 1840 to 1867, these amount to less than ten tons compared with well over 3000 tons of bar iron, 86% of which was Swedish and 14% Russian. The fact that Bowling and Low Moor irons were occasionally converted to steel is confirmed elsewhere;[2] this same source also lists the Sheffield steelmaker John Brown selling 'spring ends', as well as 'JB Best Melting Base Bar Steel', in 1862. Conceivably these could have been Bessemer steel since he had installed a converter in 1860; they could just as well have been puddled steel. In either case, they could well have been of Swedish origin, from the Swedish pig iron now being imported in quantity.

Ebenezer Jackson's Note Book quotes a 'least cost mix' for crucible tool steel in 1848 as being one third

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1 Tyzack Purchase Ledger, 1840-1867, inspected privately.

2 Sheffield City Libraries, Brittain Accounts, LD 266.

each Hk iron (a cheap Swedish grade), English iron (at £9 per ton) and steel scrap.[1] At the same time, it should be noted that, whilst this gave an ingot cost of 23s. 4d. per cwt, the typical cost of rolled tool steel bar is calculated with a material costing 28s. at the ingot stage and there is an impressive list of Swedish bar iron prices ranging from the Hk at £13.10.0. per ton to Hoop L at £32 per ton, with only the one unspecified English iron. Similarly, the Daniel Doncaster lists of blister bar prices,[2] issued regularly over the years, give either two or three English grades (in 1862 and 1864 these were confined to Chillington and JB ATLAS) with upwards of thirty Swedish and Russian grades.

The only real argument for any more extensive use of home produced iron in the crucible steel trade comes from a report in 1862.[3] This was written at a very interesting period in the history of Sheffield steel, after the release of Swedish cast iron, which had led to widespread use of the puddling process in at least three of the major Sheffield steelworks, and just before the full acceptance of the Bessemer process.

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1 Sheffield City Libraries, SJC 41.

2 There are numerous examples of these in the Doncaster Archives.

3 Gruner and Lan, loc.cit., p.769, p.776, p.783, p.785, pp.788-789, p.792, p.794, pp.803-805.

It was a time when the appetite for steel was growing rapidly and it is not unreasonable to conclude that, for two or three years, the situation was abnormal in that the crucible steelmakers were being pushed to produce what is specifically referred to in the report as 'common steel'. There are, unfortunately, discrepancies in the report which states that 40% of the output was from Russian and Swedish irons, whilst the import figures would indicate a 60% coverage. Nevertheless, the gap is a large one and could only partially be filled by imports of Swedish cast iron and the use of return crucible steel scrap. It is therefore significant that there are continual references in this 1862 report to home produced iron: puddled steel from Blaenavon pig, the use of iron from Lancashire or Cumberland (all so far Haematite irons) for making steel for common bars, files, angles, tyres, axles and machinery forgings; also some Low Moor and Bowling iron for cementation - and even that from Staffordshire and Shropshire which surely must have produced unserviceable steel! As will be seen, however, the later evidence appears to point to this period as being untypical.

Several crucible charge books covering the later years of the process have been studied. Those from Jessops and Savilles from about 1885 to 1910 have unfortunately now been mislaid; still accessible are those from Seebohm and Dieckstahl,[1] together with the Wellmeadow Steel Works book from 1895 to 1898 and numerous examples in the Doncaster archives. These latter cover a long period and one particularly interesting set of analyses comes from as late as 1940 showing both American and English irons as well as Swedish materials in their stock for cementation. The figures show all five to be of reasonably good quality but the Swedish materials were still generally superior as regards sulphur and phosphorus contents :

	Hoop L Iron	AOK Iron	Swedish Lancashire Iron	Low Moor Iron	Armco Iron
Carbon	0.08	0.08	0.06	0.03	0.02
Silicon	0.02	0.02	0.03	0.02	0.02
Manganese	0.08	0.12	0.06	0.02	0.02
Sulphur	0.005	0.004	0.006	0.017	0.015
Phosphorus	0.009	0.016	0.017	0.005	0.021

None of the charge books gives any firm evidence in favour of Bessemer's statement.[2] It is true that Bessemer steel appears in a few charges but almost invariably it is 'Swedish Bessemer' which was imported as an alternative to the Walloon or Lancashire Swedish iron; it was a material produced with care from the same raw materials and was equally pure with regard to sulphur and phosphorus contents.

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1 Sheffield City Libraries, BDR 97/1-5.

2 The latest evidence to be obtained, that from Cammell Laird and Co., is confirmatory of what has been deduced above. See p.641 and Appendix JJJ.

As a final comment on this subject, it seems appropriate to quote the evidence of an American observer on tool steel making in Sheffield, just after the First World War.[1] He implied that a little domestic material had perforce been used during the hostilities but that now Swedish iron was again freely available, albeit at an inflated price, none other was being considered for crucible steel charges.

IX The Uchatius Process

This modification of the crucible process[2] depended on the granulation of cast iron, achieved by the pouring of the liquid metal into water, and the mixing of the granules with about 20% of their own weight of powdered high grade spathic iron ore, rich in manganese, or a good quality haematite ore to which oxide of manganese was added, together with about 5% of fireclay. This mixture was then heated in crucibles to melt and refine the metal and the product cast, in the normal manner, as steel. The object was obviously to circumvent the more

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1 P. M. Tyler, 'High Speed Steel Manufacture in Sheffield', The Iron Age, 10th February 1921, pp.371-374.

2 British Patent No. 2189, F. Uchatius, 1st October 1855. It would seem that a discussion of this process could equally well have been deferred to the later chapter dealing with new routes for steel. On balance, the close affinity to the crucible process leads to its inclusion here.

costly and more time consuming standard process of refining the pig iron, cementing the resulting bar iron and then remelting the product. The yield was said to be about 6% greater than the weight of granulated pig, due to the reduction of iron from the ore by the silicon and by part of the carbon from the pig iron.

The method originated in Austria,[1] but its first major development seems to have been in the Newburn steel-works on the Tyne. A contemporary report gives an elegant description of what occurred in the crucible :[2]

> 'Each granule (of cast iron) being surrounded by the pulverised oxides, the decarbonisation takes place first on the outside of each granule and so progresses towards the centre as the heat increases, the oxygen in the ores combining with the carbon in the granules and passing off as carbonic acid gas;* if, therefore, during the process the granules could be examined, it would be found that the outside of each is entirely deprived of its carbon, the next portion partially decarbonised and the centre not de-carbonised at all; so that each granule would be composed of pure wrought iron, steel and cast iron. By increasing the heat the cast iron centre portion of the granule first becomes fluid and then falls by its own weight to the bottom of the crucible. At the same time, the earths mixed with the ores melt and rise to the top, forming a layer of scoria or dross floating on the surface of the melted iron. Each granule of melted metal has therefore in falling to pass through the rising

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1 The inventor was a Colonel in the Austrian army.

2 T. Spencer, 'On the Manufacture of the Uchatius Cast Steel', Proc.Inst.Mech.Eng., August 1858, pp.146-154.

* More correctly, this should be carbon monoxide; carbonic acid gas is carbon dioxide.

> scoria and it is in the passing through that the combination of the impurities in the metal with the alkaline earths takes place, so that the decarbonised iron on reaching the bottom of the crucible is cleansed from all impurities. The heat continuing to increase melts the outside portions of the granules and the whole is reduced to one homogeneous fluid mass in the crucible, which is then ready for being poured into the ingot moulds ... The oxides employed in this process are iron ores of the finest qualities, such as spathose and haematite, which are previously calcined and pulverised. The proportion of oxide to the granulated iron is according to the hardness of the steel required, say from 20% to 30%; the greater the quantity of oxide employed the greater the decarbonation and consequently the softer will be the steel produced'.

The advantages claimed were a rapid conversion of cast iron into steel by a direct method, a uniform quality from a predetermined mixture of cast iron and oxide and a cost less than half that of remelting blister steel, for comparable quality. It is clear that the trials at Newburn did produce some material of very acceptable quality. Within twenty years, however, the process had been abandoned here:[1]

> 'after a great number of experiments, at a cost of a little under a thousand pounds, on attempting to work it in large quantities, it was found that the product was so uncertain in the qualities necessary to good steel that the process was altogether abandoned. This irregularity of the product was probably caused by the uncertain quantity of the carbon in the pig iron used'.

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1 J. S. Jeans, Notes on the Northern Industries (London, 1878), pp.79-82. It is also reported that a Mr. Willans of Sheffield was producing steel by the Uchatius process but only on a small scale; J. S. Jeans, Steel: Its History ... (London, 1880), p.112.

As will be pointed out later, however, the process was eminently successful elsewhere, and the works set up at Viksmanshyttan in Sweden in 1859, especially to exploit the process, operated continuously for seventy years.[1]

X 'Homogeneous Metal'

Another variant of the crucible process was its use in the production of what was described as 'homogeneous metal' and first made its impact at the International Exhibition of 1862, on the stand of Messrs. Shortridge and Howell of Sheffield, in the form of tubes. The claim was that this material had all the advantages of good quality wrought iron without the presence of the streaks of slag. It seems to have been a crucible melted steel, but most certainly much lower in carbon

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1 C. Sahlin, 'De Svenska Degelstalsverken', Med Hammare och Fackla (1932), vol.IV, pp.79-91. This matter is dealt with fully in pp.529-530. The Uchatius process gave rise to some variants, two of which were patented, although there is no knowledge of their being applied. Pauvert (British Patent No. 609, 2nd March 1857) crushed heated pig iron, either through rollers or by stamping, oxidised the metal by further heating and then melted it with powdered ore and fluxes. Sicard (British Patent No.139, 17th January 1859) granulated pig iron in a centrifugal spinning device, introducing nitrate of soda or potash to oxidise the finely divided metal, which was then washed and finally remelted with various physics.

than the steels conventionally melted in the crucible. The only vague clue as to what was being done comes in a fairly early patent,[1] which probably has the shortest operative instructions of any patent of the time, the full statement reading :

> 'The novelty of my invention consists in using what is commonly known as the scale which falls off steel or iron during the process of hammering or rolling in addition to the ingredients in common use for making cast steel. I do not confine myself to the use of any quantity of the said scale as that must be determined by the particular temper of steel required for any special purpose. The object of the invention is to make a superior quality of cast steel or homogeneous metal from the commoner kinds of iron'.

The use of millscale, as an oxidising agent for carbon in molten steel, has the advantage over the use of ore in that there is no 'gangue' or earthy matter to be fluxed and no elements injurious to the steel to be introduced, since the scale is merely oxide of iron with small quantities of the oxides of the other metallic constituents of the steel. There are puzzling features, however. The straightforward addition of oxide to a relatively low carbon melt would lead to a highly erosive slag being formed, there being no excess of carbon to reduce the iron oxide as in the Uchatius process. Possibly some suitable slag forming matter was also included, such as crushed pot, clay or sand to absorb the iron oxide from the mill scale before it

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1 British Patent No. 2369, John Bennett Howell, 9th October 1856.

could cut the crucible. Even so, however, to render a lower carbon material fluid enough for casting, the temperature would have to be raised considerably.[1] Nevertheless, whatever the details, it is quite clear that this firm made quite a reputation for itself, producing ship plate,[2] boiler tubes, telegraph wire and colliery ropes from their 'homogeneous metal'.[3]

XI The Invention of the 'Dozzle'

There are, in the history of technology, a number of

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1 Whilst this would have been relatively easy within a few years, after the advent of the Siemens gas fired furnace, the Shortridge and Howell activity starts in the days of the simple coke fired furnace.

2 The use of Shortridge and Howell's 'homogeneous metal' plates in David Livingstone's paddle steamer for operating on the Zambesi was the first known use of steel as the main body material in shipbuilding. That the adventure turned out to be a disaster cannot be laid at the door of the makers of the homogeneous metal. The design was poor, the plates were too thin and the corrosion risks were underestimated. For an interesting account of this matter, see J. G. Parr, 'The Sinking of the Ma Robert: An Excursion into Mid Nineteenth Century Steelmaking', Technology and Culture, vol.13, No.2 (April 1972), pp.209-225.

3 The firm continued to produce tubes until 1971, but 'homogeneous metal', as originally made, probably ceased to be used by 1880, being replaced by purchased billet from local Bessemer and Open Hearth shops.

simple ideas conceived by a highly practical mind which have had such far reaching effects that, looking on them with hindsight, it is rather a matter for wonder that they were not evolved earlier. Such an idea came to Robert Forrester Mushet, working away in his isolated steelworks in the Forest of Dean. His own description needs must be quoted verbatim;[1] one instantly forms the impression that here is one of the great steelmakers on his home ground :

> 'In the manufacture of cast steel, the steel when melted usually is cast or poured from the melting pot or crucible, in which the said steel has been melted, into ingot moulds formed of cast iron. The ingot moulds employed are of various sizes, shapes and lengths, in order that the manufacturer of steel may be enabled to obtain ingots of the various sizes and weights he may require. Ingot moulds most commonly in use have the figure internally of a square or four sided prism, the sides being from 2¼ to 2¾ inches broad and the said moulds are from 20 inches to 42 inches in length internally.* A slight aris or bevel is usually formed upon the inside angular corners of the ingot mould so that the ingot when cast is a square prism with its solid edges bevelled off longitudinally'.

What Mushet did not say was that such moulds were made in two halves, split longitudinally, with a dovetail fitting; in addition, he did not mention the octagonal and rectangular sections used on occasion. His next comments, however, had universal relevance wherever steel was melted:

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1 British Patent No.1310, R. F. Mushet, 23rd May 1861.

* These extremes would give ingot weight of from 25 lb. to 75 lb.

> 'When steel is very thoroughly melted and heated considerably beyond its melting temperature such steel will, when poured into an iron ingot mould, undergo during its cooling and solidification a considerable degree of shrinkage and this shrinkage forms a deep tube or funnel in the upper part of the ingot, extending downward from the centre of the ingot top in the form of an inverted cone, often several inches in depth and the same thing occurs when hard steel highly carbonised is melted and poured into ingot moulds even when such highly carbonised steel is not heated considerably beyond its melting temperature. This funnel is called by steel manufacturers the 'pipe' of the ingot and cast steel, which when poured into iron moulds forms ingots with deep central funnels at the tops of the said ingots, is said to 'pipe badly'. As the portion of the ingot containing the funnel or pipe when rolled or drawn down into bar is necessarily hollow in its axis, such portions of the bar as contain the pipe are unsound and unmarketable and the piped ends of the ingot are therefore either broken off before the ingots are rolled or drawn or the piped portions of the rolled or hammered bars are subsequently cut or broken off. The necessity for breaking off and removing the pipes from the ingots causes very great waste and loss to the manufacturer, the weight of the piped portions of the ingots varying from three pounds to twelve pounds for each ingot and sometimes more'.

This was indeed a problem which had been around for over a hundred years and it should be made clear that this did not become ameliorated by the 'killing' process; this prevented honeycombed blow holes but tended to aggravate the piping tendencies, since a fully killed steel was more deeply piping. Mushet, in fact, recognised this, since the more highly carburised steel was more fully deoxidised; it is also worth pointing out that deoxidising the melt with aluminium, as was practised later, also gave an accentuated piping situation. The suggestions for alleviating the piping problems took the following form :

> 'When the ingot mould has been placed on its end in the usual position for receiving the melted steel contained in the melting pot or crucible, I pour the greater part of the said melted steel into the ingot mould in the usual manner, taking care, however, that the melter or workman who pours the steel into the mould shall stop pouring the said steel when a quantity of it from two to four pounds yet remains in the melting pot. I now introduce into the ingot mould a heated pipe of clay, or other material, as hereinafter explained, and I set the bottom end of this pipe upon the surface of the melted steel which has just been poured into the ingot mould, the said clay pipe being supported in its position by the interior sides of the ingot mould above the top of the ingot. The melter then quickly pours the steel which remains in the melting pot into the clay pipe placed on the top of the ingot and as the shrinkage takes place in the ingot the melted steel in the clay pipe falls or sinks down and by keeping the middle of the upper end of the ingot full during the solidification of the steel prevents the formation of a pipe or cavity. The ingot is then taken from the ingot mould in the usual manner and the steel remaining in the clay pipe and attached to the upper end of the ingot is broken off and the ingot thus cast without pipe or funnel'.

In this manner was the 'dozzle', as it came to be known in Sheffield, introduced. All crucible steel ingots soon were produced with dozzles and larger ingots eventually came to be made with 'hot tops' or 'feeder heads', all as an extension of the same principle. Mushet suggested that his 'clay pipe' for a 2½ inch square mould should be $2^{7}/16$ inch square, with the corners chamfered off, with a length of six to eight inches, the central hole being 1¼ to 1¾ inches in diameter,[1] the latter either straight or tapered; if tapered, the larger aperture should be placed downwards. He also suggested that they could be moulded in common clay, mixed with a fifth of its bulk of coke dust or other carbonaceous matter, to prevent cracking when heated. They could be moulded by hand (as they most frequently were in Sheffield) or by machine, and they needed slow drying before heating up for use.

By this means the loss from the ingot was reduced to a mere 1% to 2%. Quite often, with ingots up to 4 inch square, as produced from the later high frequency furnaces, the metal in the dozzle fed virtually completely into the ingot, leaving just a hollow shell within the dozzle itself, and this could be knocked off quite cleanly by a light hammer blow. Bearing in mind that Mushet's invention came only just prior to the age of alloy tool steel, with its additions of relatively costly elements such as chromium, tungsten and vanadium, the economies directly due to the use of the 'dozzle' must have been enormous and its invention certainly ranks among the most important contributions to the art of steelmaking.

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1 The remains of Mushet's crucible steel shop were bulldozed around 1966. Rummaging around on the tip so produced shortly afterwards, I found various broken pieces of 'dozzles' and they matched these dimensions quite closely.

XII The Gas Fired Furnace

In the later years of the crucible process, the one factor which had the greatest potential effect was the introduction of the gas fired furnace. Using their regenerative furnace principle, with producer gas firing, the Siemens brothers 'modernised' the Huntsman type coke fired furnace which had remained unaltered, other than by an increase in scale, for well over a century. As we have seen, the crucible size had increased, as had the number of crucibles per hole, and by 1860 the net effect of this was to obtain ten or twelve times the weight of steel per hole, compared with Huntsman's first industrial operations in Attercliffe. The main constraint in the process was the necessity of maintaining a sufficiently high temperature for the appropriate period of time, to produce liquid metal sufficiently fluid for casting. The details of the development of what is generally known as the Siemens furnace, namely the Open Hearth furnace with producer gas firing and regenerative chambers, are to be found elsewhere in this treatise; suffice it to say here that a modified furnace could be designed to take crucible pots on its 'hearth'. In the designer's own words :[1]

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1 C. W. Siemens, 'On the Regenerative Gas Furnace as Applied to the Manufacture of Cast Steel', Journ.Chem. Soc., (1868), pp.279-310. This paper also describes the gas producer used for such applications.

'In the application of the system to the fusion of steel in closed pots or crucibles, the melting chamber, containing generally twenty four pots, is constructed in the form of a long trench, three feet six inches wide at the bottom and gathered in to under two feet at the top. The sides of the melting chamber are arched both horizontally and vertically, to keep them from sinking together in working, and the work is strengthened by cross walls at intervals. The pots are set in a double row along the centre of the chamber and the flame passes from side to side, the gas and air from the regenerators being introduced alternately from one side and the other, opposite to each pair of pots. The melting chamber is closed above by loose fire-brick covers, which are drawn partly off in succession by means of a lever suspended from a pulley above the furnace, when the pots are to be charged or drawn out. The pots stand in a bed of finely ground coke dust, resting on iron plates. The coke dust burns away only very slowly, if it is made of hard coke and finely ground, and it presents the great advantage of remaining always in the form of a loose dry powder in which the pots stand firmly, whilst every other material I have tried either softens at the intense heat or sets after a time into a hard, uneven mass, in which the pots do not stand well. The process of melting carried out in this form of gas furnace is the same in all respects as that in the small air furnaces or melting holes filled with coke which are commonly employed but a great saving is effected in the cost of fuel and in the number of crucibles employed. The ordinary consumption of hard coke, costing 22s. per ton in Sheffield, is between three and four tons per ton of steel fused, while in the gas furnace the same work may be done by the expenditure of 15 to 20 hundredweight of common coal slack (worth only 5s. to 8s. per ton) at a cost that is only 5s. against 75s. per ton of steel melted. There is a further saving in the number of crucibles required, as they may be used in the gas furnace four or five, or even ten times, while in the furnaces heated by coke two or three casts are as much as are ever obtained. The lining of the furnace lasts at least 15 to 20 weeks without repair (in working day and night) while 4 to 5 weeks is the longest duration of the ordinary coke fired holes'.

Siemens' chief assistant, William Hackney, presented a paper[1] some seven years later and confirmed much of what has been set down above. He implied that the newest furnace to be installed in Sheffield was at Messrs. Sanderson Brothers works and was, it would seem, very much to the design given earlier by Siemens. He commented that the pots were rather wider and shorter than for the ordinary coke furnaces, so as to be rather more stable, and were made without the usual central hole from the plug, but were otherwise similar.[2] The furnace walls exposed to the full heat were made from the most refractory Dinas or silica brick;[3] the covers and the regenerators were in Stourbridge or other good quality firebrick. The floor plates stood a few inches clear of the brickwork and were cooled by the current of air passing below them. Hackney, however, is not as optimistic in his claims on fuel saving, suggesting that from 22 to 30 hundredweight of common small coal was needed per ton of steel melted, some 50% up on Siemens' estimate, but still quite a realistic saving over the coke fired furnace. As an appendix to his paper, extracts from a letter from Mr. E. Reynolds,

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1 W. Hackney, 'On the Manufacture of Steel', Minutes of Proc.Inst.Civil Eng., vol.xlii (1874-5), Part IV, pp.2-68.

2 This would seem to indicate the use of machine moulding.

3 Such brick was by that time being manufactured at Deepcar, near Sheffield.

manager of Messrs. Vickers, Sons and Company, give some useful details of the River Don Works practice; in addition, some information on other operations is quoted from Siemens.[1] A list of Siemens regenerative furnaces for crucible steel melting in 1880 indicates the growth of this type of furnace:[2]

Vickers, Sons and Co., Sheffield	216 crucibles
John Spencer and Sons, Newcastle	96 crucibles
Monkbridge Iron Company, Leeds	72 crucibles
Bowling Iron Company, Bradford	48 crucibles
Sanderson Brothers, Sheffield	48 crucibles
Steel Casting Company (?)	36 crucibles
Robert Marsden, Sheffield	18 crucibles

The annual production from furnaces of this type in 1879 was stated as being 3500 tons of steel.[3]

Comments are found, from time to time, indicating that control of the individual crucibles was not as close in gas fired furnaces as in the old coke fired holes; in many cases, where multiple pouring involving crucible steel was concerned, such as in the Krupp works in Germany, small temperature variations from one crucible to the next were less significant than where individual ingots of special tool steel were being produced, as was mostly the case in the latter years of the nineteenth century in Sheffield.

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1 In view of their relevance, it has been thought fit to quote these in full in Appendix PP. Further details on cost comparisons can be found in Appendix ZZ.

2 Jeans, loc.cit., p.104.

3 J.I.S.I. (1879), Part I, p.250.

It was for such reasons that special gas fired furnaces were designed and one model which seems to have gained a good reputation was the Dawson, Robinson and Pope furnace, patented in 1897 and installed at William Jessop and Sons works,[1] among other places, around 1900.[2] The main distinguishing feature of this design was that each of the melting chambers had an equal pull on the regenerators, with its own control, so that an even temperature could be maintained throughout the whole furnace. Each hole held six crucibles and the savings in fuel were said to be at least £2.10s. per ton of steel, using only 1¼ tons of slack as against 3 tons of high grade coke.[3] Harbord, in the text to which reference has already been made, pointed out the economy in fuel, the ease with which the gas could be regulated and the freedom from clinker on the pots. He judged that, notwithstanding past failures with gas furnaces, there was now every prospect of this type of furnace being very largely adopted. Strangely enough,

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1 A chance survival is a list of wages to be paid for the working of the 30 pot Gas Melting Furnace at Wm. Jessop and Sons. This document, brought to by attention by L. A. Keen, Esq., is reproduced as Appendix QQ.

2 The new works of Thos. Firth and Sons, built for the production of tool steel at Tinsley in 1907, was equipped with a furnace of this pattern.

3 A description may be found in F. W. Harbord and J. W. Hall, The Metallurgy of Steel (London, 1904), pp.235-236, or in D. Carnegie and S. C. Gladwyn, Liquid Steel: Its Manufacture and Cost (London, 1920), pp.60-61, pp.96-98.

this same argument went on until the final demise of the process and the coke fired furnaces soldiered on, the odd gas fired furnace was installed and many more were just thought about but nothing more was done. Drawings for an extension to one particular works survive, covering quite an imposing array of gas fired furnaces; in the event, however, whilst the coke fired furnaces were replaced, it was not by gas fired equipment but by electrical power in the form of the high frequency coreless induction furnace.[1]

The argument as to relative merits of the two methods went on for years. As usual, Brearley's comments are of interest :[2]

> 'Whether pot steel should be melted in a coke fired furnace, as Huntsman melted it, or in a gas fired furnace, as it might have been since the time regenerator furnaces were known, would appear to be merely a commercial consideration. But most manufacturers of crucible steel avoided gas fired furnaces, even when their use would be cheaper. There was something desirable in the coke fired steel, they claimed, which was missing from the gas melted steel. It may be wondered whether this is anything more than a lazy preference for the way of going on they happen to be familiar with. The suspicion that it might be so is supported by the fact that when electrically heated furnaces became available, both arc and high frequency induction furnaces, they were used more willingly than might have been expected, and with greater confidence than is

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1 The plans were for the Clarence Steel Works of Swift Levick and Company. I was privileged to inspect these by courtesy of J. D. Levick, Esq. The extension was first proposed in 1920, postponed in 1922 and abandoned two or three years later.

2 Brearley, loc.cit., p.84.

> justifiable to a man who realises the advantages of pot melting and what its ultimate economics might be if considered by a mind reasonably free from baseless prejudice'.

At a date as late in the history of the crucible process as 1921, the debate was still going on and F. M. Parkin, one of Sheffield's leading steelmakers, thought fit to devote an address on the subject to an audience of his fellow Sheffield metallurgists.[1] He described his experiences with the Harvey Patent Steel Melting Furnace (sometimes known as the 'New Form' Siemens Furnace) with a melting chamber 18 feet long and 3 feet 6 inches wide, taking 12 pots at a time. The general comments made in the conclusions are of value :

> 'Melters have become so accustomed to handling high speed steel during the War, with its comparatively high melting temperatures and rapid rate of pouring, that very few today can treat high carbon tool steels as they were regularly treated many years ago, and, I think, to this extent the quality of the product has suffered in consequence. Another point which I think has had a detrimental effect is the fixing of a time limit to the melter's working day. Once you attempt to make crucible steel

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1 'Gas versus Coke Melting in Crucible Steel Production', the unpublished text of a lecture given to the Sheffield Society of Metallurgists and Metallurgical Chemists on 19th April 1921.

It is interesting to note that elsewhere a newer type of coke fired furnace, but with forced draught, was installed as an economy measure. (See p.641 and Appendix JJJ).

by the clock, the quality must suffer* ... In the gas furnace, it is necessary to have every pot clear melted before any one can be teemed. In case some pots are more forward than the others, it is impossible to hold them back, as can be done in various ways in the coke furnace, with the result that some pots may have had rather more fire than the others and, if teemed straight away without being allowed to cool down (or neutralised by being doubled with one of the later melted pots) there is, of course, a tendency to ingot weakness and scorched fracture. Taper moulds should always be used and, wherever possible, doubling up should be adopted. It will be seen that it is almost impossible to get every fracture from the same heat quite alike but by watching the points mentioned it is certainly possible to reduce the variation to a minimum. It is only fair to say that I have melted almost every class of crucible steel in this type of furnace without any serious trouble at all. I might specially mention having made several hundred tons per annum of ingots for the purpose of wire making in this furnace where, if any axial weakness of the ingot was obtained, owing to hot casting, it would soon be revealed and prove more serious than a similar tendency in ingots intended for ordinary tool steel ... No trouble is experienced in the gas furnace from cold bottoms of pots and .... six rounds of high speed steel have been made regularly in twenty four hours in Sheffield... The gas furnace is of very little use to the small manufacturer with an oddment trade, as it cannot with economy be lighted up and cooled down at will. Once up to a heat it should be kept there in order to gain the maximum advantage commercially, so that it may be necessary to put ingots to stock. Light up, get maximum output by working full time and then shut down for repairs when necessary in order to reduce melting costs to the lowest possible figure.

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* It would appear from other sources that, some time in 1918, an eight hour day was proposed for crucible steel operations. Certainly from the records of Wardrobe and Company (Sheffield City Library, LD 1937) there is a note on 17th February 1918 of 'Shorter Working Day' and thereafter instead of three rounds in the day there are two, somewhat compensated by the use of 56 lb. pots instead of those with 46 to 48 lb. charges.

different 'crucible' linings and operating with slags to remove unwanted impurities, such as sulphur and phosphorus. This was a different world from that of Huntsman. Nevertheless, many of the earlier furnaces melted charges which were derived from crucible practice and even the larger furnaces were often discharged by taking from them a number of crucibles full of metal and pouring ingots in the accustomed manner. Meanwhile, the few coke fired furnaces that had survived still made a reasonable profit, as long as there were the craftsmen - the melters and teemers, the pullers out and the odd job men, 'coaky' and the pot maker, not forgetting the cellar lad - to operate them.

Now, all is but a memory amongst the very few, very old operatives who still survive. It is largely as a tribute to these and all their previous generations that this story is now being set down, before it is too late and all the records have gone.

> I do not see the slightest reason why gas melted steel should in any way be inferior to coke melted steel, provided reasonable intelligence and ordinary care are used. From the standpoint of composition it is at present superior,* costs are lower and, for the men, the furnace is much easier to manipulate once the necessary experience is obtained'.

This was almost the final comment. Within five years of this presentation, the next advance in furnace design had appeared on the scene. It could be argued that it was a logical development of the crucible process; it had a crucible of sorts, with a water-cooled copper coil wound around the outside of it and the steel was melted inside the crucible out of contact with the fuel. But there were differences in the form of mechanical devices for tilting the furnace; there was the scope for increasing the size of the operation, from the 100 lb. or so of the first furnaces to several tons;[1] there was also the possibility of using

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* Elsewhere in the paper this is explained by the poor quality of the coke available in the post war years; this gave rise to abnormal sulphur increments in the steel from the coke fired melting holes.

1 The largest high frequency furnace known to have been installed was at the Bofors works in Sweden; this held about 14 tons and was still in operation some ten years ago when I visited the works. The largest in this country is a 6 ton unit in the Firth Brown works. I have been involved in many melts made in this furnace and it is capable of producing a very wide range of materials. It is of interest to note that the manager in charge of this furnace, for its first twenty five years, had previously operated both gas fired and coke fired furnaces.

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