



Plan of land in Brencley formerly belonging to George Roberts, 1647
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MINE PITS IN BREDE

Robert Turgoose

A foray to Great Park Wood and to South Sowdens Wood in Brede revealed many mine pits. These woods are in the east of Brede parish close to the boundary with Udimore parish. They lie on south facing slopes of the Udimore ridge between the Brede and Tillingham valleys. The ridge is capped with Wadhurst Clay which overlies the Ashdown Beds.

The fields north of Great Park Wood are shown on geological maps as worked out ground. In these fields there are a number of large pits with diameters of about 25m and up to 4m deep. A pit at TQ 8554 1906 contained several rocks which on breaking showed indications of iron ore. Samples have been sent for analysis.

In Great Park Wood the area centred on TQ 8550 1870 has many circular pits some 2-3m in diameter. There is also an oval pit about 30m by 20m with a depth of 3m. All the pits had been dug in the Wadhurst Clay but were dry suggesting that they extended into the Ashdown Beds. A double charcoal platform was found at TQ 8520 1880.

In South Sowdens Wood a dry quarry is at TQ 8469 1877 and five water-filled pits at TQ 8444 1883 and TQ 8493 1880. These features follow the Wadhurst Clay outcrop. Immediately south of the B2089 the area between TQ 8430 1930 and TQ 8470 1920 contains three pits each about 50m by 20m and a depth of 5m to the water level. The same area has many smaller circular pits and quarries.

The nearest blast furnace to the sites surveyed is at Beckley, about 4km distant by a level and then downhill road. There are six known bloomeries along the Udimore ridge within 3km of the pits surveyed. The major bloomery at Chitcombe is 5.5km distant, accessible by the level ridgeway road.

We are most grateful to the woodland's owners for allowing us access.

WEALDEN SIDERITE: Determining Activation Energy and Smelting Time

Alan F. Davies

Introduction

Activation Energy value (E_a) is the minimum threshold heat energy needed to start a chemical reaction. For bloomery smelting calcined iron ore the E_a value depends on ore type, grade and carbon monoxide (CO) quality from a combusted reductant. A high E_a value means more heat must be put into a smelt to initiate and maintain a reduction reaction. Conversely a lower value means an easier start, faster reaction rate and, therefore, shorter smelt times.

Historically much research and practical work has established E_a values for many iron ores and reductant combinations. Even so only limited information is available for some variously sourced siderite ores and reductants. Expectedly from lack of any commercial need, no information seems readily available for Wealden ores.

Historically for Wealden smelters and likewise for the WIRG smelting group, smelt time is judged using experience for burden mix, other furnace operating conditions and most importantly - what worked well in the past. Even so results can still be uncertain with a need to control many smelting variables. Having an E_a value provides an important measure of ore reducibility and for setting smelt time for a burden-charge ore:charcoal mix and weight.

This article describes how an established basic method provides an Activation Energy value for calcined Wealden siderite ore reduced with charcoal. The result is compared with other published E_a values and used for predicting and comparing times for several past WIRG smelts.

Determining Ea Value

This involves a linked sequence of procedures:

1. Producing cumulative reduction time graphs for sample lumps of calcined Beacon Wood Stream (BWS1) ore for each of one of three temperatures (850°C, 900°C and 950°C)
2. Selecting and applying a ‘best fit’ reduction process model for this data. Using this model to calculate an average rate of reaction for each reduction temperature set of data
3. Inserting an average rate of reaction for each temperature into an Arrhenius equation, which links reaction rate to temperature, to calculate the ore Activation Energy value.

Procedure 1 - Producing Reduction Time Graphs

These graphs are based on oxygen weight loss from small sized ore samples as normally used for smelting, and calcined previously at 850°C for one hour.

A set of four small porcelain crucibles each contained a weighed (3-4gms) sample of calcined ore (49.53% iron with oxide oxygen of 21.23% and minerals SiO₂ 14.24%, Al₂O₃ 3.7%, CaO 5.02%, MgO 3.19%) placed on a bed of, and covered in, small charcoal grains (5mm) of 87% fixed carbon. Each crucible was closed with a loose-fitting cover.

Each set was heated in a temperature controlled furnace from room temperature to one of 850°C, 900°C or 950°C. After attaining that temperature, the first crucible was removed after a soaking time of 15 mins, a second after 30 mins, the third and fourth after 45 and 75 minutes respectively.

Reduction time graphs are shown in Figure 1. Common profiles show:

- Fast oxygen loss within the first 15 minutes followed by transition into a more constant rate of change over the next 15 minutes as the treatment time extended
- Increase in treatment temperatures produced a faster rate of reduction within the first 15 minutes followed, after 30 minutes’ treatment, by a gradually lower but constant rate for each over the remainder of the time.

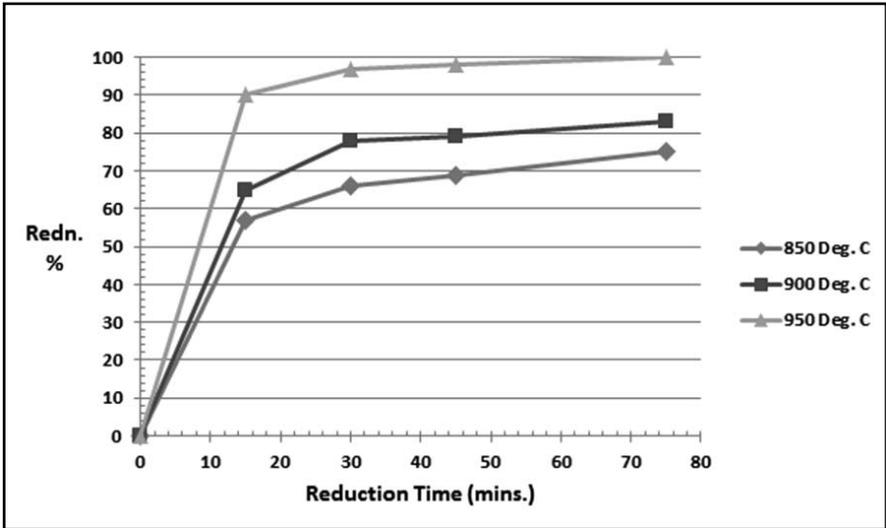
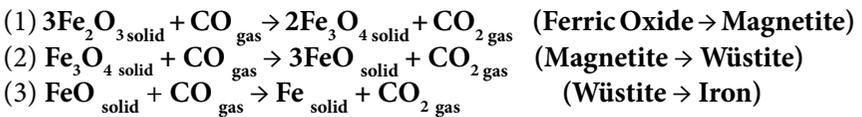


Figure 1: Calcined siderite reduction time graphs

These distinctive profiles represent ore oxides progressive reduction mechanisms.

Iron oxides reductions:



Reduction profiles show that Gaseous Diffusion Control (via Boudouard Reaction) becomes dominant after about 20 minutes into the treatment over the initial gas and phase boundary chemical reactions.

Procedure 2 – Selection of Reduction Model

Three gaseous diffusion control kinetic models were trialled for the best

overall fit (high R² Values) to the reduction graphs. The selected model¹ works well for size of ore used, assumed spherical diffusion process and for the intermediate ranges of reduction:

$$kt = [\frac{1}{2} - (f/3) - (((1-f)^{2/3})/2)]$$

where **k** = reaction rate (mol.min⁻¹), **t** is reduction time (min), **f** = fractional reduction.

Plotting points for this equation for ‘f’ and ‘t’ for each temperature produces Figure 2. EXCEL functions give, for each temperature, the best straight line equation and R² value.

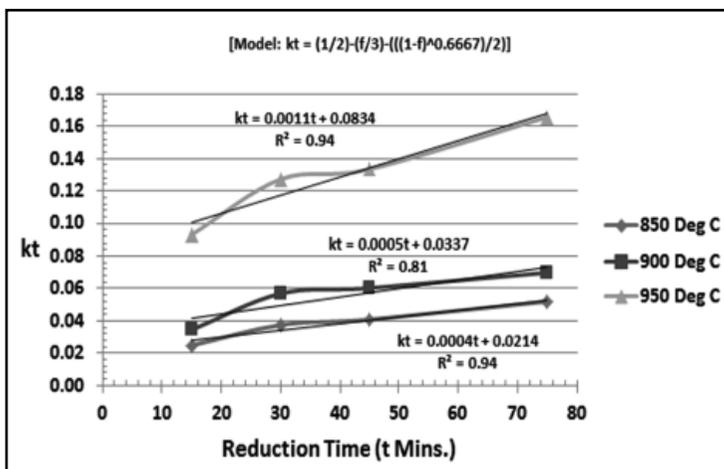


Figure 2: Gaseous diffusion control model

Each straight-line gradient gives a ‘steady state’ value for the average reaction rate in mol.min⁻¹ for each temperature. Values are shown in Table 1 and Deg. K.

Deg. C	Rate: mol.min ⁻¹	Deg. K
850	0.0004	1123
900	0.0005	1173
950	0.0011	1223

1. A. Chatterjee, *Sponge Iron Production by Direct Reduction of Iron Oxide*, 2nd. ed, PHI Learning, Delhi, 2014, 61-74

Procedure 3 - Effect of Temperature and Calculating Ea Value

Temperature influences the Reaction Rate constant (k) and is expressed by the Arrhenius equation:²

$$k = A.e^{-E_a/RT}$$

Where: **k** is Reaction Rate in mol.sec⁻¹, **T** is degrees Kelvin (Deg. C+273) for the reduction zone process, **A** is the pre-exponential frequency of reaction factor sec.⁻¹, **R** is the universal gas constant 8.3145 J. mol⁻¹K⁻¹, **E_a** is the ore Activation Energy in J.mol⁻¹ and **e** is the exponent.

This equation is important generally for determining the effect of temperature on the rate of reactions and for calculating Activation Energy. It shows how temperature alters the proportion of iron oxide above critical energy level and so is able to be reduced. Table 1 values of k for three temperatures enable the calculation of Ea. For calculations, logarithmic version of the equation gives a straight-line relationship:

$$\ln k = \ln A - E_a/RT.$$

EXCEL gives a plot of **lnk** against **1/T** with gradient = **-E_a/R** and intercept **lnA**.

	lnk	1/Tx10⁴
Upper Value	-11.9194	8.8093
Lower Value	-10.0909	7.6268
Difference	-1.8285	1.1825

$$\text{Gradient} = -1.8285 / (1.1825 \times 10^{-4}) = -15,463 = -E_a/R$$

With **R = 8.3145 J.mol⁻¹k⁻¹** gives **Activation Energy J.mol⁻¹**.

$$\text{Activation Energy (E}_a\text{)} = 128,570 \text{ J.mol}^{-1}$$

$$[128.57 \text{ kJ.mol}^{-1} \text{ or } 30,740 \text{ cal.mol}^{-1}].$$

$$\text{Pre-exponential frequency factor } A = 46,120 \text{ sec}^{-1}.$$

2. Enter 'Arrhenius Equation' into Google search for a full description

Validity of Ea Value

Calculated value is a single point estimator for Activation Energy. With no published Activation Energy values for calcined Wealden ore seemingly available, this precludes any direct comparison with findings. However, examples of values reported for other iron oxides and reductant combinations give feasible ranges of values for ores^{3,4,5,6,7,8}.

These show that Activation Energy values range widely from about 15kJ.mol⁻¹ to over 200kJ.mol⁻¹ depending on ore type, condition, stage of reduction studied, reductant type and quality. The empirically derived value of 128.57kJ.mol⁻¹ falls well within this broad range. Sun's article⁴ especially reports a similar value 127.58 kJ.mol⁻¹ for the third stage reduction of oolitic iron ore. Similarly, a value for the reduction of wüstite by CO was found⁹ to be 116.4 kJ.mol⁻¹. Kumar et al⁸ report values for mixed hematite ore fines ranging from 131 – 181 kJ.mol⁻¹ and with the carbon gasification rate being dominant.

3. S. Kumar Baliarsingh and B. Mishra, *Kinetics of Iron Ore Reduction by Coal and Charcoal*, Department of Metallurgical and Materials Engineering, National Institute of Technology, Rourkela, 2008.
4. Y. S. Sun, Y. X. Han, P. Gao and G. F. Li, 'Investigation of kinetics of coal based reduction of oolitic iron ore', *Ironmaking & Steelmaking: Processes, Products and Applications*, **41**, 10 (2014), 763-768.
5. S. Nath, *Study of reduction kinetics of iron ore pellets by non coking coal*, Department of Metallurgical and Materials Engineering, National Institute of Technology, Rurkela, 2009.
6. D. Wagner, O. Devisme, F. Patisson, and D. Ablitzer, *A Laboratory Study of the Reduction of Iron Oxides by Hydrogen*, Laboratoire de Science et Génie des Matériaux et de Métallurgie, Nancy, 2008.
7. M. C. Abraham and A. Ghosh, *Kinetics of Reduction of Iron Oxides and Ores by Carbon*, Indian Institute of Technology, Kanpur, 1973.
8. M. Kumar, P. Mohapatra, and S.K. Patel, 'Studies on the reduction kinetics of hematite iron ore pellets with non coking coals for sponge iron plants', *Mineral Processing and Extractive Metallurgy Review Journal*, **30**, 4 (2009).
9. G. J. Roman-Moguel, Kinetics of direct reduction of unagglomerated iron-ore with coal char, PhD Thesis, University of British Columbia, Vancouver, 1984.

Calculating Smelt Time – An Example

Bloomery smelting to iron involves:

- A quantity of iron oxide with an overall Activation Energy value for smelting with CO
- A fixed ratio of CO:CO₂ gas above the equilibrium value at smelting temperature to achieve iron.

An EXCEL model applies the Arrhenius equation with parameters and data from the 2015 smelt no.8, Table 3, to predict a smelt time. The ratio of gases actual to equilibrium partial pressures for a temperature is used to factor basic reduction rate calculated for that temperature.

No. 8 Smelt Parameter	Value
Reduction zone temperature	1150°C
Post Smelt Burndown Hrs.	1.0
CO:CO ₂ Gas Ratio	5
ppCO:CO ₂	0.833
Equiv. Equilibrium ppCO:CO ₂	0.7
Burden Calcined Ore Kg.	26.5
Calcined Ore Fe%	49.53
O ₂ Mols. to be Removed	351.7
Recorded Smelt Hours	5.5

Table 3: Smelt no. 8 input parameters

Model predicted smelt hours for a range of reduction zone temperatures are shown in Figure 3. The predicted smelting time of 5.6 hours compares well with the recorded 5.5 hours.

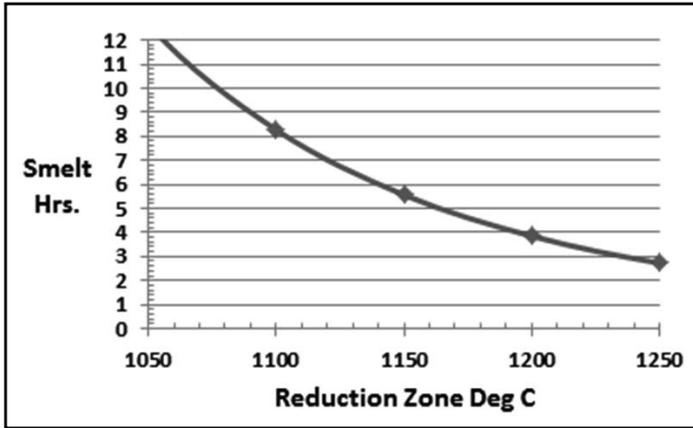


Figure 3: Reduction temperature and predicted smelt hours

Predictive Performance using Historical Data

Figure 4 compares results using other data from much earlier WIRG smelts and a different furnace.

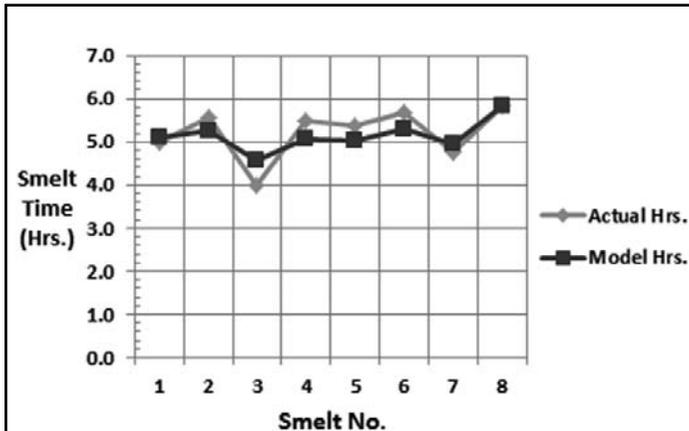


Figure 4: Comparison of predicted and actual smelt hours

Using smelt-recorded ore quantities, reported furnace temperatures and a furnace CO:CO₂ ratio of 4, shows a correlation of 0.86. Several predictions

are very close and, importantly, trends are reflected well although some marginal predictions are evident.

Conclusions

An Activation Energy Value of $128,570 \text{ J.mol}^{-1}$ is estimated empirically for calcined Wealden Beacon Wood Stream siderite ore of 49.53% iron smelted with charcoal of 87% fixed carbon. The estimated value for a pre-exponential Frequency Factor 'A' is $46,120 \text{ sec}^{-1}$.

Whilst literature mentions occasionally siderite type ores reduced under varying conditions, no values are found for comparable Wealden siderite ore with a charcoal reductant. The empirical value compares well with several ore types, iron oxides and reductant mixes reported by other investigators.

The comparatively high value for Activation Energy shows the consistent heat input needed to keep furnace reduction activity high especially during the third stage of reduction.

Reassuringly some predicted smelt times against historical actual outcomes compare very well.

THE INTRODUCTION OF A BLAST OF AIR INTO EARLY FURNACES

An explanation of why a tuyere does not have to have been sealed into a furnace wall

Jonathan Prus

It is now a common (but not universal) practice for bloomery experimentalists to offer up a tuyere to an orifice in the furnace wall, making no seal between the two. It is the purpose of this note to provide an explanation of how and why this works. This is an issue that links experimental practice to the interpretation of archaeological evidence both in the Weald and elsewhere.

As with bloomeries, there is little evidence for the detailed structure of early blast furnaces. The conjecture that there was no positive tuyere seal in early structures is (at least) worthy of investigation.

The effect that obviates the need for a seal is the result of the conservation of energy, a cornerstone of the Newtonian physics that apply to this phenomenon. The energy in question is the kinetic energy of the blown air. The energy of a mass in motion may be expressed as:

$$e = \frac{1}{2}mv^2 \quad (1)$$

Where e is the energy in Joules, m the mass of the gas in kilograms and v its velocity in metres per second. Velocity, v , is a vector, meaning that it has direction. For the purposes of simplifying the following, this fact is now treated as implicit, but it is important because the pressure with which we are concerned is generated downstream. Because energy must be conserved, a stream of air moving from a narrow diameter pipe into pipe with a greater diameter will slow down and draw extra air in behind it or build up pressure in front of it. In practice, such a system will 'try' and do both. The balance between the two ('drawing in' and 'pushing forward') depends in part on the relative size of the external diameter of the tuyere and the internal diameter of the orifice in the furnace wall.

The maximum pressure that can be developed in such a system is given by the expression:

$$P = \frac{1}{2} \cdot \mu \cdot \left[\frac{Q}{a} \right]^2 \quad (2)$$

Where P is the pressure developed given in Pascal, μ is the density of air in Kilograms per cubic meter, Q is the flow of air through the tuyere in cubic metres per second and a is the cross-sectional area of the tuyere in square metres as it enters the furnace wall orifice. The analogous structures of equations (1) and (2) means that they can easily be subjected to dimensional analysis. Alternatively, a full derivation will be supplied on request.

We may work two examples of this effect. We suppose that the density of the air, μ , is 1.3 Kg m^{-3} . Let the flow of air, Q , be $0.007 \text{ m}^3 \text{ s}^{-1}$ (a good bloomery value). Let the cross-sectional area, a , be $3.8 \times 10^{-4} \text{ m}^2$ (roughly like a 22mm. copper pipe). Then the possible pressure, P , is just over 220 Pa, or about 0.002 bar. This greatly exceeds the chimney effect in the three-metre-tall convective bloomeries found in Africa and (as an alternative comparison) the wind-blown bloomeries of Sri Lanka. Turning to numbers that are plausible for an early blast furnace, letting $Q = 0.02$ and $a = 2.8 \times 10^{-3}$ (a 60-mm. blast pipe) we could obtain a pressure of just over 32 Pa. Coupled with chimney effect, this would probably be enough to work a blast furnace.

For either a bloomery or a blast furnace, a gap between the tuyere and the furnace wall may, perhaps, have allowed inspection of the reaction area without any interruption of the blast and without exposing the furnace-master to a dangerous reflux of hot gas.

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EXPLORING BLOOMERY SMELTING DYNAMICS AND IRON FORMATION

ALAN F. DAVIES

Introduction

This scoping work looks at feasibilities for how minerals wüstite, silica, fayalite, carbon, lime and furnace gasses can interact at various temperatures in a bloomery to create iron as a burden mix descends the furnace.

Method of Analysis

Changes in energy levels between chemical reactants and product(s), usually indicated as a number of Joules (J) of heat, show whether a reaction is feasible at a given furnace temperature. For example, wüstite and silica forming fayalite gives out heat of reaction as energy (enthalpy). At the same time producing one solid product, fayalite, from two solid products reduces energy of disorder (entropy) for the reaction. These combined effects give an overall net measure of energy change (total entropy) as a positive or negative number of Joules for the reaction at a temperature. A positive value indicates a feasible reaction whereas a negative value shows it is not feasible. An important criterion is the temperature at which a reaction may either start or stop within normal smelting range.

Standard energies data and how these are used to calculate some examples of energy changes are shown in the Appendix. Importantly, several other relationships are used to determine whether reactions are likely to take place. First of these is the Eyring Equation. This equation uses energy values to calculate the relative rates of different reactions at a temperature. This helps to determine the proportions of minerals over time that are available to take part in reactions. A second relationship is Le Chatelier's Principle. This shows how a temperature change or change in the quantities of reaction products in a system normally at equilibrium, affects whether a reaction is more likely to complete or not. Finally, and again importantly, the Boudouard reaction

gives an equilibrium carbon monoxide (CO) to carbon dioxide (CO₂) gases ratio for a given temperature in a furnace. This determines whether sufficient carbon monoxide gas proportion is available at a temperature to achieve reduction of ore.

The Appendix shows also how rearranging entropy change equation gives Gibbs Energy or Driving Force for a reaction. Temperature increases producing larger negative values (< -10kJ) means the reaction is feasible and more likely. However, large positive values (> 10kJ) means the reaction will cease to give more products. Values between these boundaries indicate an equilibrium mix of reactants and products. At even higher temperatures reactions can reverse re-creating reactants from product(s).

Energy values plotted against temperature for a reaction give graphs showing whether a reaction is possible at a given temperature. These graphs can show how reactions compare, how fast they are reacting and any temperature crossover points where domination by one reaction changes for another.

It is important to bear in mind that each of these equations alone represents an ideal equilibrium process. Bloomeries, however, represent a system of many interacting processes. Even so, any one bloomery smelt will settle either into its own emergent equilibrium or failure state according to the process operating conditions set by furnace management. These conditions include the ore and charcoal qualities used, the burden ore:charcoal mix ratio, any other mineral additions, the burden feed rate, the air blowing rate at stages of the smelt, the furnace temperature profile and smelt duration including the smelt burn down time. Values selected will govern whether a smelt achieves its objectives. However, such variety is managed by setting many of these from prior knowledge or experience and only changing the one or two of interest that may vary a smelt outcome.

Smelting processes examined in this article represent key but linked steps of a smelt. Also, it shows how changes in equilibrium conditions for reactions enable a smelt to be completed. The following sections explore feasibilities and contexts for these key smelting reactions for an open bloomery system.

Reduction of Wüstite to Iron

Second stage ore reduction of magnetite by a low concentration of furnace

carbon monoxide to wüstite ($\text{Fe}_3\text{O}_4 + \text{CO} = 3\text{FeO} + \text{CO}_2$) starts at around 400°C in the upper part of the furnace shaft and completes during descent as the temperature rises towards 600°C. This provides the start point for the third stage reduction of wüstite to iron as the burden moves into hotter zones.

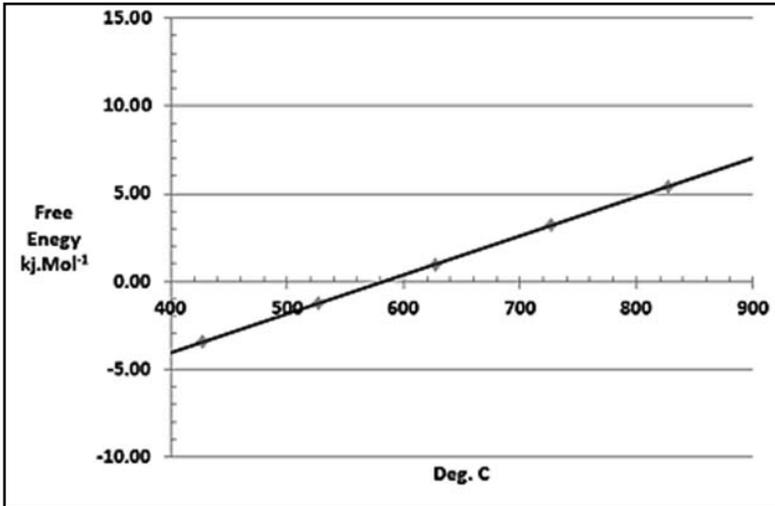


Figure 1: Decreasing feasibility of wüstite reduction by carbon monoxide

However, Figure 1 shows that above 583°C the Gibbs Energy change for exothermic wüstite reduction by carbon monoxide ($\text{wüstite} + \text{CO} = \text{Fe} + \text{CO}_2$) is just entering the positive zone and weakens as the burden heats up in descending the furnace shaft. So, the question is - how is iron being produced when this reaction route appears no longer sustainable?

Two possibilities were explored. Firstly, carbon direct reduction of wüstite ($\text{wüstite} + \text{C} = \text{Fe} + \text{CO}$) is feasible above 722°C and becomes dominant by 780°C over falling direct carbon monoxide reduction of wüstite. Secondly, the forward Boudouard reaction ($\text{CO}_2 + \text{C} \leftrightarrow 2\text{CO}$), converts carbon dioxide gas rising from the furnace hearth zone ($\text{C} + \text{O}_2 = \text{CO}_2$) and that from wüstite reduction, to form carbon monoxide. A 50:50 furnace gas mix of $\text{CO}:\text{CO}_2$ is achieved at 704°C and the critical ratio $\text{CO}:\text{CO}_2 = 4:1$ for wüstite reduction to iron is reached at around 750°C. Moreover, nucleated solid iron is transported down within a viscous slag initially as the burden descends the

furnace shaft.

With the continuous removal of two products, Figure 2 shows a stronger (more negative) Gibbs Energy driving force value and in Figure 3 a higher rate for a temperature, for the role of a gaseous Boudouard reaction in the reduction of wüstite.

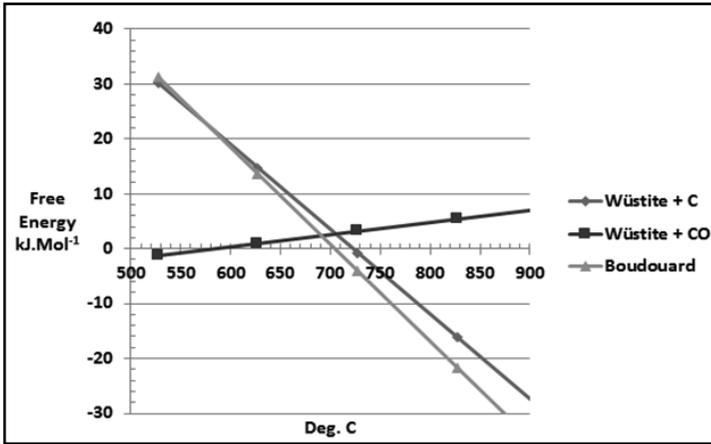


Figure 2: Comparison of reduction effectiveness

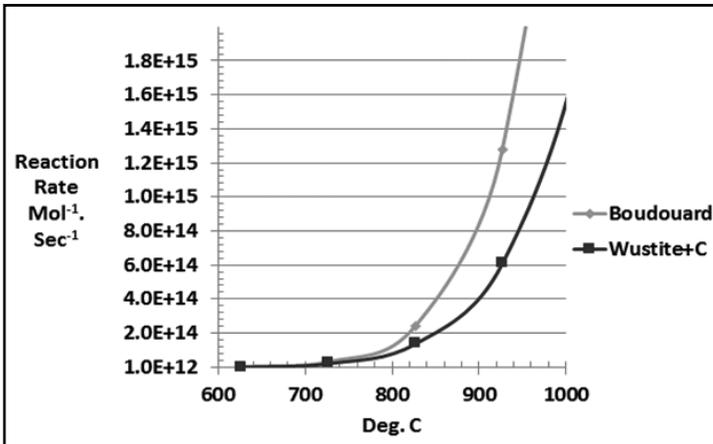


Figure 3: Comparison of reduction reaction rates

Silica Context and the Role of Fayalite Slag

However, bloomery smelting is particularly conspicuous for its silica context comprising calcined siliceous ores, high silica clay furnace structures and silica slags. Figure 4 shows that at low temperatures wüstite and silica can react strongly. Up to around 850°C the reaction driving force supports exothermic fayalite creation ($2\text{wüstite} + \text{SiO}_2 = 2\text{FeO}\cdot\text{SiO}_2$). As the temperature increases to 1234°C this effect weakens progressively until above this temperature a reverse reaction starts for the disassociation of fayalite.

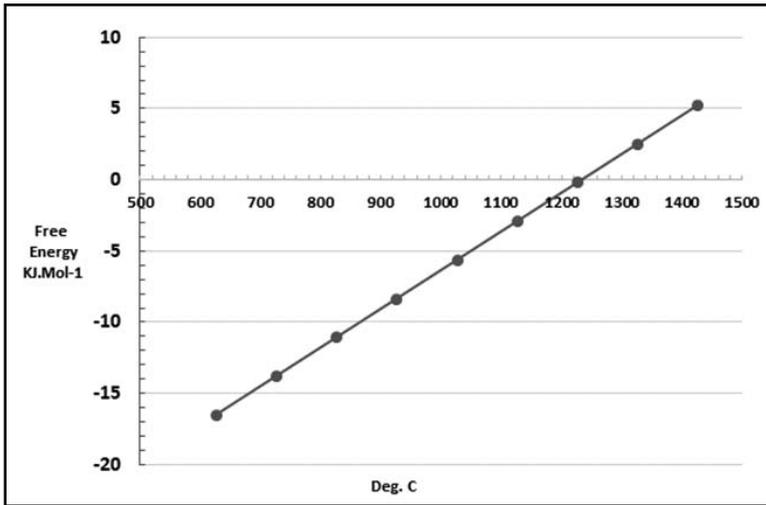


Figure 4: Fayalite formation from wüstite and silica

Early wüstite formed during the 600°C-700°C range will react firstly with ore silica to form fayalite slag giving a mix of reactants and products. Figure 5 shows a typical structure where black is porosity, white is silica and other tones represent granular calcined ore and wüstite all bonded in glassy fayalite. Furnace burden loading provides a continuous supply of ore for reduction to wüstite.

Around 600°C as wüstite forms, Figure 6 shows that the fayalite formation rate is some tenfold faster than the rate for any wüstite directly reduced via the Boudouard reaction which starts around 750°C. So, for these conditions, wüstite creates preferentially a fayalite slag, likely using additional silica from the furnace wall, than to form iron. Importantly the wüstite reduction rate

in forming iron is shown to fall slowly as the burden moves into the lower and hotter zone in the shaft. Correspondingly with rising temperature the fayalite formation rate is falling quickly. Combining these two effects gives a higher proportion of wüstite for reduction to iron as the temperature rises.

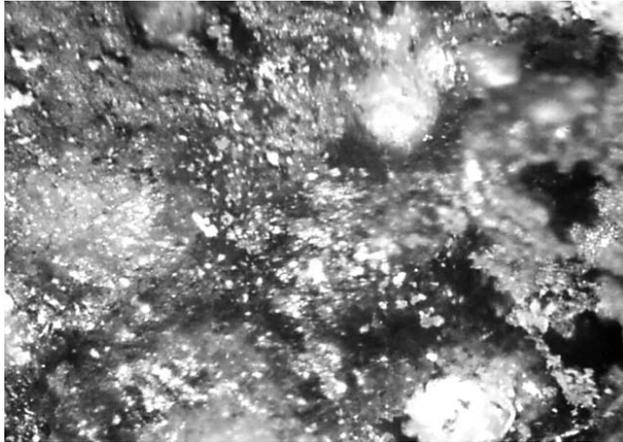


Figure 5: Fayalite slag formation and mix of reactants (x20)

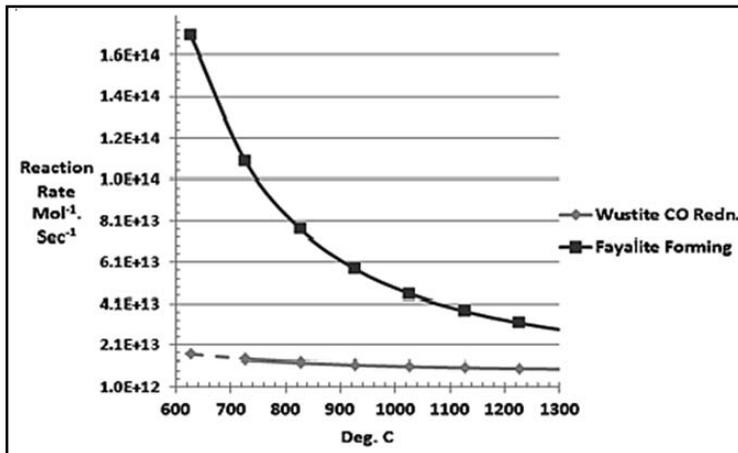


Figure 6: Reaction rates - fayalite formation and wüstite reduction

So, the rate of furnace heating, the volumetric extent of reducing zone and the shaft temperature range are factors influencing burden during its residence time in the shaft. These factors favour wüstite either to form fayalite or be metallised to iron. Indications are that slow furnace heating and longer burden residency time in the shaft favours wüstite to produce fayalite slag. This effect shows that not all bloomery iron from a smelt is produced inevitably from this reduced wüstite.

Metallisation by the Carbothermic Reduction of Fayalite

Above 829°C fayalite can be reduced by charcoal in a furnace to give iron, silica and carbon dioxide ($2\text{FeO}\cdot\text{SiO}_2 + \text{C} \leftrightarrow 2\text{Fe} + \text{SiO}_2 + \text{CO}_2$). This is a more complex process involving:

1. Diffusion of FeO in slag to the slag-gas interface
2. Reduction of FeO at the slag-gas interface ($\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$)
3. Diffusion or flow of CO_2 from the slag-gas interface to the carbon-gas interface
4. Reaction at the carbon-gas interface ($\text{CO}_2 + \text{C} = 2\text{CO}$ - Boudouard forward reaction) to regenerate CO.

An example of iron forming at slag porosity and gas boundaries is shown in an earlier note¹.

Figure 7 shows the overall energy change for the carbon reduction of fayalite producing slag metallisation. The Boudouard reaction removes carbon dioxide so maintaining forward reaction as does iron gravitation in silica slag. Above 1234°C any residual fayalite dissociates into silica and wüstite. Reduction of this wüstite can boost iron yield.

1. A. F. Davies, 'Genesis of Bloomery Iron – A Note', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd. Ser., **35** (2015), 30-31.

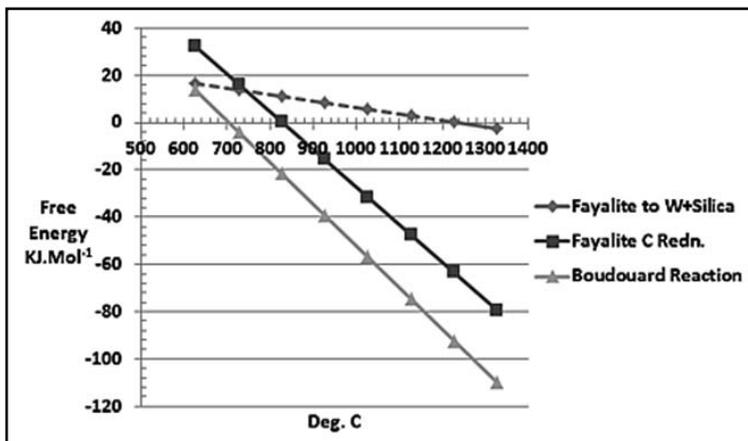


Figure 7: Carbothermic reduction of fayalite

Figure 8 shows reaction rates increasing significantly as temperature increases through 900°C with carbon reduction becoming dominant via the Boudouard reaction over slowing fayalite formation. At 1100°C or higher in the furnace hearth zone an ideally low viscosity slag enables good mobility for, and aggregation of, all iron particles to form a bloom. Furnace 'burn down' at the end of burden loading enables this activity to complete and maximise iron yield.

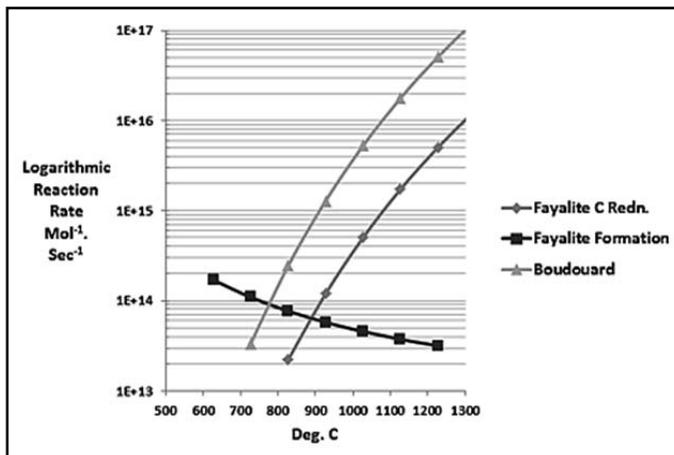


Figure 8: Reaction rates for fayalite formation and carbothermic reduction

Iron Carbide Formation

The usual aim of bloomery iron smelting is to produce a very low carbon iron bloom that can be forged easily. However, Figure 9 shows that above 1197°C iron can absorb carbon by reaction $3\text{Fe} + \text{C} = \text{Fe}_3\text{C}$, producing iron carbide and causing iron to be more like a steel. A bloom extracted from a furnace above this temperature may well contain zones of variable carbon content before this is averaged out by forging.

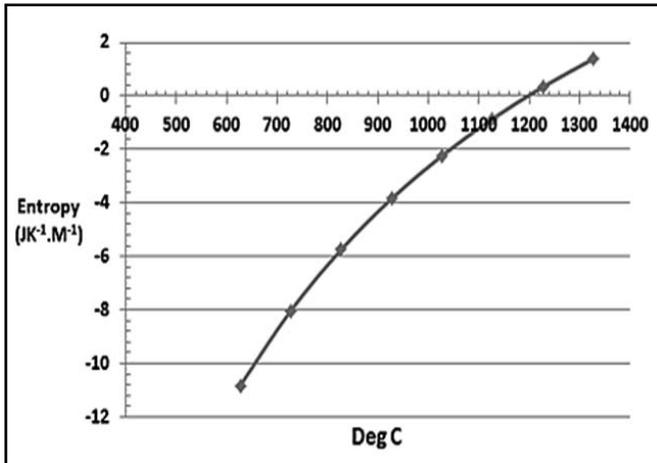


Figure 9: Feasibility for producing iron carbide in iron

Effects of Lime Additions

Other minerals either in the ore or added to the burden can form other mineral phases. For example, lime in a smelt with silica can form calcium silicate ($\text{CaO} + \text{SiO}_2 = \text{CaSiO}_3$) as wollastonite mineral in preference to wüstite forming fayalite with silica. Figure 10 shows greater driving force for wollastonite over fayalite formation. Benefits of lime include a more fluid slag at a temperature and 'surplus' wüstite for reduction to boost iron yield.

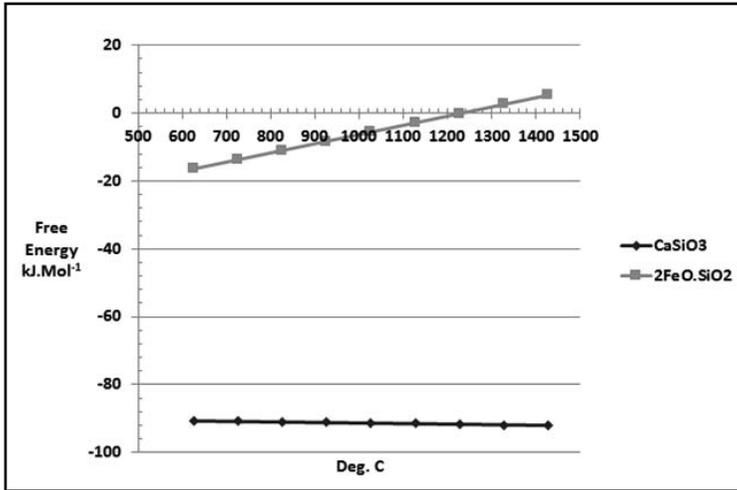


Figure 10: Wollastonite rather than fayalite forming preferentially with silica

Summary and Conclusions

This scoping article explores feasibilities for how heat, energy and reaction-rate changes for bloomery smelting processes influence fayalite slag formation, iron production and its carbon content. To illustrate findings from these basic analyses, Figure 11 brings together temperature related processes, events and interactions as the burden descends the furnace.

Conclusions show two feasible co-dependent processes creating iron. Early-stage low-shaft temperatures of 500°C+ favour initial rapid use of wüstite to form fayalite slag with silica from the ore and the furnace wall. Iron from any free wüstite forms when the burden reaches around 750°C at which temperature the Boudouard reaction achieves the reduction gas ratio. As the temperature rises the fayalite forming rate slows and as the burden reaches 800°C a second wave of reduction starts with increasing rate as the temperature rises even more. Now furnace charcoal, via the Boudouard reaction, reduces fayalite slag, releasing more iron for bloom formation. At the end of burden loading a smelting 'burn down' stage enables the completion of fayalite reduction to maximise iron yield. If the furnace hearth operates much above 1234°C fayalite slag splits into silica and wüstite which in turn is reduced and can boost iron formation.

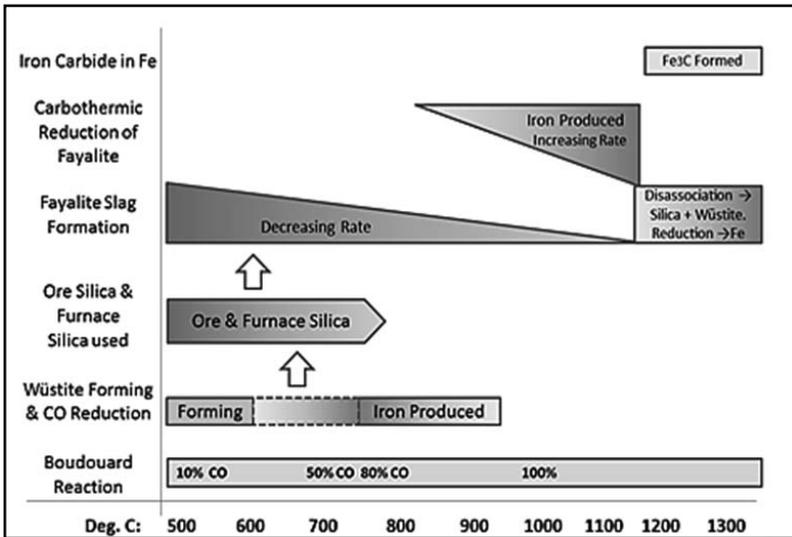


Figure 11: Schema of key furnace processes and events

Other conclusions:

- Lime additions to the burden increase iron yield from a preferential reaction over wüstite, with silica giving calcium silicate as wollastonite mineral in the slag rather than fayalite, so releasing wüstite for reduction
- To avoid excessive early smelt slag and furnace erosion minimise the time that burden is at low temperatures
- To help maximise a bloom yield of low carbon iron, maintain the furnace reducing zone temperature well above 1100°C where the carbothermic reduction rate of fayalite is highest but below 1197°C
- Above 1197°C a more 'steely' iron is likely

Tap slag formation, with its distinctive external flow form, texture and room-temperature microscopically-seen structure of dendritic wüstite in fayalite, has been excluded from this analysis as it represents a loss of iron. A good flow of tap slag late in the smelt is invariably taken as a key indicator for the presence of a good bloom yield of iron. Nevertheless, this fayalite slag formation in the lower furnace hearth zone likely represents an inevitable loss by oxidation of bloom iron by the environments of the bloomery smelting method. This slag typically contains around 14% iron oxide as wüstite in

a fayalitic matrix. Feasibly it could form from oxidised iron combining with descending iron-depleted slag in the lower furnace hearth below the reduction zone.

Appendix

Reference ² - Standard Thermodynamic Values at 25°C. ($T_K = \text{Deg.C} + 273$)

Units:	$\Delta H \text{ kJ.M}^{-1}$	$\Delta S \text{ J.K}^{-1}.\text{M}^{-1}$
FeO	-271.96	60.75
Wüstite	-263.97	65.27
2FeO.SiO₂	-1479.88	145.18
Fe (α)	0	27.28
O₂	0	205.03
C	0	5.69
CO	-110.54	197.90
CO₂	-393.51	213.68
SiO₂	-910.94	41.84

ΔH = Heat given out (negative) or absorbed (positive) during a chemical reaction
 ΔS = Measure of disorder in a substance

Wüstite reduction by carbon monoxide

Reaction:	Wüstite	+ CO	= Fe	+ CO ₂	Net Value	Units
Reaction ΔH	-263.97	-110.54	0	-393.51	-19	kJ.M ⁻¹
System ΔS	65.27	197.9	27.28	213.68	-22.21	J.K ⁻¹ .M ⁻¹

Fayalite formation from wüstite plus silica

Reaction:	2 Wüstite	+ SiO ₂	= (2FeO.SiO ₂)	Net Value	Units
Reaction ΔH =	2x-263.97	-910.94	-1479.88	-41.00	kJ.M ⁻¹
System ΔS =	2x65.27	41.84	145.18	-27.20	J.K ⁻¹ .M ⁻¹

2. J. A. Dean, *Lange's Handbook of Chemistry*, 11th ed., New York, McGraw-Hill, 1979.

Boudouard reaction

Reaction:	C	+ CO ₂	↔ 2CO	Net Value	Units
Reaction ΔH	0	-393.51	2x -110.54	172.43	kJ.M ⁻¹
System ΔS	5.69	213.68	2x 197.90	176.43	J.K ⁻¹ .M ⁻¹

Combustion producing carbon dioxide

Reaction:	C	+ O ₂	= CO ₂	Net Value	Units
Reaction ΔH	0	0	-393.51	-393.51	kJ.M ⁻¹
System ΔS	5.69	205.03	213.68	2.96	J.K ⁻¹ .M ⁻¹

$$\text{Net Value} = \sum \text{Products} - \sum \text{Reactants}$$

$$\Delta S_{\text{Total}} = -(\Delta H_{\text{Reaction}} / T_K) + \Delta S_{\text{System}} \quad (\text{J.K}^{-1}.\text{M}^{-1})$$

For a feasible/spontaneous reaction at temperature T_K then Entropy ΔS_{Total} must be **positive**.

Multiplying equation terms by (-T_K) gives Gibbs Free Energy of formation (kJ.M⁻¹)
 = -T_K.ΔS_{Total} or 'ΔG'

$$\Delta G = \Delta H_{\text{Reaction}} - T_K \cdot \Delta S_{\text{System}} \quad (\text{kJ.M}^{-1})$$

For a reaction to be feasible at T_K then ΔG must be **negative**.

Eyring Equation

An equation that gives mass action reaction rate for a chemical reaction in terms of heat and entropy of reactions (Joules), temperature and various constants. Used to provide a basic comparison between reaction rates for several processes and how quantities or proportions of products may change depending on temperature and time.

$$\text{Formation Reaction Rate } (k) = ((k_b \cdot T) / h) \cdot e^{(-\Delta H / (R \cdot T))} \cdot e^{(\Delta S / R)} \quad \text{Mol}^{-1}.\text{Sec}^{-1}$$

Variable	Value	Units
K_b = Boltzmann's Constant	1.38E ⁻²³	J.K ⁻¹
h = Plank's Constant	6.63E ⁻³⁴	J.S ⁻¹
R = Universal Gas Constant	8.3145	J.Mol ⁻¹ .K ⁻¹
T = Degrees K	Deg. C+273	K ⁻¹
e = Exponent	2.7182818	-

Le Chatelier's Principle

If a system in equilibrium is disturbed by a change in conditions such as temperature or concentration of products, the equilibrium position moves to counteract the change. This can be used to predict the effect of a change in conditions on a chemical equilibrium. The principle is used to manipulate the outcomes of reversible reactions by removing the products to increase the yield of the reaction. This is applied to show how wüstite and fayalite reductions by carbon monoxide are achieved by removing carbon dioxide and formed iron.

Boudouard Reaction

This is a reversible endothermic reaction between carbon monoxide produced from carbon dioxide and furnace carbon, giving an equilibrium mix of gases at a temperature. The reaction is $(\text{CO}_2 + \text{C} \leftrightarrow 2\text{CO})$. Lower temperatures favour backward reaction forming carbon dioxide and depositing carbon. Higher temperatures favour forward reaction forming carbon monoxide. It is important for its role in converting, using hot carbon, a rising flow of furnace carbon dioxide and reaction-product carbon dioxide gasses, to carbon monoxide. This sustains furnace reduction reactions which would otherwise stall.

'THE LOCATION OF MAYFIELD FINERY FORGE': A critique and an alternative view

J. S. HODGKINSON

The location of a possible forge on the site of Mayfield Furnace has been a source of speculation and debate for many years. The most recent contribution has been that of Cornish and Herbert in 2016.¹ This article challenges their interpretation of the evidence and the layout of the site they have postulated.

In February 1981, following a foray to the site, C. F. Tebbutt wrote this description on the site questionnaire now preserved in the WIRG field archive:

The site is reached by a well-preserved, now dry, leat c.170m long, leading from the extreme north end of the Furnace Pond bay. A hollow on the pond side indicates the site of its entrance through the bay. On the downstream side of the bay the first part has been destroyed by the later 'Coach Road'.

From thence it is well marked, banked on the south side and very deep. It was first thought to be the overspill for the Furnace but a smaller stream just south of it, and entering the main stream nearer the bay, could have served for this.

At its east end, where it finally joins the main stream, a further connecting loop shaped ditch joins the stream c.45m lower down.²

Following a further visit by members at the group's AGM in July of that year, a report in the 1982 WIRG Bulletin stated:

It was noted that a channel or leat, now dry, leads from the north end of the furnace bay to join the present stream about 150m downstream. At this

1. T. Cornish, and B. Herbert, 'The Location of Mayfield Finery Forge', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., **36**, 1 (2016), 18-26.
2. Wealden Iron Research Group, manuscript site questionnaire, Mayfield Forge? [sic], 23 February 1981.

*spot there is obvious artificial disturbance on the north bank, with another dry channel looping round to rejoin the stream further downstream. In the main stream itself, at this point and below, are forge cinder and forge bottoms. Fifty metres further, on the public footpath that follows it, the stream reaches cultivated fields named appropriately Great and Little Forge Field.*³

This and the manuscript field notes compiled at the time formed the basis of the entry in the gazetteer of *The Iron Industry of the Weald* which was first published in 1985.⁴ The entry was not revised in the second edition of 1995.

Key to the above descriptions and to Cornish and Herbert's interpretation is the assumption that the site of the forge was close to where the meagre amount of forge slag has been found. Thus attempts to locate the site of a forge by interpreting the layout of the surviving dry and water-filled channels have been constrained by that assumption. This has also distracted attention from the layout of what is essentially a blast furnace site with features that can be observed on many such sites across the Weald.

Both Cornish and Herbert's and the present writer's interpretation of the watercourses on the Mayfield furnace site have been considerably assisted by the detailed topographical survey carried out by the late Crispin Jarman for the Canterbury Archaeological Trust in 2014 (Fig. 1).⁵

In essence, Tim Cornish and Brian Herbert's interpretation can be summarised as follows:

- the forge derived its power from surplus water from the furnace pond, carried eastwards along the spillway channel on the north side of the site;
- this supply could have been supplemented by the creation of a pond in the furnace tailrace effected by the building of a dam across this channel at a point just downstream of the outfall of the stream from the boring mill pond, and adjacent to an indistinct former watercourse that joins

3. C. F. Tebbutt, 'Mayfield Forge', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., 2(1982), 9.

4. H. Cleere and D. Crossley, *The Iron Industry of the Weald*, Leicester, Leicester University Press, 1985, 343-4.

5. N. R. Bannister, and C. Jarman, Mayfield Ironworks, Wadhurst Park Estate, East Sussex, Unpublished Core Monument Record and Topographical Survey, 2014.

the spillway channel;

- a 180-degree bend in the spillway channel a short distance before it joins the furnace tailrace was man-made and intended as a pond to supply the forge;
- where the furnace spillway and tailrace meet a dam across the stream would supply the head of water to power the forge waterwheels.
- this pond could have been used to float cannon from the furnace to the boring mill;

Each element in this interpretation presents a number of difficulties.

When the furnace was in operation water from the pond would be required for the bellows wheel, and any surplus water in the pond would descend down the spillway channel, which this author contends was the deeply cut channel descending from the northern end of the pond bay, and which is clearly shown on the estate map of c.1665. When the furnace was not in use, e.g. at times when the water supply was less reliable or when a smelting campaign had finished, water would be flowing down the spillway but none would be flowing down the tailrace. Water would also flow from the boring mill pond, along its tailrace when the boring wheel was in use, and over its spillway when not or when there was surplus water available. The size of the boring mill catchment would have meant that only a very modest flow of water would have been available from that source.

The plan of the Mayfield furnace site (Fig. 1) is similar to many such sites across the Weald. Firstly, it was laid out in a valley that already had a stream running through it. Evidence of the surviving course of this original stream can be traced on the ground and is shown on the plan. After passing through the pond bay and under the old coach road bridge the furnace tailrace swings to the north and then straightens along a deep channel towards the south east. At the point where this straight channel begins the sinuous course of an earlier channel can be seen alongside it, culminating in a deeply cut 180-degree bend interpreted by Cornish and Herbert as a man-made feature. Most of this sinuous abandoned channel was used to form the end of the otherwise artificial channel that was dug to carry surplus water from the furnace pond spillway. Contrary to Cornish and Herbert, the author believes that the sinuous channel was formerly the original course of the stream along the valley bottom. The assertion that the 180-degree bend could not

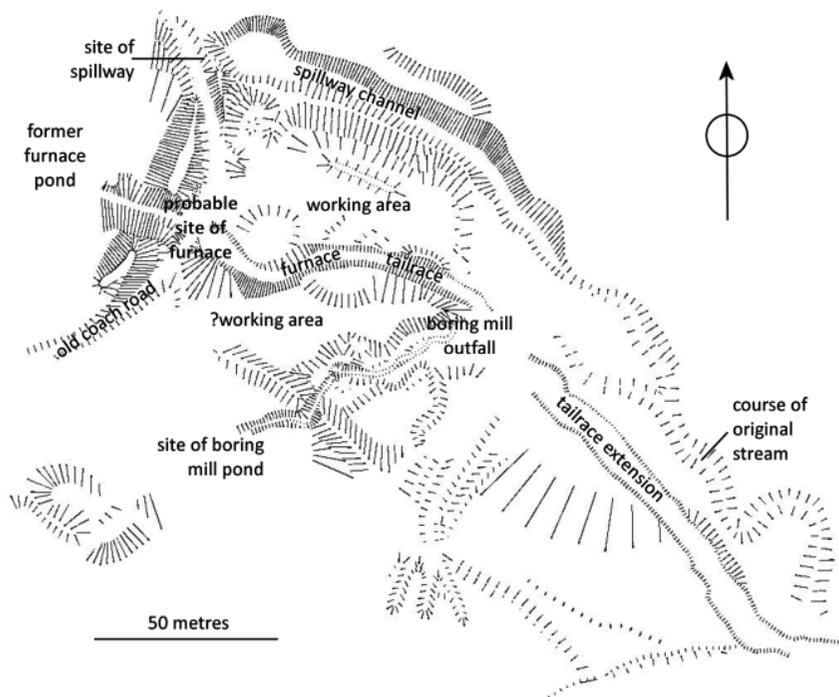


Figure 1: Plan of Mayfield Furnace site (adapted from the survey by Crispin Jarman, reproduced by kind permission of Canterbury Archaeological Trust)

have been natural cannot be explained as such deep-cut bends are common features of Wealden gill streams.

What more obviously appears to have been man-made is the straight course of the furnace tailrace downstream of the outflow from the boring mill pond. This was probably cut deeply to hasten the removal of water away from the working area of the furnace and to lower the level to below that of the spillway channel where it joins below the 180-degree bend. All of this is consistent with the typical features of a Wealden furnace site, with the addition of the separate boring mill pond and outflow.

Forges required much more water than furnaces over shorter periods of time because the wheels powering the finery and chafery bellows, even if not in use at the same time, would need to be rotated faster than the wheel at a

furnace, which was about two rotations a minute.⁶ In the case of the finery hearth, a fierce blast of air would have been needed to raise the temperature of the fire to melt the end of a cast-iron sow and reduce its carbon content; about 1300 degrees Celsius. The chafery bellows would have to produce a slightly lower temperature to forge the wrought iron bloom into a bar. Unlike blast furnaces, where the height of the stack would go a long way towards inducing sufficient up-draught to achieve a smelting temperature, with the bellows providing a consistent flow, forge hearth chimneys would be unlikely to have as much natural up-draught as a furnace, and therefore bellows at a finery forge, which would have been smaller than furnace bellows, would have to operate more vigorously and consequently consume more water. In addition the water-powered hammer, which would operate alternately with either of the finery or chafery hearths (and a second finery is not being considered here) would also need a faster rotating wheel. Operating at the speed of a furnace waterwheel and with an arm case lifting the hammer four times per rotation, the hammer would drop onto the anvil every 7½ seconds - far too slow for efficient working. At least twice that speed would probably be necessary. Thus short-period consumption of water would be greater and reliance on the vagaries of supply from a spillway could not have been adequate. The relatively slow rotation of the furnace waterwheel relied on the surface area of water on the pond to sustain its operation throughout a campaign lasting several months. The more demanding, short-term use of the waterwheels powering the forge bellows and hammer would inevitably call upon a greater volume of the water in the pond which could be replenished during periods of inactivity unavailable to the founder at the furnace. For this reason forges in the Weald had extensive ponds; in 1747 the pond at Woodcock Hammer, by no means the largest in the region, covered more than 80 acres,⁷ and the map showing Mayfield Furnace c.1665 records the furnace pond as extending to more than three acres. A greater fall of water might provide more power for a waterwheel, but it seems inconceivable that

6. J. S. Hodgkinson, 'Notes on Early 18th-century Memoranda on the making of iron', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., 15 (1995), 13-14.

7. J. S. Hodgkinson, 'Early newspapers: further references to the iron trade', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., 36, 1 (2016), 33.

the narrow linear ponds formed in the furnace tailrace and the lower reaches of the spillway channel, that Cornish and Herbert have suggested, could provide enough water to power four pairs of bellows and a hammer for any practical length of time. A greater fall of water would require a higher bay than the depth of the surviving channels suggests, and there is no physical evidence of the putative bay. There would have been periods during the summer when there would have been very little water flowing; a problem which could have been alleviated with a large reservoir of water built up during wetter seasons, but not in narrow channels.

The suggestion that the furnace tailrace could have been dammed at a point just downstream of where the boring mill outflow would have joined it also poses problems for the working area of the furnace, which would probably lie on both sides of the tailrace. The construction of the spillway channel on the north side of the site specifically included a high bank to prevent water from escaping onto the working area; such high banks have been noted on many, if not most furnace sites. No remains of banks are evident on either side of the tailrace that might have protected the working area from water overflowing if the tailrace had been used as a reservoir as Cornish and Herbert have suggested. On the contrary, the layout of furnace sites generally seems to point to a requirement to remove the water, after it had passed the furnace, as efficiently as possible. Water in the tailrace that backed up under the water wheel would hamper the rotation of the wheel and compromise the rate of blast into the furnace. This would also account for the cutting of the straight extension to the tailrace which may have been constructed if earlier use of the course of the original stream (and its 180-degree bend) had proved inadequate in channelling the water away, especially with additional flow from the boring mill. Another dam at the tailrace's confluence with the spillway channel would further hinder the efficient removal of the water.

Crucially, Cornish and Herbert have been unable to suggest a location for the footprint of a forge building and its wheel pits. Excavated examples of forge buildings at Ardingly, Chingley and Blackwater Green have shown them to be typically about 10m wide, with the adjacent wheel pits adding a further 3-4m.⁸ With three waterwheels - finery, chafery and hammer - and an

8. O. R. Bedwin, 'The excavation of Ardingly Fulling Mill and Forge, 1975-76', *Post-Medieval Archaeology*, **10** (1976), 34-64; D. W. Crossley, *The Bewl Valley*

internal configuration whereby one hearth and the hammer would be on one side of the building and the other hearth on the other, wheel pits on both sides of the forge building were essential. These and a spillway to carry away water when the forge was not in use would have been a minimum requirement. The proposed forge dam which, on their plan of the site, appears to be no more than 15m long and was intended to embay two narrow reservoirs formed by the tailrace and the spillway channel, would have been inadequate to achieve the distribution of water for the dimensions of a forge as outlined above, regardless of the insufficient water for the operation of the wheels.

In suggesting the creation of a pond in the upper tailrace, defined by the 64m contour, Cornish and Herbert concluded that this body of water could have been used for the transportation of cannon from the furnace to the boring mill. Given that the water in the tailrace would only have been available in any quantity when the furnace was in operation, and the supply from the boring mill would have been intermittent, it seems unlikely that this narrow body of water would have been either effective or convenient for the purpose suggested. There is no indication on the ground or on the map of c.1665 on which side of the tailrace the furnace stood. The construction of the old coach road in the 1760s, which took place after the furnace ceased working, has also destroyed evidence of the position of the furnace. Assuming, as seems to have been the case with most Wealden furnaces, that the casting arch of the furnace at Mayfield was on the same side as the tailrace, which would have been culverted past the furnace to prevent the risk of molten iron coming into contact with the water, access to the boring mill would have been more simply managed on a wagon via a bridge across the tailrace. Use of the tailrace by a barge would deliver a gun to the end of the boring mill water channel outfall rather than to the boring mill itself which would have been close to its pond bay; thus no advantage would be gained.

Cornish and Herbert have remarked that ‘Tudor ironworkers in a remote spot like Mayfield would find a finery forge useful for making the tools necessary for the blast furnace...’. The presence of a former palace of the Archbishop of Canterbury, upgraded for a visit by Queen Elizabeth in 1573,

Ironworks, London, Royal Archaeological Institute, 1975; C. Place and O. R. Bedwin, ‘The sixteenth-century forge at Blackwater Green, Worth, Crawley, West Sussex: excavations 1988’, *Sussex Archaeological Collections*, **130** (1992), 147-163.

suggests that Mayfield was far from being a remote spot. The fabrication of tools and the repair of the metalwork associated with the mechanisms at ironworks would have been the work of a smith, and most ironworks would have had a smithy for carrying out essential maintenance work. To equate the output of a finery forge with such a routine undertaking is to misunderstand its purpose entirely. Walloon forges produced bar iron by the decarburising of cast iron. As has already been explained this required an elaborate water management system, and it also required the consumption of a prodigious quantity of charcoal; it took about 65 acres of coppice wood at 15 years' growth to produce 75 tons of bar iron at a forge.⁹ This might be a reasonable expectation of the annual output of a forge at that time. And if access to another forge was needed, there were two others, Moat Mill and Hawksden within 5km. Steel for boring bars would be the output of specialised fineries of which a small number existed in the Weald.

That there may have been a forge at the site of Mayfield Furnace is suggested by two field names on the 1843 tithe map of the parish and a small quantity of forge cinder downstream from the furnace site. So when could this forge have existed? From its likely date of construction by Sir Thomas Gresham until it was taken over by Thomas May in 1597 the furnace produced ordnance, so no forge was required nor was mentioned in any deed from the period. After that it can be assumed that its principal product was iron sows and pigs, but the map of the site of c.1665 when it was in the hands of John Baker, and which is detailed in the representation of both the furnace and other buildings, does not show a forge. So if a forge existed then it can only have preceded the furnace.

Schubert mentions, without citation, ironworking on the Archbishop of Canterbury's manor of Mayfield, which included the future location of the furnace site, in 1545 so the possibility exists of an earlier iron works in the same location, however this reference could equally be to Moat Mill, which has been shown to have been in existence by 1544.¹⁰ Were a forge to have been built there one would expect forge cinder to be scattered around the working

9. West Sussex Record Office, Chichester, Cowdray 5128/11.

10. H. R. Schubert, *History of the British Iron and Steel Industry*, London, Routledge, 1957, 381; B. G. Awty, 'Richard and Joan Isted, Ironmasters', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., 6 (1986), 45-9.

area. However, more than a century of blast furnace operation would have effectively covered over any earlier working, the modest quantity of forge cinder found further downstream being, perhaps, all that might remain. A finery forge on what was to become the furnace site would require three water channels and the only evidence of a third channel in addition to the furnace wheel race and the overflow spillway is the one mentioned by Tebbutt in 1981, and that is too far from the main stream to have been associated with a forge building. But if the earlier works were not a Walloon forge with its separate finery and chafery but a bloomforge as has been suggested at a few other sites in the Weald, such as Woolbridge, and as a precursor to Walloon forges at Newbridge and Brookland, a single water course might be possible. An existing pond bay for such a forge would have influenced the location of the furnace that Gresham was to build. The production of ordnance was a profitable business, far more so than a forge.

In conclusion, Cornish and Herbert have taken at face value the evidence they have used to construct their interpretation: that a forge was where the slag was found, and that the small quantity of slag implied a short working life for a forge. The water supply requirements for a forge, which they have seriously underestimated, could not have been satisfied by the solutions they present, and the evidence for there being a forge at all seems far from conclusive.¹¹

11. I am grateful to Peter King for his comments on a draft of this article.

NEW FINDS AT HORSMONDEN FURNACE

Tim Smith

Horsmonden Furnace (also known at times as Brenchley, Shirrenden or Serenden) in Kent, some 10km east of Tunbridge Wells, was in use over a period of about 150 years. The furnace is first recorded in 1564, but not listed in 1717, probably ceasing operation in 1711.¹ A boring mill continued on the site until 1744 probably taking guns from Lamberhurst.² A short-lived fulling mill shared the site with the boring mill between 1719 and 1726.³

For most of the furnace period it cast guns, including during the ownership of three generations of the Browne family which lasted some 73 years from 1604 to 1677. In 1618 John Browne was said to have 200 men working for him at Horsmonden.⁴ In 1620 John Browne was appointed supplier of cannon to the king (James I) and Navy. He was given the monopoly by the king to supply ordnance throughout England, Scotland and Wales and for sole transport to foreign parts for 21 years except the supply to the Merchant Navy, the monopoly for which was held by Sir Sackville Crowe.⁵ In addition to casting iron cannon, he set up a foundry to cast bronze cannon from scrap at Brenchley.⁶ The village of Brenchley is located some 2km NW of Horsmonden furnace and the parish boundary runs through the middle

1. E. Straker, *Wealden Iron*, 1931, 281.
2. WIRG online database Horsmonden <http://www.wirgdata.org/searchsites2.cgi?siteid=589>.
3. Kent History and Library Centre, Maidstone (hereafter KHLC), P192/12/1, Kent rating assessments.
4. *Calendar of State Papers, Domestic, James I, Vol 105*, no.29.
5. *Calendar of State Papers, Domestic Charles I, Vol 429*, no. 58.
6. R. Towes, 'The casting of bronze guns in the Weald in the Seventeenth Century', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 1st ser., 11 (1977), 17.

of the site. Papers in the Hereford Record Office (Anne, the daughter of John Browne married Thomas Foley from Stourbridge) suggest the one site supported both activities, separate references to Horsmonden and Brenchley in the literature probably being the result of the site being split by the parish boundary.⁷ Searches by WIRG members have failed to find a second site in Brenchley. John Browne was also operating a furnace at Barden some 15km to the west. His monopoly was lost on the beheading of the king in January 1649, but he then transferred his allegiance of supply to the Parliamentary forces. At the restoration of Charles II in 1660, despite their late father having supplied the Parliamentary forces, John's two sons Thomas and George were once again appointed gunfounders to the king.⁸

Records of ordnance cast at the furnace show it to have been the major supplier of guns from the Weald in the mid-17th century. For example, 123 cannon were cast there in 1666 representing 30% of the 408 cast in the five furnaces supplying guns that year. Horsmonden was also casting the majority of the largest, demi-cannon of 9ft.⁹ Records for winter blowings in 1656 show 245 guns cast weighing a total of 216 tons 11 cwt sold at 15 shillings a cwt giving a total value of £3,248 5s 0d. In 1659 the total number of guns cast were 290 of total weight 214 tons 9 cwt.¹⁰

Site Visits

Straker notes the pond to be 'a fine sheet of water' and the presence of much slag and a bear in the stream. Field notes compiled by WIRG members in 1973/4 provide the dimensions of the bay (135m long and average 4m high) and state the pond is in water, and that a 'modern' spillway occurs at the

7. J. S. Hodgkinson, 'Notes on Kent Furnaces', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., **13** (1993), 8

8. *Calendar of State Papers, Domestic 1669 Vol 16*, no. 109.

9. R. G. Houghton, 'The Recovered Courthope Papers: Transcriptions', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., **3** (1983), 16

10. G. W. E. Farrow, 'Iron gun-founding in the mid-17th century – The winter blowings at Horsmonden 1656 and 1695', *Historical Metallurgy*, **18**, 2 (1984), 109-111.

southern end. A large bear and glassy slag is recorded in the stream.¹¹

A map of 1647 (see cover) shows the furnace as being below the southern end of the bay and a field named Furnace Field to the NE of the bay.¹² The OS 6in map of 1868 and 25in map of 1895 both show 'beautification' of the site in more recent times with the spillway marked as a waterfall and a second waterfall indicated some 20m downstream. No detailed survey of the site has been found recorded elsewhere.

The pond remains in good water and a footpath runs across the bay. The spillway at the southern end has a stepped construction and is evidently 'modern'. The second waterfall shown on the early OS maps has been washed away leaving a collection of masonry lumps in the stream bed including a low curved band apparently of cement and brick protruding into the stream. Brick and concrete work remains on the south bank of the stream, all of which appears to be related to later work since the bricks are evidently machine-made. A bank on the south side, perpendicular to the stream, may be the remains of a charging ramp which would be accessed from the present road running between Horsmonden and Brenchley which is also shown on the 1647 map. A large bear occurs in the stream amongst brick masonry debris complete with a 'neck' which may be the imprint of the fore-hearth. The bear showed a magnetic response only on parts of the lower side immersed in the water and has a mass of material on top. It is difficult to judge if this material is the remains of a frozen charge or if the bear has inverted when tumbling into the stream and the top material comprising the foundations of the furnace. A second possible bear occurs downstream of this but showed no magnetic response.

The northern bank on the stream stands some 1.75m high and has been eroded by the stream revealing four distinct layers above the natural clay. A top layer of darkened soil containing much slag and agglomerated debris extends to a depth of about 580mm below which is a mixed layer of dark and lighter brown staining for about 280mm, then a band of lighter brown soil for 240mm followed again by a mixed band containing some darkening of the soil for another 240mm. Below this, what appears to be a natural layer of clay extends down 314mm to water level. Thus sequential layers of disturbed

11. C. F. Tebbutt, Horsmonden Furnace, unpublished WIRG Field Notes 1973/4.

12. KHLC, U3615 P1.



Figure 1: Dimensions, hardness and magnetic response suggest this to be one of the hearth stones

material extend to a depth of around 1.340m. In this bank were found two significant objects. Firstly, a large trapezoidal stone measuring 890mm at the top, 406mm both sides and 1040mm at the base and 115mm thick (at the top right corner where accessible). Non-glassy slag adhered in places to the revealed surface (Fig 1). The stone responded to a magnet across its full area. It is proposed that this is a hearth stone which has become magnetic following heating due to the presence of some iron oxide in the composition. Swedenborg, on his visit to England in the first decade of the 18th century, says of furnaces around Stourbridge, 'The hearth itself is made of four hard stones each weighing 1 to 1½ tons [1,016kg -1,524kg]. The largest stone makes up the base of the hearth, and the other three its walls. A fifth one is placed over the tapping hole'.¹³ The stone was extremely hard and it proved

13. J. Hodgkinson and A. Dalton, 'Swedenborg's description of English Iron-making', *Wealden Iron*, Bulletin of the Wealden Iron Research Group, 2nd ser., 19



Figure 2: Conical boss with lugs and centre hole thought to be for attaching a boring bar to the water wheel

impossible to take a sample for analysis. Cleere and Crossley refer to specific quarries where especially hard sandstone was excavated for hearths.¹⁴

Also found in the stream bank at a depth of about 1m is what is believed to be part of a chuck to attach the boring bar to the hub of the water wheel (Fig 2). Once cleaned of adhering matter, the item responded strongly to a magnet and is made of cast iron. This circular boss has two lugs attached to a flat face on one side and part of a curved dome on the opposite face. One of the lugs has an irregular hole suggesting a possible means of attachment to the wheel. The other lug has a slightly raised circular imprint which may be the remains of an attaching pin. A hole measuring approximately 50mm

(1999), 51-52.

14. H. Cleere and D. Crossley, *The Iron Industry of the Weald*, Cardiff, Merton Priory Press, 1995, 246.

diameter passes through the centre. The apparent dimensions of the boss, approximating for its irregularities, are: diameter of flat face 178mm, height of lugs 50mm, height flat face to dome 114mm. A similar looking item was found during the excavation of Pippingford furnace and is illustrated by Cleere and Crossley.¹⁵ Speculation that this might have been an intermediate support bearing for the rod was dismissed on the grounds that the hole showed no evidence of polishing and that, based on the find of a boring bar at Stream Furnace, Chiddingly, the boring bar was 65mm diameter and of octagonal section. The drive end of the Chiddingly bar was rectangular in section and a hole is drilled across this presumably to pass a pin through to lock it in place.¹⁶ A loose but fixed fit of the bar into the chuck may be to accommodate any lack of trueness in fitting the chuck to the wheel, similar to a modern universal joint. The object had much agglomerated material adhering to it made up of a mixture of small pieces of glassy slag containing prills of iron, along with charcoal and sand, all cemented together with a mass of brown coloured material which on analysis was found to be hydrated iron oxide. This is possibly oxidised swarf produced during the boring of the cannon although no evidence of surviving iron turnings was found and no response to a magnet occurred. In one place the agglomerate had formed a 'stalactite' within the bank some 500mm long. A method of attachment to the wheel was illustrated by Biringuccio in 'Pirotechnia' published in 1540 (Fig 3).¹⁷

The ground below the bay is now wooded and contains much slag, darkened soil, bricks and tile. Tile and thin bricks without frogs and coarse in texture, indicative of material contemporary with the furnace, had been uprooted by fallen trees below the centre and northern parts of the bay suggest several buildings had been present. The remains below the northern end of the bay may relate to the later fulling mill which could have operated with an undershot wheel fed from the original spillway evidenced to be at the

15. Ibid., 261.

16. E. M. Trent and E. F. Smart, 'Further examination of cutting tip from cannon boring tool', *Historical Metallurgy* **18**, 1 (1984), 8-12.

17. C. S. Smith and M. Gnudi, (trans.), *The Pirotechnia of Vannoccio Biringuccio*, New York, Dover, 1990, 309.

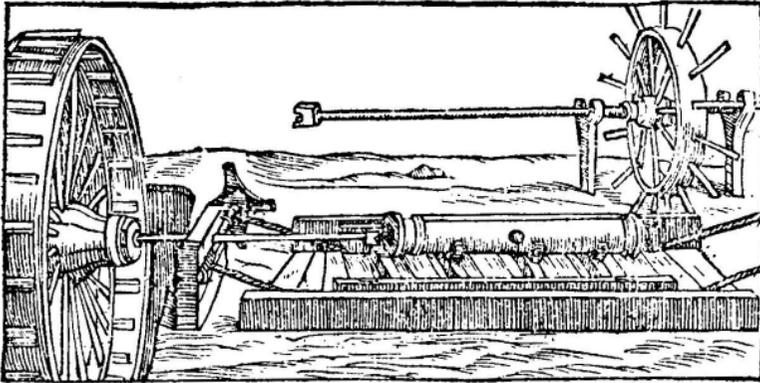


Figure 3: Illustration of boring a cannon, from Biringuccio's Pirotechnia, published 1540

northern end of the bay.¹⁸ A marshy area below the bay in this vicinity may indicate a processing area for fulling, and a lessening of the gradient to the top of the bay to the south of this may have afforded access to the building.

Below the northern end of the bay a channel runs where the woodland adjoins a field running to the stream about 100m downstream of the furnace site. This suggests a spillway was present at the northern end of the bay.

Nowhere within the working area showed any indication of copper staining to suggest that casting of bronze cannon had been carried out on the site.

In conclusion, this was evidently a very important site with a long history of activity and should be considered for scheduling as an ancient monument.

Acknowledgements

To those who attended the foray, cleaned up the finds and commented on the draft report. Site visit on February 4th 2017 by kind permission of the present owner, Rodney Gibb

18. R. Bonnett, 'Hempstead early fulling mill', *Sussex Industrial History*, 46 (2016), 43.

THE ST LEONARD'S FOREST IRONWORKS: Two previously unrecorded leases

J. S. Hodgkinson

It can be inferred from Daniel-Tyssen's account of the parliamentary survey of 1656 that the rent from the ironworks in St Leonards Forest, in the manor of Chesworth and Sedgwick, near Horsham, formed part of the jointure of Charles I's queen, Henrietta Maria, until her death in 1669.¹ The works had been leased by the Crown in 1602 to John Caryll for 60 years from Michaelmas 1601, but had suffered depredations during the civil war, though the lower forge, the larger of the two iron mills, must have been repaired as it had been sub-let to Walter Pawley when the parliamentary survey was undertaken. The Carylls' lease expired in 1661 but it has not been noted hitherto that two further leases of the works were granted subsequently. Following his father's example, Charles II included the works in the jointure for his queen, Catherine of Braganza, and it is in the records of the trustees of those estates that a lease was recorded in 1681.² The lease was granted to William Broxholme of Barrow-on-Humber in Lincolnshire, and was dated from the 25th March of that year. Its wording seems to have copied that of Caryll's lease with the annual rent remaining the same at £36 13s 4d. The two forges were not identified separately as they had been in the 1656 survey and a reference in the lease to furnaces ignores the fact stated in the survey that the furnace, at the lower forge site, had been out of use since about 1615. The term of the lease was for 31 years.

Broxholme's lease, however, cited a previous lease of the ironworks, dated 27th June 1662, to Sir Edward Greaves, Bt (1613-80), as part of a larger grant to him by Charles II of the Forest of St Leonards. Greaves was an eminent

1. J. R. Daniel-Tyssen, 'The Parliamentary Surveys of the County of Sussex, 1649-53', *Sussex Archaeological Collections*, 24 (1872), 240.

2. The National Archives, Kew (hereafter TNA), LR 2/143, ff.25-8.

doctor of medicine, the first to be given a baronetcy, who became physician-in-ordinary to Charles II.³ For someone in his position it is hard to see how he would have been active in the iron industry, but if it is seen as granting him a prestigious landholding in return for a rent that contributed towards the private income of the royal consort, it is more easily understood. The fact that the works were described as ruined in the list of 1664, and as derelict 12 years later, seems to confirm this. Such would seem to be the case too with the lease to William Broxholme (c.1626-84). He was from a well-established Lincolnshire family and had held various positions in county administration before entering parliament for Grimsby in 1673.⁴ His will indicates that he had previously acquired other properties from the Commission of the Revenue under the jointure of Queen Henrietta Maria.⁵ There is, however, a further connection between Broxholme and iron-making. In 1668, together with Sir Joseph Seldon, he had taken titular possession of the two forges at Lydbrook in the Forest of Dean when they were mortgaged by their owner, Benedict Hall.⁶ Under its terms the lease of the St Leonards works was declared void if possession had not been taken within five years. Broxholme died three years into his tenure.⁷

3. N. Moore, 'Greaves, Sir Edward, baronet (*bar.* 1613, *d.* 1680)', rev. M. Bevan, *Oxford Dictionary of National Biography*, Oxford University Press, 2004; online edn, Jan 2008 [<http://www.oxforddnb.com/view/article/11369>, accessed 10 Feb 2017].

4. <http://www.historyofparliamentonline.org/volume/1660-1690/member/broxholme-william-1626-84> (accessed 10 Feb 2017).

5. TNA, PROB 11/376/135.

6. Gloucestershire Archives, Gloucester, D1677/GG/950.

7. I am grateful to Philip Riden for drawing my attention to Broxholme's possible connection with Sussex ironworking; it has only taken 20 years to follow this up. I am grateful, too, to Christopher Whittick for commenting on a draft of this note.

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