

IRON WORKING – The Bloomery furnace & Smelting Process

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1. HISTORICAL ASPECTS - Origins & Early Processes

How, when and where man first discovered that a rather uninteresting-looking rock could be converted into a useful metal is not known; but more than four thousand years ago a simple process – now called direct reduction – was in use in the Middle East for making wrought iron. It was based on a chemical reaction taking place in a simple furnace to remove the oxygen from the iron ore. Originally finds, of pure, usable iron were rare and of meteoritic origin. Artifacts such as simple cutting tools made of a bone handle and back studded with small flakes of iron have been copied by Eskimos in Greenland. Similarly bits of a copper based tool has been found lodged into meteoritic iron; no doubt used to prize off flakes of usable iron. Archeologist deduce from this that though pure iron was used, the means whereby to produce and work it required a more inquiring mind to develop the early smelting techniques to release usable iron from its various ores.

Though iron production on an industrial scale is a relatively recent discovery, more than four thousand years ago a simple process - now called 'direct reduction' using what has become known as a Bloomery Furnace - was in use in the Middle East for making wrought iron. It was based on a chemical reaction, the removal of the oxygen from the ore.

Although iron has a strong affinity for oxygen and will, if left unprotected, revert slowly to the oxide form, as is seen in rust, there is, fortunately, another element, which has an even greater affinity for oxygen. This is carbon. If iron ore is heated in contact with carbon, the oxygen in the ore unites with the carbon to form an flammable gas, carbon monoxide. This burns away, leaving iron behind.

The earliest device for producing iron, the Bloomery, was a small furnace most probably built of clay. Charcoal, made from wood, was the fuel and the fire was fed air with manually or foot operated bellows. Small pieces of iron ore, charged into the Bloomery on top of the burning charcoal, became after some hours a little piece, or bloom, of wrought iron, usually about as big as a man's fist. With such very simple equipment, output was tiny and iron was scarce and expensive, so it was only used

for a few purposes, such as making tools and weapons, for which it was much better than anything previously available.

EARLY IRONWORKING IN BRITAIN

Ironmaking spread to various parts of the Middle East and then across Europe, reaching Britain by about 450 BC. Because the Bloomery was small and needed only clay, iron ore and timber for charcoal, it could be set up anywhere these materials could be found, so it spread fairly widely in Britain. When the Romans occupied Britain from AD 43 onwards they found an established, though still small and scattered iron industry and they expanded it, for iron was useful to them, both for weapons and for agricultural tools. Most of the Bloomery furnaces were in the Weald area of Sussex and Surrey when the Romans arrived, but they developed other areas such as the Forest of Dean and South Wales. Traces of Roman iron working can still be seen in all these areas.

After the Romans left in about AD 410 the ironworks suffered from wars and uprisings, but ironmaking never ceased throughout the Middle Ages and new uses were found for the metal.

Throughout the Middle Ages, about 13 Century onwards there were several Technically improvements to the Bloomery furnace. With the introduction of waterpower to work bigger bellows larger Bloomery furnaces could be built and simple power hammers could work the larger Iron Blooms produced. Elsewhere, where even such basic technologies did not arrive, whole communities would be involved in operating small hand and foot furnaces producing only very small quantities of wrought iron, sufficient perhaps only to make an arrow or spear head.

CAST IRON

In the fifteenth century, came the first really important development. A new type of furnace, the blast furnace, was devised in the iron-working district near Liege, in what is now Belgium. These made greatly increased outputs possible and introduced a new form of iron, cast iron. The process, known as indirect reduction, spread to Britain, where the first blast furnace was erected at Newbridge, Sussex, in 1496, and it eventually superseded the Bloomery completely.



Cast Iron Piano Frame

Cast iron was made by smelting iron ore with charcoal fuel in the blast furnace, where it melted and accumulated in the bottom (or hearth), from which it was released (tapped) at intervals of several hours. When tapped, the molten iron ran into a series of long narrow channels made in a bed of sand and arranged in the shape of a comb, where it solidified and was broken up into pieces when cool enough. A fanciful resemblance of the comb shape to a sow with its litter gave the name pigs to the pieces of iron, and the term pig iron is still used, although production methods have changed and the pig beds have disappeared.

There was not much use for cast iron as such at first and most of it was converted to wrought iron in a separate furnace called a finery, where it was heated in a charcoal fire and subjected to a blast of air which burnt out the carbon (or decarburised the iron). But cast iron did have some applications. Simple castings such as firebacks and graveslabs were made, as were cannons and cannonballs. The first recorded use of a furnace for casting cannons was in 1543, at Buxted, East Sussex. Later, as industrialization developed, new uses were found for cast iron, but even then most of it was converted to wrought iron.

Indirect reduction had several important effects on ironmaking, besides facilitating an increase in production. A blast furnace operates continuously, day and night, and needs mechanical power to work the blowing machinery. So the furnaces could only be set up where there was the necessary natural combination of iron ore, timber for charcoal and a stream or river for waterpower. Thus the iron industry settled into a small number of districts where all the basic requisites were to be found.

By the sixteenth century the Weald was Britain's biggest ironmaking area but the blast furnace and finery spread to other districts from about 1560 onwards. Indirect reduction was in use in Staffordshire by 1561/2, South Wales and Shropshire by 1554 and Derbyshire by 1582. By the end of the eighteenth century ironmaking was concentrated in the Weald, the Forest of Dean, South Wales, West Midlands, North Wales, North Staffordshire/Cheshire, Derbyshire/ Yorkshire and Furness.

2.THE VARIOUS FORMS OF IRON

In spite of living in the 'Silicon chip technology age' we still rely heavily on iron .The steel industry, though nearly vanished in the UK is still globally a major industry. Iron played a vital part in the industrial revolution (1760) and it is still indispensable to life, as we know it today.

Though the industrial processes to convert iron ore to Steel in Blast Furnaces in vast quantities were only developed in the mid nineteenth century, as long ago as 4 thousand BC man discovered the way to extract small amounts of iron from iron bearing rocks.

So what is iron and where can we find it?

What are properties and its nature? It is not the simple material that it might appear to be.

To start with a definition, iron is a metallic element with the symbol Fe (from the Latin Ferrum) and a melting point of about 1150 degrees Celsius (2100 Fahrenheit) upwards, the actual temperature depending on the form of the metal. Iron has the property of uniting chemically (or alloying) with numerous other elements, some of which confer

useful properties on it. On the other hand, it will also unite with some elements, which have a deleterious effect.

The element iron, or Fe is number 26 of the periodic system and has an atomic weight of 55.847. Its density is 7.88g/cm³, and its melting point is 1535 degrees C. It is the most common non-gaseous element after Silicon and Aluminum, in the earth's crust, of which weight of iron it is estimated to occupy approximately 5%. It is the fourth of the eight elements that make up the earth's crust, O, Si, AL, **Fe**, Ca, Na, Mg, and K. However, though abundant it is found in relatively few places in a form, which is easily usable.

Iron rarely occurs as a pure element, in its metallic or 'native form' due to its tendency to react with surrounding elements, forming an iron compound. With rare exceptions of relatively pure meteoric iron that has rained in from outer space; iron is always found as 'iron ore'. Iron can form compounds with non-ferrous metals, of which there are several types, and all need complicated processing before they become a recognisable metal with the characteristics of pure iron.

One of the elements that unite with iron very easily is Oxygen. This is what is commonly known as 'rust'. Any recently produced iron extracted from any compound unless protected will react with the air to rust. The reddish colored flaking surface of a rusty nail is actually a compound ie Iron Oxide (Fe CO_2)

In the very distant past iron subjected to heat and air has resulted in the vast deposits of Iron oxides to be found in the earth's crust.

Theses iron oxides also contain small and varying amounts of other elements in chemical combination and are mixed physically with earthy materials such as sand and clay. In appearance they are a rocky substance, varying in colour from light to dark or purplish brown.

Basically Iron making depends on getting rid of the unwanted elements and foreign matter from the ore and controlling the amount of those, which are beneficial.

Because of its ability to unite with other elements iron can take many forms but it is possible to divide it into three major groups: **wrought iron, cast iron and steel**. Today steel is by far the most important, cast iron is, still produced and wrought iron is extinct. Wrought iron is the oldest, dating back at least 4000 years.

Wrought iron, the type of iron produced in small quantities in a Clay furnace called a 'Bloomery' is a pure form of iron and has a fibrous structure. Wrought iron though pure can however contain small amounts of impurities ie slag from the smelting process. It is strong in tension, that is it resists forces tending to stretch it, and it can be shaped by hammer, squeezing or rolling with the assistance of fire (heat).

Wrought iron is no longer commercially produced – one of the last structures built of wrought iron is the Eiffel Tower in Paris (1889). Today the only source of wrought iron to be found is in old town & country post and railings and iron artifacts. For the blacksmith with an environmental conscience this is a potential source of material.

Mild Steel. Is the modern equivalent to wrought iron. It is strong and malleable and has many uses. Mild steel contains .15% > 3% Carbon content.



A Mild Steel

Cast iron, which dates from the fifteenth century, is crystalline and relatively weak in tension. It cannot be shaped by hammering but it can be melted and poured into a mould, the shape of which it will take when it cools and solidifies. A Cast iron pot for instance will break if dropped on a hard surface. The broken pieces will reveal a very grainy structure.

This is because Cast iron is an alloy of iron and carbon, containing up to about five percent of carbon. Increase the carbon content (a process that can be made to happen when hot iron is brought into contact with pure carbon in a controlled environment) the resulting iron is extremely strong and could not be bent but as a consequence the iron becomes more brittle and can be shattered by impact.

Steel (a mixture of iron carbon and other elements) is the most widely used form of iron today. It is the most versatile; it can be simple or more complex alloy, containing a number of other elements. Bulk steel manufacture only became possible after the invention of the Bessemer process in 1856.

Steels can be produced in a range of internal structure, hardness, and malleability etc and be made not to be susceptible to reacting with Air (Oxygen) that is to resist rusting. These are the Stainless steels with highly polished surfaces going into products like sink unites and surgical equipments.

3.IRON & iron ores. Forest of Dean

Iron is found as a compound combined with many other elements. Most typically in the form of an Iron Oxide or Iron Carbonate (formed in association with Limestone)

Forest of Dean iron ore

History

~500 B.C. Mining began in the Iron Age.
1930 Commercial iron mining ended.
1968 Opened as Show Mine.



Iron Ore from the Forest of Dean

Geology

Clearwell Caves are a series of natural karst caves in Carboniferous Limestone, which is known locally as the **Crease Limestone**.

200 Million years ago, the caves were filled with iron deposits, an extremely pure form of **haematite** containing more than 80% iron. Most of the mines in the area closed between 1890 and 1900 because mining became uneconomic due to the thinning of the ore with depth, and the increase in competition from cheaper Spanish ore.

The iron ore is intermingled with **ochre**, a mixture of iron oxides produced by the oxidation of the ore. It is located in pockets both in the ore and the rock.



*Different coloured iron oxides called Ochre at
Clearwell Caves- Forest of Dean*

Description

The bulk of the iron ore was mined in Roman times. It was used to make tools, weapons and later in the manufacture of machinery. Today the ore is still mined, but not for the iron any more. The main reason for today's mining is **ochre**. Ochre is a mixture of iron oxides, producing many different colours ranging through browns and reds to yellow and deep purple.

Ochre is used as pigment for various paints and for cosmetics:

- **Artist's pigment:** ochre can be mixed with several mediums and used as an acrylic, oil or watercolour.
- **Paint finish:** ochre is mixed with lime or an oil-based paint. This results in a cheap and easy to use paint for walls.
- **Cosmetics:** ochre can be mixed with vaseline or a simple, base moisturiser and placed on the face. But although ochre is a natural substance, it may cause an allergic reaction.

Clearwell Caves is the only working ochre mine in Britain. It produces 3-4 tonnes a year, which is collected by scraping the ochre from the walls by hand. The ochre is sold in the shop on the premises; the colours of the ochre are not blended, which produces a large variety of colours, varying from pocket to pocket.

The underground tour is unaccompanied and takes the visitor through nine well-lit caverns or **churns** as they are known locally. Some artificial pools and plenty of flowstone of various colours including white, red and green makes the mine appear like a natural cave. Other features include **Barbecue Churn** complete with toilets and barbecues. The show section includes only a fraction of a complex which covers 245 hectares and comprises of hundreds of kilometres of passages which zig zag up and down the strata of the limestone from east to west at an angle of 15°. It has been mined to a depth of 180 metre below the surface. Since the mine closed the water level has returned to its normal level of around 120 metres. There are displays of minerals, mining tools and machinery. Traces of older mining techniques such as fire-setting and use of picks may be seen on the walls. Stout footwear is recommended, however the mine is unsuitable for the less mobile.

A fine two storey surface building of local stone, in typical Forest of Dean style, houses several vintage engines and a compressor. It also contains a tea room which sells snacks and refreshments, a Museum of mining relics and a Gift Shop which even sells caving lamps. Parking is free and there is a large picnic area.

Deep Level Visits can be arranged for the more adventurous groups (about 10 people). They involve some climbing, crawling and getting dirty. Experienced guides ensure that the trips are educational and interesting. Helmets and lamps are supplied. Telephone for details.

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4.FUEL – Charcoal

For the best results to smelt iron ore in a furnace wood is first converted to charcoal (which will provide the necessary heat and most importantly the right gaseous atmosphere. The oxygen that is in association with the iron ore has fortunately a greater attraction to the Carbon as it burns in an oxygen-reduced environment. The burning charcoal will produce Carbon Monoxide (CO) and will attract the Oxygen from the iron ore to be expelled in the form of Carbon Dioxide (CO₂) – being one the products of combustion. The forced air via the Tuyeres at the base of the Bloomery furnace will produce sufficient heat to maintain the smelting process that essentially takes place about 2/ 3rds of the way up the furnace.

Charcoal is best produced from 2 year seasoned hard woods. Traditionally large piles of wood were put into a Charcoal Clamp, covered with soil and set alight in the centre of the clamp. The internal combustion was controlled by reducing or increasing the impute of air which was introduced by natural draft along channels at the base of the clamp.

The traditional methods of producing charcoal necessitated that about one third of the clamp wood was burnt to produce sufficient heat to char the remaining wood.

A more efficient process using the retort method can be used to produce good quality charcoal. Seasoned wood is staked in a metal bin through a sealable and air tight entrance (it is best to insulate the bin) .The bin has an exhaust pipe attached near to the entrance.

The bin is sealed and heat (using scrap wood) is provided under the bin. Firstly water is driven off in the form of steam and then after an hour or so of heating Pyrogenic gases expelled from the bin start to ignite in the flames under the bin. At this point the fire underneath does not require to be replenished as the exhaust gases continue to sustain the heat required to char the wood within the metal bin.

To achieve the reduction of iron from the ore about 2:1 weight of fuel to ore will be required.

5.SMELTING PROCESS – using a Bloomery Furnace

General Technology of Iron Production

The production of iron metal from an ore, is an integrated process. This means that there is a succession of separate actions and processes, in which the *product* from one action or operation is the *starting point* of the next.

The base material for making iron is ore. To gain the iron contained in the ore, the mineral structure has to be broken up and unwanted materials removed. This can start by what is called mineral dressing, or in other words the upgrading of the ore, through physical operations like Comminution (breaking) or chemical operations such as roasting (heating). Next, ore and fuel, usually charcoal, are fired in a furnace in a reducing atmosphere. This operation is called smelting. Air-supply for the burning fuel is provided by forcing the air through pipes, or by natural draught, caused by the chimney effect of the furnace.

During smelting the iron minerals are reduced and broken up by reaction with the burning fuel. The unwanted minerals and elements, of which silicon (SiO_2) is the most important, react with part of the iron oxides from the ore and with the fuel ash, and form a liquid slag. It is possible to add extra agents to the furnace, called fluxes, to lower the melting temperature of the slag. The slag envelops and transports the reduced iron, in particles or flakes, downward through the furnace, protecting it from reoxidisation. The final product of smelting, besides ash and slag, is called a 'bloom'. This is a rough, often spongy mass, containing metallic iron flakes and nodules that have sintered together, mixed with bits of slag, partially reduced ore, unburnt fuel and parts of furnace clay. The bloom gives the pre-industrial iron production technology its name of 'the bloomery process'.

When insufficiently pure, the bloom has to be refined. This is done by hammering the bloom to smaller pieces and sorting out the iron particles. These fragments are then forged, often in an open furnace with a forced air-supply. This means that the iron fragments are heated until red-hot and soft, and subsequently hammered to squeeze out remaining slag and consolidate the fragment into a larger workable size. This piece of iron can then be worked into an artefact in a Blacksmith Forge.

Iron Ore Processing:

1. Ore

Besides iron minerals, an ore is composed of non-ferrous elements and minerals, also called gangue or impurities. The gangue can be separated into main and trace elements. The most common non-ferrous minerals are SiO_2 , Al_2O_3 , CaO , MnO_2 , MgO , K_2O and TiO_2 , and can be found in varying ratios in most iron ores. The presence of trace elements, like Sn, Ag, Zn, Ni and As, differs in each ore-body and might allow the determination of which ore led to which slag or object.

Ores are found in a many forms, ranging from sands that have to be sieved to tough rocks that have to be broken up with considerable force. Many classifications are possible, but a division by the chemical composition of the iron mineral is most common. This does not necessarily mean that the iron mineral is also the most prevalent component. In this way three main groups can be distinguished. Similarly, the individual ores are generally named after their main iron mineral. Still, the distinction between ores used here is rather arbitrary; it does not take into account the reducibility or availability of the ore:

- Oxides (Fe_xO_y), for example: Magnetite (Fe_3O_4); Haematite (Fe_2O_3); Limonite $\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$.
- Carbonates (FeCO_y), for example: Siderite (FeCO_3)
- Sulphides (FeS_y)⁵, for example: Pyrite (FeS_2); Marcasite (FeS_2 , in nodules)

Not only the iron content of an ore determines its 'value', but also its overall structure and ease of procurement. For example, some Magnetite ores are extremely rich in iron but very dense and therefore difficult to reduce.

Any iron ore needs to have a sufficient concentration of iron minerals for conversion to metallic iron, but the reducibility and availability of ore will influence the willingness to use lower-grade ores. Thus it is clear that mineral composition, both of the iron mineral and gangue, and availability of ores must have had their influence on the technological paths chosen in ironmaking history.

2. Mineral dressing

To gain iron, from ore, the composite structure has to be broken up. This can only be done by the reduction process, or 'smelting'. Some preparation of the ore, or 'mineral dressing' is possible. Some ores, like very hard Magnetite ores and hydrated ores like Limonite, are difficult to smelt without any prior treatment. Two methods are used to upgrade ore in preparation for smelting: Comminution and Roasting.



Dressed Iron Ore

3. Comminution

Comminution is the physically breaking of the ore into smaller lumps, often with hammers or stones. During mining, some Comminution of the ore always takes place. This may be followed by more crushing and grinding, further reducing the size of the ore. This allows the removal of visible impurities, and the smaller size of the ore nodules ensures better reducing during the smelt. The ore should be broken up to about 50 mm diameter pieces.

To avoid losing the broken iron it is helpful to place a tarp under say an iron block on which the rock is hammered

4. Roasting

A second step in preparation of ores for smelting is roasting. This is the heating of ore in an open, oxidising, fire, within a temperature range of 500-800 °C. The ore is either put on piles of wood or in a shallow basin with the wood on top. It is important to allow a maximum access of air, but no tuyères or bellows are needed because of the relatively low temperature.

Some iron ores have a high water content – this is driven off by roasting.

Hydrated ores like Limonite are roasted to remove the water. Carbonate ores are roasted at 500 °C to remove the carbon dioxide and break up the ore nodules. Dense oxide ore is often hard to reduce and can be roasted, which will both turn it into haematite ($4\text{Fe}_3\text{O}_4 + \text{O}_2 \rightarrow 6\text{Fe}_2\text{O}_3$) and make it softer, due to the expansion which goes with the reaction. In general, roasting causes ores to break up into smaller bits, ensuring a more effective smelt, but is not needed for all ores.



Roasting Temperature 500 °C to 800 °C

5. Smelting

Smelting is the firing of ore and fuel in a furnace to remove unwanted material and produce raw iron. What sets iron apart from other metals, is that it stays solid during a smelting operation. In a way one could say that not iron but the unwanted minerals are smelted.

An example of an ancient clay Bloomery furnace constructed at Clearwell caves – Forest of Dean



*What the poor guys back then had to use
(Bloomery Furnace)*

Iron Carbonate Ores – Extremely pure form of haematite from the Forest of Dean

The ore that comes from the mine consists of iron carbonate. To move from the iron carbonate and other impurities to pure iron, we must separate the iron from the carbon and oxygen. However, iron and oxygen have a very strong affinity for each other. Therefore, we must provide the oxygen with another molecule that it likes more. CO (carbon monoxide) is that molecule and (the CO comes from the combustion of peat or wood or charcoal) during the roasting process, heat is applied to the iron carbonate FeCO_3 , yielding Ferric oxide FeO and Carbon dioxide CO_2 . The CO_2 goes off in the form of a gas, while the FeO attracts more oxygen to form Fe_2O_3 . This is what is used in the bloomery.

So, we begin the smelting process with Fe_2O_3 . To remove the oxygen from the Ferric oxide (Fe_2O_3) is very difficult because iron oxides are very stable compounds and cannot be reduced without extreme heat; heat that would have been impossible for the Romans to obtain with the fuels they used. Instead of employing heat alone, however; we may add a reducing agent to attract the oxygen away and leave pure iron. "The reducing agent used in the bloomery process is carbon monoxide (CO), resulting from the combustion of carbon." The carbon monoxide combines with the oxygen from the ferric oxide (Fe_2O_3) to form carbon dioxide (CO_2), which goes off as a gas, leaving pure metallic iron (Fe) behind.

Now that we know the chemical processes that take place within the bloomery, we can focus on the physical aspects of the bloomery

The primary fuel in ancient bloomeries was charcoal (burnt wood or reeds). Peat and coal could have been used and were occasionally, but they did not burn hot enough so charcoal made from a hardwood, such as oak or ash, was used because it was free from impurities and could produce the temperature required to smelt the iron. With the proper fuel chosen, we must now move to the construction of our bloomery. The furnace needs to be airtight, so as to prevent the access of undesirable air into the interior. If oxygen is allowed to enter the furnace it will recombine with the reduced iron (Fe) and we will end up with iron oxide again. A Bloomery built from Clay will be easy to construct and sufficiently air tight. So now we have the fuel (charcoal) and an airtight bloomery, and all we need is to fire it up.

The furnace should be preheated, to dry out the clay and reach a temperature of about 450 C. To achieve this entrance (the slag tapping hole is left open). When every thing is heated up then the Slag tapping hole is sealed up; the furnace filled with charcoal and air, provided by the bellows introduced via the tuyeres located at the bottom of the furnace. Preheating the furnace should eventually bring the temperature inside the bloomery up to around 1200°C+.

The bloomery takes advantage of the fact that heat rises, so if the bottom of the bloomery is sealed tight to prevent oxygen from coming in, then as the heat rises through the top of the furnace, no oxygen from outside will be able to enter, thereby allowing the reducing process to take place.

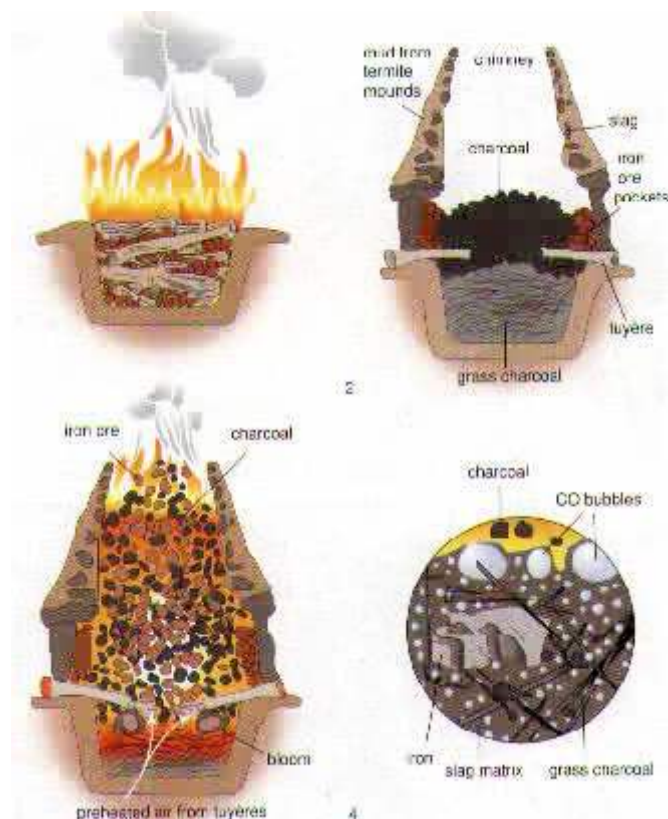
Once the temperature is about 1050 C, small additions of ore and charcoal, probably no more than 2 lbs of each, fuel & ore at a time can be put into the top of the shaft (this process is called 'charging' the furnace). The ore moves slowly down the furnace shaft, through increasing temperatures, until it collects in a spongy white-hot mass at the bottom of the furnace.

The burning charcoal and the oxygen supplied by the bellows produces the reducing agent, carbon monoxide (CO), which reacts with the ore when the two come into contact, drawing oxygen from the iron oxide and forming carbon dioxide (CO₂) which leaves as a gas, while free iron particles remain and collect at the base of the furnace along with some impurities of silica (also known as gangue) to form a slag at the base of the furnace.

Meanwhile, the iron oxide begins to react with the silica and other impurities from the ore to form a slag in which the many iron particles are trapped. The formation of the slag protects the iron from reoxidising as they pass in front of the tuyeres, where the atmosphere is extremely oxidizing. Below the tuyeres, slag drains to the bottom of the heath to form a pasty mass and the iron particles come together above the molten slag to form a Bloom. The final bloom is a porous lump of iron, containing some refractory silicates and bits of unreduced ore and unburnt charcoals.

The bloom is then removed through the front archway or through the top of the bloomery. The amount of iron would depend upon the time spent and the amount of ore added to the bloomery. It is thought that a skilled Roman smelter could produce about 20 kg of iron in one day.

Diagrammatic description of The smelting process.



Detail Chemistry of the Bloomery Smelting Process

Many processes take place during a smelt, and different areas of the furnace may show different actions at the same time. Simplified, the main process is the reduction of ore, by carbon from the fuel, at a sufficient temperature. To achieve both an adequate temperature and an adequate yield of iron, the fuel/ore ratio needs to be high, at least 2:1, but more often much higher. At higher ratios, less iron will end up in the slag.

Furnace gasses, CO_2 , are the result of the combustion of the fuel near the air-inlets, and rise up through the furnace. The ore that is charged travels downward and is gradually reduced until it reaches the combustion zone, which is in front of the air inlets. The rising Carbon dioxide CO_2 comes into contact with unburnt fuel and is converted into carbon monoxide CO , which makes the gasses highly reducing. When the CO meets unreduced ore, it converts it into iron by extracting its oxygen. No reduction takes place at temperatures below 1000-1100 °C, the melting point of slag⁶, or when the CO - CO_2 ratio is lower than 3:2. In the cases of Haematite or roasted Limonite or Siderite ores, the reduction steps will be along the following lines:

- $3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2$
- $\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2$
- $\text{FeO} + \text{CO} \rightarrow \text{Fe (metal)} + \text{CO}_2$

When the ore is in direct contact with solid carbon, the reduction might follow:

- $6\text{Fe}_2\text{O}_3 + \text{C} \rightarrow 4\text{Fe}_3\text{O}_4 + \text{CO}_2$
- $2\text{Fe}_3\text{O}_4 + \text{C} \rightarrow 6\text{FeO} + \text{CO}_2$
- $2\text{FeO} + \text{C} \rightarrow 2\text{Fe (metal)} + \text{CO}_2$

In theory, smelters can manipulate the CO - CO_2 ratio in the furnace to influence the final result: below 1% of CO_2 gasses in the furnace results in cast iron (which does liquefy during smelting, and therefore requires temperatures around 1500 °C), between 1 and 3% will result in steel, and above 3% will result in bloom iron. In practice, the result will be a very heterogeneous bloom with differing carbon contents⁷.

At the same time, the unwanted minerals have to be removed. To do this a slag has to form by reaction of some of the iron oxide from the ore with the unwanted minerals, predominantly SiO_2 , according to the reaction:

- $2\text{FeO} + \text{SiO}_2 \rightarrow \text{Fe}_2\text{SiO}_4/2\text{FeO}.\text{SiO}_2 \text{ (Fayalite)}$

Theoretically, this means that all slag would consist of only two components, FeO (wüstite) and SiO₂. Depending on their reducibility or chemical nature however, other gangue minerals and trace elements from the ore, as well as elements from the furnace clay and fuel ash will enter the slag. Not reduced or partly reduced iron oxides may also enter the slag. The different components all have their influence on, among other factors, the melting temperature of a slag, and therefore on the operating temperature of the furnace, which must lie at least somewhere between 1100 and 1200 °C. The final composition of slag also depends on furnace temperature, atmosphere and whether it is run off, 'tapped', from the furnace or not. The slag also serves to protect the formed raw iron from reoxidising in the oxygen rich combustion zone.

The clay used in construction of the furnace and possible air-pipes is subjected to the high furnace temperatures as well. If sufficiently heated it may melt, resulting in Vitrified Ceramic, or even dissolve in the slag. The clay may even help the formation of slag by lowering its melting point or its viscosity. The same applies to the ashes formed by the fully burnt fuel.

To help the formation of slag, smelters may add a fluxing agent or 'flux'. This is an extra ingredient, for example lime, Calcium Carbonate (Ca O) that is charged to the furnace, to help lower the melting temperature or viscosity of the slag, identical to the possible reaction of the clay. In general, the application of fluxes is considered common in copper production, but rather rare and in general unnecessary in iron smelting.

6. Refining

The raw iron, or bloom, produced during smelting is generally not solid enough to be forged immediately into finished products. The bloom needs to be consolidated first. The way this is performed depends on the amount of impurities left in the bloom during the smelt. At least the bloom has to be hammered which will considerably reduce its volume. Sometimes the bloom needs to be broken up into small pieces, the impurities removed, and the selected bits of raw iron are then welded together in the forge by repeated heating and hammering.



Refining the Bloom

Efficient smelting operations can achieve a high quality bloom that just need some hammering, often when still hot, to expel adhering slag and charcoal; i.e., most of the consolidation of the iron already takes place during the smelt. Average operations will need more extensive hammering, often combined with reheating, which might be performed as part of the forging operations. Some operations result in a very unconsolidated, heterogeneous bloom, which might be subjected to a second smelting operation, usually performed in a separate, smaller, so-called 'refining' furnace. The broken up bloom together with iron rich slag is fired at high temperature, producing slag and a higher quality bloom that can be forged.

7. Forging/Smithing

Forging is the operation where the consolidation of raw iron is completed and the resulting metal shaped into a finished product. Forging is carried out by repeatedly heating the iron in a hearth and hammering it on an anvil. The hearth may vary from a shallow open hole in the ground to rather large furnace structures, called hearths, and is operated at temperatures around 1200 °C, which is necessary to render the incorporated slag fluid.

During forging almost all remaining slag is squirted out of the iron, although some will always remain. The resulting pores in the iron are closed and their surfaces weld together. A useful analogy is the squeezing of a sponge. Unlike a sponge however, iron undergoes a plastic deformation, which means that the pores stay closed and the iron forms a solid mass that can be shaped into an object, using various techniques. Often the term Smithing is applied to these techniques, but it is not always practicable to make a distinction between forging and Smithing operations since the last in a way is no more than the final stage of the first.

The slag that is squeezed out during forging will end up in the bottom of the forging hearth, and usually differs from smelting slag in that it is more or less magnetic. This is caused by reoxidising in the forge of (part of) the wüstite (FeO) to magnetite (Fe_3O_4).

6.Materials & equipment. Method of construction of a Bloomery Furnace

12 firebricks

2 twelve-inch ceramic flue liners

Chicken wire

Regular fencing wire

Two metal plates

Tuyeres (two 3 foot metal 3^{1/4} inch diameter pipes)

Two hand-operated bellows

Some form of shelter over the furnace

Wheel Barrow and Spades

Iron Ore – 35 > 50 lbs can be managed in a day in the Bloomery constructed

Clay Mix

Clay

Sand

Water

Straw

Fuel

Charcoal

Wood

Portable Forge

Charcoal / coke

7.Recorded Process

Waldorf College Iron Smelt at Upper Grange.

Day 1

Introduction to Iron ore and the Bloomery Furnace.

Briefly described formation of Forest of Dean iron ore - Clearwell Cave a natural Karst cave system formed in carboniferous Limestone, which is known locally as the Crease Limestone.

200 millions years ago the caves were filled with iron deposits that came in with the water, first seeping through the acidic bogs that covered the limestone deposits. The acidic iron rich ground water first dissolved the limestone rock to form a large underground cave system. As the water dissolved the limestone there was also a slow precipitation & depositing of iron from the iron rich water. Locally the iron ore bearing rock is called Brush Iron, as the striations of iron deposits resemble brush fibres. The Forest of Dean iron ore bearing rocks also show evidence of different coloured iron oxides called Ochre – which is still mined today.



Iron Oxide known as Ochre

We tested the iron ore with a magnet and found no attraction and so we deduced that the iron is locked in with other elements in the form of a compound. Our smelting procedure is to release the iron by a 'reduction' process in the bloomery furnace and separate out all the other elements, which will flow to the bottom of the furnace and form the slag. The iron will hopefully form into what is called a 'bloom' above the slag.



Nonmagnetic iron ore

Bloomery Furnace

The construction of a basic updraft chimney furnace often made of clay and stones built to a height of about 3 to 4 feet was described and a dry run using fire bricks and 2 round chimney liners (12" height X 12" diameter) was tried out.



The Bloomery Furnace

Iron Ore Preparation – Dressing & Roasting

Part of the preparation of iron ore before smelting is Iron Ore 'Dressing', which consists of two important processes. One is the break up the larger lumps of iron to about 'Kidney bean' size pieces (Comminution). This will increase the surface area of the material when put into the furnace. The other process to prepare the iron ore for the Kiln is to 'Roast' it in a high oxidising fire (approx 500 c). In this situation the Carbon will be released from the mother Iron ore (chemically, an iron Carbonate with other minerals and elements present) this process will take place by the action of heat and oxygen in the fire. The Carbon elements combine with the Oxygen to go off in the form of Carbon Dioxide gas.



*Roasting the iron ore
in a metal bin*

Chemically: Iron Carbonate: $\text{Fe CO}_3 \rightarrow \text{Fe O} \uparrow \text{CO}_2$ (gas given off). The Fe O attracts more Oxygen to form $\text{Fe}_2 \text{O}_3$ (Ferric Oxide) This is the way we get rid of the C (carbon element) now all that remains is to take out the Oxygen element so leaving pure iron (Fe)

This will be done in a controlled furnace environment, in a reducing environment, where the burning charcoal (Carbon Monoxide) starved of Oxygen will attract the Oxygen from the Iron Oxide (Ferric Oxide: FeO_3) combining with the Oxygen to go off as a gas CO_2 leaving the pure Iron (Fe) behind to flow amidst the molten slag and come together to form the Bloom in the base of the kiln above the slag.

Slag melting temp 1200 C, Iron melts at 1400 C

Firstly, the iron ore was weighed, in all a 10 ILt bucket full weighed in at 50Lbs.



Weighing the iron ore

Then the quantity of fuel required @ 2:1 was worked out. It was estimated that we would require 100 Lbs plus to process our quantity of ore. Extra will be required for the 'preheat' and the 'after burn' of the smelting process.

Roasting Test

A small piece of iron ore was put in forge and heated for about 10 mins.

After heating the iron ore it was observed that there were changes. It looked greyer in colour,' slightly lighter in weight and more open in structure. To our amazement our magnet now attracted it.

It was observed that there were parts of the iron ore that even after roasting did not show any magnetic attraction.



Roasting test



Roasted & Magnetised Iron

Different types of iron

Wrought Iron

We looked at a rod of iron produced from another smelt and a bar of old 'wrought iron' and observed that it had a distinct linear fibrous structure, this iron which is the product of a Bloomery furnace or similar technique is pure iron (Fe) with a small amount of slag still imbedded in it. On heating it in the forge to an orange heat, it could be worked but not as easily as the mild steel square rod that was also heated to the same temperature. (Wrought iron needs to be Yellow/ White hot to work, mild steel will burn at this heat and works well at a lower heat ie an orange heat.) Wrought iron is no longer produced and can only be found as a source material in old fencing, gates and Victorian decorative ironwork.



*Examples of a Wrought Iron Bar
Note rusting pattern*

Mild Steel

A bar of mild steel was tested first by bending it. It bent relatively easily and retained its position.

When beaten cold only slight marks could be seen.

Later it was heated to an orange heat and beaten out to a point. This showed how malleable it was. Further test with a file showed that it could be easily filed away – and if sharpened to an edge would become blunt quickly.

Mild steel has its characteristics on account that it contains only .15%. % > 3% Carbon content

The addition of Carbon to iron determines its hardness but also brittleness.



Manufactured Mild Steel, round and square

Spring Steel

A leaf spring from a lorry was stood upon, it bent but when the weight was taken off it returned to its original position; unlike the mild steel rod.



Spring Steel- Leaf Spring suspension

On beaten cold with a hammer, no marks could be seen – it therefore appeared harder than the mild steel.

A further heat test was then done with a spring coil from a car. It was heated and then plunged into water to cool it rapidly (quenching). On striking it with a hammer it shattered. The end of the broken rod had a 'graining structure' compared to the mild steel bar. We deduced that the coil had received a shock after heating having been plunged into cold water.

On a further test, a heated piece of the same coil, to an orange heat was beaten with a hammer. This time it did not shatter but behaved more like the mild steel bar, ie it was malleable and could be beaten into a shape.

What gives spring steel its properties is that it contains more carbon than mild steel, typically 0.6% > 0.8% Carbon content

Spring steel is a good source of iron to make tools that have to be hardened after making. A knife, for instance made of spring steel and hardened to the right temper will hold a keen edge.

Cast Iron

A cast piece of iron was subject to a hammer blow. It broke in two relatively easily with the broken pieces showing a very grainy structure.

Cast iron has typically 2.5% > 3.5% Carbon content.

It is produced in a Blast furnace and poured into moulds on the factory floor, moulds that resemble a mother pig suckling her young; hence the name of this type of production ie Pig iron.

It can be cast into any shape ie various car parts but is not malleable like spring steel and mild steel.



Cast Iron

Preparation of Clay Mixture

To build our Bloomery Furnace we require a large amount of clay mixed with sand to use as a mortar between fire bricks and for an insulating layer around the 12" chimney liners that will be used to create a small tower about 3' high. To a wheelbarrow of clay, water and generous amounts of sand were mixed to produce a workably plastic mix. For the outer insulating layer straw will be added, this will help bind the clay together and the straw will add to the thermal value of the clay mix.

A dry run using firebricks on how best to construct the base of the furnace was attempted and the square base design thought to be preferable with the flue liners placed on top.



Clay mix being prepared by three eager young men

DAY 2

Fuel required for the Smelting

A trip was made to Ruskin Mill to empty the charcoal bins that had been loaded with 'Stick wood' and fired a few days previously.

The burn produced about 65 Lbs of charcoal.

Air Supply – Bellows

For the smelting process air has to be introduced into the Bloomery Furnace via a pair of bellows. We had to work out the Litres / min that our bellows could produce. A double action wooden box bellows and a 'Heath Robinson' bellows made using a bicycle wheel with fins enclosed in a wooden casing were tested as to how much air they could produce in a minute. The aim was to have available about 120 –150 Litres / min between the two bellows.



Chinese hand operated Box Bellows connected to Bloomery Furnace

The Box Bellows measured in at 67 Litres / min and the Bicycle bellows at 34.7Litres / min, not sufficient to meet the desired rate.

The performance of the bellows needed to be improved, possibly by using a larger diameter out flow pipe. It appeared that small-attached pipe restricted the air output flow. These bellows are operating at low pressure and therefore not able to force a large volume of air through a small diameter outlet pipe.

Day 3.

Bloomery furnace construction

Three rows of firebricks were put together with the clay mix to form a small rectangular base on which to support the two sections of chimney liner. The dimension of the base was 18 inches X 18 inches X 9 inches high. This is where we expect to collect the bloom. At the point where the chimney liner sits on the brick base is where the two Tuyeres will be inserted pointing at about 20 degrees into the base. To accommodate the pipes using a stonecutter two sections of the chimney liner were cut out. At the same time two small holes were made to later accommodate the pyrometer probes that will be inserted into the furnace to monitor temperatures.



The partly built furnace was left to air dry over the weekend. All that remains now is to wrap chicken wire around the chimney liners and daub it with a thick layer of clay, sand and straw mix. This will help insulate the Bloomery furnace and hold things together should there be any fractures to the furnace during heating up to the required smelting temperatures of 1050°C

Roasting Fuel preparation.

To roast our iron ore we will need a large quantity of wood. A donation of old pallets were broken up to pieces about 12" > 18". We will roast our iron ore laced between layers of wood in a metal drum. A temp of 500>800°C will be sufficient (see explanation for Roasting & chemical changes to Iron ore Page 13)

Wood will also be required to light a fire in and around the Bloomery furnace to assist drying it out and hardening the clay before 'charging' it with Iron ore and charcoal. Ideally we should reach about 800°C within the furnace before the actual Pre-heat charge, which will consist of a full charge of charcoal only.

Day 4

Roasting the Iron Ore.

Two metal bins with air holes around the base were used to roast the 50lbs of iron ore. Firstly a fire was lit in the bins and when sufficiently hot fire had been achieved we then sprinkled on the small lumps of iron ore and then covered it with another layer of wood; which in turn was sprinkled with iron ore. This process was repeated until all the iron ore was distributed between the two bins.

This process went on for about 5/6 hours the fire was allowed to burn down with occasional turning on the charcoal embers to assure complete combustion.

After roasting a few pieces proved to be magnetic. The other noticeable change was a colour change of the ore from browns to a greyer colour. It also appeared that a small lump was somewhat lighter and open in structure after roasting. It was also observed during roasting that the seemingly dry pieces of iron ore, on being subject to about 500°C sweated out water.

Bloomery Furnace Construction – continued

To the clay and sand mix already made chopped straw (about 5 > 10cm lengths) was added. This will help to bind and hold the 'daub' mix before it is hardened.

To secure the two flue liners and provide a 'key' for the clay, sand & straw daub insulation a few rounds of chicken wire held firmly in place with fencing wire were wrapped around the 2' high flue.

Then a generous amount of clay daub mix was thrown onto the chicken wire, resulting in about a 4" layer at the base and tapering off to about 2" at the top of the flue.

Historically Bloomery furnaces were built entirely out of Clay sometimes containing suitable refractory stones.

We have used the principals of an updraft & forced air furnace but using in part modern Building materials.

In our instance by increasing the thickness of the flue liners with daubed clay we hope to achieve a more stable and insulated structure.

The furnace was then warmed up with a slow ember fire to assist drying everything off in preparation for the actual smelting.

Day 5

Smelting

A stick fire was first lit to warm the Furnace and continue to dry out the outer clay layer. At this stage the slag Tapping hole was left open to get a good up draught. The internal temperature rose quickly to 500 > 800⁰ C

As the pallet wood used contained nails we decided to take out the embers and sift out the nails.

Pre-heat

After an hour the slag hole was bricked up, made airtight and the furnace was charged with a full load of charcoal.

With the furnace effectively air tight from below we now had to introduce air from the two bellows via the tuyeres. This first load was of charcoal took at least a half hour to reach the required temp of 1050°C at the lower point, the hot spot between the tuyeres. A constant temp of 850°C was recorded at about 2/3rds up the furnace.

We decided to charge our furnace every half hour with weights of 3lbs of iron ore about 6 lbs of charcoal.

The first charge of 17 was made at 10.30am (see chart on next page)

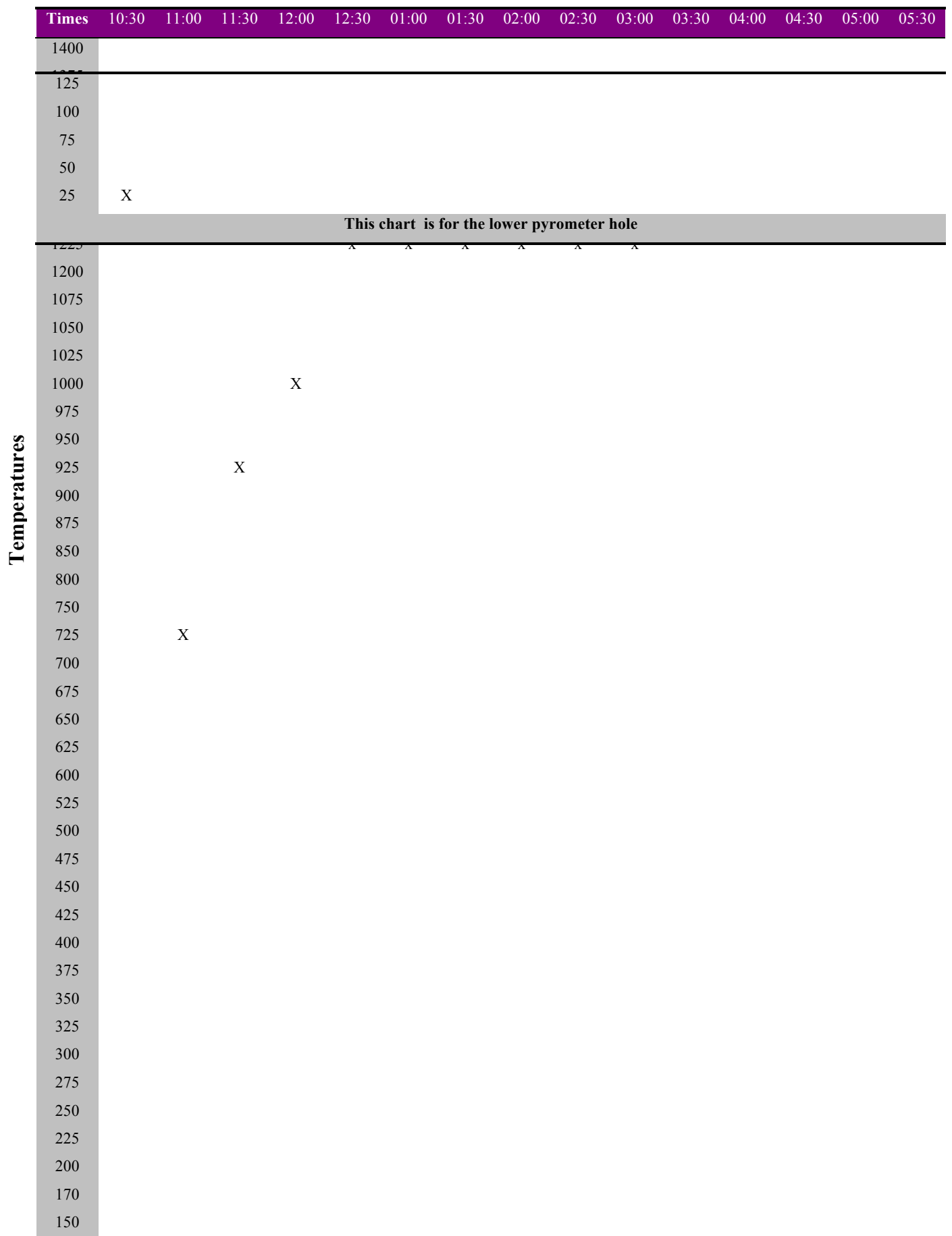
Initial observations showed that we had sufficient air to maintain a good internal temperature within the range of 1200°C > to a constant 850°C at the upper measurement.

We could tell that we had a good reducing atmosphere as seen by the gentle blue & magenta flames seemingly hovering above the charcoals.

Having filled the chimney after a period of burning the whole stack of charcoal would suddenly slump down causing a shower of sparks to rise.

We could observe that the flame expansion and contraction was a direct result of the rhythm of the box bellows.

For a period during the middle of the day we decided to add a new charge every 15 mins. At this point it was not possible to add the required amount of charcoal. However we were later to discover that this did not appear to affect our result.



At midday we decided to change the bicycle bellows for a hand cranked forge as it appeared that although we had a good working temp within the furnace it demanded

much energy to work the bellows. Having fitted the new bellows not only were they easier to use but also introduced a greater volume of air into the furnace. This was noticed by the increase to flames and heat in the upper section of the Furnace. Unfortunately by midday we had burnt out the probe of the lower pyrometer. For this to happen we must have had temps in excess of 14000⁰C. Later in the afternoon the upper Pyrometer probe also burnt out.

Towards evening the flame above the furnace was easier to observe and our furnace was working at its optimum. The last charge was added at 5:30

Iron ore and charcoal recording

(1 bucket of iron ore usually added every 1½ half hour though we had 3 15-minute intervals at around half way)

10:30 am – 1 bucket = 3lbs iron ore

11:00 am – 1

11:30 am – 1

12:00 am – 1

12:30 am – 1

01:00 pm – 1

01:30 pm – 1

01:45 pm – 1

02:00 pm – 1

02:15 pm – 1

02:45 pm – 1

03:15 pm – 1

03:45 pm – 1

04:15 pm – 1

04:45 pm – 1

05:15 pm – 1

05:45 pm – 1 last charge

Total of 17 charges at 3lbs per bucket = **51 lbs of iron ore.**

Total charcoal used = **88lbs.**

Burn Down

The furnace was allowed to burn down about half way and then loaded to the brim with a further 5kgs of charcoal for the burn down.

The burn down took about an hour during which time we discussed how we were going to access the Bloom. It was decided that we would detach the tuyeres, carefully prize the furnace chimney from its base pushing it backwards; this should give us easy access to the bloom that should be nestled below the tuyeres.

We prepared the various tools required to initially work the bloom, a wooded stump and large wooden mallet several pairs of large tongs and leather gloves.

Everything went according to plan and we successfully managed to coup the chimney revealing a very large bloom that appeared to almost fill the lower furnace chamber. The bloom proved somewhat difficult to get out and needed prizing away from the bricks, eventually we got a large lump out and started to gently beat it with the wooden mallet to encourage the bloom to squeeze together.

Day 6

On the following day the first thing was to weigh the bloom. It weighed in at 20lbs. The bloom had distinctly different structures; in parts it was very smooth and metallic looking whilst other parts were rough. These areas of the bloom were attracted by the magnet. It was noted however that some pieces of bloom were not attracted by the magnet. We deduced that these were only slag.

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Forging/Smithing

The next job was to break up the bloom into smaller pieces and heat them to an orange heat in the forge. On beating the heated bloom it broke into smaller pieces. There was no evidence of the iron welding together. On cooling all the broken pieces including the dust remained magnetic.

This proved to be somewhat disappointing but it later turned out that we had produced what is called 'short iron'; behaving somewhat similar to Cast iron.

Day 7

This was the final day and we decided to go to visit Clearwell caves and take along a piece of our bloom. We made an appointment to meet with Ray, the Proprietor and he offered to take us down the caves.

He was extremely interested in the bloom that we had managed to achieve in our furnace; he said that all other trials had not produced such a successful bloom. He was aware of the problem that the Clear Well caves iron ore can produce a 'short iron' not so easy to forge weld into an iron bar.

Unfortunately he did not know the secret in unlocking the short iron bloom.

We discussed the possibility of breaking the bloom up and subjecting it to another bloomery furnace process.

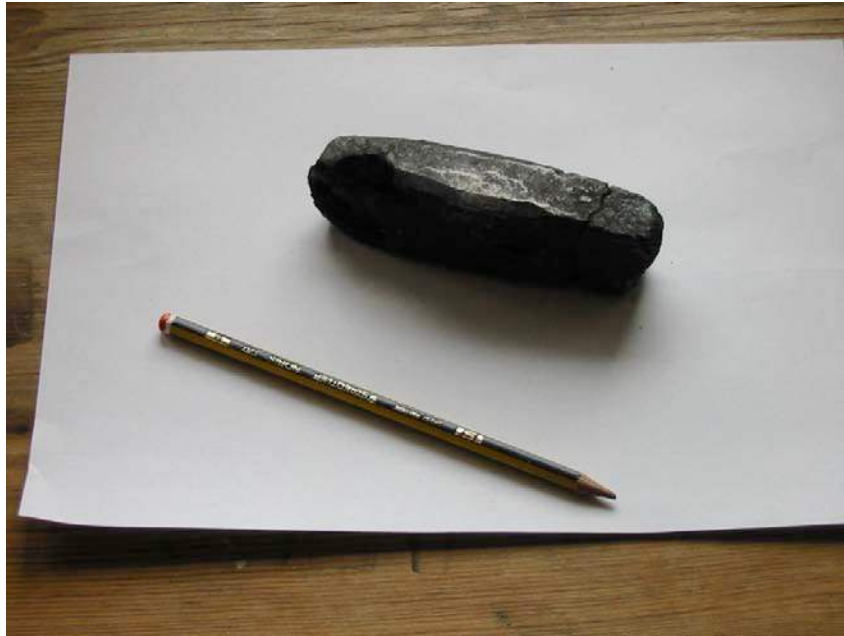
We had a very interesting tour of the mine and could see for ourselves the scale of the operations of iron ore excavations at various periods. It was clear that iron ore extraction required courage and was hugely labour intensive. Conditions were exceedingly hard and always hazardous, whatever over the centuries the minor improvements.

Ray was very happy to put on his large fire mantle piece in the tearoom a piece our bloom along side other examples of iron oxides.

We had a good day and went home satisfied in the knowledge that within 7 days we had managed to recapitulate in essence what was some 4000 years of man's fascination and technology to produce perhaps the most elusive of all metals, iron .

One week later

A large piece of Bloom was given to a local Blacksmith who had some previous experiences in smelting and forging Blooms. He said he would give it a go.



*Finally the first piece of Bloom that successfully began
to forge down into a substantial Iron bar*

To my great surprise the evening before the students who had been involved with the smelting were to give their presentations on the Bloomery Smelt the Blacksmith handed me a forged Bloom – clearly coming together nicely.

This achievement was most welcomed by the students who otherwise would have been left a bit shortchanged after all their hard work.

Forging the Bloom

The bloom consist of Iron and other impurities, ie the slag. Filing the bloom reveals the particles of iron which now have to be forge welded together to form a solid iron bar. This is achieved by heating the bloom to a forge weld heat, squeezing and beating it which separates out the slag which falls away onto the anvil.

The first stage in forging the Bloom is to heat it up to a white heat. As the bloom is large it requires turning in the forge to acquire an even heat throughout.



Heating the bloom in the forge

The white hot bloom was then held in a large leg vice and gently squeezed from all directions .



Squeezing the Bloom in a leg vice the bloom in the forge

The first attempts to forge the bloom were unsuccessful, on beating the hot bloom it crumbled rather than forged welded together. We later discovered that the iron extracted is a short, hot iron.

The heated bloom was then gently tapped from all directions, squeezing it into a ball shape. Large amounts of slag fell away. On cooling the bloom is returned to the forge to be reheated. It was discovered that when fractures occur in the bloom whilst beating it, the bloom was treated with borax on the next heat which greatly assisted forge welding the iron back together.



Hammering the Bloom on the anvil

To process a fist sized bloom to an iron bar 2" by ¾" took repeated heats and was three hours work.



Forged Iron Bar



Bloom and Iron bar

The amount of energy and time spent in producing this small iron bar, sufficient for a few arrow heads, makes one truly value this "heavenly metal" .

Bernard Graves (for The Hiram Trust) Spring 2005