"Carried on at a Very Great Expense and Never Produced Any Profit": The Albemarle Iron Works (1770-72)

James Harvey Brothers  
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"CARRIED ON AT A VERY GREAT EXPENSE AND NEVER PRODUCED ANY PROFIT"

THE ALBEMARLE IRON WORKS (1770-72)

A Thesis
Presented to
The Faculty of the Department of Anthropology

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Arts

by
James Harvey Brothers IV
2001
APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of

Master of Arts

James H. Brothers IV

Approved, December 2001

Norman F. Barka

Lyle E. Browning

Theodore R. Reinhart
Dedication

This paper is dedicated to Tate Thompson Brady (1922-1993), an avocational archaeologist. Tom devoted his life to rediscovering and documenting the Iron Industry of Virginia. His papers, now at The Virginia Historical Society, will provide a rich source of information for those researching Virginia Iron for years to come.
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Acknowledgments

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And finally, my Committee, Dr. Norman Barka, Dr. Theodore Reinhart, and Lyle Browning, who allowed me to go where my research took me. And gave me the time to get it right.
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ABSTRACT

The 18th century iron blast furnaces of the British North American Colonies were among the most costly and complex operations of their time. Once blown in they operated for an average of 10 months. Consumption of raw materials (iron ore, charcoal, and flux) and production of iron was measured in tons per day. They also had to have a dependable water supply to run their blast mechanism. And last a furnace had to have a market for the hundreds of tons of iron they produced. A transportation network was required to move raw materials to the furnace and to move iron to markets.

The location of a furnace was not random and had a profound effect on its commercial viability. Furnaces were deliberately located to maximize resource utilization and the locations selected had a profound influence on their commercial viability. Where the owners properly weighed the various factors that contributed to a successful furnace the enterprise prospered. When mistakes were made, viability was impaired and the venture often failed.

John Old and John Wilkinson devoted seven years determining the right location for the Albemarle Iron Works blast furnace (44AB72). Wilkinson also organized a well financed partnership of local Virginians and Pennsylvania ironmen to underwrite the construction and operation. Yet Albemarle was "carried on at a very great expense and never produced any profit..." (Walker 1791), failing after less than a year of operation. This paper utilized archival records, site reconnaissance, PIXE (particle-induced x-ray emission), and SEM (scanning electron microscope energy dispersive X-ray) to demonstrate that although many factors contributed to the failure, the proximate cause was high concentrations of titanium in the ore used and that the ore came from the Martin Mine.
"CARRIED ON AT A VERY GREAT EXPENSE AND NEVER PRODUCED ANY PROFIT"

THE ALBEMARLE IRONWORKS (1770-72)
INTRODUCTION

The importance of iron has been recognized through the ages and around the world. It was, and is, an essential element of society. Pliny the Elder (Roman scholar 23-79 AD) wrote:

For by the aid of iron we lay open the ground, we plant trees, we prepare our vineyard trees, and we force our vines each year to resume their youthful state, by cutting away their decayed branches. It is by the aid of iron that we construct houses, cleave rocks, and perform so many other useful offices of life. [quoted in Wertime 1962:3]

While in the late 16th century Bartholomaeus Anglicus wrote:

[Iron is] more needful to men than the use of gold...Without iron the commonalty be not sure against enemies; without dread of iron the common right is not governed; with iron innocent men are defended; and foolhardiness of wicked men is chastised with dread of iron. And well-nigh no handiwork is wrought without iron: no field is eared without iron, neither tilling craft used, nor building builded without iron.

As Great Britain gradually industrialized after 1500, demand for iron rose dramatically. Per capita consumption, under 10 lbs. in 1580, climbed to over 25 lbs. by 1740 (B. Thomas 1986:149). The introduction of the blast furnace and finery forge in the late 15th century and their rapid spread during the 16th century, allowed the British iron industry to meet demand. But, beginning in the early 17th century Britain was forced to import iron in ever increasing quantities. Imports of Swedish bar iron were only 1,000 tons in 1650. But by 1700 Sweden was supplying over 12,000 tons of bar iron (Åström 1982:129; Hildebrand 1958:14). By 1760, with total imports of over 45,000 tons, England imported more iron than it produced (Hildebrand 1958:14).

This was in direct opposition to the prevailing economic theory,
mercantilism. This called for the maximization of national wealth by a variety of means, one of the most important of which was maintaining a positive balance of trade. Exports were encouraged and imports, especially finished goods, discouraged. Tax policies were tailored to encourage and protect domestic industry and agricultural production. The goal was self-sufficiency and maximized exports. Sea power, both naval and mercantile, was crucial to control foreign markets and ensure delivery of domestic products. Colonies were seen as an "in house" source of cheap raw materials and a market for manufactured goods. Colonies should be encouraged to produce raw materials that could be converted into finished goods in the mother country, and discouraged from manufacturing anything that could be made in the mother country.

The North American colonies did serve as a source of raw materials for English industry and as a market for English manufactured goods. By the 1750s England's colonies provided 33% of imports and bought 20% of England's exports. By the 1770s the colonies were providing 37% of imports and buying 42% of exports (McCusker and Menard 1985:40).

It was initially hoped that Virginia, like Mexico and Peru, would be a land paved in gold, silver, and jewels. If not, the primary mission of The Virginia Company was to discover what "commodities" could be grown, mined, or harvested in the new colony to fuel England's home industries. Early explorers found that there were many possibilities.

The role to be played by the new colony was laid out by a number of early 17th century English authors. Lord de la Ware in his 1610 treatise A True and Sincere declaration of the purpose and ends of the Plantation begun in Virginia wrote:

Lastly, the appearance and assurance of Private commodity to the particular undertakers, by recovering and possessing to themselves a fruitfull land, whence they may furnish and provide this Kingdom, with all such necessities and defects (Copper, Iron, Steel, Timber fo ships,
yards, masts, cordage, sope ashes) under which we labour, and are now
enforced to buy, and receive at the curtesie of other Princes, under the
burthen of great Customs, and heavy impositions, and at so high rates in
trafique, by reason of the great waste of them from whence they are now
derived, which threatens almost an impossibility long to recover them, or
at least such losse in exchange, as both the Kingdome and Merchant, will
be weary of the deerenesse and peril. These being the true, and essential
ends of this Plantation....[de la Ware, 1610]

Sir Francis Bacon in his essay "of Plantations" (Bacon 1625) Said the following
concerning the proper products of the Virginia plantation:

Wood commonly aboundeth but too much; and therefore timber is fit to
be one. If there be iron ore, and streams whereupon to set the mills, iron is
a brave commodity where wood aboundeth.

Nicholas Ferrar, Sr., one of the earliest of the London Company's Adventurers
and the father of one of its best known members, wrote that plantations were "for
a supply of those commodities which we were fain to fetch from other countries
at intolerable rates..." (Skipton 1907).

Primary among these commodities was iron. According to contemporary
accounts, The Virginia Company invested over £4,000 in the establishment of an
ironworks on Falling Creek, just south of Richmond. The destruction of the
works by the Powhatan Indians in 1622 ended not only the first ironworks in
North America, but also contributed to the revocation of the company's charter
by the King. But, it did not end the dream of large-scale production of iron in the
colonies. Maurice Berkely, the son of the Ironmaster killed at Falling Creek, tried
to rebuild the ironworks in 1623, but failed. Sir John Zouche attempted to
reestablish the works between 1634-38, but all he achieved was the debts he
complained of in his will (Zouch 1904 [1636]). William Byrd I considered
building an iron works at Falling Creek in 1685, but ultimately built only a mill.
In New England a number of iron works were established, including Saugus and
Braintree. None were successful. Small-scale manufacture of iron in bloomeries
flourished throughout the colonies.

It was not until Alexander Spotswood built the Tubal Works probably in 1720 that a blast furnace was again operational in Virginia. Unlike its predecessors, Tubal was successful and remained in blast for over 40 years. Once again iron production became an important goal of England’s North American Colonies. One of the major proponents of iron was pamphleteer and ironmonger, Joshua Gee. In 1720 he wrote:

unless we import about 20,000 Tun of foreign Iron per annum, our Manufactures cannot be compleatly carry’d on... [which costs] 240,00 l. ... and if so great an Advantage as bringing the said Commodities from our Plantations could be brought to pass, it would augment our Navigation to the Plantations to more than double what it now is; and not only be an additional Employment to our Ship-Builders, and all others concern’d therein, as well as to our Sailors and Seamen [Gee 1720:10-11]

Gee was a partner in the Principio Company, who established a number of blast furnaces in Maryland and Virginia in the 1720s. In 1730, as part of a Parliamentary lobbying campaign, he wrote:

The making and supplying ourselves with Pig and Bar Iron from the Colonies is also very material, since Foreigners draw between two and three hundred thousand Pounds per Annum from us for that Commodity... Now if Encouragement was given for making Pig-Iron in our Plantations, that we might be certain of a Supply, then all Places in this Kingdom where there is Water enough, and a sufficient Quantity of Wood, might have Forges erected upon them; and where Furnaces would not answer so well as Forges, they might be converted to that Use also. This would be a general Benefit to the Nation, and keep up all the Woodlands in the Kingdom to their full Value. [Gee 1738:68-71]

Another pamphleteer wrote Reflections on the Importation of Bar Iron from Our Own Colonies of North America (Library of Congress [LC] HF2044 .172 1757:3), proclaiming "That Iron, as a Metal, is of infinitely more real Use than Gold, is a Fact too obvious to stand in Need of Proof".

Iron was vital for the growth of the Virginia colony, and Virginia is
important to the history of the American Iron Industry. The first American iron was made at Jamestown (1608), the first commercial ironworks was at Falling Creek (1619-22), the first successful blast furnace was the Tubal Works (1720-63), and the first double air furnace (foundry) was at Massaponax (1732).

Almost every facet of colonial life from agriculture to warfare required iron. During the American Revolution Virginia was a major supplier of cannon, shot, and other critical military supplies. The ironworks in the Richmond/Fredericksburg area were recognized as critical to the war effort, and targeted by British forces under the command of Gen. Benedict Arnold, LTC Tarleton, and LTC Simcoe in 1781 (Tarleton 1787). During the American Civil War, Richmond was again a military target. Not only because it was the capital of the Confederacy, but also because Richmond’s industry was a major factor in the Confederacy’s ability to wage war.

Men like John England in Maryland, Alexander Spotswood in Virginia, and Peter Hasenclever in New York and New Jersey started the American iron industry. By 1750 Britain’s North American colonies produced more iron than Great Britain, and by some estimates 1/7th of the world’s total (U.S. Bureau of the Census 1960:746; Bining 1938:134). Over half of this was produced in Maryland and Virginia (U.S. Bureau of the Census 1960:762; Bergstrom 1980:136).

Most of this iron was produced in charcoal fired cold blast furnaces. The 18th century iron blast furnaces of the British North American Colonies were among the most costly and complex businesses of their time. They required an enormous capital investment both for construction and acquisition of land, required large crews of skilled and unskilled labor, and operated continuously for months at a time. They consumed tons of raw materials, which had to be delivered to a relatively tight schedule, and produced tons of cast iron a day. Furnace managers also had to take a longer view than their industrial
contemporaries. Forests, for the production of charcoal, were managed and cut on a 15-30 year cycle.

Unlike earlier industrial complexes, blast furnaces were owned by groups of investors, not craftsmen. The day to day operation of a blast furnace required the orchestration of a diverse team of workers: colliers, founders, fillers, miners, teamsters, etc. But, in a revolutionary break with the past, the man in charge was often a professional manager, not a master craftsman. Frequently, he was also the bookkeeper. Unlike most 18th century industries, blast furnaces did not produce consumer goods. Pig iron was an intermediate product that required additional processing. Furnaces either worked the pig iron into wrought (bar) iron at a company owned finery forge or sold it to independent forge owners or iron merchants (mongers). Blast furnaces represented such a radical departure from earlier manufacturing, that Edward Heite (personal communication 1998) has called the blast furnaces of the Chesapeake both the first modern industry and the first just in time industry.

Given the scope, both in terms of capital requirements and operations, it is not surprising that colonial blast furnace operators invested a considerable amount of time in site selection.

In 1619, when Falling Creek was being built, the population of Virginia was not large enough to absorb the output of even one blast furnace. Initially, the only market large enough was England. In the early 1700s it was still the English market, not that of the Chesapeake, that motivated the construction of blast furnaces like the Principio, Bristol, and Baltimore Companies. But, as the colonial population grew, so too did the local demand for iron. And if it made little economic sense for England to import iron from Sweden and Russia, it made even less sense to transport it across the Atlantic to the Colonies.

By 1775 sixteen blast furnaces and numerous bloomeries and forges had been constructed in Virginia. The Albemarle Iron Works (1770-72), South Garden, Virginia, was established just prior to the start of the American
Revolution. It was not a pioneer blast furnace, the process was well understood when the company was formed on 28 December 1770. Two of the partners, John Old and John Wilkinson, spent seven years finding the right spot for "seating & putting in repair a Furnace Forge... & the necessary buildings for making Piggs & Bar Iron & also common & Flask castings" (Walker-Page 1770b).

To all appearances they did an excellent job of site selection. The South Fork of the Hardware River would provide a dependable source of power for the water wheel. The area was well wooded and had abundant beds of iron ore. Wilkinson put considerable effort into convincing a number of Virginians to put up sufficient capital to finance the project. Yet with all their attention to detail the company failed during its first year of operation. It was "carried on at a very great expense and never produced any profit" (Walker 1791).

This paper will concern itself with the rise and fall of the Albemarle Iron Works which is located southwest of Charlottesville (Figure 1) in South Garden, Virginia (Figure 2). A variety of means will be used to study the problem(s) that caused Albemarle to terminate operations in the Spring of 1772. These include archival resources (deeds, letters, depositions, property records, etc.); research into the metallurgy of charcoal cold blast furnaces; examination of the ore; site reconnaissance and evaluation; and analysis of slag recovered from the site. The slag was analyzed using PIXE (proton induced X-ray emission), SEM (scanning electron microscope energy dispersive X-ray analysis), and microscopy. Since there is no documentary evidence that the ore used at the furnace came from the Martin Mine, comparison of the slag and ore analysis will used to confirm the connection.
Figure 1. Map of Virginia showing the location of the Albemarle Iron Works.

Figure 2. Location of the Albemarle Iron Works and Martin Mine. Dillwyn 100K USGS Quad.
GOALS AND OBJECTIVES

The Albemarle Iron Works Albemarle (44AB72) has been the subject of a number of earlier studies. The 1880 U. S. Census included a Report on the Mining Industries of the United States (exclusive of precious metals): With Special Investigations into the Iron Resources of the Republic and into the Cretaceous Coals of the Northwest. (Pumppelly 1886 and 1991:263). Included was an assay of ore collected at two sites in North Garden, including the Martin Mine. William Bowron also included the North Garden ore in The Practical Metallurgy of Titaniferous Ores (1883:162). The Rev. Edgar Woods (1901 and 1932:56-57) in his Albemarle County in Virginia discussed the furnace and the Martin Mine. In 1960 Prof. Robert S. Young, of the University of Virginia did a survey of the Martin Mine and his findings were published in the Virginia Department of Mineral Resources Bulletin 77 (Nelson 1962:69). Thomas V. Dagenhart, Jr. and Gary L. Maddox, also from the University of Virginia (1977:360-363), looked at the geology of the Martin Mine. The ore was included in Geology and Virginia (Dietrick 1970:24), Minerals of Albemarle County (Mitchell 1988:2, 9-10), and Minerals of Virginia (Dietrick 1990:41, 226). Finally, in 1992 William W. Reynolds published 'An Account of the Albemarle Iron Works' in The Magazine of Albemarle County History.

Each of these works told part of the story of the failure of the Albemarle Iron Works. Bowron (1883), the 1880 Census (1886 and 1991), Nelson (1962), Dietrick (1970 and 1990), and Mitchell (1988) were concerned solely with mineral resources and did not discuss the furnace. Rev. Woods’ work was a history of Albemarle County and the ironworks was a minor, two page, entry. Like many early county histories, it was often anecdotal, based on secondary sources, and contained numerous errors. He proposed that it was some "foreign ingredient" which caused the failure.
Dagenhart and Maddox were geologists and were therefore primarily concerned with the Martin Mine and its ore. Although they did look at some of the Albemarle Iron Works documents held at the University of Virginia, their history drew heavily on Rev. Woods (1901 and 1932:56-57). They referred to William Twaddell as the "mine foreman" and wrote that the "mining venture never appeared to be too profitable partially due to mismanagement by John Wilkinson and partially because of the poor quality of the ore" (Dagenhart and Maddox 1977:360). Their metallurgical analysis was based on Bowron's 1883 'The Practical Metallurgy of Titaniferous Ores'. Their interpretation suffered from a lack of understanding of iron making and an understandable geological bias.

Reynolds' article is both a good synthesis of the earlier work, and excellent archival research. He uses the documents to correct most of the earlier works' historical errors. Reynolds looked at a number of possible causes for the failure. He too, based on Dagenhart and Maddox, concluded that it was titanium that caused the failure.

The goal of this paper was to analyze all of the possible factors that could have contributed to the failure of the Albemarle Iron Works, and determine the cause. The research employed all previous known work, as well as archival material and site reconnaissance to create a comprehensive history of the Albemarle venture. Numerous works, both historical and modern, on the manufacture of iron were used to determine the possible causes for Albemarle's failure. Metallurgical texts and slag analysis (PIXE, SEM, etc.) was used to determine the proximate cause. A secondary objective was to determine if the Martin Mine was the source for the iron ore used at Albemarle.

A short overview of the history of iron making and the technology employed in the colonial era is included as a framework for understanding the problems encountered by the Albemarle Iron Works. It is also hoped that it will prove of use for others researching the colonial iron industry.
CHAPTER 1: Iron

Iron is the fourth most common element in the earth's crust. Of the metals, only aluminum is more abundant. But, unlike copper and gold, iron is rarely found in metallic, "native", form. Native iron is found in usable quantities only on Disko Island west of Greenland (Craddock 1995:101-103; Rostoker and Bronson 1990:41; Wertime and Muhly 1980:11). Most iron is found as an oxide and must be chemically altered before it can be used. Some metallic iron is found in meteors (Craddock 1995:103-109). But, outside of sagas and fairy tales, where it often provided the metal for the best magic weapons, meteoric iron is very rare and has rarely been a major source of iron. The exception being China where there is evidence that early smiths used smelted and meteoric iron interchangeably (Wagner 1999:1).

The importance of iron to the Virginia colony cannot be denied. And by the 18th century, iron permeated every aspect of life. But, each required a slightly different "iron" with different working properties. An iron worker of the 18th century was concerned with a wide variety of operational characteristics including: melting temperature, malleability (ability to shape with a hammer), fluidity in casting, ease of welding, hardness, and ability to hold an edge. Iron was, and is, so adaptable because it is a family of materials. It is usually used as an alloy with other elements, seldom in a pure metallic form. The physical characteristics of any iron alloy are largely determined by the other trace elements present. These properties could be substantially altered by the inclusion of small amounts of carbon, phosphorus, sulfur, copper, manganese, silicon, titanium, and other elements. Sometimes the inclusions conferred benefits, others were injurious. Sometimes the benefits were use specific. The most important inclusion is carbon, it determines the overall working characteristics of the iron
(whether the resulting alloy is wrought iron, cast iron, or steel).

Bar, Pig, and Steel: The Types of Iron

Although there are an infinite number of iron alloys, all fall into three broad categories based on carbon content- wrought iron, cast iron, and steel. A fourth historic type, phosphoric iron, is no longer used. None is pure metallic iron, each is an alloy or a composite. Although, all three are generally over 90% metallic iron, they behave very differently. The devil is in the details and in this case what makes up the rest of the alloy determines the character of the whole. Each type of iron has uses for which it was better suited. Superiority or inferiority is use specific, not inherent in the type of iron. How they were used and the quantities of each demanded by the marketplace have varied through time. As uses and demand changed, new production technologies were developed. A detailed description of how they were made will be covered in a later chapter.

Bar Iron

As much as 90-95%, of the iron used in the 17th and 18th centuries was bar (bloom or wrought) iron. Today wrought iron would be described as "a metal-fiber composite ... [a] mixture of pure iron and particles of slag". It could be hammered, twisted, and filed into almost any shape without breaking. Wrought iron can be worked either hot or cold and it only stress (hammer) hardens mildly. This means that it can be hammered or bent repeatedly without making it brittle (Gordon 1996:8). Bar iron only rarely needs to be annealed to relieve stress. It has less than 0.15% carbon and a melting temperature around 1,500°C. The best bar iron had small, uniformly dispersed particles of slag. It was
malleable and strong, deriving these properties from both its metallic and non-metallic constituents.

Wrought iron could be "case hardened" by placing it back into a fire and allowing a thin layer of steel to form on the outside. This was a common practice with tools and parts of machinery or weapons (Gordon 1996:7-10).

Bar iron is not a finished product. It was sold for use by forges, blacksmiths, farriers, and others to produce a wide variety of "wrought iron" objects including: nails, hinges, lock plates, horseshoes, hooks, machine parts, barrel hoops, iron tires for wheels, etc. (Figure 3). It has been estimated that as much as a third of all British bar iron was turned into nails during the 17th and 18th centuries (Flinn 1959:147).

Wrought iron was either made in a bloomery (directly from ore) or by decreasing the carbon content of pig iron in a finery forge (called decarburizing, fining, or refining). The carbon was removed by melting the pig iron in an oxidizing fire. The pig would be fed into the hearth directly in front of the air blast. As the pig melted, the carbon was literally burned out. Some decarburization also resulted from the oxidizing action of the slag (see chapter for a detailed description). The bloom was then hammered to reduce the slag content and convert it to a more usable form, often called bar iron.

Prior to 1783 the terms fining and refining were used interchangeable in the West. But, after the European invention of puddling in 1783, refining and fining often refer to two very different processes. Whereas fining retains its old meaning, refining is the term used for the (usually) coke fired oxidation of silicon as part of the puddling process. Thus, historic documents prior to 1783 may use either term to describe decarburization. But, references to refining after 1783 usually refer to the removal of silicon, not carbon. By using the term "fining" for decarburization, modern authors can differentiate between the two processes and avoid confusion.
Figure 3. Wrought iron products. Photo by author.

Figure 4. 18th Century Virginia Pig Iron. Top- Bristol Company 1742. Middle- Chiswell’s Furnace. Bottom- Fredericksville Company 1736. Photos by author.
If pig iron had a high silicon content, the silicon had to be removed. Oxides of silicon are more difficult to reduce than iron and require high temperatures. These are hard to achieve in a charcoal cold blast furnace and did not become a significant problem until after the adoption of hot blast in 1840. The higher temperatures in the hot blast furnaces developed at that time reduced significant amounts of silicon into the melt which had to be removed.

Bloomeries produced the majority of European iron until the late 16th and early 17th century. Currently, it is very difficult to distinguish between bloomery iron and fined cast iron. However, with further advances in the analytical tools available, it may be possible in the near future. Because of the lower operating temperature of bloomeries, bloomery iron may have generally lower levels of silicon, phosphorus, and sulfur (Rostoker and Bronson 1990:11). But, the same result can be, and was, achieved by using an ore that was low in phosphorus and sulfur and running a colder furnace.

**Pig Iron**

Cast iron is an alloy of iron and 2-4.5% carbon, with silicon and other trace elements. The amount and chemical makeup of these inclusions affects its mechanical properties, in both molten and solid states. Where pure iron melts at 1550°C, the melting (liquidus) temperature of cast iron falls between 1550°C (0% carbon) and 1143°C (4.3% carbon). Cast iron is virtually slag free and cannot be hammered or worked hot, but must be molten to be worked. Pig iron could be cast into more complicated shapes than were possible with wrought iron, but it was brittle and broke easily if stressed. Hammering pig iron results only in small pieces of pig iron.
Figure 5. 1773 cast iron stove plate by Isaac Zane. Photo by author.

Figure 6. Cast iron objects. Photo by author.
When molten iron was tapped out of a blast furnace it was cast into various shapes, thus "cast iron" (Figures 3, 4, and 5). Early blast furnaces were small and a day's production was frequently cast into one large piece. This was called a sow or "sow iron". As furnace capacity grew the sows became increasingly unwieldy. To reduce the weight, side channels were added. To the iron workers this looked like piglets suckling at a sow and so the smaller pieces were called "pig iron" or pigs (Figure 4). The large central channel was still sometimes referred to as a sow into the 1700s.

During the 17th and 18th century cast iron was used for three purposes—cast into pigs for future use, sold, or cast into finished products. Most was either sold or, in a vertical monopoly, transferred to finery forges. These decarburized the pig iron, converting it to bar iron. This was the most common use of cast iron until well into the 19th century. Until then the market for cast iron products was very small and there was little need for separate foundries. Most colonial blast furnaces doubled as foundries, making enough cast iron objects to satisfy local demand. Instead of being run into pigs, cast iron could be ladled or run directly into molds to make a variety of products. Wooden patterns could be pressed directly into the sand floor of the casting shed to make flat castings like stove plates and firebacks. Three-dimensional objects like kettles or cannon were cast in multipart molds called flasks.

Pig iron was classified by the "color" of the fracture surface: white, gray, and mottled. The physical properties, and color, of cast iron were largely determined by the speed it was cooled and to some extent the temperature of the furnace and chemical composition of the iron. The faster the iron cooled the more likely it was to form white iron. Conversely, a slow cooling iron tended to be gray. A hotter furnace would cause the iron to take up more silicon. Silicon promoted the formation of gray iron. This process was not fully understood until
the late 19th century. Until then furnace masters had to work by trial and error, and errors resulted in unusable iron. Sulfur, in even minute quantities, resulted in white iron. Phosphorus increased the fluidity of cast iron, encouraged the formation of grey iron, and depressed the solidification temperature.

White iron is extremely hard, practically impossible to chisel or file, and was generally avoided by ironmasters because it was so difficult to work. It is still considered "unmachineable" by modern ironworkers. Its hardness is the result of most of the carbon taking the form of iron carbide (Fe$_3$C, cementite). White cast iron is more brittle than other cast irons, but also much more resistant to abrasion. Until recently it was used to make plow blades and is still used in rock crushers and grinders. The ancient Chinese used it to make plows as well as digging and cutting tools. Experimental archaeology has shown white iron to be excellent for gravers and arrowheads, and suitable for axes and other chopping tools. It can be converted to gray iron by placing it in a furnace and holding it at red heat. This causes the cementite to decompose into ferrite, a low temperature form of pure iron, and graphite. The technique was used by the Chinese as early as the third century BC (Wagner 1993 and 2001:64), but does not appear to have been used in the West until the 19th century (Rostoker and Bronson 1990:17-18; Gordon 1996:257).

Gray cast iron consists of ferrite, pearlite (plates of cementite in a ferrite matrix), and graphite flakes. It is the graphite that causes the fracture to look gray. The graphite is also responsible for gray iron being easier to work. On modern machines it acts as a lubricant. The flakes also break up the structure of the iron and make it more resistant to cracking. Gray iron is softer than white or mottled iron and is easier to work. It can be cut and filed. Gray cast iron was the preferred product of European blast furnaces during the colonial period.

Mottled iron is composed of a combination of white and gray iron. Rather
than conferring the benefits of both, it results in an iron with the shortcomings of both. Although a number of mottled iron objects have been found, it does not appear to have been deliberately made. But, rather have been the result of poor control of the smelting process (Rostoker and Bronson 1990:18).

The Chinese began using cast iron as early as the 4th or 5th centuries B.C. (Wagner 1993 and 1999). During the Han dynasty (206 BC-220 AD) cast iron was in wide use in China for products as diverse as plows and cooking pots (Wagner 2001). It is not understood why Europeans made so little use of cast iron. The technology for the production of cast iron and casting it into useful shapes existed in Europe. Tylecote has demonstrated that both the Greeks and Romans experimented with cast objects. Even though cast iron pots have been found in European contexts as early as 100 AD, the blast furnace and the ability to produce large quantities of cast iron do not occur until much later. The primary impetus appears to be the manufacture of cannon and munitions in the 14th and 15th century (Tylecote 1976:57, 1987:325-327).

While iron cannon balls are common in the late 15th century, the first English domestic products did not appear until the next century. Cast iron pots appeared in 1543, followed by firebacks and stove plates in 1548, and firedogs in 1573 (Rostoker and Bronson 1990:117). Demand for cast iron domestic products remained low, during the 16th and 17th century 95% of the output of the Rievaulx blast furnace was converted to wrought iron (Schubert 1957:246). But the demand for cast iron products grew and by the mid-19th century cast iron products dominated the market. It was cast into a variety of shapes including: pots, kettles, frying pans, firebacks, and cannons (Gordon 1996:10-11). In the 19th century it was used for boilers, decorative ironwork, and structural members as well.
Steel

Steel is an alloy of iron with 0.5-2.0% carbon, composed of varying quantities of cementite, ferrite, martensite, and pearlite. Martensite is formed by rapidly cooling a hot piece of steel. This process is called quenching. Generally, steel’s properties are intermediate between wrought and cast iron. It is neither as brittle as cast iron, nor as malleable as wrought iron. But it is hard like cast iron. The higher the carbon content the harder and less malleable it becomes. At temperatures above 900°C it can be forged like wrought iron. Steel can also be hardened by cold hammering. Most importantly steel holds an edge.

Much like bronze, steel becomes much harder and stronger when hammered cold. And it has been proposed that cold working is a carry over from bronze smithing. Cold worked steel is at least equal to bronze in terms of toughness and wear resistance. But, it is also brittle, especially if its carbon content is much over 0.5%.

Steel is the only iron that can be hardened by quenching. This is accomplished by plunging red hot steel into a liquid. Quenching also results in brittle steel. Annealing is a technique for returning bendability or malleability to steel at the expense of hardness. The steel is placed into an oven or fire and heated at a low temperature for an extended period of time. Through a combination of quenching, hammer hardening, and annealing an ironsmith can achieve almost any combination of hardness and malleability.

Until the introduction of such technologies as the Bessemer Converter in the late 19th century, steel was both rare and expensive. The value attached to steel can be seen linguistically. Most languages have separate terms for steel and other forms of iron. The words for steel generally carry connotations of value and desirability. It was used only in such items as swords or muskets, expensive
tablewares, or in small pieces welded into wrought iron tools for cutting edges.

During the 17th and 18th centuries steel was made in Europe and America by adding carbon to bar iron or removing carbon from pig iron. The former method (cementation) formed a thin layer (or blister) of steel on the outside of a bar by heating it. This could be done one bar at a time, but many bars could also be packed in powdered charcoal and heated in a sealed container (called a coffin or chest). The longer the bar was heated with carbon the more was absorbed, but the upper limit seems to be, fortuitously, 1.5%. The process, once understood, was reasonably controllable and steelmakers could consistently achieve a carbon content of 0.5-1.5%. But, the bar was only steel on the outside and still wrought iron on the inside, and the iron had to be left in the furnace for 6-20 days (Barraclough 1976; Gordon 1996:173-176). Bars could be welded together to form an iron and steel sandwich (shear steel) or melted together to form a homogenous steel (crucible steel). Until advances in both metallurgy and technology allowed iron makers to accurately control the chemistry of iron, it was very difficult to remove just enough carbon from pig iron to transform it into steel. However, "Natural, German, and Cullen" steel were produced as early as the 1500s (Barraclough 1976:65-66; Gordon 1996:12; Rostoker and Bronson 1990:121-25).

In Japan, the Middle East, China, and Italy it was found that bars of wrought iron (low carbon) placed in a crucible with molten pig iron (high carbon) would result in steel. In 4-6 hours the carbon in the molten pig iron diffused into the wrought iron resulting forming steel (Barraclough 1976:83-86; Biringuccio 1966:67-70 [1540]; Rostoker and Bronson 1990:125-126). If a high enough temperature could be achieved to melt the wrought and pig iron, good homogenous steel resulted. In Europe this technique was no longer used by the mid 17th century (Rostoker and Bronson 1990:126). It was replaced by
cementation, which although it took longer and did not produce as high quality steel, produced a larger quantity. But, after 1855 a growing amount of English steel was made in crucibles, not with blister steel, but by melting together Swedish pig and wrought iron (Barraclough 1976:83-84). By the end of the 19th century both blister and crucible steel had been eclipsed by new technologies like Bessemer and Siemens.

**Phosphoric Iron**

In pre-industrial times there is increasing evidence that there may have been a fourth type of iron, phosphoric. A detailed description of the effects of phosphorus on iron is contained in Chapter 6 and the modern iron and steel industry's attitude on phosphorus were clearly stated by Turner in 1900.

It is not necessary to search for phosphorus, most irons contain more than is needed, and the care should be to keep it within limits. [Turner 1900:204].

While it is true that small amounts of phosphorus (under 0.2%) make iron and steel much stronger and harder, modern metallurgists often see only that it inhibits carburization (needed to form steel) and causes it to be cold short (brittle at room temperature). The fact that phosphorus makes iron brittle and inhibits the formation of steel overshadowed all its other effects.

As a result, early iron that contains phosphorus is often viewed as inferior. This perception was reinforced by the fact that most phosphoric irons were low in carbon. Since steel was the "ideal" modern iron, high phosphorus, low carbon iron was poor quality by definition. By extension, phosphoric iron was seen as an indicator that the smelter used bog ore, an inferior ore.

It is becoming increasingly clear that although the injurious effects of
phosphorus were among the first recognized by ironsmiths, so too were the benefits. And for some purposes the benefits outweighed the disadvantages, and were actively exploited by early iron workers.

Steel was difficult to make because the carbon content was very hard to control. But phosphoric iron, with many of the same properties as medium steel, was easy to make. All that was required was a high phosphorus ore. Early iron workers, rather than being forced to use bog ore, may have actively sought it to make high quality phosphoric iron.

Metallographic studies of early iron indicate that rather than avoid phosphoric iron, early iron workers deliberately produced it and preferentially used it where steel like qualities were required. For instance phosphoric iron was frequently used in early weapons and tools (Craddock 1995:238; Rostoker and Bronson 1990:22). There is evidence that wealthy individuals in the Middle Ages may have had two swords. A high phosphorus one to use during the summer campaigns, and a low phosphorus one for the winter (Rostoker and Bronson 1990:22).

As the technology for manufacturing steel became more reliable and steel became more available, the demand for phosphoric iron declined. By the time the Albemarle Iron Works was founded, the use of phosphoric iron had all but disappeared. As the demand for cast iron grew in the 18th and 19th century phosphorus' ability to increase the fluidity of cast iron once again became important. But phosphoric iron ceased to be a substitute for steel and its harmful effects predominated (see Chapter 6).

The Hierarchy of Iron: Steel, Wrought, and Lowly Cast

For most of its history there was pecking order or hierarchy of iron. Steel
was recognized as a superior material worldwide. Cast or pig iron was frequently characterized as inherently inferior to the two other forms of iron. This rank ordering was due to a number of factors—market forces, a lack of understanding of metallurgy and reliance on alchemy, and available technology.

Until the introduction of modern mass production techniques in the late 19th century, demand for steel always outstripped supply. Steel was seldom produced directly. It was the result of additional processing of wrought or cast iron. The methods involved putting another form of iron back into a fire.

In the alchemical tradition, fire was a purifying agent. Iron was made up of "pure", liquid mercury and a combustible earthy sulfur. Fire was used to purify the iron by burning out the sulfur or dross. Aristotle described steel as purified iron. Until the advent of modern chemistry steel was viewed as "clean" or "pure". While wrought iron and especially cast iron were dirty (Wertime and Muhly 1980:5). Cast iron especially was seen as "foule, blacke, and dark", (Monardes 1574 as quoted in Wertime and Muhly 1980:5), crude (Hartley 1957:171), or raw.

The established hierarchy was a logical one grounded in the alchemical tradition. Cast iron when subjected to the purifying action of fire was converted to wrought iron. Wrought iron when further purified by fire, became steel.

Further justification was the result of market forces. Until the middle of the 19th century Europeans used much more wrought iron than cast iron. Cast or pig iron was seen primarily as a raw material requiring additional processing before it could be used. Again the process of converting pig iron to wrought iron involved the purifying action of fire. In both the European fining and puddling processes this is often referred to as bringing the iron to "nature". In historic documents this processing involved the removal of "impurities". As a result of the additional processing time and costs, wrought sold for more than cast iron. It
could be fined into wrought iron or subjected to even more time consuming and expensive processing to convert it to steel. The alchemical prejudice was reinforced by the technology used. Cast iron was the cheapest form of iron, because it required no additional processing. Steel was the most expensive because it required the most.

But, the primary cause of the deep-rooted feeling that cast iron was inferior resulted from a total misunderstanding of the true nature of iron. It was a direct outgrowth of the alchemical tradition of both Europe and Asia. Fire was used to remove impurities. Cast iron that was subjected to fire became wrought iron. Wrought iron when treated with fire became steel. Something that requires "refining" or "purifying", must be inferior.

But, the only impurity removed was carbon. If a higher carbon content makes cast iron inherently inferior to wrought iron, then it follows that steel must be inferior as well, because steel is also contaminated with carbon. European ironmasters were "purifying" cast iron by removing carbon, to convert it to wrought iron. At the same time their primary method for making steel was to add carbon to wrought iron. Had European ironmasters understood the chemistry of iron, they might have produced significantly more steel earlier and at a lower cost.

Many modern researchers continue to characterize cast iron as an inferior form of iron. This is the result of a lack of understanding of the chemistry of iron and a perpetuation of an historic bias. Modern researchers cite cast iron as inferior because historic sources say it was and because historic sources state that impurities must be removed to convert it to wrought iron. This is totally incorrect and ignores all has been learned about the metallurgy of iron over the last 300 years.
Figure 7. Map of Colonial Blast Furnaces
CHAPTER 2: A Short History of Iron Making

The first iron was made about 4000 years ago. It is generally acknowledged that iron technology initially developed in Anatolia (modern Turkey) and Southwest Asia. From there it spread across Europe, Africa, and Asia.

The earliest furnaces were of the bloomery type and closely resembled contemporary copper and bronze furnaces. They converted iron ore directly into a "bloom" of low carbon iron. Two basic types were in use, bowl and short shaft furnaces. The least complicated was the simple bowl furnace. It consisted of a depression in the ground. Ore and fuel were loaded directly into the hole. Blast was provided by some form of bellows. The smelt had to be halted when the bowl filled with slag and then both the bloom and slag were manually removed. The bloom was then hammered to reduce the slag content and convert it into a usable form. While simple structurally, the bowl furnace is also very inefficient. The hot gas escapes out the open top and has little time to react with the ore.

Over time the bowl furnace was elaborated and made larger and more efficient. This was done primarily by increasing the depth and diameter of the furnace. This allowed more time for the hot combustion gases to reduce the iron ore, decreased thermal loss, and increased the size of the bloom. Provision was also made for the tapping off of the liquid slag, so that the furnace could operate for longer periods. Eventually the sides became high enough that the bowl became a shaft. A detailed discussion of the construction and operation of various kinds of early bloomery furnaces can be found in Early Metal Mining and Production (Craddock 1995), Early Iron Production- Archaeology, Technology and Experiments (Norbach ed. 1997), The Coming of the Age of Iron (Wertime and Muhly 1980), Metals in Antiquity (Young et al. 1999), and the publications of R. F.

Had no other factors been involved, furnaces would have continued to increase in height, increasing efficiency; and in size, increasing yield (bloom weight). But, there was very little change in furnace size from the rise of the Roman Empire until the late Middle Ages. There were a number of reasons for this "stagnation", but chief among them was power limitations. A man with a hammer is limited to working a fairly small bloom. The volumes and pressures of air required for large furnaces were beyond the capability of human muscles. As a result, the Roman and early Medieval armies were supplied by armies of bloomers.

All of this changed with the application of water power. Interestingly, monasteries were the vehicle for the spread of water power. With the introduction of water power the size of the bloom grew an order of magnitude from around 10kg to 100kg (Blick 1991:14). So integral a part of iron working did the water powered hammer become, that the word "hammer" becomes a synonym for a forge in English.

Shaft bloomeries are divided into low bloomeries and high bloomeries. The transition point is not well defined. But at some point the walls grow high enough that it becomes a high bloomery. The additional height allowed a greater amount of the heat to be absorbed by the charge and less exhausted to the atmosphere. It also subjected the ore to a longer exposure to a reducing atmosphere. The result was increased efficiency and fuel economy, with a higher percentage of the ore being converted to metallic iron.

However, some other fundamental changes occurred. The taller the furnace stack, the longer it took for the charge to work its way to the hearth. The bowl, dome, and low bloomeries were batch operations. At the end of the day, the operator shut them down. At some point, this ceased to be an option with the
high bloomery. Additionally, a man powered bellows was no longer able to force air through the resistance of the burden.

The drive for increased yield and fuel efficiency is the basis for one of the theories of the development of the blast furnace. This postulates a relatively seamless transition from the high bloomery to the blast furnace. The shaft continued to increase in height until it required a water driven blast. At some point the bloomery became tall enough that it was capable of producing both a bloom of low carbon iron or liquid high carbon iron (cast iron). This was accomplished by manipulating the ratio of charcoal to ore. Using more charcoal resulted in cast iron. The transition to a true blast furnace occurred when it was no longer possible to use one furnace to produce the two varieties of iron.


**An English Context**

With two exceptions, the early development and use of iron and iron technology in the British Isles did not differ substantially from what took place in Europe. Because of Britain’s geographic position, off the western edge of Europe, technology generally arrived later. For instance Britain did not make the transition from bronze to iron until 800-550 B.C. The second difference was that
the shaft furnace seems to have gone out of use after the Roman era.

Although iron technology first developed in Anatolia and Southwest Asia, the innovative center quickly moved to Europe. Most of the technological advances, including the blast furnace, developed in Northern Europe. Following the construction of the first English blast furnace in 1496, the flow of technology transfer changed dramatically. The ironmasters of the United Kingdom achieved clear technological superiority by the early 1700s and most of the technological advances made during the 18th and early 19th centuries were British. By 1800 Britain was the largest producer of iron and steel in the world. By the mid 19th century the United Kingdom produced as much iron and steel as the rest of the world combined.


**The Invention and Spread of the Blast Furnace**

"Less conspicuous than the castle but more significant for the long future was the above-ground reduction furnace, feeding iron to local forges whose smiths shaped it into parts for plows, spades, pitchforks, and shoes for horses" (Gies 1994:80-81). The blast furnace has been called the greatest technological achievement of the Middle Ages (Forbes 1950:117). It was one of the essential building blocks of the Industrial Revolution, but it may not be European in
origin. The debate is a classic independent invention versus diffusion argument. While the Chinese clearly developed the blast furnace and finery first, there is no conclusive evidence of technology transfer. In addition, archaeology supports the independent European development of the blast furnace from the bloomery.

There is clear evidence of iron technology transfer from the West to the East. Archaeology supports the introduction of iron metallurgy and the bloomery into China from the West via the Scythians and Siberia (Wagner 1999:1). The Chinese were using blast furnaces at least 1500 years before their appearance in Europe and Africa (Wagner 1999:5). The Chinese also appear to have developed the finery by the 1st century BC (Wagner 1999:7) and the mature water powered blast furnace was in common use by the 3rd century BC (Gilmour 1999:89).

The earliest blast furnaces appear in Europe about the same time that people like the Polos of Venice (12547-1324) opened routes to China and the East. Ronald Tylecote pointed out the similarities between the Chinese and Norse vertical shaft water wheel and that the Scandinavians traded with China via Russia as early as the 7th century (Gordon and Reynolds 1986:114). Donald Wagner found some similarities between early Swedish and Chinese blast furnaces (Gordon and Reynolds 1986:114).

Had the entire Chinese system been used in Europe, it would be a clear case of technology transfer. But there are substantial differences in the way that cast and wrought iron were made in China and Europe, and the Chinese blast furnace was only used as far west as modern Iran. It can be argued that the blast furnace is a classic example of form follows function, it's form dictated by technological necessity not technology transfer.

The mainstay of the European iron industry for over 2000 years was the bloomery. It provided the majority of European iron until the 1600s. The Chinese
used the bloomery, introduced from the West, for only a few hundred years before switching to the blast furnace (Wagner 2001:64-65). By the 1st century BC the Chinese were producing wrought iron in fineries, a technique not used in Europe until the Middle Ages (Wagner 1997:12-14 and 1999:7). By the 1300s the Chinese developed a form of puddling (Needham 1958:fig 25), a technology that was not used in Europe until 1783. The Chinese used hinged fans, piston bellows, and double action piston bellows to provide the blast. Europeans used bellows until the late 18th century, when they were replaced by blowing tubs (a piston).

If the blast furnace was independently invented, where and when continues to be the subject of numerous articles, papers, and conferences. Up until recently there was a general consensus that the blast furnace was the natural result of the evolutionary growth of the high bloomery. Gerhard Sperl demonstrated a nearly seamless transition from the bloomery to the blast furnace in the Austrian Alps during the period 1541 to 1775. Using both documents and archaeology he established a sequence of furnace types, *rennofen - stickofen - flossofen - hochofen* (Gordon and Reynolds 1986:113).

According to this theory, the blast furnace represents the ultimate development of the shaft furnace. The shaft bloomery continued to increase in size and in Northern Europe developed into a variety called a high bloomery (in German *stückofen*). These had all of the characteristics of a blast furnace, including a water powered blast. But, they were designed to produce low carbon wrought iron. The iron was not tapped out, but removed as a bloom. But by increasing the ratio of charcoal to ore they could produce cast iron. Erik Tholander and Stig Blomgren (1986) have proposed that they all did produce some pig iron, either as a by product when a little too much charcoal was added, or deliberately. Tholander and Blomgren go so far as to speculate that much if not all early European cast iron was made in dual purpose high bloomeries.
(Tholander and Blomgren 1986:79-80). From the dual purpose high bloomery, it was a short step to a full time blast furnace. All that was required was to heighten the walls a little, and charge more charcoal.

Over the last twenty years there has been a great deal of work devoted to early sites. Much of this information has been presented at conferences held in Plas Tan y Bwlch (Wales), Sweden, and Jutland. Unfortunately very little has been published in English. A number of blast furnace sites have been identified in Sweden and North Central Europe dating to the 13th century (Gordon and Reynolds 1986:114; Magnusson 1985; and Jockenhovel 1997). Documentary evidence for blast furnaces does not appear until the 15th century (Straker 1969:39-40; Awty 1987).

There is little doubt that the blast furnace and the two hearth finery/chafery system of converting cast iron to wrought iron was introduced into Great Britain from either Northern France or Southern Belgium. The finery/chafery system was called the Walloon process after the people (Walloons) and region of Wallonia. But, where, and when, was the first true European blast furnace? The location and date continue to elude researchers.

The question of technology transfer is also still problematic. While Wagner and others have concluded that China received the bloomery from the West via the Scythians, the origin of the blast furnace is far from settled. Clearly the Chinese developed the technology long before it appeared in the West, but neither an archaeological or documentary connection has been demonstrated.

**North American Colonial Context**

Very little iron was used in the Americas prior to the arrival of Europeans. Various American Indian and Eskimo groups made extremely limited use of
meteoric, native, and Japanese iron. The only known usable deposits of native iron are on Disko Island west of Greenland (Rostoker and Bronson 1990:41; Wertime and Muhly 1980:11). Japanese iron arrived attached to fishing floats and pieces of fishing boats. There was no pre-contact smelting of iron.

American iron production had a slow start. The population of the initial colonies at Jamestown and Massachusetts Bay could not absorb the output of a blast furnace. There is documentary and archaeological evidence that bloomeries were established to supply some of the iron needed by the fledgling colonies. As early as 1608 John Smith was touting "chissels" made from Virginia iron (Smith 1608 and Arber 1910:9). There is evidence that production of iron in New England began shortly after the arrival of the Pilgrims in 1620.

Both the Virginia Company and the leaders in New England saw North America as an ideal place to manufacture iron that could be exported to England. And both sought to establish blast furnaces. But, the early furnaces were either destroyed, like Falling Creek, or failed after a short run, like Saugus and Braintree (Hartley 1955, 1957), and New Haven (Gordon 1996:57). They were replaced by a bloomery based industry more suited to the low density population of North America, but capable of supplying the local market. By the end of the 17th century most of the iron used in the colonies was supplied by colonial bloomeries.

The situation changed dramatically in the 18th century. In the first quarter of the 18th century blast furnaces were built in Virginia, Maryland, New Jersey (if Tinton Falls is a blast furnace it was built in 1682), and Pennsylvania. The furnaces of Virginia and Maryland were intended primarily to produce pig iron for export to England. Some failed, others thrived. But for every one that failed, others were started and iron production rose steadily until the outbreak of hostilities with Great Britain in 1775 (Gordon 1996:59-69).
The first official record of iron production in the British North American colonies is found in customs records and a report to Parliament from 1750 (House of Lords Record Office 1750) covering the period 1710 to 1749. The first iron to reach Britain was one ton of bar iron from Nevis and two tons of bar iron from St. Christopher (both islands in the Caribbean) in 1717. 1718 shows bar iron exports from Nevis, Barbados, and Virginia/Maryland (the data for Virginia and Maryland are often commingled because the ships originated from Chesapeake ports). The first pig iron was 15 tons from Virginia and Maryland in 1723.

At their colonial zenith American blast furnaces annually produced over 30,000 tons of pig iron, bar iron, and castings. This may seem paltry by modern standards (over 1 billion tons annually). But, in 1700 world production was only about 300,000 tons (Wertime 1980:xviii). 30,000 tons is a substantial portion of total world production (Bining 1938:134; Wertime 1980:xviii). As a production unit, the British North American colonies were the world's third largest producer of iron (Gordon 1992:5).

More significantly, the American colonies out produced Great Britain. This is particularly significant when one considers the disparity in population. In 1700 the 13 colonies had a total population of approximately 275,000, while Great Britain had over 5,000,000. By 1760 the colonies had grown to 1.6 million, and the United Kingdom to over 6 million people. By then the American colonies were producing almost four times as much iron per capita as the mother country, a difference that contributed to the American victory in the Revolution.

It should be remembered that although a great deal has been written on the colonial and English iron industry, the story is far from complete. Most of what is know has been derived from the records of individual iron works or official colonial documents. A lot of excellent research has been done on individual iron works. But, most of this is contained in locally produced
publications, and it has only been in the last few years that any attempt at a synthesis has been attempted. Most of the compiled data has been derived from official British Government documents and they were only concerned with the export trade. There is very little data available on local markets or colony to colony trade, since this trade was largely unregulated and untaxed. This information is stored away in archives all over the United States and Great Britain, contained in company records and personal letters. Only a few of these, like the U. S. records of the Principio Company have been studied (Whitely 1887; May 1945; Robbins 1972, 1986). As a result what is readily available, is best viewed as indicative of trends rather than as hard numbers. Total iron production was probably higher, as were exports.

Throughout the colonial period the Chesapeake was the center of North American iron production. Virginia and Maryland dominated the colonial export market. It was not until the 1760s that New York and Pennsylvania enter the export market. But, their iron was absorbed by the domestic market (one reason it is very difficult to develop hard data on production) Virginia and Maryland continued to be the largest exporters of pig iron and bar iron up to the cessation of trade in 1775, accounting for more than half of all exports (U. S. Bureau of the Census 1960: 746-748 and 762-765; HLRO 1750). Peter King, working with company records in England, has found that one English firm, Edward Knight & Company, purchased almost 7,000 tons of American pig iron between 1728 and 1757 (personal communication 1999 and 2000).

Contradictory British policy towards iron production and the domestic demand for iron lead to a slow, but inevitable growth of the colonial iron industry. Beginning in 1660 with the Navigation Acts and again in 1750 Great Britain belatedly tried to regain control of both the politics and economy of the Colonies. While a great deal was made of these attempts at regulation by various
Patriots, including John Adams, the laws were almost universally circumvented. However, the animus that grew out of these and other laws were a primary reason for the American Revolution. And, the inability of the English government to enforce the laws allowed for the creation of the industrial infrastructure that enabled the United States to fight and win the American Revolution.

**Virginia and the Birth of American Iron Manufacturing**

Iron was important from the very first for the Virginia colony. In a letter of 1608, CPT John Smith reported to London that he had sent them "two barrels of stones, and such as I take to be good Iron ore at the least" (Smith 1624 and Arber 1910:444). In 1610 Sir Thomas Gates reported "iron-ore ten miles in circuit, of which we have made trial at home; that it makes as good iron as any in Europe" (Pearse 1867:8). William Strachey wrote in *The Historie of Travell into Virginia Britannia* (1953:132 [1612]):

Sir Tho: Dale hath mentioned in his Letters to the [Worthies] of the Councell of a goodly Iron Myne, and Capt Newport hath brought home of that mettell so sufficient a tryall, as there hath bene made 16. or 17. tonne of Iron, so good as the East Indian Merchants brought yt of the Virginia Company, preferring yt before any other Iron of what Country soever.

In 1612 Alexander Whitaker proclaimed, in *Good Newes From Virginia*:

As for Iron, steele, ... they have rather offered themselves to our eyes and hands, then bin sought for of us. [Whitaker 1613 and Brown 1890, II:578]

Not surprisingly a blacksmith, James Read, was listed among the "first Planters" who arrived in 1607 (Smith 1624 and Arber 1910:390). The first "iron works" in the British North American Colonies was a blacksmithy at Jamestown, Virginia. It was required to maintain the colony's tools, make new ones as
required, and repair weapons and armor. Read, and his successors, also made bloomery iron on a small scale. John Smith wrote that "our best commoditie was Yron which we made into little chissels." (Smith 1608 and Arber 1910:9). As the population of the colony grew, the next logical step would be a full-time bloomery. A purpose built bloomery would also have been able to provide all of the bar iron necessary to sustain the colony.

There is archaeological evidence that bloomeries were built in Virginia in the 17th century. John Cotter reported that he found smelting debris at Jamestown (Cotter 1958:110-112 reprinted in 1994). Three other sites show possible evidence of iron smelting: Flowerdew Hundred (44PG92, Markell 1994: 56-57), Falling Creek (44CF0007), and the Drummond site. David Harvey has examined the artifacts from Cotter's excavation and discussed them with Dr. Cotter. He also observed the Flowerdew excavation. Mr. Harvey concluded that both were blacksmithies and not bloomeries (personal communication 1997/98). Outside of Jamestown, the Drummond Site is the best candidate for a 17th century bloomery (Harvey 1989a:47).

During 1999, Jamestown Rediscovery, excavated two features that appear to be bloomery hearths (one was removed intact for later study). The features were associated with JR100, a rowhouse/warehouse complex, believed to be associated with John White (1630s/40s). According to David Harvey the slag "is visually consistent with bloomery materials: it is magnetic, has entrapped charcoal, and in the x-ray it has a honeycomb structure with a network of dense metal and glass" (D. Harvey, N. Luccketti, and W. Kelso, personal communication 1997-2000). Preliminary analysis of one sample has confirmed that it is bloomery slag (Robert Gordon and Blye Straube e-mail March 9, 2000).

Potentially, the most significant 17th century site is the iron works at Falling Creek (44CF0007). Clearly it was the intention of the Virginia Company to
build an ironworks at Falling Creek, including a blast furnace. In 1618 the company "sent 150 persons, to set up three Iron works; profe having been made of the extraordinary goodnesse of that Iron" (Kingsbury 1933:115). Unfortunately, many of the men, including the ironmaster died. Replacement personnel were dispatched in 1621. But, to date the limited excavations at Falling Creek have yet to prove that a blast furnace was built there or produced any 17th century artifacts.

A geophysical survey of Falling Creek performed in September of 1999 indicated that there are structures on the south side of Falling Creek. Further, a large magnetic anomaly was found that is consistent with a fired blast furnace hearth and was tentatively identified as the 17th century blast furnace (Jones and Maki 1999:11). This identification needs to be confirmed by excavation.

The site of the first blast furnace in what became the Unites States is hotly contested. Clearly Falling Creek (1619-22) predates Hammersmith (Saugus 1647). For that matter the blast furnace built at Braintree, MA (1645) predates. But, Braintree was an abject failure, abandoned shortly after it was built because of a inadequate water supply and insufficient ore deposits (Hartley 1957:100-109). Hammersmith (Saugus) was also a business failure, producing poor quality iron and shortly after it’s founding was seized by the colony for debts.

The first successful American blast furnace was either Lewis Morris’ at Tinton Falls, New Jersey (est. 1682) or Alexander Spotswood’s Tubal Works (est. 1719-20) in Virginia. But, very little is known about Tinton Falls. Pending additional research, judgment about what operated at the site and its success or failure must be withheld.

There is no question that the Tubal Works was a success. And so Alexander Spotswood and the Tubal Works probably deserve to be "enshrined" as the first successful blast furnace in America. It was certainly the first of the
export oriented ironworks that along with the furnaces and forges of the Principio Company, Baltimore Company, and Bristol Company formed the basis for the Anglo-Chesapeake Iron Industry, the birthplace of the American iron industry and the American Industrial Revolution (Heite 1983:133-181, 2000 Gunston Hall Conference).

Beginning in 1607, Virginia played an important role in the development of the American iron industry. The first iron manufactured in North America (to date) was made at Jamestown. The first blast furnace was built at Falling Creek. The first successful blast furnace was the Tubal Works. The Chesapeake area, Virginia and Maryland, were the center of the British North American iron industry until around 1750.

Virginia's Colonial Blast Furnaces

From 1607 to 1775, the Colonial Period, as many as 16 blast furnaces were built in Virginia. Construction took place in three distinct phases, both temporally (Table 1) and geographically. Each phase was farther into the interior of Virginia (Figure 7). There was also a significant shift in market emphasis between Phase II and Phase III. The furnaces of Phase III were primarily built to serve the domestic market, while the earlier furnaces were export oriented.

The first iron works in North America was built at Falling Creek (44CF0007). Its location just west of the James River was ideal for providing pig iron for export. Both documentary evidence and a 1999 geophysical survey of the site (Jones and Maki 1999) support at least limited production before the Powhatan Indians destroyed it in 1622. It is also likely that a bloomery operated at Falling Creek.
Table 1. Colonial Blast Furnaces—
By Phase, with Dates of Operation

<table>
<thead>
<tr>
<th>Furnace Name</th>
<th>Dates of Operation</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Begin</td>
<td>End</td>
</tr>
<tr>
<td>Phase I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Falling Creek Iron Works</td>
<td>1619</td>
<td>1622</td>
</tr>
<tr>
<td>Phase II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubal Works Spotswood)</td>
<td>1720</td>
<td>1763</td>
</tr>
<tr>
<td>Bristol Iron Works</td>
<td>1721</td>
<td>1757</td>
</tr>
<tr>
<td>Accokeek (Potomac) Fu.</td>
<td>1726</td>
<td>1753</td>
</tr>
<tr>
<td>Fredericksville Fu.</td>
<td>1728</td>
<td>1760</td>
</tr>
<tr>
<td>Chiswell Fu.</td>
<td>1733</td>
<td>1740</td>
</tr>
<tr>
<td>Neabsco Fu.</td>
<td>1737</td>
<td>1829</td>
</tr>
<tr>
<td>Occoquan Fu.</td>
<td>1755</td>
<td>1773</td>
</tr>
<tr>
<td>Grymes' Recovery Fu.</td>
<td>1757</td>
<td>1771</td>
</tr>
<tr>
<td>Phase III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zane's Old Furnace</td>
<td>1768</td>
<td>1774</td>
</tr>
<tr>
<td>Albemarle Iron Works</td>
<td>1771</td>
<td>1772</td>
</tr>
<tr>
<td>Marlboro Iron Works.</td>
<td>1772</td>
<td>1795</td>
</tr>
<tr>
<td>Callaway Fu.</td>
<td>1775</td>
<td>1779</td>
</tr>
<tr>
<td>Mossy Cr. Fu.</td>
<td>1775</td>
<td>1841</td>
</tr>
<tr>
<td>Oxford Iron Works (2)</td>
<td>1775</td>
<td>1817</td>
</tr>
</tbody>
</table>

The second phase of Virginia blast furnace construction opens at Spotswood's Tubal Works in 1716 and ends with the construction of Grymes' Recovery Furnace in 1757/58, a total of eight furnaces. Following the construction of Spotswood's blast furnace at the Tubal Works (44SP12, 1716-1720), in what is now Spotsylvania County, a number of furnaces began operation. The Bristol Iron Works (44WM44) was formed in 1720 and constructed a furnace on Bristol Mine Run, Westmoreland County, sometime after May 27, 1721. John Tayloe was both a partner and the North American agent for the company. Accokeek (44SP53, historically called Potomac), a subsidiary of the Principio Company, was established on July 24, 1726. Augustine Washington owned the land and later became a Principio partner. Charles Chiswell was a
partner (as was Gov. Gooch) and the manager of Fredericksville Furnace (44SP43, 1728) and the owner/operator of Chiswell's Furnace (44HN0118, 1733). Neabsco (44PW629) went into blast in 1737. The last two furnaces built during this period were Occoquan (44PW605, 1755) and Grymes' Recovery (44SP208, 1757/58). All of these were in Tidewater and the Piedmont of northeast Virginia.

The construction of Spotswood's blast furnace inaugurated a period of what William Byrd II termed "mine madness", and an explosive expansion of the colonial iron industry (Gordon 1996; Heite 1983; Lesley 1859; Paskoff 1976, 1983; Pearse 1876; Swank 1892). Numerous blast furnaces were constructed in Virginia (K. Bruce 1930), Maryland (Singewald 1911), and Pennsylvania (Bining 1938; Paskoff 1976, 1983; Pearse 1876) and The Principio (E May 1945; Robbins 1972 and 1986; Whitely 1887) and Baltimore Companies (K. Johnson 1953 and 1959) were established in Maryland.

By the end of this building spree the American iron industry was centered on the Chesapeake (Heite 1983 and 2000) and producing more iron than those in the United Kingdom (U.S. Bureau of the Census 1960:746, 762-764; Bining 1938:134; Bergstrom 1980:111 and 136; Heite 1983 and 2000). By 1730 over 1700 tons of pig iron was annually exported to England, almost entirely from Maryland and Virginia (U. S. Bureau of the Census 1960:762, HLRO 1750). MacPherson's *Annals of Commerce* (1805; Bishop 1966:599 [1868]) said that by 1731 "Iron in pigs is one of the things makes Virginia and Maryland so valuable to the United Kingdom".

The principal goal of these blast furnaces was to export pig iron to England. The Virginia furnaces were in the upper Tidewater and northeast Piedmont. Neabsco, Occoquan, Bristol, and Grymes were located in Tidewater along the Potomac and Rappahannock rivers. Accokeek (Potomac), Chiswell, Fredericksville, and Tubal were in the northeast Piedmont, in most cases not far
from the fall line. All were built along rivers that connected to the Chesapeake and thence to England.

But the burgeoning colonial population provided a growing market as well. Virginia grew from 72,000 to 346,000 people and the colonies from 275,000 to over 1.5 million between 1700 and 1760. The building of the Massaponax double air furnace by Alexander Spotswood (1727-30) marked a turning point in the marketing emphasis of Virginia's ironmasters. Double air furnaces were special foundry furnaces habitually associated with the production of cannon in Great Britain. But even if Massaponax was used to produce cannon, it also produced large quantities of cast iron consumer goods.

Phase III, the last colonial period (1760-1775), opened with the Chesapeake drainage still producing over half of America's iron and saw the establishment of seven iron works (Zane's Old Furnace, Mossy Creek, Callaway's, Albemarle, Marlboro, and Oxford). The new furnaces were to the west of the previous phase, following the frontier into the western Piedmont and The Valley. There was also a shift in market emphasis. This was due to a number of factors. The population of Virginia (over 500,000), and the coastal colonies, had grown large enough to absorb the output of America's blast furnaces. Relations with Great Britain deteriorated throughout this period and culminated in the outbreak of hostilities in 1775. The new blast furnaces were also far enough from the coast that shipping pig iron to England became increasingly unprofitable. Some ironmasters, like Isaac Zane, initially shipped pig iron to England, but soon shifted to the American market.

At least four blast furnaces were built in the western Piedmont during the period 1760-1775 (Albemarle, Callaway's, and two at Oxford). The Albemarle Iron Works (44AB72) was just south of Charlottesville in South Garden, VA. It operated from 1771-1772. Callaway's (44CP155) was built just east of Lynchburg
after 1773, and remained in operation at least until 1778. At that time it was either sold to David Ross, becoming part of the Oxford Iron Works, or was closed when Callaway and his partners built the Washington Furnace in Rocky Mount. The Oxford Iron Works (44CP169), also just east of Lynchburg, was operating as a bloomery by 1772. David Ross acquired it in 1775 and he added one, and possibly two, blast furnaces prior to 1781.

According to oral tradition, the first furnace "west of the Blue Ridge" was built at Mossy Creek, Marlboro, Isabella, or Grant's in 1760. Obviously there cannot be four "firsts" (Pearse 1876:14; K. Bruce 1930:21). But neither Mossy Creek, Isabella, nor either of Isaac Zane's furnaces was built by 1760. The only information available on "Grant's" is the VDHR site survey form submitted by T. T. Brady. It is very unlikely that Grant's was established by 1760, and the slag noted by Brady may be the result of road building.

The first furnace constructed in The Valley was Zane's Old Furnace (44FK46, also called Marlboro Old Furnace and later the site of Taylor's, 44FK45). Isaac Zane became involved in 1767, the furnace was in operation by 1768. He built a new furnace, Marlboro Iron Works (44FK50), in 1772. Both furnaces are just to the west of the Great Wagon Road and south of Winchester. Mossy Creek, or Miller's Iron Works (44AU4800 was built farther down the Valley sometime after June 1, 1774. All three works were constructed primarily to supply the influx of settlers moving down the Valley from Pennsylvania. They also wagoned pig iron to Falmouth and Alexandria and sold through merchants in Philadelphia. Zane did sell some pig iron to England, but found that it was unprofitable.

The American Revolution provided a major impetus to the iron industry. From 1770 to the end of the American Revolution. Unfortunately, this boom was short lived and many of Virginia's furnaces did not survive much beyond the
end of the Revolution. The demand for iron generated by the war was both a boon and a bane. The Continental Congress and the various former colonies were very willing to order iron and iron products, but were unable to pay their bills, both during and after the war. This left many furnaces in severe financial difficulties, and ruined others. British partners also created major legal problems for some ironworks. The Principio Company, for instance, was put out of business as a result of the legal morass created when Maryland confiscated its assets as “British” property.

A number of figures and families appear over and over again in the records of the early iron industry of Virginia. Spotswood founded the Tubal furnace between 1714 and 1720 and later constructed the air furnace, a foundry not a blast furnace, at Massaponax. Contrary to repeated claims, he was not involved in any other ironworks. Charles Chiswell was both a partner and the manager of Fredericksville and later set up his own furnace in Hanover county. The Bristol Company was formed in 1721. Its American agent/partner was John Tayloe. Tayloe later built Neabsco Furnace in 1737 and provided financial backing at Occoquan (est. 1755). His withdrawal as a financial backer of Occoquan in 1760 was the proximate cause of its failure. He was also involved financially in Benjamin Grymes' iron empire. When Grymes' efforts collapsed, Tayloe became the owner of Grymes' Concord Forge.

The business fortunes of Virginia's colonial furnaces varied considerably. Some were in blast for only a couple of years, others functioned for decades. The first and one of the shortest lived, Falling Creek, was destroyed by the Powhatans in 1622 after perhaps only a few months of operations. Albemarle was shut down after less than a year. At the other end of the spectrum, Neabsco remained in operation for over 90 years. The average life of a furnace was 28 years (Table 1, Colonial Furnaces).
American production of 30,000 tons of iron in the mid 1700s, and Virginia production of as much as 3,000 tons (from blast furnaces alone) may not seem very important today. But, the American colonies out produced the mother country and per capita Virginia produced at least twice as much iron as Great Britain. Without the armories, cannon foundries, and repair facilities at Fredericksburg, Westham, Point of Fork, and elsewhere there would have been far fewer muskets, shot, and cannon available for the Continental Army (K Bruce 1926, 1927).

The British recognized the importance of these, and other, industrial facilities and organized raids to destroy them. In 1781 LTC Banastre Tarleton, commander of the British Legion, LTC Simcoe, and Gen. Benedict Arnold were sent to the Richmond area to destroy the iron works (Tarleton 1787:297-298). Gen. Benedict Arnold destroyed Providence Forge, Archibald Cary’s mill, and Cary’s Forge during the same year.

On a local scale, bloomeries continued to supply much of the iron needed on the frontier. And cottage industries were often a part of the plantation economy, just as they were of Roman villas or medieval manors and monasteries. Many large plantations were integrated communities that not only produced surplus agricultural goods, but also most of the small manufactured goods required for their operation. It was often cheaper and more efficient to produce such things as nails and horseshoes, rather than purchase them. Economies of scale led many large plantations to deliberately build excess capacity into their cottage industries, such as blacksmithies, farriers, and naileries. The surplus was sold for cash or, as in Virginia, bartered for tobacco or other crops. For example, Monticello produced nails for much of the surrounding area and Montpelier had a large blacksmithy that by 1778 generated over half of the plantation’s income (Dermody 1992; Lewis and Dermody 1990; Lewis 1992).
Industrial Slavery and the Iron Plantation

One of the basic tenets of Southern history and archaeology is the centrality of slavery and the slaved based plantation. Slavery and the plantation are often viewed as so central to the Southern experience that they are seen in all aspects of Southern history. Many authors erroneously state that the iron plantation is an outgrowth of and an industrial variation of the Southern slave based agricultural plantation, and that most iron plantations were financed with plantation money. They also incorrectly conclude that the iron plantation is unique to iron production in the Chesapeake region. This emphasis on slavery and the "plantation" aspect of Southern iron works is shared by most papers and books written on the ante-bellum iron industry of the South (Bruce 1968[1930]; Dew 1966, 1974, 1994; R. Lewis 1974a, 1974b, 1978; Sanford 1993:61-62; Parker et al. 1996:183-191).

Although there is a superficial resemblance between iron and agricultural plantations, the premise that they are unique to the South, an outgrowth of the agricultural plantation, and financed primarily by wealthy planters are incorrect. All of these papers, articles, reports, and books overlook a number of crucial facts. Industrial slavery and the iron plantation were not unique to the South. Neither was the plantation system. The plantation, iron plantation, and industrial slavery predate the founding of the British North America colonies. The iron plantations of both New Jersey and Pennsylvania were largely operated with slave labor, while Saugus Iron Works in Massachusetts used transported prisoners of war. Even the word "plantation" predates the Virginia Colony. Virginia is frequently referred to as a "plantation" or the "plantation". And finally, merchants, ironmongers, and members of iron families, not wealthy
planters, started the majority of Virginia’s colonial iron works.

Industrial slavery was not invented in America, but was a worldwide practice of great antiquity. For instance, "The Romans ... employed large bodies of servile workers" in the ironworks of Roman Britain (Straker 1969:28 [1931]) and throughout the Empire. Neither was industrial slavery confined to the southern colonies. It was also common in Pennsylvania (Bining 1938:99-102, Miller 1951:93; Swank 1892:188), New Jersey (Hodges 1997:9; Pierce 1957:133), Delaware, and Maryland (Walker 1966:305). To date, there are no indications that slave labor was used at New England or New York ironworks. But, Saugus (Hammersmith) did use transported Scots rebels. The extent to which industrial slaves were used outside of the South has been largely ignored and deserves further study. A recent study has revealed that enslaved Blacks made up at least 10% of the population of Monmouth County, New Jersey from 1680 to 1784 (Hodges 1997:12-14). Because both Pennsylvania and New Jersey chose not abolition, but gradual emancipation, slavery persisted in both Northern states until well into the 1800s. But, it should be noted that it took a war to free the slaves of the South.

The idea that the Iron Plantation was a singular outgrowth of the Southern Plantation system is equally mistaken. It is a misreading of the global historical record. Iron plantations predate the colonization of North America and were established in all major iron producing countries (including the United Kingdom, Sweden, and Russia) in the 15th to 18th centuries. If it was a development of any preexisting system, the iron plantation was the direct lineal descendant of the Roman Villa and Medieval Manorial and monastic tradition. The English, Spanish, Portuguese, French, and Dutch established large agricultural "plantations" throughout their colonial empires. Slave labor was used at many, if not most, of these.
The iron plantation was also as common in New Jersey and Pennsylvania as it was in Virginia.

New Jersey's iron plantations, resembling in particular those of Pennsylvania, were feudal establishments and often self-sufficient, or nearly so. [Pierce 1957:17]

During the eighteenth century, the iron industry of Pennsylvania was organized largely on plantations. Many of these consisted of several thousand acres. The mansion house, the homes of the workers, the furnace and forge or forges, the iron mines, the charcoal house, the dense woods which furnished the material for making charcoal, the office, the store, the gristmill, the sawmill, the blacksmith shop, the large outside bake oven, the barns, the grain fields, and the orchards were part of a very interesting and almost self-sufficing community. In some respects, the iron plantation resembled small feudal manors of medieval Europe. [Bining 1973:19-20 (1938)]

Iron plantations flourished in the middle even more than in the southern provinces [Bridenbaugh 1950:61]

The word "plantation" was not developed to describe the Southern slave based agricultural plantation. In English "plantation" was a synonym for colony. Thus, in 1610 Lord de la Ware wrote A True and Sincere declaration of the purpose and ends of the Plantation begun in Virginia and in 1625 Sir Francis Bacon wrote an essay entitled "On Plantations". The colony established in Massachusetts was called Plymouth Plantation.

The iron plantation was not an adaptation of the southern agricultural plantation system to address an industrial problem. It was a logical economic response to the environment and the requirements of an iron plantation was essentially the same in the Northern and Southern colonies. The structure of the iron plantation allowed the owners to maximize their economic return and minimize operational disruptions. A complete understanding of the underlying economic reality reveals that most resembled small towns, because they were
small towns with an industrial complex. The blast furnace complex had the same population, 200 to 300 people, as a small town and required the same service infrastructure. Most included saw mills, gristmills, forges, workers housing, company stores, smithies, etc. because they were needed.

Falling Creek, the first ironworks in America was started by the Virginia Company the same year that John Rolfe discovered tobacco, the economic basis for Virginia's agricultural plantations, and the year the first slaves were sold in Virginia. Obviously Falling Creek's physical organization could not be derived from a system that did not yet exist.

The contention that only the owners of large plantations had the financial resources to start ironworks is also incorrect. With a few exceptions, the iron plantations of Virginia, Maryland, New Jersey, New York, and Pennsylvania were begun by partnerships of investors, only some of whom were planters. The majority of the colonial investors were merchants, many of whom were already involved in the iron trade (Paskoff 1983:xvii; Ince 1991; Heite, personal communication 2000). Many were English ironmongers (iron merchants) or owned fineries that needed steady supplies of pig iron.

Plantations played a large part in the life and economy of the Southern coastal plain and piedmont. As such they are the legitimate concern of those studying the colonial South. But, intensive study "beyond the big house" in the closing years of the 20th century made it increasingly clear that the stereotypical plantation system is no more accurate than most stereotypes. The plantation system was much more robust and complex than the agricultural slave based monoculture model that has held sway for the last two hundred years. The same level of effort needs to be applied to the industrial plantation.
The Direct Process (Bloomery)

Iron ore and charcoal are added to the hearth

Iron ore is heated by burning the charcoal, starting a chemical reaction

Iron and gangue combine to form a liquid slag

Iron rich (40-60%) fayalitic slag is tapped out of the hearth as needed

Skulls (mossers) are discarded as needed (mossers)

Bubbly/ropey tap slag is discarded

Reduced metallic iron forms a "bloom" in the bottom of the hearth

Bloom is removed from the hearth and consolidated with sledge hammers

Bloom is repeatedly heated and hammered to remove and distribute slag and to weld the iron into a solid bar

Wrought iron bar is ready for sale

Hammer scale is produced

Figure 8. The Direct Process (Bloomery)
The Indirect Process
(Blast Furnace)

Iron ore, flux and charcoal are charged into the furnace

Iron ore and flux are heated by burning the charcoal, starting a chemical reaction

Gangue, flux, and some iron melts to form a liquid slag

Reduced metallic iron melts and pools in the bottom of the hearth

Iron poor (<5%) slag is tapped out of the hearth as needed

Liquid iron is tapped out as needed

Glassy furnace slag is discarded

Iron is run into pigs for sale to forges and foundries

Liquid iron is tapped out as needed

Iron is run into molds

Foundry remelts pig iron

Cast iron products are ready for sale

Loop/bloom is removed from the hearth and consolidated by sledge hammer

Loop/bloom is repeatedly heated in a chafery and hammered to remove and distribute slag and to weld the iron into a solid bar

Wrought iron bar is ready for sale

Bubbly/ropey tap slag is discarded

Hammer scale is produced

Figure 9. The Indirect Process (Blast Furnace)
CHAPTER 3: Producing Iron in the Colonial Period

Probably the most widespread misconception about making iron is that the burning of charcoal (or other fuel) melts the iron out of the ore. The manufacture of metallic iron is a chemical and not a strictly thermal process. Pure metallic iron, as well as most forms of iron ore, all melts at over 1500°C. The silica (SiO₂) that makes up a large portion of the ore melts above 1713°C. This high a temperature only occurs in a very small area surrounding the tuyere, the rest of the furnace is considerably colder. Even if the ore could be melted, the iron is chemically bound to oxygen and until the oxygen is removed by reduction no metallic iron would be created. If you get iron ore hot enough, the result would not be metallic iron, just very hot ore.

A number of very dissimilar techniques were used around the world to produce iron. The iron making technology used at the Albemarle Iron Works was English in origin. The company planned to build a (Walloon/English) finery forge and cold blast charcoal furnace. There is no evidence that the forge was ever completed. But years after the company failed, John Old built a bloomery forge (Old’s Forge).

Regardless of which process was used the objective and the underlying chemistry were the same. An iron smelter must fulfill three primary requirements to make iron.

1) Generate and maintain a high enough temperature to allow the chemical reaction to take place.
2) Provide a reducing atmosphere.
3) Provide a way to separate the nonferrous elements from the iron, usually by forming a slag.

Generally, all iron smelting devices require: a source of iron (ore or scrap),
fuel, an air blast, and a reducing atmosphere. Fuel is needed to heat the iron ore, because metallic iron cannot be formed at temperatures below 700°C (Tholander and Blomgren 1986b:151). An air blast is required to cause the fuel to burn hot enough to hasten the chemical reaction and by the 18th century to allow the formation of a liquid slag. The reducing atmosphere separates the iron ore, an oxide of iron, into metallic iron and oxygen and prevents the reformation of iron oxide. Additionally, a blast furnace requires a source of carbon, because cast iron is a carbon-iron alloy.

The overriding consideration is the reducing atmosphere. An oxidizing atmosphere would produce only iron oxide (rust). Reduction is accomplished by producing a compound with a greater affinity for oxygen than iron. In historic iron smelting the reducing agent is carbon monoxide (CO). The more carbon monoxide that is produced and the longer the iron oxide is exposed to it, the more efficient is the production of metallic iron. The chemical transformation is fairly complex, but basically it can be expressed as:

**Figure 10. Reduction Reaction**

\[ \text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2 \]

Oxide of iron + Oxide of carbon = Iron + Oxide of carbon

(ore) (gas) (metal) (gas)

(Rostoker and Bronson 1990:25)

In reality at least five separate reactions (from top of hearth/furnace to bottom) are taking place (Bohm 1986:16 [1927]; Tholander and Blomgren 1986a:151).
Iron ore and fuel are charged (loaded) into the top of the furnace stack or bloomery hearth. In a blast furnace a flux is added as well. As the charge descends it is heated by the hot gases flowing upward from the tuyere and reacts with the carbon monoxide (CO) to form metallic iron. For this reason it is critical that the charge be permeable and not obstruct the gas flow. Air (O₂) is injected into the bottom through the tuyere(s). The forced air (blast) combines with the fuel (carbon) to form heat, carbon dioxide (CO₂) and carbon monoxide (CO). The carbon monoxide (CO) reduces the iron oxides as they descend toward the tuyere(s), eventually forming metallic iron (Fe). The metallic iron falls to the bottom where it is either tapped out of the blast furnace as liquid iron, or it forms a mass called a bloom.

Once the iron ore reaches a minimum temperature of 275°C hematite (Fe₂O₃, a form of iron oxide) combines with carbon monoxide (CO) to produce magnetite (Fe₃O₄) and carbon dioxide (CO₂). Magnetite is reduced by carbon monoxide to form wüstite (FeO, another form of iron oxide) and more carbon dioxide. Above 700°C the wüstite reacts with carbon monoxide to form metallic iron (Fe) and carbon dioxide. In a blast furnace the iron cannot melt until it has absorbed carbon. The exact mechanism is still under debate. The carbon is either absorbed from carbon dioxide, carbon monoxide, or directly from contact with the hot solid carbon (charcoal, coke, and anthracite). Once it melts the iron
trickles down the stack and then passes through the slag bath and collects in the hearth or crucible until it is tapped out.

At the level of the tuyere (almost at the bottom) the incoming air blast oxidizes carbon forming carbon dioxide (CO₂) and carbon monoxide (CO). As the carbon dioxide (CO₂) passes over the hot solid carbon it converts to carbon monoxide (CO) in the Boudouard reaction (Tholander and Blomgren 1986a:151; Rosenqvist 1983:238). For a more complete understanding of the process, detailed discussions can be found in Erik Tholander's Experimental Studies on Early Iron Making (1987); Tholander and Blomgren's "Influence of the Ore Smelting Course on the Slag Microstructures at Early Ironmaking, usable as Identification Basis for the Furnace Process Employed" (1986); Chapter 10: The Manufacture of Pig Iron in the Blast Furnace (Burgo 1999) in The Making, Shaping and Treating of Steel-Ironmaking Volume; Fundamentals of Steelmaking (Turkdogan and Fruehan 1996); or Ivar Bohm's A Study of the Blast Furnace Process. (1982 [1927]). A synopsis of Bohm's data is available in Gordon's American Iron (1996:116-118). Rosenqvist's Principles of Extractive Metallurgy (1983) is still one of the standard texts on the details and thermodynamics of the reactions.

During the colonial period there were two processes used to make iron, the bloomery or direct method (Figure 8) and the blast furnace or indirect process (Figure 9). The bloomery or direct process required only a single step to convert iron ore and charcoal directly into wrought iron, slag, and hammerscale. The indirect process required two steps to make wrought iron. The first was the conversion of iron ore, flux, and charcoal into cast iron and glassy slag in a blast furnace. In the second step cast iron, usually in the form of pigs, was fined into bar iron, slag, and hammerscale by the oxidation of the carbon in a finery. The second step is called either fining or decarburization. The Albemarle Iron Works used the indirect process and utilized a blast furnace.
There are three major differences between the bloomery and blast furnace processes. The first is that in a bloomery the iron never completely melts, but forms into a pasty mass called a bloom. While in a blast furnace the iron becomes fully liquid and is tapped out to form cast iron.

The second difference is efficiency. By the 18th century, blast furnaces could recover over 90% of the available iron. Only a small percentage of the iron in the original ore was recovered in the bloomery process. This is because up to 70% of the iron is bound up in the slag in the form of fayalite (2FeOSiO₂) and wüstite (FeO). Blast furnace slag has very little iron, containing primarily silica (SiO₂) and lime (CaO).

The last difference is operational scale. Bloomeries make iron in small discontinuous batches. A late 18C bloomery hearth could produce a ton of iron a week. Blast furnaces, even small ones, operated continuously and made at least a ton of iron a day. Modern iron and steel plants produce thousands of tons a day.

The Iron Plantation

The colonial American iron plantation typically consisted of a blast furnace, finery forge, casting shed, raw material storage buildings (ore, limestone, and charcoal), ironmaster’s house, worker’s housing, office, store, agricultural buildings, and blacksmithy (Figure 12). It was also fairly common to find a mill and sawmill. Other trades, such as wheelwright, coopers, carpenters, cobblers might also be present. Plantations located on navigable rivers had piers, some even owned small fleets of ships (Richmond Will Book 7:354; Pierce 1957:137). And like agricultural plantation, an iron plantation often had excess capacity that was made available to its neighbors, for a price.

The iron plantation is best understood as an industrial adaptation of a pre-
existing European economic tradition, rather than as an industrial variant of the Southern slave based agricultural plantation system (see pg. 49-56). The plantation system, whether for agricultural or industrial purposes, was the direct lineal descendant of the Roman villa, Medieval manor, and European monastery. The use of the plantation system was a logical response to the economic and geographical requirements for manufacturing iron. It allowed its owners to maximize their return while minimizing operational disruptions. The iron plantation was not confined to the South, but was repeated where ever iron was made in North America, including New Jersey, Pennsylvania, New York, Delaware, and Maryland (see pg. 53-54; Bining 1938:19-20; Bridenbaugh 1950:61; Pierce 1957:17). It was also common throughout 17th and 18th century Europe.

The iron plantation was especially well adapted for blast furnace operations. Blast furnaces, unlike smaller iron operations like forges and smithies, required thousands of tons of charcoal and iron ore per year and large work forces. Because of its fragility, charcoal could not be moved much more than five miles. As a result it was generally impractical to out-source charcoal. This meant that a furnace had to own or control thousands of acres of forest. In the British North American colonies it was possible to acquire thousands of acres of land. In places with high population densities, like England, furnaces achieved the same kind of control through long term leases and purchase agreements of coppices and other wooded areas. How about withies and coppicing?

Because an iron plantation was simultaneously an agricultural plantation, a small town, and an industrial site its infrastructure needs were often greater than either a traditional Southern plantation or a small town. And just as agricultural plantations had to provide their own support, so too did iron plantations. The population density of the surrounding countryside was not able to sustain the required artisans and craftsmen.
Some of the common features of the iron plantation were natural outgrowths of the requirements of the blast furnace. In England most of the wood that was converted to charcoal was grown in coppices. It was cut when it was the correct size. America’s furnaces, at least initially, used virgin forest and the wood came in all sizes, but much of it from large trees. In order to convert these to charcoal the wood had to be split, additional work for the colliers. Early on, ironmasters realized that they could use the water power in their millponds to run saw mills as well as furnaces, hearths, and hammers. Whereas an English ironmaster had a limited supply of wood, his American counterpart often had more than he needed. He could convert the large trees to sawn lumber, both for his use, and for sale and still have enough wood for charcoal. Contrary to popular opinion iron furnaces did not destroy the forests that surrounded them. As ground was cleared of timber for conversion into charcoal some was put into crops while some became pasture. But most was maintained as timberlands for future charcoal production. There is ample evidence for the multiple reuse of charcoal pits and therefore the repeated timbering of forests.

Many ironmasters, like Chiswell and Spotswood, built and maintained roads to move raw materials and finished products. Most also owned wagons and draft animals to haul charcoal, ore, and finished iron. The wagons had to be kept in repair and the animals cared for. This required teamsters, farriers, blacksmiths, wainwrights, and herdsmen. The workers and animals also required food. Given the condition and reliability of the transportation network in colonial America, it should come as no surprise that most ironmasters raised their own food and livestock. Land was cheap and depending on outside sources could result in shortages like the one that shut down Fredericksville in 1732 (Byrd 1928:330 [1732]).
Figure 12. Plan of Hopewell Furnace National Historic Site
Figure 13. Saugus Iron Works National Historic Site.
Figure 14. Hopewell NHS, furnace and casting house. Photo by author.
Figure 15. Hopewell NHS, Company Store, Ironmaster's House, and Barn. Photo by author.
Given their geographic isolation iron plantations often had to provide for all of their worker’s needs, including housing. At Hopewell this included both family housing and a boarding house for single workers (Figure 12). Worker's housing is also preserved at Batsto, NJ. At Hopewell and Isaac Zane's Marlboro Iron Works meals were served in a workers dining room. Principio, Batsto, and Hopewell had company stores. Workers frequently were paid with company store credits.

No complete colonial iron plantations have survived. But, Saugus Iron Works National Historic Site in Massachusetts, Hopewell Furnace National Historic Site in Pennsylvania, and Batsto Historic Village in New Jersey, taken together present a fair idea of what one looked like. Saugus (Figure 13) has only the core industrial buildings (reconstructed on the original foundations) and the ironmaster's house. It includes not only the furnace, but also a finery, chafery, slitting mill, and smithy. Unfortunately, the reconstructions often owe more to Diderot’s Encyclopedia and the artistic sense of the architects, than what was recovered archaeologically. As a result it is fair to say that Saugus is the finest late 18th century French ironworks, built on 17th century English foundations in the world. At Batsto only the domestic structures are preserved (ironmaster's house, company store, barns, workers housing). Hopewell is the most complete (Figures 13 and 14), but the present structures are the result of considerable reconstruction. It has not only the blast furnace, but also all of the structures associated with making iron (charcoal house, cooling shed, casting house, and charcoal pit) and the "village" (ironmaster's house, worker's housing, store, office, blacksmith, and school) and farm. Hopewell has neither a forge nor mills.

Slavery, until it was finally outlawed, provided a substantial portion of the workforce on iron plantations throughout the American colonies, not just in the South. To date, there is no evidence that enslaved workers were used in New
York or New England. However, very little research has been done on the extent of slavery outside of the South. Only recently it was discovered that a sizable number of slaves were present in the northern colonies. It is entirely possible that they were used in the manufacture and processing of iron. Slaves did make up a large proportion of the work force at iron works in Delaware, Maryland, New Jersey, and Pennsylvania.

The colonial iron plantation consisted of an iron production facility (blast furnace, forge, bloomery, smithy, etc.), forest (charcoal production), mines (iron ore, building stone, and limestone), a village (housing, store, etc.), craftsmen (carpenter, wheelwright, blacksmith, cooper, millwright, etc.), a farm, and frequently mills (grain and lumber). It provided both finished (firebacks, stoves, kettles, etc.) and intermediate (pig and bar) iron products to its neighbors and distant markets. Excess capacity also provided finished lumber and other goods and services to its neighbors.

**Preparations**

Before iron could be made all of the raw materials had to mined, manufactured, or prepared, and brought to the smelting site. Most of the raw materials arrived at the furnace ready to use. Some benefited from additional processing. Most could be prepared in advance, but it was rare for an iron works to have more than a few weeks supply stockpiled prior to initiating operations. While it might have been possible to stockpile all of the materials needed to run a bloomery or finery forge for a year, the huge quantities used by a blast furnace, cost made this impossible. But, more important than cost and sheer bulk, some raw materials, especially charcoal, deteriorated in storage.

As geological and metallurgical science matured, numerous processes
were developed for ore processing. Today most ore is enhanced through "beneficiation". This series of processes concentrates the iron oxide, separates it from the gangue, and forms it into lumps correctly sized for a particular furnace type (Poveromo 1999:614-637). Pre-industrial metallurgists achieved similar results by hand sorting, crushing, washing, and roasting ore (Craddock 1995:11, 53, 147, 156-167).

A common problem for all the raw materials was water absorption. This was especially true for charcoal, which is extremely hygroscopic. Materials were stored in buildings to prevent water absorption and ore and lime might be roasted prior to charging them into the furnace to remove water. It was more efficient to remove the water prior to charging the material into the furnace, because energy that would otherwise heat the ore and speed the reduction process had to be used instead to evaporate the water. This retarded the point at which reduction began in a blast furnace, increased fuel consumption, and reduced the amount of iron produced. Just the difference in atmospheric humidity could make an enormous difference (Craddock 1995:193; J. E. Rehder, personal communication 1998).

With the exception of ensuring that the materials were all appropriate sizes, only the iron ore habitually received additional processing. Size was important for a number of reasons. Too small and, like powdered charcoal, the ore and flux would impede the flow of hot gases through the furnace, slowing the reduction reaction. Too large and some might not fully react as it passed through the furnace. This wasted fuel because although not contributing to the chemical reaction, large lumps of reactant still absorbed heat. In the case of iron ore, it also reduced the yield of the furnace. In a blast furnace, any ore that passed through the reaction zone without being reduced would have become incorporated into the slag and not converted to metallic iron.
Shell flux could be used as is. Limestone, if it was not already in usable
sized pieces, had to be broken up. Both shell and limestone could be converted into
lime by burning. Just prior to being charged into the furnace charcoal might be
sieved to remove dust, but it was not usually necessary.

Three techniques were common to enhance the quality of iron ore—sorting,
washing, and roasting (calcining). Iron ore (see Chapter 7) seldom occurs without
some impurities. All three methods could be used to increase the efficiency of a
furnace by decreasing the amount of gangue charged. Today additional
techniques such as magnetic separation are used.

Some hand sorting occurred in all cases. The mining of ore is itself a form
of sorting. Rocks that were obviously not iron ore were not moved to the furnace.
Following washing, in many cases, ore was hand sorted to remove large pieces of
non-ferrous rocks. Although there are no records showing that hand sorting was
used at the Albemarle Iron Works, it is reasonable to assume that some visual
inspection of the ore took place. Due to the visual similarity between magnetite
and ilmenite (see Albemarle Ore, Chapter 4), this may have resulted in more
titanium rich ilmenite being sent to the furnace.

Ores that were bedded or contaminated with either clay, sand, or other
nonferrous materials were usually washed. This benefited the furnace in two
ways. It reduced the amount that had to be moved to the furnace for each ton of
iron produced. It also improved the efficiency of the furnace because fuel was
not used to heat up and slag off the sand and clay. For instance, washing
Oriskany limonites reduced the ore's weight by 20-50% (Holden 1907:408-410).
Unknown to the 18th century ironmasters some sulfur and alumina was also
removed by washing. But this also added water to the ore, which had to be
removed either by air-drying or roasting.

Ore roasting (calcining) was common in the 18th century. Roasting
accomplished a number of things. Some impurities could be reduced or removed entirely. Sulfur (in ores with a pyritic component), carbon dioxide (in carbonate ores), and water (both in hydrated ores and absorbed from the atmosphere) could be removed by roasting. Roasting also fractured and fissured the ore lumps. This increased the surface area, sped up the chemical reaction in the furnace, and reduced fuel consumption. It also made the ore brittle and made reducing it to the proper lump size easier. In some cases it changed the chemical composition of the ore.

Even "dry" ore contains some water as it would tend to absorb it from the atmosphere over even a short time. Adams' reported that on even a dry day a gossan limonite had 5-6% water (Adams 1892:213). Roasting limonites drives off the water, while roasting carbonates does the same for the carbon dioxide. Under oxidizing conditions (heap or stall), roasting converts limonites and carbonates to hematite (Fe₂O₃), or the gamma form maghemite. Under more reducing conditions (as in a permanent oven/furnace) magnetite could form.

The effects of roasting can be quite significant. Singewald compared two carbonate ore samples from the Arundel formation in Maryland (Singewald 1911:256).

<table>
<thead>
<tr>
<th></th>
<th>Unroasted</th>
<th>Roasted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>33.82</td>
<td>44.49</td>
</tr>
<tr>
<td>Mn</td>
<td>3.92</td>
<td>2.73</td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>14.30</td>
<td>15.01</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>3.38</td>
<td>3.22</td>
</tr>
<tr>
<td>Lime (CaO)</td>
<td>1.24</td>
<td>0.43</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.044</td>
<td>0.058</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.296</td>
<td>trace</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>19.95</td>
<td>0.82</td>
</tr>
</tbody>
</table>

The iron content of the Muirkirk Furnace ore was increased by almost 1/3 as a result of roasting and the CO₂ and sulfur were almost totally eliminated.
Sometimes roasting was done at the mine, other companies roasted their ore just prior to charging it into the furnace. It did not require an elaborate oven or even forced draft. Early roasting operations often were little more than piles of wood or charcoal and ore, burned in the open, in shallow pits, or trenches. Later, permanent ovens were constructed by some iron works. It is not known if the ore for the Albemarle blast furnace was roasted, but the technique was used in Virginia. William Byrd described method used at Chiswell's Fredericksville Furnace in 1732.

At our return we saw near the furnace large heaps of mine [ore] with charcoal mixed with it, a stratum of each alternately, beginning first with a layer of charcoal at the bottom. To this they put fire, which in a little time spreads through the whole heap, and calcines the ore, which afterwards easily crumbles into small pieces fit for the furnace. [Byrd 1928:334 [1732]]

An ironmaster had to carefully estimate what he needed and when. Edward Heite has called the blast furnace the first just in time delivery industry (Heite 1971b, 1992). Stock piling too much resulted in its absorbing water and adversely effecting fuel efficiency. The materials also cost money or labor that were not available elsewhere. Maintaining adequate capital reserves was a continuous problem for the costly blast furnaces. But, woe betide the ironmaster who ran out of materials. Restarting a furnace meant beginning the campaign afresh, which required preheating the stack for several days, wasting a great deal of charcoal. The process for "blowing in" a furnace was time consuming and used a great deal of fuel.

The Bloomery

A bloomery is a relatively simple, inexpensive, but also inefficient method for
Figure 16. Rockley Smithies, A Bloomery; Courtesy of D. Crossley (Crossley and Ashurst 1969:22)
Figure 17. A 1556 Bloomery; A- Bloomery Hearth, B- Charge, C- Slag Vent, D- Bloom, E- Wooden Mallets, F- Hammer, G- Anvil (Agricola 1950:422 [1556])
Figure 18. Bloom and bar from the Rockbridge Bloomery, Lexington, VA. Courtesy Lee Sauder and Ellen Martin, photo by Ellen Martin.

Figure 19. 17th Century Bloomery slag from Rowley/Boxford, MA. Photo by author.
Figure 20. Water Powered Hammers, from Hassentratz (1812:Plate 47b).
converting iron ore directly to wrought or bar iron. They were also commonly used to "try" or test ore prior to the 19th century.

Bloomeries were so inefficient that blast furnaces sometimes used bloomery slag in place of iron ore (Straker 1969:94; Lenik 1974:11). Blooms were made one at a time in a discontinuous batch process and varied in size from a few pounds to hundreds. Hermelin reported that in 1783 a (New Jersey) bloomery with two hearths could expect to make "not more than 70 tons per year" (Hermelin 1931:57 [1783]). This is comparable to the 20-30 tons per hearth per year reported by Crossley for British 18th century bloomeries (1990:1554).

Bloomeries were the primary source of iron in the British North American colonies during the 17th century. In the early 18th century, as the population and demand for iron grew, blast furnaces displaced bloomeries. But they persisted in areas where local demand and access to external markets could not support blast furnaces. Bloomeries could still be found on the frontier and in places like the DELMARVA peninsula well into the 19th century (Heite 1974

Bloomeries came in a variety of sizes and shapes. Early ones, like the 1986 reconstruction at Williamsburg, based on descriptions in H.R. Shubert's *History of the British Iron and Steel Industry* (1957:149-152), are virtually indistinguishable from blacksmith hearths. They could be constructed in a couple of days and required 2-3 workers. The Williamsburg bloomery was 6' square and 3' tall and was constructed of brick. The hearth was only 2' deep and 18" square. It had a single tuyere and the blast was from a hand pumped bellows. This kind of bloomery would probably have been roofed or enclosed in a semi-permanent earth fast building and was capable of producing only a few pounds of iron at a time (Harvey 1986, 1988, 1989a, and 1989b).

By the 17th century, the standard English bloomery had water powered bellows and large water driven mechanical hammers. This increased the size of
bloom that could be produced and worked. Later bloomeries often had more
than one bloomery hearth and a separate hearth was added to reheat the bloom
prior to hammering. Efficiency was also increased with the introduction of the
Catalan process (Gordon 1996:98; Percy 1864:278-315; Tylecote 1962:300). The
addition of hot blast, a more complete understanding of the chemistry of iron
making, and other technological developments enabled 19th century American
ironmasters using the American Bloomery Process to rival the efficiency of the
blast furnace (Gordon 1996:96-98).

Rockley Smithies (Figure 16) is one of the most complete English
bloomeries excavated to date and represents a further development in the
bloomery. It operated during the 16th and 17th centuries and had four hearths,
three with water powered bellows (Crossley and Ashurst 1969:10-54).

The operation of a bloomery is fairly simple. Figure 17 is a depiction of a
bloomery from Agricola's 1556 De Re Metallica. At the rear is the bloomery hearth
(A), surrounded by piles of ore and charcoal. These were added to the hearth in
alternate layers. Air (the blast) was pumped into the hearth through a tuyere to
increase the heat produced by the burning charcoal. As it burned carbon dioxide
and carbon monoxide gas formed. They heated the ore above them as they
escaped out the top of the open hearth. Some of the iron oxide was reduced to
metallic iron by the carbon monoxide and dripped to the bottom of the hearth.
Along with entrapped slag, it formed a mass called a bloom (Figure 18). Most of
the iron oxide and gangue formed a molten fayalitic (Fe2SiO4 or
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Because of the differences in the chemistry, where a blast furnace needs a
flux to form a slag, a bloomery does not. Iron oxide from the ore acts as the flux.
This is one of the reasons bloomeries are so inefficient. Bloomery slag forms
through the fusion of würtite (FeO) and silica (SiO2) to form fayalite (Fe2SiO4 or
2FeO\cdot SiO_2). Where blast furnace slag usually has less than 5% iron oxide, bloomery slag has at least 30% and can have 60-70% (Rostoker and Bronson 1990:91-91; Straker 1969:92-99). The slag also coats the bloom preventing it from reoxidizing. If too much slag formed it was tapped from the hearth and discarded (Figure 17 C). Bloomery tap slag (Bachmann 1982; Gordon 1995, 1997; Tholander and Blomgren 1986) is dark in color, heavy, porous, and has a ropy/knuckly appearance (Figure 19).

Once the bloom was large enough it was removed from the hearth. The bloom was an irregular spongy mass of red hot low carbon iron and semi-molten slag (Figure 18). It was not usable without additional processing. First it was consolidated. Then it was repeatedly heated and hammered to expel excess slag and forge weld it into a solid mass. Then it was hammered into an ancony. Sometimes anconies, or even blooms, were offered for sale. But, usually these were further hammered to convert them to bar iron or merchant bar. This final step is depicted in the foreground of Agricola’s woodcut (Figure 17). There a hammerman is converting the bloom into merchant bars with a small mechanical hammer (Figure 17 F and 18). Colonial American bloomeries and forges generally used a much larger 4-500 lb. water powered helve or tilt hammer (Figure 20).

Bloomeries not only made bar iron (Figure 18), but also steel and sometimes cast iron. The Chinese used the bloomery for steel production until the 1st century BC (Gilmour 1999:87-90; Needham 1980:514-520 and 539). It was not unusual for some steel to be produced. This has been demonstrated archaeologically and in some of the experimental bloomeries like those at Williamsburg (Harvey 1986, 1988, 1989a, and 1989b) and Rockbridge Bloomery in Lexington, Virginia (Lee Sauder, personal communication 1999). To make steel the operator need only increase the charcoal to ore ratio. The presence of manganese also promotes the formation of steel (Tylecote 1987:167).
According to recent theories, high bloomeries could be used to make either wrought iron or cast iron by varying the ration of charcoal and ore charged. More charcoal resulted in a hotter fire and more carbon being absorbed by the iron. The result was cast iron (Gordon 1995:71; I. Keesman and G. McDonnell, personal communication 2000).

A bloomery fulfilled other purposes. In the 17th and 18th century one could not send ore samples out for analysis. An ironmaster performed his own. When building an iron works, it was common to build a bloomery first. This was used to "try" the quality of the iron ore. The assumption was that if good iron could be made with the ore in a bloomery, it would in a blast furnace as well. While this was generally true, because the chemical reaction in the two processes was different, it did not work. Although there is no proof, given the care with which John Old and John Wilkinson selected the site for the Albemarle Iron Work's blast furnace, they probably did try the ore in a bloomery. Unfortunately, titanium is one of the exceptions. Titaniferous ores that can be smelted in a bloomery with little or no difficulty, can cause problems in a blast furnace (see pages 202-217).

There were two additional advantages that accrued from constructing a bloomery first. A bloomery was much less expensive and time consuming to build. David Harvey's bloomery at Williamsburg took only twelve man days to build (Harvey 1988:30). By constructing a bloomery first, an iron works could begin producing bar iron and generating income. Once the blast furnace was completed, the bloomery could continued in use as a part of a finery forge, or as a forge or smithy.
Figure 21. The Blast Furnace (after Tylecote 1987:339)
Figure 22. Blast Furnace Configurations (after Hasenfratz 1812:Pl 21)
The Blast Furnace

The blast furnace (Figures 21 and 22) was a marked improvement over the bloomery in terms of efficiency and production capacity. Once the importance of lime as a flux was understood and implemented after the middle 1600s blast furnaces were able to convert over 90% of the iron in ore to pig iron. Early furnaces (1400-1600) produced only 1-200 tons per year. But by the end of the 18th century capacity had increased to 1,000 tons per year. During the colonial period average American production was 4-600 tons. While the blast furnace represented a marked improvement in efficiency and production capacity, it also required a much larger capital investment and was much more expensive to operate.

An English blast furnace was a truncated stone or brick pyramid measuring from 15 to 30' square at the base and as much as 30' high (Figures 21 and 22). The top may have been open or had a chimney, hatch, or even a roof to keep rain out of the top of the furnace. Furnaces were usually built against the side of a hill or the back side of a dam (bay). This allowed the ore, flux, and charcoal to be stored in buildings level with the top of the furnace. A charging bridge (Figures 21) led from the top of the stack to the side of the hill. Sometimes the charging bridge was covered, sometimes it was just a ramp with a rail or curb. The ore, flux, and charcoal were loaded (charged) into the furnace with wheelbarrows or baskets.

The base of the stack had at least two arches built into it (Figures 21 and 22). The working, or casting, arch allowed access to the hearth (Figure 22 W). There the founder could tap out the slag and molten iron onto the casting floor. The other was the tuyere arch (Figures 21 and 22 T). The tuyere was a nozzle through which the air blast was injected into the bottom of the furnace. Over
time the number of tuyeres increased, late 18th century blast furnaces might have arched openings on all four sides (Figure 22). During the colonial period the blast was injected by bellows or blowing tubs. These were usually powered by a water wheel until the introduction of steam power in the late 18th century. A common blast device in Southern Europe was a trompe was used in some parts of Europe, but was seldom used in Britain or the Americas.

The exterior of the furnace provided both structural support and insulation. It was usually made of either dressed stone or brick. Many furnaces also had either a wooden frame around them, or metal tie rods or beams to strengthen them. This helped to prevent cracking caused by the expansion and contraction resulting from the intense interior heat of the furnace. Figure 21 shows just a plain stone structure. Between the structural exterior and the refractory interior was a layer of sand (or other material) to insulate the interior of the furnace and help buffer the constant expansion and contraction of the furnace lining caused by temperature fluctuations.

The inside of the furnace was shaped like two hollow pyramids or cones butted base to base. The interior surface was made of fire brick or sandstone or some other high temperature resistant (refractory) material. The inside was widest where the two cones met, called the bosh. Furnaces of the 17th and 18th centuries had boshes from 6 to 8' wide. The area below the bosh was the hearth. It was here that liquid iron pooled with slag floating on top. This was usually made of a temperature resistant stone (refractory), but could also be made of fire brick. A new hearth was installed when the old one wore out. The lining of the stack was repaired between firings. Occasionally the entire stack would be torn down and rebuilt.

Boshes and hearths were originally square, an easier shape to build in stone. But, it was common knowledge that it took a couple of weeks to achieve
peak production after the installation of a new hearth. It was also known that after a campaign both the bosh and hearth had rounded out. By the mid 1600s it was discovered that the working in period for a new hearth was the time it took for the new hearth to erode into a rounded shape. Installing a round or elliptical hearth avoided the break in period and increased iron production. Sharpley Pool Furnace, Astley, Worcestershire built in the early 1650s is the earliest English example of a deliberately round hearth and bosh (P. Brown 1982:16).

The hearth was constructed of especially heat resistant material, usually sandstone. For it was here that the 1200 to 1400°C liquid iron and slag collected prior to being tapped. The hearth had two holes in it at the casting or working arch. The upper was called the cinder notch and liquid slag (cinder) would be tapped out through it. The bottom taphole was were the iron was tapped out. Both holes were usually kept plugged up with fire clay. The plug was removed to tap the furnace.

The charge was added through the opening at the top of the furnace stack. The charge was made up of carefully measured layers of charcoal, lime, and ore. The charcoal oxidized in the vicinity of the tuyere(s), releasing heat, CO₂ (carbon dioxide), and CO (carbon monoxide). As the hot CO₂ passed over and around the charcoal it was converted to CO (the Boudouard reaction). The hot carbon monoxide flowed up the stack, bathing the charge (burden) as it moved down the stack and increased its temperature. The high temperature and reducing atmosphere drove a number of chemical reactions. The two most important were the reduction of iron oxide to metallic iron and the formation of a liquid slag. If the furnace was operating correctly most of the gangue moved into the slag and was tapped out through the cinder notch. The metallic iron also absorbed carbon. This lowered the iron's melting temperature and the iron became molten and dripped down into the hearth.
The founder controlled the furnace by monitoring the amount and color of smoke exiting the stack, the color and viscosity of the slag, and the viscosity of the liquid iron. His control of the process was extremely limited and he had very little immediate effect. The amount of air injected into the furnace through the tuyeres could be varied, but not a great deal. An increase in air flow would increase the stack temperature. He could also vary the amount of each raw material charged at the top of the stack. But, this would not effect the furnace until it had moved down the stack, a matter of hours. In this way he could alter the composition of the slag. Increasing the ratio of fuel to other materials would eventually lead to the furnace operating at a higher temperature making both the slag and the metal flow more freely. But, it could result in the metal taking up more silicon or other non-ferrous elements.

The high carbon liquid iron would flow into the crucible (hearth) at the very bottom of the furnace. How often the molten slag and iron could be tapped, depended on the size and efficiency of the furnace. The slag would be discarded. Slag piles are a common sight at abandoned furnaces. The iron could be run directly into molds, but was usually run into pigs in the sand of the casting house floor. Pig iron got its name because it resembles a litter of piglets suckling at a sow. Pig iron in the 18th century is sometimes called sow iron.

The following is a description the operation of a furnace in Staffordshire in 1686.

When they have gotten their ore before it is fit for the furnace, they burn or calcine it upon the ground, with small charcoal, wood, or seacoal, to make it break into small pieces, which will be done in three days, and this they call annealing it or firing it for the furnace. In the meanwhile they also heat their furnace for a week's time with charcoal, without blowing it, which they call seasoning it; and then they bring the ore to the furnace thus prepared, and throw it in with the charcoal in baskets- i.e., a basket of ore and then a basket of coal. Two vast pairs of bellows are placed behind the furnace and compressed alternately by a large wheel turned by water, the fire is made so intense that after three days the metal will begin to run;
still after increasing until at length in fourteen night's time they can run a sow and pigs once in twelve hours, which they do in a bed of sand before the mouth of the furnace.... The hearth of the furnace into which the ore and coal fall is ordinarily built square, the sides descending obliquely and drawing near to one another like the hopper of a mill; where these oblique walls terminate, which they call the boshes, there are set four other stones, but these are commonly set perpendicular, and reach to the bottom stone, making the perpendicular stone that receives the metal. [Turner 1900:10]

Prior to blowing in a furnace at the beginning of a campaign, it had to be preheated or seasoned. This was done in a variety of ways. The entire stack could be filled with charcoal, lit at the top, and allowed to burn to the bottom and then refilled and allowed to burn up. Or the stack could run just with charcoal for 2-3 days and then be charged normally. The following is an early 18th century (1722-40) account of the initiation of a campaign at the Leighton Furnace, Yealand Redman, Lancashire, UK:

they put in Fire for two or three Days before they begin to blow, which they call Seasoning, at first they blow gently, gradually increasing till in about three Weekes Time the fire will be so intense that they can run a Sow and Pigs once in about twelve hours [Schubert 1957:431]

The furnace at the Durham Iron Works in Pennsylvania averaged slightly over 60 hours from being lit off to first iron during 1879-89 (Fackenthal 1890).

Once a furnace was blown in (blast applied) it was run 24 hours a day, 7 days a week for months. Campaigns in the 14th and 15th century might only last a few weeks. But, as iron masters gained experience in both furnace construction and operation, campaigns became longer and longer. Until the 1600s furnaces might have three to four short campaigns a year. In Britain 16th century campaigns averaged a little under 11 weeks (range of 3-36 weeks). This had increased to 24 weeks by 1650 (range of 8 to 49 weeks). By the beginning of the 18th century British furnace campaigns averaged 34 weeks (range of 20 to 52). In 1593 Richard Pegg of Shipley near Bradford, Yorkshire said "No man can make
any good profit or gayne by any furnace for iron unles there bee water enough to keepe the same on worke by XX or XXX weekes” (Schubert 1957:243). During the 18th century American blast furnaces normally stayed in blast for 9 or 10 months (30 to 40 weeks). Records indicate that one American pattern was to start a campaign in March and end right before Christmas. Many furnaces shut down in the winter because of the danger of losing blast if the wheel pond froze. In England, where the winters are not as cold, a campaign often ran through the winter.

With the introduction of steam and electric powered blast, campaigns could last years. Furnaces were run until they had to be shut down for maintenance, usually due to erosion of the lining. In the 1870s the Tecumseh furnace in Alabama ran continuously for seven years, one month, and eighteen days (Gordon 1996:115).

**The Finery Forge**

The blast furnace was a marked improvement in efficiency and production capacity, turning out as much iron in a day as a bloomery did in a week. But until market demand changed in the 19th century it had one glaring drawback, it produced the wrong kind of iron. Blast furnaces produce high carbon cast iron and most applications called for low carbon wrought iron. Until a means was found to convert cast iron to wrought iron, the blast furnace was virtually useless. What was needed was a way to remove unwanted carbon from the cast iron, to decarburize it, and convert it to a malleable form of iron. Until the introduction of stamping and potting in the 1750s and puddling after 1783, this was accomplished, in the West, in a finery forge.
Figure 23. Plan of the Upper (Finery) Forge at Valley Forge. Figure 7 in H. Schenck, The Upper Forge at Valley Forge (IA 1992:26). Courtesy of the author and The Society for Industrial Archaeology.
Figure 24. 18th Century Finery Hearth (Diderot 1959: Plate 95 [1762-72])

Figure 25. Hammering the Ancony (Diderot 1959: Plate 97 [1762-72])
It is often assumed that cast iron was converted into wrought iron by hammering out the impurities. Hammering cast iron will not change it to wrought iron, it will only transform it into little pieces of cast iron. Decarburization takes place prior to hammering. Hammering expels slag and evenly distributes what remains. It does not remove carbon.

A number of methods were developed for decarburizing cast iron. In China puddling was invented very early and the finery process may not have been used. In the West, prior to the development of stamping and potting in the 1750s and Cort’s puddling process in 1783, decarburization was performed in a finery forge. There were a number of regional variations (Schubert 1957:272; Percy 1864:580-581). Percy (1864:579-619), but the Walloon, and German process predominated in British North America. The Walloon method used two separate hearths, the finery for decarburization and the chafery for reheating. The German process used only one hearth and was practiced in parts of the colonies with heavy concentrations of Germans (e.g. Pennsylvania and the Valley of Virginia).

The conversion of cast iron to malleable or wrought iron was a two step process. First, cast iron was converted into a loop or bloom of low carbon iron by burning out the carbon. This bloom is virtually indistinguishable from the bloom produced in a bloomery hearth. Second the bloom was hammered into an ancony or bar, just like in a bloomery.

As in blooming, a common misconception was that the carbon (impurities) were hammered out of the iron. This is true not only of many modern authors, but also of numerous historic descriptions. The conversion of the iron (decarburization), or fining is actually accomplished before the hammer is used.

Figure 24 shows an 18th century finery hearth. The bellows are on the left and feed into a single tuyere. The pig iron was slowly fed into the hearth through a hole in the back wall of the hearth (no. 7). The tip of the pig is drip melted in
the highly oxidizing fire at the nose of the tuyere, the hottest place in the hearth. The partially decarburized iron, along with entrapped slag, forms a bloom or loop at the bottom of the hearth. The worker labeled Fig 2 (the finer) is manipulating the bloom or loop as it forms in the bottom of the hearth. He would repeatedly lift it up into the oxidizing fire and remelt it until the carbon was removed. Once the bloom was formed, the process is identical to the bloomery. Fig 3 is consolidating the bloom with a sledge hammer. In Figure 25 the hammerman, Fig 1, is forming and working the ancony under a power hammer. The process continues as in the bloomery, with the ultimate product being bar iron or merchant bar. The hammer is used to forge weld the iron into a solid mass and expel slag incorporated into the bloom during the fining process.

A Walloon finery forge had at least one finery hearth, one chafery hearth, and a power hammer. This is the design used at Valley Forge (Figure 23). Each hearth and the hammer usually had separate water wheels. By the middle 1600s the majority of English finery forges had two finery hearths. Beginning in 1600 a "double finery" was developed that had three finery hearths, one chafery, and two hammers (Schubert 1957:274). The layout of the building; placement of the hearths, hammer, bellows, and anvil; and size of the hearths has been recovered archaeologically from a number of sites including Valley Forge (Schenk 1982, 1988, 1992; Schenk and Knox 1985, 1986), Potts Wilson Iron Forge (Troup et al. 1978), Ardingly (Tylecote 1986:219), Chingley (Tylecote 1986:160), and King’s Forge (Kemp 1987).

Most of the cast iron worked at finery forges was in the form of pig iron. This was either bought from a blast furnace or supplied by one that belonged to the organization. The records of the Knight’s forges show that scrap iron, broken castings, and worn out forge plates were also used. These were both purchased and recycled from the forge (Ince 1991:36). Scrap was also used at American
forge (H. Schenck, personal communication 2000).

The Foundry

Unlike a bloomery or blast furnace a foundry cannot make iron from ore. Its raw material is cast or pig iron that must be produced in a blast furnace. A foundry is an iron works that remelts pig iron and casts it into finished products. The only purpose built foundry in colonial Virginia was Alexander Spotswood's double air furnace at Massaponax. However, most, if not all, of the blast furnaces in Virginia were used to cast finished products. In this operational mode the liquid iron instead of being cast into pigs or sows was cast in other shapes.

Figure 26. Air Furnaces (Hassenfratz 1812:Plates 7 and 38)

Air furnaces were structurally quite different from blast furnaces. They were charged through doors on one end or in the side of the furnace, not from the top. The pig iron, broken castings, and fuel were loaded separately and did
not come into contact. Instead the heat and flame from the fire were drawn across and deflected onto the pig iron and then exhausted through a chimney on the far side of the furnace. Although, numerous plans of air furnaces (Figure 26) exist, no description of Spotswood's Massaponax furnace exists. During the 19th century cupola furnaces largely replaced the air furnace. These resemble small blast furnaces, but are made of cast iron plates, rather than masonry or brick.

Colonial era foundries made two distinct types of castings- flat and flask. Flat castings like stove plates and fire backs could be cast directly in the sand of the casting floor. They were decorated on only one side. The other side was open to the air. Founders used wooden patterns to impress the desired shape into the sand floor. Molten iron was either ladled or tapped into the impression. Hollowware like kettles, firedogs, and skillets were flask cast. A wooden or plaster model was used to form an impression in a two part sand or loam filled mold. The model was removed and the two sides put together. These molds could only be used once. In the 19th century reusable cast iron and steel molds were developed. Molten iron was ladled into the top of the mold, filling the void. Large castings like cannons and lawn rollers were mold cast in vertical pits. The mold for a cannon was called a gunflask. It was made and then lowered into the casting pit, muzzle up. Iron was tapped directly into the mold from the furnace hearth.

Modern foundries can also cast steel. But, again they cannot produce steel. They remelt steel purchased from a steel plant.
Figure 27. Location of the Albemarle Iron Works and Martin Mine. Dillwyn 100K USGS Quad.
Figure 28. Location of the furnace stack. From USGS 7.5 Quad.
Figure 29. Ruins of the furnace stack. Photo by author.
CHAPTER 4: History of The Albemarle Iron Works

The Albemarle Iron Works (44AB117) was built just south of the intersection of Rts. 712 and 631 in South Garden, VA (Figure 27). The furnace was constructed on a terrace next to the South Branch of the Hardware River (Figure 28). Very little is left, the furnace stack is a small mound of tree and brush covered stone (Figure 29). On the wooded hillside above the ruined stack are the foundations of a number of buildings. In the hillside, the trace of the headrace for the water wheel is clearly visible. Most of the company records were lost in a fire at John Wilkinson’s house. All that remains are a handful of letters, deeds, and depositions in the lengthy lawsuit that finally ended the company and a river full of slag.

The Albemarle Iron Works was built during the last period of colonial blast furnace construction. By this time the problems inherent in furnace construction and operation had been largely solved. Its location was well suited to provide iron for the growing Piedmont market and also to ship pig iron down the James River to Tidewater and the rest of the world. Yet, the blast furnace was in operation for less than a year and it was not until almost a decade later that John Old, one of the partners, built a bloomery to supply the area with bar iron. The company dissolved amidst such acrimony that the resulting lawsuit took over 20 years to settle.

The men who conceived the iron works were all from iron families in Pennsylvania and Maryland. John Old made his first trip to Albemarle County in 1764 and moved there in 1778. In 1766 John Wilkinson, John Lee Webster, and Nathaniel Giles became involved. While Wilkinson moved to Virginia and took over organizing the company, Webster and Giles soon left the company.

Wilkinson, Giles, and Webster were Quakers (Reynolds 1992:44; Wright
Giles was Webster's cousin and both families were involved in a number of iron works in Maryland and Pennsylvania including: Spring Forge and Cornwall Furnace, PA (Spring Forge Journal; Miller 1951:103) and Cumberland Forge and the Bush River Iron Works, MD (Reynolds 1992:43-44; Sutherland 1982:365-369; Account books of John Lee Webster, 1747-1793, Library of Congress MMC 1068, Ledger B:119 [LC Webster B]). Wilkinson is often mentioned in connection with Cumberland and Spring Forge (Reynolds 1992:44; LC Webster B:119; Spring Forge Journal).

The "Olds" were involved in a number of iron works in Pennsylvania. But it may be two different families, or two branches of the same family. Most entries concern James Old, his brother William (Cremers 1986:54) and his sons John, William, and Davies. They are involved in Cornwall, Hopewell, and Reading Furnaces and Speedwell, Quittapahilla, Windsor, and Poole Forges (Bining 1973 [1938]:47; Cremers 1986:53-74; Walker 1974:32, 35, 37, 421). James may also have been involved in Spring Grove Forge, which was built by his son-in-law Cyrus Jacobs (Bining 1973 [1938]:130; Cremers 1986:60).

William Reynolds (1990 and 1992, and personal communication 2001), in spite of an extensive search of records in the United States and Great Britain, could find no evidence that the John Old of the Albemarle Iron Works was related to the James and William. However, it may be more than coincidental that John named two of his five sons James and William (Reynolds 1990b:292-293) and that James had a son John. The John Old of the Albemarle Iron Works first appears in 1758 as a forgeman in the Lancaster County, PA tax rolls. From 1762-1768 he was on the Berks County tax list (Reynolds 1992:42). In 1773 he bought part of Spring Forge on 7 December 1773 (Reynolds 1992:42; Berks County Deed Book 12:54-59) and ultimately owned a 2/3 share.
Figure 30. Plat of Albemarle Iron Works holdings (Reynolds 1992:58-59).
Reconnaissance and Land Acquisition: 1764-1770

John Old and John Wilkinson spent seven years looking for suitable sites for iron works in Albemarle and Augusta Counties. Old first traveled to the South Garden area in 1764. He made at least thirteen trips to the area prior to moving down from Pennsylvania in 1778. Wilkinson followed in 1766 (Reynolds 1992:43-45).

The land acquisitions of the Albemarle Iron Works are shown in Appendix D and were platted (Figure 30) by William Reynolds (1992:58-59). During this early period the company was called John Wilkinson & Company (Reynolds 1992:46) or the Virginia Works (LC Webster B:259 and 265).

The first recorded deed was for land purchased in 1768 by Nathaniel Giles, John Lee Webster, and John Wilkinson (Albemarle County Deed Book V:135). This ten acre plot belonged to John Gillum and contained a "Mine Bank". However, there is an entry in John Lee Webster's Account Books (LC Webster B:259) dated 21 March 1768 "Virginia Works to Cash Delivered to Dr. Nathan Norton". This may be for the land later referred to as coming from William Sutherd, but for which no deed has been discovered.

After 1768, Wilkinson moved to Virginia to facilitate land acquisitions and find local partners for the venture. He bought additional land in 1769. On 20 February he purchased 98 acres south of Carters Bridge on west side of the Hardware River (Albemarle County Deed Book V:80). This is part of the property that later became known as the "forge tract". The next day he finalized acquisition of 5.75 acres from David Cook in the "ragged mountains" (Albemarle County Deed Book V:65). According to Wilkinson's 1769 agreement with John Old and The (Richmond) Enquirer notice of 18 June 1814 this tract included an iron
On 30 January 1769 John Old lent Wilkinson £1000, in return Wilkinson agreed to repay the loan or deed 1/2 share in

the following Tracts of Land and Mine Banks Viz: One Tract bought of John Gilham with it a Mine Bank in Albemarle County and Colony of Virginia, One Tract of Land with a mine Bank bought of William Sutherd in the County of Albemarl; one other Tract of Land with a mine Bank Bought of David Cook; as well the above mentioned tracts or Parcels of Land and Mine Banks as also all other Lands which he the said John Wilkinson has made entries of & secured in Albemarl, Amherst, and Augusta Counties in the said Colony of Virginia [Wilkinson 1796]

The bond was transferred by Old to William Cabell on September 16, 1771, (Cabell 1771) and later to his son Nicholas Cabell. It formed the basis for the 1788 lawsuit.

Land acquisition accelerated in 1770, prior to the formal formation of the partnership in December. By March the company was being referred to as the New or the Albemarle Company. On 12 May 1770 Wilkinson patented 7 tracts of land (Royal Patent Book 38:886-893) for a total of 2345 acres. All of these were along the South Fork of the Hardware River. However, only six of them appear in the public auction list of company property (The Enquirer vol 11(12), 18 June 1814). The omitted property is 311 acres on the "North Waters of the South fork of Hardware River and on one of the Ragged mountains called Fitz's mountain" (PB38:887). It is possible that this was where Wilkinson built his home. With these acquisitions the company controlled 2458.5 acres. But, neither the site of the blast furnace or the finery forge was purchased until after the company was formed.

**Partnership and Failure: 1770-1772**

The Albemarle Iron Works was formed on 28 December 1770 with the
expressed purpose of "seating & putting in repair a Furnace Forge a grist & saw mill all ready built & the necessary buildings for making Piggs & Bar Iron & also common & Flask castings". The company initially consisted of Dr. William Cabell, COL Edward Carter, Dr. Thomas Walker, John Wilkinson, and Alexander Trent (Walker-Page 1770b; Thomas Walker 1791). A number of authors, including William Condit (1959:6), have reported that Thomas Jefferson was a partner. This is based on one document, an "Acct of Sums paid Furnace" (Walker-Page nd). One side lists the partners and the sums they advanced for the works. Jefferson's name is on the back. He is not included in any of the other company documents, including the lawsuits that dissolved the company, nor does he ever mention involvement in the furnace. As mentioned earlier, John Old loaned £1,000 to Wilkinson in 1769 for the company and is listed on two of the 1769 deeds. But he was not a partner until he purchased half of Edward Carter's share on September 21 1771 (Walker-Page 1771).

While the lack of punctuation allows various interpretations of the agreement, other documents (see below) make clear that the company planned to repair and operate pre-existing grist and saw mills and to construct a blast furnace at South Garden and a finery forge 1km (1/2 mile) southeast of Carter's Bridge (see TT Brady files). It is unclear from any of the extant documents where the mills were located. None of the deeds mention standing structures or mills. Both the furnace site and the forge site had mills during the 19th century (Gilmer 1864). According to field notes compiled by T. T. Brady (1979) and William Reynolds (1990a) there is no evidence, either structural or slag, that the forge was ever completed. However, numerous documents from the 18th and early 19th century refer to the area using the term "forge" or "forge tract". Both T. T. Brady and William Reynolds concluded that either the forge was never built or it was completely obliterated by later mill construction (Reynolds field notes 1990).
John Old built a bloomery forge (44AB115) 5km (3 miles) northwest of Carter's Bridge sometime after he moved to Virginia in 1778. This frequently confused with Albemarle's forge, and is sometimes erroneously called a blast furnace. The site was investigated three times (1 March 1981, 15 January 1990, and 17 November 1990) by T. T. Brady, William Trout III, Harry Webb, and William Reynolds (William Reynolds, personal communication 2001 and field notes 1990; T. T. Brady field notes 1990). The slag found at the site is consistent with a bloomery forge. A sample of metal was tested by Froehling & Robertson, Inc. of Richmond, VA (F&R File Number: R-56-011). They concluded it was wrought iron from a bloomery (T. T. Brady letter 9 May 1990, and 28 May 1990).

**John Wilkinson**

In his 1791 deposition Thomas Walker stated that in December 1770 "It was discovered that the works were not in such a state as to produce any profit, whereupon it was agreed that the manager John Wilkinson should go in to complete the works..." (Walker 1791). Wilkinson stated he was "appointed by the parties to carry on and manage the said mills and works" (Wilkinson 1792).

With the loss of the company records in a fire at John Wilkinson's house and in the absence of any other documents, it is impossible to determine what he accomplished during the first half of 1771. At the very least Wilkinson repaired the mills and began work on the blast furnace. The reference by both Walker (1791) and Wilkinson (1792) to "works" leaves open the possibility that he may have completed the furnace. He must also have developed the mine site(s).

Five more parcels of land were acquired by the company during this period. Both the furnace tract, 145 acres on the south fork of the Hardware River (DB5:300), and the 2 acre forge site south of Carters Bridge (DB5:304) were
purchased on 10 January 1771. Three more charcoal tracts were bought on 10 January (153 acres DB5:306) and 10 May (240 acres DB5:317 and 240 acres DB5:317). The later two parcels, because of their location south of Carters Bridge, were probably intended to supply the forge.

John Swan

However much he may have done, Wilkinson's work was not entirely satisfactory. On 18 July 1771 the other partners published the following notice in the Virginia Gazette:

Mr. John Swan, of Albemarle County, is by us appointed to draw for all Goods, Monies, Provisions, &c. for the Use of the Iron works, we are concerned with in the said county; and that any Order, or Orders, drawn by any other Person [Wilkinson], will not be paid or accepted by the Company.

WILLIAM CABELL
EDWARD CARTER
ALEXANDER TRENT
THOMAS WALKER

What prompted this action, what was the intent of the notice, and what was the significance of the omission of Old and Wilkinson?

Again the two extant documents, the notice itself and Wilkinson's 1792 affidavit, do not clarify why the four signatories felt compelled to take this action. The Gazette notice states only that Swan was the sole agent authorized "to draw for all Goods, Monies, Provisions, &c. for the Use of the Iron works". This argues for Swan's role as financial only and implies that Wilkinson continued to supervise the construction of the iron works. This is supported by Wilkinson's 1792 affidavit which states that he was responsible for building the iron works and operating the mills

and continued to do so until the 17th of (Sept) 1771 when the
management and direction of the said works were taken out of his hands and a certain William Twadle put in his stead... [Wilkinson 1792]

Two other authors who have worked with the iron work's documents, Natalie Disbrow and William Reynolds, came to different conclusions on the role of John Swan. Disbrow wrote:

Many were the trials and tribulations of this partnership. Wilkinson was charged with inefficient management [Disbrow 1941:11]

Disbrow maintains that Swan was placed in full charge of both operations and finance at the works. William Reynolds arrives at a different reading of events:

John Wilkinson was put in charge of the furnace operations initially, and managed the works until September 1771, i.e., while the furnace was under construction. During the summer of that year, concern arose about his ability to manage finances, causing the partners to place nearby resident John Swan in charge of those affairs. Wilkinson's managerial weakness must have extended beyond financial affairs, since he was replaced as manager of the iron works on 17 September by William Twaddle. [Reynolds 1992:50]

A limited role for Swan (e.g. financial only) is also supported by who he was. Unlike Wilkinson, Old, and Twaddell; he did not have an iron background. He was a local, and given the rural agricultural nature of Albemarle county he is unlikely to have had iron experience. As a result, Swan would not have been qualified to oversee the completion of the furnace. It is reasonable to conclude that Wilkinson continued to oversee the construction of the iron works, while Swan took charge of the company's finances.

Regardless of Swan's role in the Albemarle Iron Works it is clear the public announcement of his appointment in the Virginia Gazette was made to prevent Wilkinson transacting business in the company's name. Wilkinson was not only one of the partners, but also was responsible for setting up the company. His name was on many of the early deeds and he had been responsible for repairing
the mills and building the blast furnace. People naturally associated his name with the company and a clear statement that he was no longer in charge may have been necessary.

What, if anything, is the significance of only four of the partners signing the *Virginia Gazette* notice? The omission of John Wilkinson is understandable. Even if the notice in the *Virginia Gazette* concerns Swan's appointment in the limited role as purchasing agent or book keeper, Wilkinson, as senior partner, was unlikely to be happy. He had invested more time and money than anyone else in the project and cannot have been pleased at any diminution of his span of control. He did not sign the Gazette notice, because the change was forced on him by the other partners. That Old did not participate is also easy to explain. Although he was financially involved, having lent money to Wilkinson in 1769 (Wilkinson 1796) and participated in some of the land acquisitions, he did not formally become a partner until he purchased half of Edward Carter's share on September 21, 1771 (Carter 1771).

Because of the lack records it will probably never be known why John Swan was given financial control of the works in July and William Twaddell was hired in September 1771. Obviously the other partners found John Wilkinson’s performance unsatisfactory. But whatever his shortcomings, it did not prevent them from reappointing him to manage the mills after the furnace was shut down in 1772.

**William Twaddell**

The arrival of William Twaddell in September, was not accompanied by a printed notice. Swan may have continued to run the company’s finances. But after Twaddell’s arrival, there is no further mention of Swan. In the two extant
letters written by Twaddell he clearly commits company money. It may be that the partners did not feel it was necessary to announce the change. Unlike Wilkinson, Swan had no reason to transact business in the company's name after Twaddell's arrival and his name was not habitually associated with the company.

There are only two documents from the furnace's "operational" period, both written by Twaddell. On October 16, 1771 he wrote to William Cabell from "Albemarle Furnace", complaining of a lack of money and beef.

I Bought Seventeen Beaves of Mr. Andrew Rusael by whom have Drawn an order on you for Forty-two Pounds. which I hope you'll not take amiss as I had no other way to raise the Money and we were quite out of Beef. I have since I see you been with Doctor Walker and Colo. Carter to get som Money but got none. and we are in great want of some to pay for Several Articles now wanted. the Doctor told me he thought he was as much out if not more than any of the rest of the owners; he included the Draft on you whic sh I told him you accepted off.

Dr.Jf if you can Raise at present any more Money than will pay off Mr. Rusael please to send it me or let me know & I will come or send for it. & as I am pretty well assured you know the want of Money at the Works at present hopes you'll excuse me in Urging for it so much... [Twaddell 1771]

On 16 January 1772 he wrote Thomas Walker about wood for the blast, a lack of millwrights and sawyers, and complaining of a lack of money.

I have sent the Negroes home without getting the Wood out at the Furnace as I proposed: as I thought we could do without it for this Blast. They have just cut 155 Coards Good. What Stops us most at present is for want of Millwrights and Sawyers as there is none of the Millwrights yet come and Mr Henderson has not sent the Sawyers I agreed with him for at Court but am daily expecting them- You'll please to send yours as Soon as possible also a little Money as we are very much in want of some at present. [Twadell 1772]

When the blast furnace was completed and blown in is unknown. There is no reason to believe that it was completed prior to Twaddell becoming manager.
in September. It seems probable that Twaddell finished it and blew it in.

By the late 18th century it was common to run American blast furnaces for 9-10 months, from March to December. Running a furnace through the winter months risked losing blast if the wheel pond froze. However, a pond did not suddenly freeze. It required an extended period of sub-zero weather and this would give the ironmaster time to blow out the furnace. But, it also was not cost effective to blow in the furnace in September or October and then terminate the campaign after only a couple of months. Because, like an oven, a blast furnace must be pre-heated prior to running iron and that uses charcoal. But, it would not have made sense to leave it idle until March either.

Very little is known about the initial operation of new colonial blast furnaces. While it makes economic sense to "get the feel" of a new furnace during a standard 9-10 month campaign, it is possible not everyone would do it that way. Some ironmasters might prefer a series of shorter campaigns. There are records of 18th century blast furnaces with a series of short campaigns, rather than one long one. But, since what an ironmaster was doing during the initial campaign was adjusting the ratio of charcoal:ore:flux to find a mix that worked for that blast furnace, there seems little point in a series of short campaigns. This would only increase costs by increasing charcoal use.

The documentary record is unclear. Twaddell makes no mention of the furnace being in blast in his 16 October 1771 letter to Dr. Cabbell. But he does send the letter from "Albemarle Furnace" (Twaddell 1771). Although Twaddell wrote of "this blast" in a letter dated 16 January 1772 (Twadell 1772), there is not enough detail to determine if "this blast" refers to one already in progress or one about to start. So the blast furnace may have been blown in as early as September 1771 or even after 16 January 1772.

The October letter makes no mention of any operations at the iron works.
But the Twaddell feels he must buy seventeen cattle because "we were quite out of Beef" (Twaddell 1771) indicates that he is feeding a large number of people. In his January letter the mills are idle awaiting the arrival of millwrights and sawyers. But, he has just released an unspecified number of Negroes, presumably slaves, who have been felling timber for coaling. He refers to either a blast in progress or one that he anticipates initiating in the near future.

Who was William Twaddell? Where was he from and why was he hired? Again the limited survival of company documents is a severe hindrance. Only four documents survive, the two letters he wrote as ironmaster, the transfer of half of Carter’s share to John Old on 21 September 1771 that he witnessed (Carter 1771), and John Wilkinson’s 1792 affidavit.

Once the Albemarle partners concluded that Wilkinson was not qualified to run the company, it was natural that they look to the iron making communities of Maryland and Pennsylvania for a replacement. Both colonies had numerous iron works and the partners had connections there.

Unlike many others associated with the Albemarle Iron Works, very little is known about William Twadell. A William Twadell appears on the tax rolls of Chester County, Pennsylvania in 1771 and again from 1779 on. According to a notice in the *Pennsylvania Evening Post, 7 July 1777*, a William Twadell was involved in the operations of Pennsgrove Forge (Reynolds 1992:51). This may, or may not be the same man.

John Wilkinson’s 1792 affidavit must be considered suspect. Wilkinson spent the most time and invested more of his fortune than any of the other partners. He felt he should have run the iron works and clearly did not like Twaddell. Wilkinson wrote that he managed the works until:

the 17th of (Sept) 1771 when the management and direction of the said mills and works were taken out of his hands and a certain William Twadle put in his stead (and from that time everything went to destruction while
said Twaddle continued) that said Twaddle continued to manage said works from the 17th of Sept. 1771 until May 1772, when said works were entirely stopd and broken up, and said Twaddle discarded in that on the fourth of June the parties met [at Blenheim]... while Twaddle continued manager in which time the works was ruined through the conduct of said Twaddle... [Wilkinson 1792]

The only other comment on Twaddle's management was in Thomas Walker's 1791 affidavit. That the "works which were carried on at a very great expense and never produced any profit..."

However, a good deal can be inferred from the documents, especially the two letters. The cost of erecting a blast furnace, buying the land for coaling and mining ore, and hiring the skilled work force to run it were enormous. But considerable sums of money must also be spent to purchase the raw materials or supply the workers producing them prior to blowing in. A furnace required liquid funds to pay the workers and/or buy the food and raw materials needed to feed them and the furnace. Assuming that Albemarle Iron Works went into blast on or around September 17th, the partners should have provided Twadell with enough money to pay for supplies, raw materials, and salaries. That he was still short of cash in January after complaining in October, indicates either that he was fiscally irresponsible or that the partners wanted positive control on expenditures.

While restrictive cash management policies may be a reflection of the bad experience the partners had with Wilkinson, they could still adversely effect the operation of the furnace. Run out of any of the raw materials and the campaign ends. Starting and stopping a blast furnace is inefficient and costly. Because once it cooled down, it could take up to a week to raise the interior temperature high enough to resume smelting.

Two things are readily apparent from the two letters- Twaddell was in
charge of both the iron works and the mills, and the company continued to have money problems. In both letters Twaddell stresses his "want" of money and pleads with both William Cabell and Thomas Walker for relief. In the first letter he wrote that he bought cattle and needs additional funds "to pay for Several Articles now wanted". In the second letter he writes that "we are very much in want of some [money] at present".

The financial and operational arrangements and work force of the Albemarle Iron Works are unknown because of the loss of the company records. Most late 18th century American iron works used a mix of free and slave workers. That Albemarle used slaves is clear in Twaddell's second letter. "Negroes" were used to cut wood for coaling. The majority of "Negroes" at the time were slaves. In the same letter Twaddell wrote he still does not have either the "Millwrights" or "Sawyers" from Mr. Henderson and he urged Thomas Walker to send his "as Soon as possible". These were probably slaves because while Virginia had a well developed market in skilled and semi-skilled slaves, there is no evidence that a similar market existed for Whites. Given the labor market in late 18th century Virginia, it is likely that Albemarle employed primarily slaves for the less skilled positions (wood cutters, furnace fillers, teamsters, etc.) and filled "skilled" positions (founder, etc.) with Europeans. This would have continued until slaves could be leased, bought, or trained to replace them.

While both types of workers had to be housed and fed, the free workers also had to be paid. Leased slave labor also had to be paid for, but pig iron or bar iron probably would have been acceptable. Money was also required to pay for supplies, the "Several Articles now wanted". Apparently William Twaddell was having trouble, because of tight monetary policy. How much this may have affected operation of the furnace is unknown.
The second letter also brings in to question William Twaddell's ability to manage a blast furnace. On 16 January 1772 Twaddell wrote "I have sent the Negroes home without getting the Wood out at the Furnace as I proposed: as I thought we could do without it for this Blast. They have just cut 155 Coards Good".

One major difference between a forge and a furnace is the operational scale. A forge is a discontinuous batch process. It normally shuts down at night and it employs 2-5 workers per hearth. Each finery hearth can produce 30-40 tons of iron a year. An 18th century blast furnace is a much larger operation that runs continuously for months and requires at least 20 people and a large support crew of woodcutters, colliers, carters, etc. Annual production of a blast furnace is an order of magnitude greater, 4-800 tons. On 16 January 1772 Twaddell wrote:

155 cords of wood is enough to produce 4-5,000 bushels of charcoal. This is enough charcoal to operate a forge for a year. But it is only enough for two to three weeks of blast furnace operations, 20-30 tons of pig iron (Schallenberg 1977:444). Running out of charcoal would have forced Twaddell to shut down the furnace. It took weeks to coal a load of wood (see Chapter 6, pages 161-164).

This letter is a clear indication that William Twaddell came from a forge background and may not have been qualified to run a blast furnace. This is true even if he already had charcoal on hand. Because this small an addition would have made so little difference that he should not have asked for the woodcutters.

The documentary record leaves no doubt that the furnace was blown out in May 1772. The partners permanently shut it down after a meeting at Blenheim, Edward Carter's home, on the 4th of June 1772 (Wilkinson 1774b and 1792). There is an extant 1772 inventory of Albemarle IW including entries for "In the Mill... In the Kitchen... mine Bank... In the Smith Shop" (Walker-Page 1772). There was no entry for a blast furnace, a bloomery, or a forge. But the inventory
Wilkinson laid all the blame for Albemarle's failure at William Twadell's feet. He claims to have continually warned the other partners of Twadell's mismanagement and his readiness to step in and resume operational control of the iron works. "and from that time [17 September 1771] everything went to destruction while said Twadell continued... the works was ruined through the conduct of said Twadle" (Wilkinson 1792). The other partners apparently did not share John Wilkinson's misgivings and left Twaddell in charge until the furnace was blown out in May 1772. The owners met on the 4th of June 1772 at Blenheim and agreed to cease furnace operations (Wilkinson 1792).

The Twilight Years: 1772-1816

Although the partners agreed to shut down the blast furnace on 4 June 1772, this did not result in the end of the company. Numerous proposals were made to restart the blast furnace and finish the finery forge. John Wilkinson was again appointed to run the mills and land acquisitions continued.

On 20 June 1772 Thomas Walker recorded patents on four tracts of land in Augusta County (PB40:706, 708, 711, and 717) totaling 2780 acres and one in Albemarle County of 332 acres (PB40:709). The property in Augusta was for a second blast furnace. Although the partners never built anything on the land, another company built an iron works on the property and this further complicated the law suit that finally broke up the Albemarle Iron Works. On 1 August 1772 he patented an additional 226 acres in Albemarle (PB40:780). The Albemarle land was in the hills just to the north or the blast furnace site and was probably intended to supply charcoal. With this land the blast furnace would have had a total of 3032.25 acres.
The furnace remained idle at least until the start of the American Revolution, in spite of repeated pleadings by John Wilkinson:

I shall not agree to Selling my part of the Workes as Proposd by you & Coll Carter, when at your House last. I am Willing & Ready to do my part towards Putting the Furnaces in Blast Early in the Spring on the footing agreed to by the Company at the last Meeting at Blenheim and to have the Wood Coal which is cut this Fall, I have wrote Mr Old & parte That I shall not goe to Pennsya as I In Treat and have wrote him as Pressing as Pasable to not fail Coming The 1st of [unreadable] Mr Hunter thinks That a Sale would be to the loss of Every Partner if sold as Proposd. [Wilkinson 1774a]

By Iron Workes I have got in Debt & by Iron Workes I am in Hopes to get out of Debt that I can once more call my Self a Freeman. [Wilkinson 1775]

And attempts by Old to rent or lease it:

Mr Old Left this... a letar from him Monday last. Dated at Dr Walkers 3d Instant in which, he offers 500 a year for the Workes as a rent for ten Years. & that Mr Walker aproves of Renting to him, or at the Rate of 500 for Each ones part in proportion to what He hold. [Wilkinson 1775]

On June 17, 1776 the Fifth Virginia Convention authorized Westham Foundry. The very next week the Convention advanced £1000 to "Thomas Walker and Company" to reopen the Albemarle Iron Works. Virginia advanced an additional £2000 to restart the furnace on December 22, 1777. In the legislation it is an "old furnace [that was] yet standing, tho' somewhat out of repair" (Swank 1892:269).

In the interval between the two appropriations, John Old secured control of the furnace. He was already a partner, because he had purchased half of 's share on 21 September 1771. On April 1, 1777 he bought out Edward Carter and Thomas Walker. As part of the agreement Old was to deliver one ton of pig to Walker and a half ton to Carter. "The Iron to be delivered as soon as it can be made at the said Workes" (Carter 1777). On April 4th William Cabell rented
his sixth part, & the Land thereunto belonging for & during the term of
 ten Years to commence from the first day of October next, in consideration
 of which the said John Old doth oblige himself and his heirs &c to pay to
 the said William Cabell the sum of £50 per annum during the above said
term of ten Years. Also to repair the Furnace & build a Forge on
Hardweare River where the Company formerly began one; both of which
at the end of the term hereby granted are to be delivered up in good
tenantable Repair. [Cabell 1777]

In this document John Old is still referred to as "of the County of Birks in the
State of Pennsylvania".

Wilkinson, Old, and Trent petitioned Virginia for money to reopen the
furnace. As stated above they advanced £2000 and appointed John Coles and
Nicholas Lewis to hold the funds. The money was transferred to Wilkinson and
in May 1778 John Old moved to Albemarle County.

There is no conclusive evidence that the Albemarle Iron Works ever
produced pig iron. On 28 June 1774 John Wilkinson wrote Thomas Walker "Collo
Carter's Wagons Wagoned the Pigg Iron to the River" (Wilkinson 1774b). This,
and a 19 May 1778 entry in William Cabell’s commonplace Book (Cabell CB
1117:7:411), have been cited as proof that Albemarle produced iron (William
Reynolds 1992:53 note 21). But, it should be remembered that Cabell, Trent, and
Walker were merchants and frequently bought and sold both pig and bar iron
(Walker-Page 1769, Walker-Page 1770a; Cabell CB:1117:6:593-594). The 19 May
1778 entry in William Cabell’s commonplace Book reads:

19. Cut & marked 10 Piggs & mouv'd out one Bore, & Mov'd 18 Sowe Piggs. [Cabell CB 1117:7:411]

But, what is being described has nothing to do with pig iron, it concerns the
marking of swine (like branding cattle), prior to setting them out for the summer.
It is a common Spring time activity on pig farms.

There is no evidence that Albemarle ever delivered any pig iron to
Westham or any other forge or foundry. While there is no evidence of production, "the furnace" persists as a place until 1780. John Coles' Account Book lists two sales of goods "at the furnace" on June 5, 1779 and March 1, 1780 (Coles).

In his *Notes on the State of Virginia* Thomas Jefferson mentions a mine operated by John Old in 1781, but no furnace or bloomery (Jefferson 2001:26 [1787]). The mine provided iron ore for the bloomery that John Old built sometime after he moved to Virginia in 1778. Its remains (44AB115) were located by TT Brady in 1981 on the northwest side of state Route 631 where it crosses the North Fork of the Hardware River. Old's (Bloomery) Forge is often erroneously identified as a furnace. But, the site has none of the glassy slag characteristic of blast furnaces. It does have large amounts of forge slag and at least one masher/skull, characteristic of a bloomery or finery forge. A bloom of low carbon iron collected at the site was analyzed by Froehling & Robertson, Inc. (T. T. Brady field notes; F&R Richmond office, File No. R-56-011).

After the iron works was shut down, John Wilkinson was again appointed to manage the companies milling operation. He did so until at least 1788 when he reported working on the head race troughs (Wilkinson 1788). There are numerous references to repairs to the mills and dams.

The end of the Albemarle Iron Works was neither neat, painless, or swift. The dissolution of the company was initiated by Nicholas Cabell. He retained John Breckenridge to foreclose on a Wilkinson mortgage in July 1788. Dr. Walker turned to John Marshall, future chief justice, on 4 August 1790 to force the liquidation of the company. Depositions were taken from the surviving partners and Nicholas Cabell. But, like so many court cases of the period this one assumed a life of its own. To further complicate matters, Dr. Walker discovered on 6 July 1792 that Archibald Stewart was erecting an iron works on the Albemarle Iron Works property in Augusta County. There was a dispute over the validity of the
deeds and land patents. Further complicating the suit, all of the original partners, except John Wilkinson, died by 1794. More delays resulted from the deaths of the heirs and executors of the various estates. John Wilkinson, the last of the original partners died in 1813.

On 18 June 1814 a notice was published in The [Richmond] Enquirer.

Sales at Auction.

Iron Company Lands For Sale.

What followed was a detailed enumeration of all of the holdings of the Albemarle Iron Works, including the disputed lands in Augusta.

The above lands will be sold in pursuance of a decree of the Court of Chancery for Richmond District, between the Representative of Thos. Walker, dec's Complainant, and the Representative of Wm. Cabell, dec'd, and others, defendants.

The lands in Albemarle, will be sold to the highest bidder, at Mrs. Cleveland's tavern on the road between Cock's mill, in the said county of Albemarle, on Monday the 25th day of July...

The lands in Augusta will be sold to the highest bidder, in the town of Waynesburg, in the said county of Augusta, on Monday, the 1st day of August... [The Enquirer Vol 11, No. 12. 18 June 1814]

Most of the land in Albemarle were finally sold in 1816. The sale of the Augusta property was delayed pending the settling of a suit by Major Dowell, Samuel Steele, Archibald Stewart, and Alexander Hall. This group of partners had built an iron works on some of the land. They lost their suit on 24 February 1820 and the land was again advertised for sale (Reynolds 1992:56; Cabell Papers, VHS Mss1:c118a33-34).
CHAPTER 5: Blast Furnace Site Selection

In order to be successful, a manufacturing company must meet certain minimum criteria. The most critical is the production of a product that people want to buy at a price that allows the company to make a profit. In order to make a profit, the cost of production must be lower than the sale price. The cost of production includes the gathering and processing of raw materials and their conversion into a marketable product. The processing of raw materials and manufacturing process requires power. A company must also have the ability to move raw materials to the facility and products to market. Lastly, it must have leadership and good management.

The requirements for a successful metallurgical operation were discussed by Vannoccio Biringuccio in *La Pirotechnia* (1540), one of the earliest books on metallurgy. Biringuccio was a successful ironmaster of Sienna, Italy. He emphasized the importance of maximizing resource utilization in the site selection of a metallurgical facility.

...one of the first considerations which you must make... [is to] examine the availability of the things you need, and the supplies that are found there, as, for instance, the wood, water, and food supply, all of which must be abundant. There must be enough wood for the needs of the mine, to make charcoal for smelting, roasting, refining, and other fires, in addition to the wood necessary for... constructing machines, huts, and other similar things. Then it is necessary to see that the sites for erecting the machines have good air and plenty of water with good falls. For convenience in making charcoal it is necessary to have wood near by,...

...But of all the inconveniences, shortage of water is most to be avoided, for it is a material of the utmost importance in such work because wheels and other ingenious machines are driven by its power and weight. It can easily raise up large and powerful bellows that give fresh force and vigor to the fires; and it causes the heaviest hammers to strike, mills to turn, and other similar things whose forces are an aid to men as you can see, for it would be almost impossible to arrive in any other way at the same desired ends because the lifting power of a wheel is much stronger and more certain than that of a hundred men. For this reason it is...
necessary to take the greatest care not only as to the places where the said machine is to be constructed but also to make it as strong as necessary and as convenient as possible for the bringing of the ore and charcoal there, so that with each one of these operations there is a saving of time, effort, and expense. Each one alone lightens the labor, and the nearer they are together the better. But because it is not always possible to have everything convenient you must decide whether it is more profitable to have the charcoal or the ore close to the building; then make this as near as possible, depending on the convenience of the water. If possible, it is better that the charcoal, the machine, and the mine [ore] be all together in one unit, but this is not possible except when they are so located by chance. [1966:22-23 (1540)]

In 1732 William Byrd found himself in possession of iron mines. Rather than succumbing to what he described as the prevailing "mine madness", he determined to find out what was required for a successful iron works. He made A Progress to the Mines (Byrd 1732) and while visiting some of the operating furnaces of Virginia, picked the brains of the men responsible for them. While conditions in Virginia were very different from those of 16th century Sienna, Italy, the guidance Byrd received was remarkably similar to that of Biringuccio.

[Charles Chiswell] assured me that the first step I was to take was to acquaint myself fully with the quantity and quality of my ore. For that reason I ought to keep a good pick-ax man at work a whole year to search if there be a sufficient quantity, without which it would be a very rash undertaking. That I should have a skillful person to try the richness of the ore.... He told me, after I was certain my ore was good, and plentiful enough, my next inquiry ought to be, how far it lies from a stream proper to build a furnace upon, and again what distance that the furnace will be from water carriage; because the charge of carting a great way is very heavy, and eats out a great part of the profit.... If I were satisfied with the situation, I was in the next place to consider whether I had woodland enough near the furnace to supply it with charcoal, whereof it would require a prodigious quantity.... That two miles square [4 square miles, 2560 acres] of wood would supply a moderate furnace; so that what you fell first may have time to grow up again to a proper bigness (which must be four inches over) by the time the rest is cut down.... [Byrd 1928, 325-326 (1732)]

[Col. Spotswood said] that if I had ore and wood enough, and a convenient stream of water to set the furnace upon, having neither too
much nor too little water, I might undertake the affair with a full assurance of success. Provided the distance of carting be not too great, which is exceedingly burdensome. That there must be abundance of wheel carriages, shod with iron, and several teams of oxen, provided to transport the wood that is to be coaled, and afterwards the coal and ore to the furnace, and last of all the sow iron to the nearest water carriage, and carry back limestone and other necessaries from thense to the works; and a sloop also would be useful to carry the iron on board the ships, the masters not being always in the humor to fetch it. [Byrd 1928:343 (1732)]

The location of a blast furnace was not random. The requirements for a successful ironworks were understood by Virginia's ironmasters and that knowledge was applied to the site selection process. The pattern of furnace distribution closely resembles merchant flour mills. Both were resource constrained, relying on water power and raw materials to operate. In the case of blast furnaces these were ore, flux, and charcoal, while merchant mills require grain. Both produced more than can be absorbed by the local market. Both required access to a transportation network that allowed the movement of raw materials to the site and finished products to market.

Virginia has an abundance of iron ore (see Chapter 6), but not all could be converted into iron using the technology available in the 17th and 18th centuries. Impurities (especially phosphorus, sulfur, and titanium) precluded the use of some of Virginia's ore (see Chapter 7). Limestone and shell for use as flux was readily available throughout the colony.

Blast furnace operators required huge tracts of forest for the wood they needed to convert to charcoal, to fuel the smelting process. Initially large tracts of land were relatively easy to acquire. But, over the course of the 18th century new furnaces had to be built farther and farther west where land was still cheap and available..

Unlike today it was not possible to ship raw materials long distances to an iron works. The passage of heavy ore and pig wagons did considerable damage
to even the best 18th century roads. Roads were unreliable and rain or snow could close them for weeks. The cost of wagonning iron to market was a substantial portion of the cost of production. Over land transport could cost eight times as much as moving cargo by water (B Thomas 1986:139), and could make the difference between a profit and a loss. For instance in 1768 Hopewell Forge paid a little over £3 a ton to move iron to Philadelphia and still made a profit of £2. But a Forge in York, PA with the same cost of production would lose £1 for every ton of iron it sold (Eggert 1994:25). Many furnace owners had to construct their own roads and bridges and were actively engaged in promoting the building and improvement of public roads.

As a result furnaces were deliberately located where ore, charcoal, and flux were found in close proximity to a stream that could be harnessed to power the blast and forge hammers. With only a few notable exceptions, Virginia blast furnaces were located on or near navigable waterways. Virginia had a wealth of waterways. These were used not only as sources of power to run bellows and hammers, but also as roads. Some could be used in their natural state, while others required extensive improvement. Impound dams were built to insure a continuous water supply for furnaces and mills. Wharves were built and numerous projects were initiated to improve the navigability of many of Virginia's rivers.

An additional factor that the iron masters did not consider, because they embodied it, was leadership. Anything as complicated and capital intensive as a blast furnace required a strong leader to guide the project, an experienced manager to ensure the delivery of raw materials, a talented bookkeeper/marketer to ensure the furnace's financial health, and an experienced ironmaster or founder to supervise the furnace's operation. This was especially true in a society that was predominantly agricultural. In England and
her American colonies agricultural land was the road to riches and had been for
generations. There was considerable resistance to industry. It took a certain kind
of man to defy the conventions of what were and were not the proper pursuits of
a "gentleman". Some were willing to put up money to establish furnaces, few
were willing to get their hands dirty ensuring that the enterprise succeeded. It
should come as no surprise that many early iron entrepreneurs were not English.
Almost all, however, came from "iron" families.

All of these factors were well understood by the first Virginia
Industrialists. A great deal of care and effort went into the location and
evaluation of potential sites. Given the amount of money involved in the
construction of a furnace complex, a mistake could, and sometimes did spell
financial ruin.

Beginning in 1764, John Old (of Pennsylvania) made at least twelve trips
to Virginia looking for locations for iron works. He was followed in 1766 by John
Wilkinson (also of Pennsylvania) and John Lee Webster (of Baltimore). In 1768
Nathaniel Giles, John Lee Webster, and John Wilkinson purchased land in
Albemarle County (Albemarle County Deed Book V:135). All of the men where
from iron families associated with furnaces and forges in Maryland and
Pennsylvania. After 1768, Wilkinson moved to Virginia to facilitate land
acquisitions and find local partners for the venture. The analysis that follows will
demonstrate that these requirements were well understood by John Old and John
Wilkinson when they selected the site for the Albemarle Iron Works.

Iron Ore

Iron ore has three attributes that can impact the operation of a blast
furnace- quantity, quality, and distance from the furnace. The Albemarle iron ore
could have come from at least three different sources, as three properties were specifically mentioned as containing ore. However, oral history and the slag analysis performed as part of this study confirms that the iron ore used came from the Martin Mine (see Chapter 8).

The Albemarle Iron works owned at least three separate "ore banks". Although only the Martin Mine shows evidence of mining, the deposit there is sufficiently large that Andrew Hunter purchased the land and invested a considerable sum to reopen the mine in the 1870s and build a blast furnace on the site (Hunter quoted in the Charlottesville Daily Progress July 20, 1963). The inclusion of the deposit in the 1880 census also indicates that the deposit was considered commercially important. If both Hunter and the U.S. Government considered the deposit of commercial value in the late 1800s, it was certainly large enough to sustain the operation of an 18th century cold blast furnace.

Iron ore in general, and the Albemarle ore in particular, is discussed in detail in Chapter 6 (see pages 130-148). Wilkinson and Old did not have access to either a modern geologist or a laboratory. Prevailing practice was to smelt a sample in a bloomery. While this would not have revealed the titanium, it should have revealed the high phosphorus content. But, as the phosphorus is in the biotite-nelsonite, it is possible their sample was skewed. The assay performed in the 1880s showed that the ore contained 46.69 to 52.52% iron (Pumppely 1886:263; Bowron 1883:162). This is considerably higher than many Virginia ores (see pages 130-139). In terms of iron content the ore was "good".

Neither is the 3.5 miles from the Martin Mine to the blast furnace site excessive. Most colonial Virginia iron works were located within a mile of their ore. Only Mossy Creek had a similar distance, 2-3 miles. The 3.5 miles might have been a problem during periods of extended wet weather. While it added to the cost of running the furnace, it does not appear to have a role in the failure.
Flux

Like iron ore flux has three measurable attributes—quality, quantity, and distance from the furnace. But while the source of iron ore is often known, neither the source or type of flux used at specific colonial blast furnaces is commonly available. Generally this is due to the unavailability of company records, as at Albemarle. But, even where records exist, the fluxing agent is seldom discussed in sufficient detail to determine the source or type used. Even where the type of fluxing agent used and source is known, it is often difficult to determine quality and quantity available. Also because the amount of flux used was considerably less than either charcoal or iron ore, the distance factor is not as critical. For instance, Alexander Spotswood imported limestone from England, yet operated the Tubal Works successfully for decades.

It is clear from the amount of lime (CaO) found in the slag that Albemarle used a lime flux. PIXE (Table 6) analysis showed that the slag contained between 18.65% and 30.62% lime. This high a concentration can only have resulted from the deliberate use of a calcium based fluxing agent. This would have been more than enough to flux most ores and is consistent with prevailing 18th century blast furnace practices. As a result, flux is unlikely to have played a role in the failure of the blast furnace at South Garden, VA.

Charcoal

Charcoal was made from wood harvested from forests (see pages 153-164). The charcoal available to a blast furnace was directly related to the acres of forest
owned by an iron works. It has been assumed that, at least initially, all land acquired was forested and available for charcoal production. Forested lands would be widely available on the frontier in settled areas on land that was not suitable for agriculture.

This model holds for the land acquired by the Albemarle Iron Works. Much of the land was on hilly terrain, inappropriate for farming. Most of the land was patented, rather than purchased from previous owners, a clear indication that it was on the frontier.

The more land owned by an iron works, the less constrained the supply of charcoal. Historic documents indicate that 18th century blast furnaces consumed about 150-240 bushels (Temin 1964:65; Hunter 1929:262-263) or two tons of charcoal (Gordon 1996:116) for each ton of iron produced. Computations conducted by a number of authors (see the discussion of charcoal pages 153-164; Gordon and Malone 1994:86; Gordon 1996:36-38; Mulholland 1981:33; Bining 1938:63) indicate that an acre of forest could sustain production of 500-1,200 bushels of charcoal. Thus a blast furnace producing 600-800 tons of iron a year would require 3,000-8,000 acres (Bining 1938:63-64; Gordon and Malone 1994:86; Hammersley 1973:606).

The Albemarle Iron Works purchased or patented a total of 3772.25 acres in Albemarle County, enough to supply the blast furnace with charcoal. But, only 2432.25 acres was for the furnace, 1338 acres was for the finery forge. If the company had to rely solely on these parcels, they would have had difficulty sustaining operations. But, most of the surrounding land is too hilly for farming and wood or charcoal probably was available from neighbors. However, this is a sustainability issue and would not have had an impact on production for years. It could not have caused the failure of the furnace during its first year of operation.
Water Power

It is impossible to tell how much water was available at a particular site 200 years ago. Even if weather patterns are known, the flow of a particular stream is not. A number of highway departments, including the Virginia Department of Transportation use the drainage of a stream, in square miles, as a way to measure flow. This data can be used as a surrogate to estimate historic flows. These numbers, as well as actual flow data, are periodically published by the U.S. Geological Survey (USGS).

The Albemarle site (highlighted) has a drainage of 41.48 sq. miles, 4.5 miles downstream from the furnace site (the figure should be adjusted downward to account for measurement below the furnace). Most other colonial Virginia blast furnaces had less water available (Table 2).

Table 2. Blast Furnace Hydrographic Data

<table>
<thead>
<tr>
<th>Furnace Name</th>
<th>Distance from Furnace</th>
<th>Drainage in Sq. Miles (miles)</th>
<th>Reference (page)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occoquan Fu.</td>
<td>1 upstream</td>
<td>594</td>
<td>102</td>
</tr>
<tr>
<td>Falling Creek Fu.</td>
<td>2 upstream</td>
<td>54</td>
<td>268</td>
</tr>
<tr>
<td><strong>Albemarle IW</strong></td>
<td><strong>4.5 downstream</strong></td>
<td><strong>41.48</strong></td>
<td><strong>243</strong></td>
</tr>
<tr>
<td>Chiswell Fu.</td>
<td>0</td>
<td>36.31</td>
<td>181</td>
</tr>
<tr>
<td>Accokeek Fu.</td>
<td>6 downstream</td>
<td>18</td>
<td>109</td>
</tr>
<tr>
<td>Mossy Cr. Fu.</td>
<td>3 downstream</td>
<td>15.29</td>
<td>27</td>
</tr>
<tr>
<td>Neabsco Fu.</td>
<td>2 upstream</td>
<td>11.24</td>
<td>103</td>
</tr>
<tr>
<td>Zane's Old Fu.</td>
<td>4 downstream</td>
<td>11.17*</td>
<td>142</td>
</tr>
<tr>
<td>Oxford Fu.</td>
<td>0</td>
<td>10.08</td>
<td>35</td>
</tr>
<tr>
<td>Marlboro IW</td>
<td>0</td>
<td>8.47</td>
<td>61</td>
</tr>
<tr>
<td>Fredericksville Fu.</td>
<td>0</td>
<td>5.2</td>
<td>171</td>
</tr>
<tr>
<td>Tubal Works</td>
<td>0</td>
<td>3.29</td>
<td>143</td>
</tr>
<tr>
<td>0</td>
<td>1.66</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>Grymes/Recovery</td>
<td>0</td>
<td>2.9</td>
<td>146</td>
</tr>
<tr>
<td>Bristol IW</td>
<td>0</td>
<td>1.54</td>
<td>149</td>
</tr>
</tbody>
</table>

*Drainage of Furnace Run at mouth minus drainage of Fall Run at Furnace Run.
The only colonial furnaces known to have had water problems were Tubal and Fredericksville. Only two furnaces, Falling Creek and Occoquan, had more water available. Accokeek, Mossy Creek, Neabsco, and Marlboro operated successfully for years with less than half as much water flow. Based on this data, water power should not have been a factor in the failure of the Albemarle Iron Works.

**Market Access**

Like most blast furnaces, the Albemarle Iron Works could produce considerably more pig iron and castings than could be absorbed by the local market. For the furnace to be financially successful, it had to have access to external markets. In 18th century Virginia this generally meant access to a navigable river.

One potential drawback to the Albemarle site was its distance from a navigable river. But, the 20 miles that pig iron would have to be wagoned to the James River was not an insurmountable obstacle. Other colonial blast furnaces had similar distances to cover (Tubal-15, Fredericksville-25). Both the Marlboro Iron Works and Mossy Creek sent pig iron overland to Falmouth and Alexandria, VA and thence to Philadelphia and the rest of the world by ship. In the case of Marlboro this meant a 75 mile trip by wagon, even farther for Mossy Creek. In spite of this, Marlboro operated for over 20 years and Mossy Creek for over 60 years.

**Site Selection and the Albemarle Iron Works**
In all Wilkinson and Old spent seven years searching out and acquiring the land for the Albemarle Iron Works. John Wilkinson appears to have understood the selection process and done a commendable job. The site they chose along the South Fork of the Hardware River appears to meet or exceed the requirements laid out by Biringuccio in 1540 and William Byrd in 1732. The hills contained abundant supplies of rich iron ore, and the company acquired at least three. The same hillsides had enough timber to provide years of charcoal. The river had a good flow, better than all but two of Virginia's colonial blast furnaces, and more than enough power for the intended blast furnace and finery forge. The only apparent drawback to the site was that it was neither on a navigable river, nor particularly close to one.

Yet with all the care exercised, the company failed in less than a year. In spite of the prudence and diligence with which Old and Wilkinson chose the site, it had a fatal flaw, titanium. But, given the state of metallurgy in the 1770s, there was no way for the partners to know that the ore at the Martin Mine contained titanium.
Figure 31. Map of Virginia Iron Ores (Watson 1907:192, 427)
CHAPTER 6: The Constituents of Iron Production

The technology of iron production has undergone dramatic change over the centuries. It evolved from craft to industry and vastly expanded in scale. Edward Heite has argued that it was the iron industry, and not textiles, that began the industrial revolution. He has argued that both in terms of company organization and operations, the blast furnaces of the 18th century were the first modern industries and the first just in time manufacturing processes (1992:123-28 and personal communication 1997).

An iron works is no longer a one man operation in a hut. Today they employ thousands and encompass thousands of acres. While a 15th century blast furnace produced less than 100 tons of iron a year, today production is 1000s of tons a day. A single modern blast furnace produces more iron annually than was used in the entire world in 1700. The delivery of raw materials is no longer by horse drawn wagon, but by bulk carrier (ship) and railroad car. Furnaces are no longer charged by the basket full or wheelbarrow, but by huge mechanical buckets holding tons of material.

But with all the changes in the technology, the underlying chemistry and objective has remained unchanged- iron oxide (iron ore) and scrap iron are converted into usable iron. And to do so still requires a source of iron, flux, and energy.

All iron smelting requires a source of iron. Although some scrap iron was used, until the 20th century most iron was manufactured directly from ore. Today a large proportion is reclaimed from scrap. Blast furnaces required a flux to form a liquid slag of the non-ferrous portion of the ore (gangue). Until the introduction of steam power in the 19th century, moving water was used to power both the air blast for the furnace and hammers for subsequent processing.
of the iron. In the United States charcoal, produced from wood, was used as a fuel and as the source for the carbon needed to form cast iron. Anthracite and coke did not come into use until the second quarter of the 19th century.

**Iron Ore**

The kind of iron ore available drives the rest of the furnace operation. Three factors govern the suitability of iron ore for a particular furnace operation and subsequent use: form of the ore (chemical composition and physical characteristics), iron content, and nonferrous components (gangue). The higher the iron content and the less gangue, the less of everything else is required to produce a ton of pig iron. The perfect commercial iron ore would consist solely of iron oxides. Most of the ore used in today's blast furnaces has been subjected to "beneficiation". This is a series of mechanical and chemical processes that concentrated the iron oxide by separating it from the gangue, and then forms it into pieces correctly sized for a particular furnace type (Poveromo 1999:614-637).

18th century ironmasters were more limited in what they could do to improve their iron ore. But, many ores were washed to remove some impurities. And most ores were roasted or calcined. This not only removed impurities, including water, but also caused the ore to crack and become more porous. This increased the surface area and accelerated the reduction process in the furnace.

The amount of gangue present is important. But, equally important are the specific minerals present. They can effect both the smelting process and the iron produced. Some ores have inclusions that are beneficial, others detrimental. The blackband ironstones of Great Britain are a good example. These were initially thought to be a worthless form of coal. It was later discovered that they were a coal and ferrous carbonate mixture. The ore could be roasted (calcined) without
the addition of fuel. This burned off the coal and the resulting ore contained between 50% and 60% metallic iron (Greenwood 1907:33). A shale-like ore was discovered in Westphalia that contained lime and was self-fluxing (Percy 1864:203). Phosphorus, a common inclusion, makes iron more fluid and thus easier to cast. But, it also makes cold iron brittle. Sulfur makes hot iron brittle. A detailed discussion of the effects of these and other chemicals on iron, and furnace operation, is contained in Chapter 6.

<table>
<thead>
<tr>
<th>Class and Name</th>
<th>Chemical Composition</th>
<th>% Iron by weight</th>
<th>Common Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limonite</td>
<td>HFeO₂</td>
<td>62.85</td>
<td>Hydrous or hydrated iron oxide</td>
</tr>
<tr>
<td>Goethite</td>
<td>Fe(OH)</td>
<td>62.85</td>
<td>Ferrous-ferric oxide</td>
</tr>
<tr>
<td>Lepidocrocite</td>
<td>Fe₃O₄</td>
<td>72.36</td>
<td>Ferric oxide</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Fe₂O₃</td>
<td>69.94</td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td>Fe₂O₃</td>
<td>69.94</td>
<td></td>
</tr>
<tr>
<td>Ilmenite</td>
<td>FeTiO₃</td>
<td>36.80</td>
<td>Iron-titanium oxide</td>
</tr>
<tr>
<td>Carbonate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siderite</td>
<td>FeCO₃</td>
<td>48.20</td>
<td>Iron carbonate</td>
</tr>
<tr>
<td>Sulfides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iron pyrite</td>
<td>FeS₂</td>
<td>51.26</td>
<td>pyrites</td>
</tr>
</tbody>
</table>

Taken from Holden (1907:402-491) and Poveromo 1999:569-570

Iron occurs naturally as a number of minerals (Table 3): limonite and goethite (hydrated ore which contains both iron oxide and water), hematite (Fe₂O₃), iron pyrite (FeS₂), gossan (a form of limonite), magnetite (Fe₃O₄), bog ore (a form of limonite), siderite (FeCO₃), and ilmenite (FeTiO₃). Depending on what other minerals are present, iron ore can contain from 36.8% (ilmenite) to 72.36% (magnetite) metallic iron.
During the 19th century geological surveys were performed throughout the United States by both state and federal governments. The result was a series of publications that described the mineral resources of the United States. Many states went on to establish geological services. In Virginia the Division of Mineral Resources of the Department of Mines, Minerals, and Energy continues to study the mineral resources of the Commonwealth. But, generally only those resources that were considered commercially exploitable were studied. As technology has changed, so too has the desirability of various kinds of iron ore. But throughout history, and today, it is the oxides that have provided the bulk of the world’s iron. Carbonates were used only where oxides were not available. Pyrites, although containing vast quantities of iron, have never been commercially exploited for iron, but have been used to produce sulfuric acid and sulfur.

Thus in 1907 Holden wrote:

The iron ores of Virginia [Figure 31] may be grouped according to their character and occurrence into eleven classes. Listed roughly in the order of their [commercial] importance these are as follows: any limonite, limestone limonite, Blue Ridge limonite, fossil hematite, Blue Ridge hematite, pyrite gossan, pyrrhotite gossan, Piedmont magnetite and specular hematite, limestone magnetite, pyrrhotite and titaniferous magnetite. Of these the first five include most of the iron ore now mined in the State. [Holden 1907:407-408]

Many of the iron ore deposits exploited in the 17th and 18th centuries were no longer considered commercial grade and not included in these surveys. Bog ore, which provided the ore for Braintree and Saugus in Massachusetts and probably Falling Creek in Virginia, were not even mapped. Over the course of the 20th century there has been a shift away from limonites to magnetite and hematite ore. So, although Virginia has abundant ore reserves (Figure 31), there are no active iron mines.
Limonite and Goethite

The most important iron ore in Virginia, both historically, and in terms of existing quantity is limonite. Limonite is a term used for a number of soft brown hydrous (containing water) iron oxides. In historic documents they are often called brown hematites. Today many geologists use the term goethite instead. All are made up of varying amounts of goethite (HFeO₂) and lepidocrocite (FeOH) and can contain up to 62.85% iron, 27.01% oxygen, and 10.14% water (Poveromo 1999:57). Virginia limonite deposits are described by Holden (1907:402-491) in terms of both how they formed (shallow residual, fault, limestone, gossan, and bog ore) and geographic names (Oriskany, New River, Cripple Creek, Great North Mountain, and Blue Ridge).

While limonite could contain up to 62.85% iron, because of impurities, it seldom did. For instance a typical Oriskany limonite, brown hematite the most commercially important iron ore in Virginia, contains:

iron 43.25%
silica 21.57%
phosphorus 0.38%
manganese 1.29%

The ore is normally washed to remove any clay and roasted to remove water. Washing usually reduces the ore mass by 20 to 50 per cent (Holden 1907:408-410).

Bog Ore (Limonite)

Bog iron is a type of limonite (hydrated iron ore) and is formed by the precipitation of iron from ground water by bacteria. The iron forms a crust
around particles of sand or other material on the bottom of wetlands. Theoretically it can contain up 53% Fe (Gordon 1996:28). At Batsto the bog ore deposit was over a foot thick (personal observation). Bog iron tends to be high in phosphorus (Gordon 1996:58). Unlike other ores, bog iron is a renewable resource. The same ore bed could provide a continuous supply of ore, but it takes up to 20 years for usable bog ore to reform (Gordon 1996:28).

The extent of bog ore deposits is unknown. It is no longer considered a commercial grade ore, and has not been mapped. But, numerous deposits exist throughout the coastal plain of the United States and it was used in the 17th and 18th centuries. Saugus (Hammersmith) in Massachusetts, Falling Creek (probably), and most of the furnaces in the coastal plain of New Jersey used bog iron (Pierce 1990).

**Gossan Limonite**

While pyrite and pyrrhotite (see below) contain too much sulfur to be used as an iron ore, gossans do not. Pyrite gossan, pyrrhotite gossan, and gossan limonite are sulfur free limonites that form by natural weathering and bacterial (*Thiobacillus ferroxidans*) action at the top of a pyrite/pyrrhotite deposit (Charles 1980:158-159; Pigott 1982:20). The Virginia gossan limonite cap averages 30' thick, but can be as much as 60' (Adams 1884:527-535, 1892:196-215; Boyd 1884:39; Holden 1907:419-421; Moxham 1893:133-38; Watson 1907:190-209). Gossan deposits were probably used by many of the charcoal furnaces of Virginia. During the 1880s W. H. Adams found numerous open pit mines along the periphery of the pyrite belt in gossan in close proximity to the blast furnaces at Tubal, Accokeek (Potomac), and Fredericksville (Adams 1884 and 1892).
Hematite

Hematite (Fe₂O₃) contains up to 69.94% iron and 30.06% oxygen (Poveromo 1999:570). It is often referred to as fossil hematite or as oolitic, Clinton, Rockwood, and dyestone. Hematite is abundant in the Appalachians from New York to Alabama, but was not used extensively until the 19th century. The average composition of fossil hematite is (Holden 1907:416-418):

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>40.84%</td>
</tr>
<tr>
<td>Silica</td>
<td>21.70%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.36%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.15%</td>
</tr>
</tbody>
</table>

Blue Ridge hematite (iron 35-42) was not exploited until the 1880s. It was mined extensively in Roanoke, Bedford, and Botetourt counties. The average composition of Blue Ridge hematite is (Holden 1907:418-419):

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>38.94%</td>
</tr>
<tr>
<td>Silica</td>
<td>35.26%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.38%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.22%</td>
</tr>
</tbody>
</table>

Magnetite

Magnetite (Fe₃O₄) contains up to 72.36% iron and 27.64% oxygen (Poveromo 1999:570). It is present in four distinct areas (see Map) and sporadically elsewhere. The Piedmont magnetites form a discontinuous rough line from Grayson county in the south to just beyond Lynchburg. Limestone magnetite is found at the southern end of the Blue Ridge iron ore area in Giles and Washington counties. The Piedmont magnetite is usually found in leads up to 12' thick. Some deposits have been mined to a depth of 200'. Limestone magnetite is often found in association with other iron ores. The deposits worked
to date have been 30-45' wide and up to 30' deep. In some cases the ore occurs as lumps in a clay matrix (Holden 1907:421-422). Magnetite deposits have also been found associated with some of the metamorphic rocks of Albemarle, Bedford, and Carroll counties (Dietrick 1970:24).

According to Stoughton (1908:15), magnetite "is often mixed with other impurities, such as silica, titanium, and phosphorus". Many of these ores are uneconomical either because of their low iron content, or because the large amount of titanium interferes "with blast furnace smelting".

"Titanium is found with iron in several important iron-bearing deposits... It cannot be easily separated from iron by mechanical means because it is usually in chemical combination with the iron as FeTiO3- (Lankford 1985:579).

Titaniferous magnetite (2-15% titanium, Poveromo 1999:570) has been found in the nelsonite deposits of Nelson (Roseland), Roanoke (Vinton), Albemarle (North Garden), Grayson, and Amherst counties (Dietrick 1970:39 and 1990:226, 226; Holden 1907:422-423). None of the deposits were considered appropriate for use in making iron in 1907 (Watson 1907: 232, 300-302).

Ilmenite

Ilmenite (FeTiO3) contains 36.8% iron, 31.57% titanium, and 31.63% oxygen (Poveromo 1999:570). It "is an opaque, iron black mineral, having submetallic lustre and differing from magnetite, which it resembles, by its crystalline form and weak magnetic properties (Watson 1907:232). It "is a common accessory mineral in metamorphic and igneous rocks of the Piedmont and Blue Ridge provinces" (Dietrick 1990:198-199). And, as at the Martin Mine in North Garden, VA, is usually found in magnetite deposits (Holden 1907:407). When the concentration of titanium exceeds 2% it is termed titaniferous
magnetite (see above, Poveromo 1999:570).

Nelsonite is a Virginia mineral that combines primarily ilmenite or rutile and apatite. It is relatively uncommon and occurs in commercial quantities only in Nelson and Roanoke counties (Dietrick 1970:39; Watson 1907:232 and 300-302).

**Pyrite and Pyrrhotite**

Pyrite (Fe$_2$S) is found throughout Virginia. Mineable deposits exist in a belt from Fluvanna to Fairfax county. Pyrrhotite (FeS) is a magnetic pyrite and occurs primarily in the Piedmont. The largest concentration is contained in the "Great Gossan Lead" in Carroll, Floyd, and Grayson counties. Pyrite and pyrrhotite cannot be used as iron ores because of their high sulfur content, 48.74% and 34.06% respectively (see Chapter 6- Trace Elements: Effects and Remedies). However, the upper layers of pyrrhotite and pyrite deposits often weather to a usable limonite (see above)

**Carbonates (Siderite)**

Iron carbonate (FeCO$_3$) is also called siderite. It contains up to 48.2% iron, 37.99% carbon dioxide, and 13.81% oxygen (Poveromo 1999:570). It occurs in three primary forms: ordinary brown carbonate, day ironstone, and blackband. Carbonate ore that contains large amounts of day is called day ironstone. When bedded day ironstones also contain coal they are called blackband ores. A detailed description of the Maryland deposits can be found in *Iron Ores of Maryland, with an Account of the Iron Industry* (Singewald 1911:232-291). Clay ironstone and blackband ores played a major role in the iron industry of Great Britain (especially in Scotland and South Wales), but they were much less importance in the United States. Carbonate ores are not present in Virginia in commercial quantities and were not mined for use in early furnaces. However, day ironstone was used in most of the early blast furnaces of Maryland, including those of the Principio Company. The same mines probably supplied ore for the Accokeek (Potomac), Neabsco, and Occoquan blast furnaces (Singewald 1911:132).
Figure 32. Location of the Martin Mine. Dillwyn 100K USGS Quad.
Albemarle Ore Analysis

While the ore sources used by some colonial blast furnaces, like those used by Isaac Zane's two furnaces south of Winchester are known, in the absence of documentary evidence or trace element analysis, it is impossible to say with certainty what was used by the rest. However, open pit iron mines have been discovered in the immediate vicinity of a number of early furnaces (Adams 1892; T.T. Brady field notes; Spears and Upchurch 1997). It is reasonable to assume, given the state of 17th and 18th century roads, that iron ore would have been mined close to the furnace. The evidence indicates that many of the colonial iron works used some form of limonite. Many (Accokeek, Tubal, Chiswell, Fredericksburg, Occoquan, and Neabsco) probably used a gossan limonite. Later Accokeek, Occoquan, and Neabsco used a Maryland ore, perhaps a carbonate. The Albemarle Iron Works appears to be the only colonial blast furnace to use magnetite.

According to local tradition Albemarle's ore came from the Martin Mine in North Garden, Virginia. The mine is located just west of the town of North Garden, on the northeast slope of Cook Mountain (Figure 32). The site has been the subject of a number of investigations beginning in the 1760s.

The Albemarle Iron Works acquired three tracts of land in 1769 for the iron ore they contained (Albemarle County Deed Book [Albemarle DB] 5:65, 80, and 135). One was a ten acre parcel purchased by John Wilkinson, John Lee Webster, and Nathaniel Giles from John Gillum (Albemarle DB5:135). It included an iron mine on the eastern slope of Cook Mountain. Survey was a somewhat inexact practice in the 18th century, so it has not proved possible to definitively locate the ten acres. But, it probably contained the Martin Mine. Of these tracts, only the Martin Mine shows evidence of mining.
No other mine workings have been located to date. Since there is no physical or documentary evidence that any of the other ore bodies were exploited, it is reasonable to assume that the Martin Mine provided Albemarle’s iron ore. But as there is no conclusive documentary evidence (Reynolds 1992:60-64), one of the goals of this paper was to demonstrate a link. Neither have any dateable artifacts been recovered from the site. But, no archaeology has been done at the site. Dr. Robert S Young and his geophysics class from the University of Virginia conducted the only systematic survey in March of 1960. They used a Sharpe Model A-2 Vertical Intensity Magnetometer and the intent of the fieldwork was geology, not archaeology (Nelson 1962:69). Part of the purpose of the present study is to use trace element analysis to confirm or deny that the Martin Mine provided Albemarle’s iron ore.

Very little remains of the Martin Mine. The mine itself is a 200’ long by 30’ wide 30’ deep pit on the northeast side of Cook Mountain. In addition there are a few related documents from the 18th and 19th century. These show that the site was mined in the 19th century, probably 1873. There is no conclusive evidence that the site was mined in the 18th century, or that it provided the ore used at the Albemarle Iron Works in 1771-72. The only surviving record of mining is from Andrew Hunter’s post Civil War mine. There is a 1873 letter that directs the Durrettts to open a mine (Hunter quoted in the Charlottesville Daily Progress July 20, 1963) and a list of wages owed to “labourers in mine” in South Garden with an end date of September 30, 1873 (Evans-Sibert Family Papers, 1849-1900, VSL 27770).

Andrew G. Hunter, of Detroit, Michigan, rediscovered the mine while serving in GEN Sheridan’s army during The Valley Campaign of 1864-65. During one of the sweeps down The Valley, Sheridan’s troopers occupied the train station at North Garden. Hunter was assigned to guard duty. And during the
long uneventful day he became bored and started throwing rocks at birds. He soon realized the "rocks" were iron ore. He carefully noted the location and in 1870 he purchased the Martin property and acquired the mineral rights to a number of other surrounding properties. Hunter hired William Durrett and [Lorenzo] Sibert to begin mining operations (Charlottesville Daily Progress July 20, 1963). In 1873 he wrote to William Durrett's brother Marcus.

> Before I left Virginia I lost all confidence in his [Sibert] attending promptly to the mines.
> I will feel oblige by your telling Mr. William Durrett to go straight ahead with the opening and not wait for Sibert a single hour.
> In this lease you may as well leave Sibert out and put in your name for a quarter, F.H. Ichbaum, Joseph H. Berry and myself for a quarter each. [Hunter quoted in the Charlottesville Daily Progress July 20, 1963]

Either William or Marcus Durrett must have acted on the letter, because a list entitled "South Garden Alb Ct- A List of balance due to labourers in mine" and dated September 30, 1873 exists (Evans-Sibert Family Papers, VSL). But despite Hunter's continuing interest and the over $1,000,000 he raised, the mine project was a failure. Hunter returned to Detroit and the Martin property was offered at public auction on June 22, 1874 (Evans-Sibert Family Papers, VSL).

The mine's failure has usually been attributed to the quality of the ore. (Woods 1932:57; Dagenhart and Maddox 1977:360). But, in the absence of documents showing that iron companies tested Hunter's ore and rejected it, such a conclusion is speculative. In fact, there is documentary evidence that the cause of the failure was entirely different. In the 1873 letter, Hunter wrote:

> As you know, the total value of Iron ores is but small and very little freight by rail destroys their value.
> Now all existing furnaces are situated so far off these ores as to involve too much freight. We have therefore concluded that it is not the best policy to sell much ore to distant furnaces, but to go on and raise enough capital to build large furnaces. [Hunter quoted in the Charlottesville Daily Progress July 20, 1963]
According to this letter, it was transportation costs, not ore quality that doomed the North Garden mine. The ore was too far from existing furnaces to sell at a profit. However, had Hunter built a furnace, or furnaces, and tried to use the ore from the Martin Mine there might well be documentation on the ore quality.

The earliest historic documents concerning ore quality post date the end of mining by a decade and are also the first quantitative analyses of the North Garden ore. The first was conducted as part of the 1880 U.S. Census. The Census included a volume entitled *Report on the Mining Industries of the United States (exclusive of precious metals): With Special Investigations into the Iron Resources of the Republic and into the Cretaceous Coals of the Northwest.* (Pumpeley 1886 and 1991). The report includes a series of maps showing mine locations, charts, and a description of each of the mines and the ore(s) present. The Martin Mine is number 617.

The latter mine ("Betty Martin", on Mrs. Martin's land) has been abandoned for some time. Some ore is said to have been shipped from it. Open cut, 20 to 30 feet deep.

These two small mines [Martin and Betts] are near each other and contain, apparently, precisely similar ore. They were sampled as one, from 30 to 40 tons of ore in piles at each place.

617. North Garden. Magnetite and limonite (intimate mixture). One half mile north of railroad station, at North Garden, Albemarle county, on Mrs. Bett's land; also one-quarter mile northwest of station, on Mrs. Martin's land.

617 Analysis: Iron, 46.69 per cent.; phosphorus, 0.055 per cent., titanic acid, present; phosphorus ratio, 0.118. [Pumpeley 1886:263]

William Bowron reported similar data in his 1883 article, "The Practical Metallurgy of Titaniferous Ores". He wrote that the North Garden ore contained (Bowron 1883:162):

\[
10.97\% \text{SiO}_2 \quad 6.53\% \text{TiO}_2 \quad 52.52\% \text{Fe}
\]

That the Martin Mine was included in an official U.S. Government list of
iron ore, suggests strongly that the authors did not consider the ore unusable. The stated purpose of Bowron's paper was to develop interest in "large masses of ore that are now accessible to market and are lying idle only on account of the titanic stigma" (Bowron 1883:159). His entire point, and that of subsequent papers by Rossi (1893 and 1897), was that by the 1880s titaniferous ores could be successfully smelted.

Thomas Dagenhart and Gary Maddox (1977) conducted the most detailed analysis of the ore, and the first done using modern scientific methods. They subjected the ore to a battery of tests including: XRD (X-ray diffraction), spectrochemical, and optical analysis. Unfortunately, for this study, they were geologists and were more concerned with the other minerals present than the iron ore. Due to the death of the professor who supervised the work and the transfer of the Geology Department's files and specimens, it has proved impossible to track down their raw data. What remains, coupled with Pumpelly and Bowron's data, still gives a fairly complete picture of the Martin Mine ore.

The Martin Mine ore body consisted of eight primary minerals. They are listed in Table 4 in order of importance.

**Table 4. Primary Minerals at the Martin Mine**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td>Fe₂O₄</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>FeTiO₃</td>
</tr>
<tr>
<td>Apatite</td>
<td>(CaRE)₅(PO₄)₃(FOH)</td>
</tr>
<tr>
<td>Biotite</td>
<td>K(MgFe)₃(AlFe)Si₃O₁₀(OHF)₂</td>
</tr>
<tr>
<td>Grunerite</td>
<td>Fe₇Si₈O₂₂(OHF)₂</td>
</tr>
<tr>
<td>Hornblend</td>
<td>(CaNa)₂-₃(MgFeAl)₅(AlSi)₈O₂₂(OH)₂</td>
</tr>
<tr>
<td>Zircon</td>
<td>ZrSiO₄</td>
</tr>
<tr>
<td>Garnet</td>
<td>Mn₃Al₂(SiO₄)₃</td>
</tr>
</tbody>
</table>

(Magenhart and Maddox 1977:363)

Magnetite (Fe₂O₄) is one of the chief components of the nelsonite-like
deposit (Dietrick 1990:226). "It occurs in dark grey-black dull to submetallic masses often associated with ilmenite and minor [amounts of] apatite and biotite" (Dagenhart and Maddox 1977:362).

Ilmenite (FeTiO₃) contains both iron and titanium. In the Martin Mine it occurs commingled with magnetite as well as "a major component in a rock similar to biotite-nelsonite" (Dagenhart and Maddox 1977:362-363). While titanium is common in the iron ores of Virginia, it is seldom present in concentrations above 1%. As stated earlier when the concentration of titanium exceeds 2%, magnetite is termed "titaniferous" (Poveromo 1999:570). Rossi (1893:842) considered any ore with over 6% TiO₂ to be "highly titaniferous". The ore at North Garden contained 6.52% TiO₂ (Bowron 1883:162).

Ilmenite also closely resembles magnetite visually. It too is a black mineral with a submetallic lustre (Watson 1907:232). It could easily have been mistaken for magnetite, as apparently was the case at a late 19th century Pennsylvania furnace. Egleston noted that they had been using an ore with 5-6% titanium for years without knowing it (quoted in Rossi 1893:866).

Nelsonite is a titanium ore first described by Watson et al. in 1913 and present in commercial quantities in Nelson and Roanoke counties, Virginia. At the Martin Mine most of the ilmenite, biotite, and apatite is present as biotite-nelsonite.

The eight primary minerals consist largely of iron (Fe), oxygen (O), and titanium (Ti). They contain smaller amounts of aluminum (Al), calcium (Ca), fluorine (F), magnesium (Mg), phosphorus (P), potassium (K), rare earths (RE), Silicon (Si), Sodium (Na), and zirconium (Zr). Chemical analysis of the apatite, showed that it contained large amounts of rare earths. Some apatite samples were up to 3.2% rare earths (Dagenhart and Maddox 1977:362-363). Many of these elements have little or no effect on smelting or iron, but some do. For
instance, the effects of titanium and phosphorus are discussed in Chapter 6. The complex elemental mix present in the Martin Mine ore, should allow trace element analysis to confirm or deny that the Albemarle blast furnace used its ore.

The iron ore that was mined at the Martin Mine was primarily magnetite. But, it contained so much ilmenite, a titanium/iron ore, that the 1883 analysis showed it had 6.53% TiO₂. Because of their visual similarity, it is very possible that the 18th century owners of the Albemarle Iron Works could not differentiate between magnetite and ilmenite. The ore also contained apatite, a phosphorus mineral, with high concentrations of rare earths. The effect(s) of the titanium and phosphorus will be discussed in Chapter 6 and are central to the problems experienced by the furnace.

**Flux**

Contrary to what is often written, iron is not produced by melting it out of the ore. Neither a blast furnace nor bloomery was capable of achieving a high enough temperature to melt the ore. And even if they were all that would result is molten ore, not metallic iron. Iron is separated from the ore in a series of chemical reactions, and only then is it melted. These reactions create a liquid slag out of the gangue (non-iron parts of the ore), and drive off the oxygen reducing the iron oxide to metallic iron. In an ideal smelter, all of the iron is converted to metallic iron and is either tapped out of the furnace as liquid iron (blast furnace) or removed as a bloom (bloomery). and all of the non-ferrous elements (gangue) are converted to slag. The reaction is either self-fluxing or a flux is added as part of the charge. Self-fluxing means that the iron ore contains a fluxing agent.

Fluxes are chemicals that are added to a furnace to facilitate the formation of a liquid slag and foster the reduction of iron oxide to metallic iron. They
usually operate to lower the melting temperature of the slag, decrease slag viscosity (thickness), or increase the percentage of iron recovered from the ore.

Historic bloomeries were generally self-fluxing, the iron in the ore acting as a flux. Very rarely was a fluxing agent deliberately added to the bloomery charge prior to the mid-19th century. A molten slag formed when iron in the ore, in the form of wüstite (FeO), combined with the silica (SiO₂) to form a silicate called fayalite (Fe₂SiO₄):

\[
2(\text{FeO}) + \text{SiO}_2 \rightarrow \text{Fe}_2\text{SiO}_4
\]

Fayalite is liquid at the normal operating temperatures found in a bloomery hearth (1200°C). But, bloomeries are inefficient because iron is required to form the slag. Up to 70% of the iron can be lost to the slag. A lime flux can be charged into a bloomery. But the addition of small amounts of calcium does not make the slag either more fluid nor lower its melting temperature (Rostoker and Bronson 1990:83).

In rare instances blast furnaces were self fluxing. But, unlike bloomeries where this was the result of the reaction chemistry, self fluxing blast furnaces only occur where the ore contains the correct amount and the right kind of impurities or where the furnace is run inefficiently. In the later case, it is possible for a blast furnace to be operated without a flux, if the ore is left in large enough pieces that some reaches almost to the hearth unreacted. This prevents all of the iron oxide being reduced to metallic iron and leaves some wüstite (FeO) to form a fayalitic slag, just like a bloomery. But just like a bloomery, much of the iron will be lost to the slag.

To operate efficiently a blast furnace must have a flux. The use of flux has a long history, but it is unclear exactly when or how the use of calcium based
fluxes occurred. In England, it has been proposed that the use of flux resulted from the bedding of iron ores with limestone. In the Wadhurst Clay formations in The Weald are thin layers of Cyrena limestone composed of the shells. Some of the limestone has siderite crystallized in the interstices. This was used as an iron ore and was self-fluxing (Cleere et al. 1995:13). Once ironmasters recognized the importance of the limestone, and that it was not just another iron ore, the idea became transportable to areas without Cyrena limestone. Evidence supports the contention that the deliberate use of flux did not gain widespread acceptance in England until the middle 1600s. By that time the deliberate use of flux, usually in the form of limestone, enabled blast furnace operators to recover over 90% of the iron in their ore (Gordon 1996:103).

Normally a blast furnace flux contains large amounts of calcium (Ca). This combines with the silica (SiO$_2$), and any other impurities, to form a liquid silica-lime glass:

$$\text{CaO} + \text{SiO}_2 \rightarrow \text{CaSiO}_3$$

Silica (SiO$_2$), which makes up most of the gangue, has a melting (liquidous) temperature of around 1700°C. This is well above the temperature possible in a cold blast charcoal furnace. The addition of a calcium (Ca) fluxing agent allows the formation of a slag that remains liquid below 1400°C (Rosenqvist 1983:296; Rostoker and Bronson 1990:198). The addition of calcium (Ca) also results in a more fluid slag. And although very little iron is incorporated into blast furnace slag, a calcium based flux will replace most of it, increasing the furnace's efficiency and iron production (Gordon 1996:103; Straker 1969:94-98; Tylecote 1962:286-303).

While in a blast furnace very little iron is lost to the slag as fayalite, more
may be lost as small prills of iron entrapped in the slag. This is because, for the iron to be tapped out of the furnace, it must pass through the slag to reach the hearth. Some is always in transit and is this iron is lost when the slag is tapped. The amount of metallic iron in the slag is a function of the thickness (viscosity) of the slag. Rostoker and Bronson calculated that it could take from 12 minutes to just under 7 hours for droplets of iron to pass through only 6 cm of slag (Rostoker and Bronson 1990:81, 199). The slag bath in a blast furnace is usually considerably thicker.

Historic American furnaces usually used limestone (calcium carbonate-CaCO\textsubscript{3}), shells (also calcium carbonate), or dolomite ((CaMg(CO\textsubscript{3})\textsubscript{2}) as a flux. The Hammersmith furnace in Saugus, Massachusetts used a Nahant gabbro that allowed the formation of a slag with 12 per cent lime (Gordon and Malone 1994:71; Gordon 1996:236). This may have contributed to some of the problems experienced at Saugus. In Virginia limestone, both domestic and imported, and oyster shell were used as flux. In the 19th century some furnaces burned the limestone in kilns or bought lime to use as a flux (Percy 1864:518-520).

**Water Power**

Every step of the iron making process demanded power. This was initially provided by either human or animal muscles, but these could only produce small amounts of iron. Additionally, using a sledgehammer to consolidate and forge a bloom into a bar of usable wrought iron was hard, time consuming work. If a lot of iron was needed, it required large numbers of small bloomeries. This is why there are thousands of bloomery sites scattered across Roman Europe, the Roman armies required armies of bloomsmiths.

By the time iron working was introduced into North America the use of
water powered hammers in both bloomeries and finery forges was well established. Waterpower permitted larger furnaces, which produced more iron. A bloomery or finery forge’s 400+ lb. helve or tilt hammer substantially reduced the time to work iron into bars.

Water was converted into mechanical power a number of different ways including: a wheel (horizontal and vertical), a turbine, or a trompe. The horizontal water wheel is not very efficient, but is mechanically very simple. It was often used in small grain mills, but it was vertical water wheels that predominated for industrial purposes, including the iron industry. Early turbines were not very efficient and were hardly ever used by the iron industry. Trompes were fairly common in Southern France and Spain, usually associated with Catalan forges. But they were seldom used in the English or Northern European tradition.

Trompes cannot provide mechanical power, only blast. So they could not be used to power hammers or turn millstones. They use falling water to create a vacuum that acts as an air pump. The trompe had the advantage that it provided an almost infinitely variable volume of blast. Varying the volume of falling water controlled the force of the blast. But the trompe had several drawbacks. The air was moist, requiring more fuel. A trompe was less efficient than a wheel (only 10-15%), but it required more water (Percy 1864:285-292).

For most iron works vertical water wheels provided power for the hammer and blast. The water was either impounded behind a dam in a wheel pond or diverted directly from the stream to the wheel. If the iron works and the dam were not collocated, the water had to be brought to the wheel. A channel or headrace was constructed from the dam to the iron works. The channels were usually earthen or made of wood, sometimes they were masonry, and on a few occasions rock cut as at Albemarle. The Tubal Works used pipes. Just before the
water reached the wheel it passed through a flume. This was usually a wooden
trough, with a gate at the end that could be raised or lowered to control the
amount of water going to the wheel. The wheel was mounted in a wheel pit.
After turning the wheel, the water continued downstream in a tailrace. It was not
uncommon for the tailrace to be used as a canal to bring boats to the ironworks
to load pig iron, castings, or bar iron (Howell and Keller 1977:32-47).

The amount of power generated was a function of the volume or velocity
of water, the fall (vertical distance from headrace to tail race), and wheel type. A
rough approximation of the horsepower generated by a wheel is:

\[
\text{horse power} = \frac{(\text{fall}) \times (\text{width of wheel}) \times (\text{efficiency})}{3} \quad \text{(Hay 1969: 26-29)}
\]

Vertical water wheels are named for the point the water hits the wheel: undershoot, breastshot or breast, pitchback, and overshot. Except for the
undershot wheel, power is generated primarily by the weight of the falling
water, not its velocity. The undershot wheel is rotated by the velocity of the
water itself. As a result it requires much more water to develop the same amount
of power. Undershot wheels typically generate only 3-7hp and are the least
efficient. With an overshot or pitchback wheel the water drops onto the wheel at
or just beyond the top. The pitchback rotates opposite to the direction of the flow
of water (Howell 1977:32-45). They can produce up to 150 hp (Terry Reynolds,
Michigan Tech, personal communication 1998). The breast wheel derives power
both from the movement and weight of the water. The terms low, mid, and high
denote where the water hits the wheel. The relative efficiencies of the various
wheel types below (Table 5), was provided by Stafford M Linsley, Lecturer in
Industrial Archaeology, The University Newcastle upon Tyne (personal
communication 1998).
Table 5. Efficiency of Water Wheels (by Type)

<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooden Overshot</td>
<td>50-60%</td>
</tr>
<tr>
<td>Wooden Pitchback</td>
<td>60-65%</td>
</tr>
<tr>
<td>High Breast</td>
<td>75-80%</td>
</tr>
<tr>
<td>Unshrouded Low Breast</td>
<td>35-50%</td>
</tr>
<tr>
<td>Undershot</td>
<td>20-25%</td>
</tr>
</tbody>
</table>

The diameters of some colonial wheels are known, either from documents or archaeology. But, except in cases like Saugus where the actual wheel is discovered, it is impossible to accurately calculate the power generated by a furnace's wheel. A rough approximation can be made in those cases where the size of the wheel is known (i.e. Tubal from Byrd's narrative) or from the size of the wheel pit and from an estimate of the fall. The fall can be fairly accurately measured, where the headrace is visible in the terrain above the furnace, as at Albemarle. The diameter of the wheel can be assumed to equal the fall. However, again the clearance between the flume and the wheel is unknown, as is the amount of the wheel that extended into the wheel pit. If the wheel pit and headrace are visible an approximation of the power generated at a particular furnace can be calculated. But, the fall may include part of the wheel pit. The width of the wheel cannot exceed the width of the wheel pit, but the amount of clearance is unknown. Without a piece of the wheel, the width is only approximate. To refine these estimates, excavation of the wheel pit would be required.

But, even where the wheel dimensions are known, true power generation figures cannot be calculated, they must be measured. For that not only the wheel, but also the machinery it drove must still exist. Without these there is no way to compute the true mechanical efficiency of the mechanism at each furnace. Energy lost to friction or poorly made gears is at best a guestimate.
Since reliable and comparable data is seldom available for ironworks, a surrogate for available waterpower was needed. The volume of water in cubic feet per second (cfs) was chosen to represent the potential waterpower available at each blast furnace site. But the cfs of a stream is weather and environmentally dependent. Actual cfs would require that each stream be physically measured. And comparable data would require that each stream have undergone similar weather. The Virginia Department of Transportation uses drainage area as a rough approximation of water flow. One square mile equals one cubic foot per second (cfs) of flow. The U.S. Geological Survey and Virginia Department of Environmental Quality periodically publish the Compilation of Surface-Water and Water-Quality Data-Collection Sites on Selected Streams in Virginia. This lists all of the hydrological data collection stations either in use or having been used by a variety of agencies. One of the data recorded is the drainage area of particular waterways.

There are a number of excellent sources on dams and waterpower. Leffel’s Construction of Mill Dams, and Bookwalter’s Millwright and Mechanic (1881) contains detailed directions and illustrations on the siting and construction of dams and calculating power generation. Oliver Evans’ classic The Young Mill-Wright and Millers Guide (1972 [1850]) is concerned with grain mills, but contains a wealth of material on the siting of mills and mill machinery. A more recent work with a great deal of information is The Mill at Phillipsburg Manor Upper Mills and a Brief History of Milling (Howell and Keller 1977). Water Power on the Sheffield Rivers (Crossley et al. 1989) is a survey of iron mills on the rivers around Sheffield, England. The book includes not only maps and photographs, but also considerable archival data on a variety of ironworks.
Fuel (Charcoal)

Fuel is required to provide heat to drive the chemical reduction of iron oxide to metallic iron. Although it has now been demonstrated that wood can be used as a fuel to make iron (Nørbach 1997:59-62; Gjerlof and Sørensen 1997:67-72), charcoal provides two to three times the heat per kilogram of wood. Until the introduction of hot blast and other furnace improvements in the 19th century charcoal was the preferred metallurgical fuel. During the 18th century charcoal was also the most costly and most time sensitive raw material. More people, wagons, and draft animals were involved in "coaling" than in any other aspect of furnace operations.

Until techniques were developed to allow the use of other fuels, charcoal was the best metallurgical fuel and was used exclusively in European and American blast furnaces. Charcoal supplied three essential ingredients for the blast furnace process. First it supplied the heat necessary to drive the chemical reaction. Second charcoal supplied carbon that when combined with iron produced the alloy cast iron. Third, and most importantly, when combined with oxygen, it formed carbon monoxide (CO), essential to the reducing atmosphere required to form metallic iron from iron oxides.

Charcoal has one additional advantage, it is almost pure carbon. The process used to convert wood to charcoal drives off volatiles (water and wood alcohol) and oxidizes most other impurities. The working characteristics of iron can be dramatically altered by even minute quantities of some common elements, such as phosphorus and sulfur (see Chapter 6). It was just such impurities that precluded the use of coal and coke until the late 18th century and resulted in the endurance of the charcoal iron industry.
Although charcoal would appear to be an almost perfect fuel for iron smelting, there were problems and that is why modern blast furnaces use coal, coke, or natural gas as fuels. Charcoal is fragile, it is extremely hygroscopic (absorbs water), and is not a consistent density.

Charcoal was also fragile and tended to crush. This limited not only how far it could be transported, but also how high it could be piled and how many times it could be handled. While powdered charcoal was used to make steel in the cementation process, it was useless in a cold blast furnace. It hindered the flow of the hot gases through the charge and slowed down the entire process. The poor condition of colonial roads generally meant that charcoal could not be moved more than 5 miles from where it was made to an iron works. Many contend that the fragility of charcoal also inhibited the growth of blast furnaces. If the weight of the column of raw materials in a blast furnace was too heavy it would crush the charcoal and choke the furnace. However, many 19th century American charcoal blast furnaces rivaled the height of coke and anthracite fueled ones (Schallenberg and Ault 1975:351; Schallenberg and Ault 1977). It may be that increased height, like the adoption of coke and anthracite as fuels, required the invention of the steam engine and more powerful blowing engines.

Charcoal's ability to absorb water, and the consequences, have been understood for centuries. Biringuccio (1966:176 [1540]) wrote that charcoal must be kept dry because otherwise "it is then not good for use in works of fire because of the moisture that it absorbs, for it drinks in water as if it were a sponge". Biringuccio also wrote that 'all charcoal works more easily ... if it is placed under cover as soon as it has been made, so that it may not absorb humidity from the air or from water standing outside" (1966:179 [1540]). By the late 19th century more empirical data had been collected.

Fresh charcoal, as also reheated charcoal, contains scarcely any water, but
when cooled it absorbs it very rapidly, so that, after 24 hours, it may contain 4 to 8 per cent. water. After that time the absorption of water proceeds more slowly, but of course the dampness of the air, the species of wood, the greater or less porousness of the charcoal, the kind of protection, etc., have an influence to hasten or delay the absorption of water. After the lapse of a few weeks, the moisture of the charcoal may not increase perceptibly, and may be estimated at 10 to 15 per cent., or an average of 12 per cent. [Svedelius 1875:22-23]

During his copper smelting experiments J. T. Merkel found "considerable differences in the moisture content of the charcoal [he used] at different times of the year and the quantities of water introduced into the furnace from this source were quite significant" (Craddock 1995:193). J. E. Rehder has calculated that the total effect of the humid air of midsummer (water in the air and water absorbed by raw materials) could increase fuel consumption by up to 25% (J. E. Rehder, personal communication 1998). The additional fuel was absorbed converting the water to steam. This reduced the overall stack temperature and seriously degraded the fuel efficiency of the furnace.

The weight of charcoal varied considerably from batch to batch and depended on the kind of wood "coaled". While charcoal suitable for smelting operations could be made from virtually any tree, there were variations in density and carbon content (Birkinbine 1884). Hardwoods, especially oak, make a denser charcoal (Svedelius 1875:24 and 205). England and her North American colonies preferred hardwoods like oak and beech. Some American blast furnaces used pine. In Sweden and Prussia, at least by 1872, most charcoal came from firs and spruce (Svedelius 1875:1-2). The part of the tree and its age also mattered. Branches and young trees make stronger, denser charcoal than mature tree trunks (Rehder 2000:57; Svedelius 1875:5). This means that in addition to providing a continuous supply of charcoal, coppicing also produced superior charcoal.
Presumably ironmasters knew this and would preferentially choose branches or coppiced wood from hardwoods for coaling. There is archaeological evidence that this was occurring at least as far back as the Roman occupation of Britain (Huntley 1987, 1989, 1995). The long history of coppicing in Britain may, in part, be responsible for the marked preference for hardwood charcoal by English ironmasters. In North America this would have provided another incentive to build saw mills. The tree trunks made better lumber than charcoal. Archaeologically it means that carbon-14 dates derived from charcoal storage will be fairly close to the operating dates of the iron works. If more old growth trunks were used the carbon-14 dates could be off by hundreds of years.

This variability could have an effect on the operation of a blast furnace because until the late 19th century raw materials were measured volumetrically, not by weight. During a study of 50 charcoal furnaces in the 1870s, John Birkinbine found that the weight of a "bushel" used to measure charcoal varied by as much as 25% (Birkinbine 1879:150).

**Forests, Coppices, and Forest Management**

Charcoal is made by the controlled burning of wood (Figures 33 and 34). Blast furnaces used tons of charcoal, which required massive amounts of wood. By the mid-18th century a blast furnace could produce as much as 800 tons of iron a year. Consumption estimates range from 1/4 to 1 acre of forest converted to charcoal for each ton of iron produced in a cold blast furnace. A blast furnace required a constant supply of charcoal and as a result needed access to large tracts of forest.

There is an ongoing debate over what effect, if any, bronze and iron works, and other pyrotechnologies, had on the forests of Asia, Europe, and later
the Americas. While it is true that metallurgy required large quantities of charcoal made from trees, there is reason to question the theory that beginning in the Bronze Age metallurgy was the cause of widespread deforestation in Europe and Asia (Hartwell 1967:95; Horne 1982; Rehder 2000:156-157; Rothenberg and Blanco-Freijeiro 1981). Many modern authors make reference to the massive ecological devastation caused by American iron works. These effects were the result of wood cutting, mining, solid industrial waste, and the clouds of black smoke from the blast furnace stacks (Barber and Wittkofski 1999:313; Russ and McDaniel 1994:27).

In many cases the claims for massive deforestation are based on erroneous assumptions. Constantinu estimated that the charcoal used in the copper mines of Cyprus used 150,000 km$^2$ of forest, sixteen times the total area of Cyprus. But, they operated for over 3,000 years. Rehder’s calculations show this required only 13.2 km$^2$ per year, 0.15% of the area of Cyprus.(Rehder 2000:157). Similar calculations for the lead and silver mines of Lavrium, Greece and the mines at Rio Tinto, Spain also failed to consider the time span and natural regeneration of forests. When these are taken into account, the area required to support Lavrium shrinks from over 10,000 sq. km of forest to only 50 km$^2$ (Rehder 2000:156-157).

Craddock (1995:193-195) points to similar data from the silver mines at Rio Tinto, Spain, iron works of England’s Lake District, and copper smelters in Cwmystwyth, Wales. All of the wood required to fuel operations at Rio Tinto could have been produced from coppices within a 40 km radius of the mines. This would have been difficult, but possible. Deforestation would have resulted in even worse problems as the wood would have to have been transported even father. Evidence from the Lake District shows that deforestation was due not to the iron works in the area, but to charcoal burners supplying households.

Environmental studies showed a strong correlation between the onset of
copper and bronze working and the replacement of deciduous forests with peat in Wales and south-west Ireland. However, more recent paleobotanical studies at a number of mines have shown that any environmental effects were localized and of short duration (Craddock 1995:195). While early metallurgy did have environmental effects, it was not the sole cause of the reduction of Europe's forests. There are very few scientific studies of the environmental effects of the iron industry. Kaminski's 1995 study of the Roman iron industry in Britain concluded the effects were localized and ephemeral. The spread of agriculture, increased population, and climate changes now appear to have been more important factors in deforestation.

Until 1950 there was a general consensus that the expansion of the British iron industry during the 17th century had disastrous consequences for English forests. There are numerous apocalyptic reports of the condition of English forests as a result of the depredations of ironmasters beginning as early as the late 13th century (Pearse 1867:7; Scrivenor 1854:69).

Similar apocalyptic views are expressed in the works of many modern American authors and were commonly held by the public in the 19th and early 20th century (Gordon 1996:43). Barber and Wittkofski wrote that "The production of charcoal to provide fuel for the iron furnace resulted in devastating environmental effects.... Considering the impact of the belching black smoke produced by the furnace... (Barber and Wittkofski 1999:313). And Russ et al. claimed the area owned by Longdale Iron Company "is recognizable today as a result of the devastating environmental effects accompanying the processes of iron manufacture" (Russ and McDaniel 1994:27).

The reality was quite different. Most blast furnaces in Britain were supplied by managed woodlots or coppices and therefore could not lead to deforestation. Coppices are a form of managed forest designed to produce a set
quantity of wood of a particular size forever. Rehder (2000:158) has calculated
that 169,000 acres of coppice would have supported the entire English charcoal
iron industry at its height, 1720-45, This represents only 0.40 per cent of the
available land area.

Most American blast furnaces got their charcoal from managed forests. In
1884 Birkinbine noted that unlike the operators of sawmills, iron companies
managed their forests for the long term, and many had reforestation programs.
"Therefore, in one sense charcoal iron workers are destroyers of forests, in
another sense they are conservators of them. [They] more than any other one
industry [are] the protectors of forests" (Birkinbine 1884:3-4). Gordon and Malone
(1994:86) estimate that an acre of Mid-Atlantic forest produced 500-1,200 bushels
of charcoal per year if harvested on a 20 year rotation. The largest charcoal blast
furnace operating in New Jersey in 1850 required between 3,300 and 7,700 acres
(Gordon and Malone 1994:86). 18th century blast furnaces produced considerably
less iron. But, were also less efficient and used more charcoal per ton or iron
produced.

While 18th and early 19th century colliers were not overly concerned with
slope erosion, neither were they capable of the kind of damage inflicted by a
modern mechanized clear cut. There are very few contemporary descriptions of
the environmental effects of charcoal ironmaking. None support the modern
descriptions of wholesale environmental destruction. Unlike coke ovens and
coke fired blast furnaces, charcoal blast furnaces burn cleanly and emitted "no
smoke" according to 19th century informants (Gordon 1996:124). In Robert
Gordon’s most recent work on the Salisbury iron district of Connecticut, he
found very little evidence to support the catastrophists.

Salisbury residents rarely (if ever) mentioned the environmental effects of
ironmaking in their letters, newspapers, or reminiscences: they saw the
landscape as tolerable, or unremarkable. Mid-nineteenth-century visitors
to Salisbury commented on the spectacle of hot metal and heavy forge hammers rather than deforestation, dust, or piles of slag. These visitors came for fishing, mountain rambles, and peaceful relief from the hustle of the city. They found the forges and furnaces points of contrast adding variety to the region's scenery. When Henry Ward Beecher wanted to take a summer vacation in a region having mountains and fast-running streams well stocked with fish... [he went] to Salisbury... [Gordon 2001:115]

"Today we know that nationally, the clearing of land for agriculture and lumbering was responsible for 99 percent of the consumption of forest land. The overall impact of ironmaking on American forests was slight" (Gordon 1996:43).

In the Salisbury district, the long-term environmental consequences of nearly 200 years of mining and ironmaking-those we see today- are minimal. The deep mines are now lakes fringed by woods or lawns. New vegetation has transformed the smaller mines into wooded hollows in hillsides and has grown over the surrounding spoil piles. Silt deposited from the wash water the miners discharged onto surrounding lowlands is now wetland, grass covered, or has been built upon. The heavy use of the regions renewable fuel and power resources has also left only small traces. Forest uncut since its last coppicing is now well wooded with substantial trees. [Gordon 2001:115]

In fact rather than destroying woodlands, the charcoal industry preserved vast tracts of forest. And once the iron industry no longer needed charcoal, the land returned to forest, often becoming the nucleus for state and national parks and forests (Gordon and Malone 1994:86; Gordon 1996:44).

But, perceptions are important. The imagined disaster in Great Britain was viewed as a potential boon in the Americas. The seemingly limitless expanses of American forests greatly impressed the early explorers. Furthermore, as long as America was covered in forests it could not be farmed. The clearance of forest by iron works was seen as a very positive side effect. Robert Johnson pointed this out as early as 1609 in his tract *Nova Britannica*...

from thence we may have Iron and Copper also in great quantitie, about which the expense and waste of woode... will be no hurt, but great service
to that country. (Johnson 1609 and Force 1836 I, No 6:16).

In his 1664 *Sylva, Or A Discourse of Forest-Trees, And The Propagation of Timber In His Majesties Dominions*, John Evelyn says:

>Certainly, the goodly rivers and forests of the other world [America] would much better become our iron and saw mills than the exhausted counties. [Pearse 1876:7]

**Making Charcoal: Charking and Coaling**

In the 17th and 18th century charcoal was made in open piles called charcoal pits, colliers hearths, pits, coaling pits, forest clamps, forest kilns, or meilers (Figures 33 and 34). In the 19th century a variety of techniques were developed that resulted in higher yields and stronger charcoal (less susceptible to crushing). These included beehive ovens, kilns, and retorts. Using the open pile method a good collier could get 30-35 bushels of charcoal per cord of wood. With the introduction of the charcoal kiln in the 19th century the yield rose to 45 bushels per cord. The number of cords of wood per acre varied as well. But, on average an acre could produce 30-40 cords of wood every 25-30 years (Gordon 1996:36-38; Mulholland 1981:33; Bining 1938:63).

Charcoal, made with proper care from good material, retains distinctly the texture of the wood; its color is black, fracture glossy, and when it falls upon any hard object it produces a ringing sound.... If such a piece of charcoal is burned in the open air, it will be consumed without flame or smoke. [Svedelius 1875:20]

Numerous excellent descriptions of the "coaling" process are available. But, whether it is in Biringuccio's *Pirotechnia* (1966 :176-179 [1540]), Evelyn's *Sylva: A Discourse of Forest Trees* (1644:100-103), Svedelius' *Hand-Book for Charcoal Burners* (1875:26-151), or Jackson Kemper's 1940 *American Charcoal Making In the Era of the Cold-blast Furnace* the technique was essentially the same. Kemper's has
the added benefit of being in modern English and thus easier to read and understand. The following description is taken from Kemper.

The wood was cut to uniform 4' lengths and allowed to dry or season. Two different diameters were cut- lap-wood was 1.5-4" in diameter, while billets were 4-7". Lap-wood came from branches, while billets were split out of the trunk. In a managed forest, very little splitting had to be done, because the trees were harvested when they were the right diameter for billets. Colliers frequently cut wood during the winter, because high winds did not allow coaling until the late spring. High winds during the winter and early spring made it impractical to coal then. Once seasoned the wood was hauled to the pit.

The pit was made in a clearing in the woods (Figure 33). A level spot 30-40' in diameter was cleared of all vegetation. Once prepared "charcoal pits" were used over and over again. This eliminated the need to prepare a hard packed level area for every burn. A pit would hold 25-50 cords of wood, about the wood from an acre of forest.

A triangular chimney was constructed at the center of the pit (a large log could be used instead). Then the wood was carefully stacked, from the center out, with as little space as possible between the billets (Figures 33). This was continued until a low domed shaped structure was completed (other shapes were used). Then all of the cracks and air spaces on the outside of the pile were filled in with small pieces of wood. If the wood had been stacked correctly it was a reasonably solid structure. Then the pile was covered with several inches of leaves and sealed with dirt or charcoal dust. This required a layer of a few inches on the sides and up to a foot on the top and shoulders. The advantage of reusing an old pit was that charcoal dust could be used to seal the surface, rather than dirt. This prevented contamination of the charcoal. The chimney was then filled with kindling and chips.
Lighting the kindling and chips in the chimney fired the pit. Once it was burning, it had to be constantly watched. Charcoal was only made if the pile was kept sealed and burned slowly. The speed of combustion was controlled by opening small holes at the foot of the mound on the side that needed to burn faster. If a flame broke through the covering of leaves and dust it had to be quickly smothered or all of the charcoal would burn up. Sometimes the surface would require "dressing" with additional leaves and dust to eliminate hollows and soft spots. If the pile were charring properly it would give off puffs of gray smoke (Figure 34). White smoke meant that it was burning too fast.

It could take as long as two weeks to burn a 40' pit. A team of three colliers normally managed up to nine pits simultaneously. Once all of the wood had been converted to charcoal the pile had to be raked out. This was done very slowly because of the danger that the charcoal would burst into flame. A little was raked out at a time and at the first sign of flame it was smothered with charcoal dust. After the charcoal had cooled it was loaded into wagons and moved to the furnace. There it was stored in a shed until it was charged into the furnace (Kemper 1941:1-25).

Most descriptions of charcoal making illustrate how it was done. The most detailed being Svedelius (1875) or Kemper (1941). A detailed discussion of the various techniques used in Great Britain can be found in Woodcolliers and Charcoal Burning (Armstrong 1978) and Charcoal and Charcoal Burning (Kelley 1986). Those interested in the technical aspects of how the process works, should consult J. E. Rehder’s The Mastery of Uses of Fire in Antiquity (2000:55-62). Paul T. Craddock (1995) provides a short overview of European techniques.
Figure 33. Charcoal- preparing the pit (from Diderot 1959:pl 1 [1762-72])

Figure 34. Charcoal- burning the pit (from Diderot 1959:pl 2 [1762-72])
CHAPTER 7: Blast Furnace Problems and Remedies

The blast-furnace, to persons not practically acquainted with its working, may appear a very simple kind of apparatus, and not likely to get out of order. But, it is far otherwise; and to be managed with success requires much skill, which can only be acquired by long experience. It is, in reality, extremely sensitive, its action being affected by trifling causes.... It is liable to serious disorders, which demand prompt and energetic treatment... [Percy 1864:494]

The keynote of successful operation of the blast furnace is regularity. I have tried in preceding chapters to make a picture of the delicate equilibrium which must be maintained between enormous forces, and I have tried to show that variations of only 1 or 2 per cent. were enough to affect seriously the results of the operation, while a change of 5 or 6 per cent. might be fatal. [J. Johnson 1918:346]

Although Percy and others make reference to "serious disorders" that might effect a furnace, there is very little discussion of the problems and even less of remedies in the literature. Mechanical problems were not addressed, presumably because everyone knew about them and what to do. There was no need to waste paper on descriptions of repairs to blowing machines or how to replace a faulty tuyere. Everyone who worked around blast furnaces knew what could go wrong and what to do when it did. To some extent, such descriptions could only be generic as blast furnaces were still largely purpose built and no two were alike. Unfortunately, this leaves modern researchers with very little to work with. There is little or no information on routine maintenance, how or when repairs were performed, how long they took, or whether or not they could be done without taking the furnace completely off line. Obviously, catastrophic disasters caused the cessation of operations. But there is very little information about day to day operations and maintenance during a campaign.

The chemical side is discussed at greater length, but generally only in terms of the effects on the iron being produced. There is very little on how to
keep the chemistry inside the stack in balance. As the understanding of iron metallurgy grew during the late 19th and 20th century the amount of space in texts on iron and steel making devoted to actual furnace operations also grew. Although it is certainly still not true that one could learn how to run a blast furnace from books, it is also probably not as necessary to spend years working at a furnace. That there is more to the making of iron than what can be learned out of a book was graphically demonstrated at Tannehill Furnace, Alabama in 1976. It was thought that it would be a great demonstration and a lot could be learned by actually running an historic blast furnace. And a lot was, but not all of it what the organizers had in mind. In spite of oxygen lances and all of the 20th century’s metallurgical knowledge "there never seemed to be quite enough heat, and what iron finally did emerge was not fluid enough to run into the prepared molds" (Vogel 1985:256-257). In other words, it was a failure.

Before discussing how specific things effect the blast furnace process and the iron itself, it is important to understand the differences between historic and modern blast furnaces and their operation. Changes that took place both in and around the furnace during the 19th and 20th centuries have given ironmasters much greater control over what went on in the furnace and how the resulting iron performed. An ironmaster of the 17th and 18th centuries monitored what was going on inside the furnace by what he could see outside. The clues to furnace operation were visual- such as the color and amount of smoke coming from the stack and the color, consistency, and fluidity of the slag and iron. His control of the process was very limited. His role was entirely reactive and he could only effect the operation at the margins. Only rarely could he react while a problem was developing. Usually the ironmaster’s first indication of a problem was when it arrived at the hearth in the form of slag or bad iron, by which time the "problem" had traveled the length of the furnace stack and was hours old.
An 18th century ironmaster was not a metallurgist, and did not understand what was going on inside his blast furnace. He understood what worked, but only because it had worked before. The historic founder knew only where his ore and flux came from and the results he had achieved by using them in the past. Chemistry was in its infancy. It was not until the last quarter of the century that Lavoisier disproved the phlogiston theory. Any changes in chemical composition that were not visually obvious would go undetected until and unless they had a noticeable effect on the operation of the furnace or the behavior of the iron that was produced.

Where a modern ironmaster carefully measures what goes into his blast furnace, it was not until late in the 19th century that weighing charges became commonplace. As late as 1879 John Birkinbine wrote about how many bushels of charcoal a cord of wood produced and the average number of bushels of charcoal it took to produce a ton of pig iron. Birkinbine also noted that a "bushel" of charcoal varied considerably, from 1.43 to 1.59 ft$^3$ and from 18 to 22.5 pounds (1879:150). The historic founder told his people how many baskets or wheelbarrow loads of each raw material to put in the furnace. But "full" is in the eye of the loader and could and did vary considerably. The amount charged probably also varied by the time of day. It is natural for loads to get a little lighter toward the end of a twelve hour shift.

The degree of control over the iron making process and magnitude of the changes possible was transformed during the 19th and 20th centuries. The differences begin even before the raw materials are charged into the furnace. Today's ironmaster knows what is going into his furnace. He knows the exact composition of his raw materials and the automatic loading devices charge precise amounts. Today's founder sits at a control console and can "see" what is going on inside of his furnace. He can fine tune the charging process to correct
problems before they become serious or to make iron particularly suited for a specific use.

As a result, it is rare for a modern blast furnace to have serious problems. This was not the case during the era of cold blast charcoal furnaces. Very often the first indication that something was wrong was when nothing reached the hearth, or when what reached the hearth was not what was expected.

In many cases the remedies available are not much different today than they were 200 years ago. But, today an ironmaster knows why something works and exactly how to cure a problem. In the 18th century the remedies were used because they had worked before. If the problem persisted, the process was repeated until something happened. As John Percy wrote almost 100 years after the period covered by this study:

The chemistry of Iron, notwithstanding all that has been done of late, is yet very imperfect; and some even of the elementary branches of the subject are extremely obscure. The so-called compounds of iron and carbon, for example, are in this category. The chemistry of Steel is, if possible involved in still greater obscurity. Problems of the highest chemical interest in connection with the Metallurgy of Iron and Steel await solution. [Percy 1864:iii-iv).

During the 18th century people still believed in phlogiston and oxygen had not yet been discovered. But, even with all of the scientific advances, electron microscopes, and other apparatus available to modern metallurgists, mistakes can still be made. In the not too distant past the people in charge of operating two continuous casting furnaces at a huge plant belonging to one of the big three auto firms managed to convert one of the furnaces into a 100 foot tall cast iron column. They froze it, a very expensive mistake. The furnace had to be completely torn down, cleaned out, and rebuilt.

So what could go wrong and what could be done about it? The discussion that follows will be in two parts- the first covering mechanical problems, the
second chemical. There is some overlap, as chemical problems can cause mechanical ones. And mechanical problems can influence the chemical composition of the iron produced.

Mechanical Problems

Cold blast charcoal furnaces were relatively simple and durable, but equipment wears out and has to be repaired or replaced. The length of the campaign, the time a furnace was left in blast, was determined by a number of factors. In the 18th century weather and the need for periodic maintenance were paramount. Unlike today, historic ironmasters had no way of knowing the condition of the inside of their blast furnace. Experience was the guide. Over the life of a blast furnace, the ironmaster developed a pretty accurate idea of just how long he could operate before he would be forced to stop. The hearth and the tuyere(s), because of the intense heat, experienced the most severe wear.

After a furnace cooled down after being blown out at the end of a campaign, it was carefully inspected. It was common practice to replace any parts, such as the hearth lining, that were not expected to last through another campaign. This was reasonably well documented.

Very little, however, is known about day to day maintenance of cold blast charcoal furnaces. It was not the kind of thing that was written down in company records and very few day books or commonplace books have survived. Compounding the problem, "maintenance" was not an issue that was addressed in the "classic" texts such as Agricola (1950 [1556]), Bell (1884), Fairbairn (1865), Percy (1864), or Truran (1855). Percy devoted just over 2 pages (out of 934) to "Derangements in the Working of the Blast-Furnace" (Percy 1864:494-496). Interestingly, the same number of pages is all that Burgo devotes to "Blast
Furnace Irregularities” in the latest version of *The Making, Shaping and Treating of Steel* (Burgo 1999:743-745). To a significant degree, it is still true that experience is the best teacher.

**Blast Problems**

Loss of blast can be caused by a number of factors and is catastrophic if not quickly remedied. The most obvious cause is the failure or stopping up of the tuyere. The piping that carries the pressurized air from the blowing apparatus to the tuyere can also fail. The blowing device may fail. Finally the power source may fail.

Before the introduction of hot blast, there is little or no evidence that tuyeres failed. Theoretically tuyeres should not fail, because they were made of durable materials like metal or ceramics. Over time the end eroded, but at a predictable rate. When a tuyere did fail or become fully obstructed, the results were immediate and serious. Since pre-19th century blast furnaces had only one tuyere, its loss meant a complete loss of the blast. If the blast could not be restored the furnace would freeze (see below). Although there are no records of a tuyere being replaced during a campaign, it should have been possible to break it out of the wall inside the tuyere arch and put in a new one.

In the years immediately following the introduction of hot blast, tuyere failure was much more common. The higher temperatures of hot blast caused the tuyere to erode faster. In response, the industry developed tuyeres that were cooled by circulating water through them, or encasing them in a water filled jacket. This significantly reduced erosion, but introduced a new problem. If the water tuyere developed a water leak and the water get into the furnace, it was instantly converted to live steam with explosive force. There are numerous tales
of exploding furnaces. The explosion usually demolished the stack and injured or killed many of the crew.

A common problem was the partially blockage or plugging up of a tuyere by the accumulation of slag. Although the highest temperature in the blast furnace are in the combustion zone at the end (nose) of the tuyere(s), the temperature falls off rapidly and the air going into the furnace was cold. Slag tended to solidify on the end. In a low pressure system, like a bellows or blowing tub driven blast, it was also possible for molten slag or iron to enter the furnace end of a tuyere. Over time the build up of congealed slag cut down the air flow and slowed the smelt. Eventually, if not remedied, the buildup could stop the blast. The remedy was to periodically ram a metal rod through the tuyere to clear any obstructions. Beginning in the 19th century tuyeres have built in viewing ports. This allowed the ironmaster to see what is going on inside the furnace and also to check for obstructions. There were also easy open ports that allowed for clearing the tuyere.

Bellows and blast tubs operated at a low enough pressure that a ruptured blast pipe was unlikely. With the introduction of steam driven blast engines, much higher pressures were possible. The risk of a blow out increased. The introduction of hot blast resulted in additional problems. The hotter the blast the more it tended to erode the sheet metal or cast iron pipes that carried the air to the tuyere. Since the pipes were almost fully exposed, periodic inspection and even repair should both have been relatively easy. This is true with hot blast as well, except that the pipes had to be allowed to cool.

Bellows or blowing tubes were made of wood and leather. A carpenter could repair failure of either fairly quickly. The loss of a blade on the water wheel would have also been a relatively simple problem to fix. Given the robust construction of the wheels, the catastrophic loss of a wheel was fairly unlikely.
The entire blast mechanism would be repaired or replaced as necessary when the furnace was blown out at the end of a campaign. Steam driven blast engines would pose more of a problem, but do not come into use in the United States until the second quarter of the 19th century. Here given the nature of the steam engine and blast cylinder, repairs might not be possible by furnace personnel or local artisans. The furnace might have to be shut down while parts were ordered or an outside maintenance expert brought in.

Water driven blast furnaces had all of the problems experienced by any water mill. Seasonal variation in rainfall or protracted drought might force a furnace to shut down. But, as the mill pond slowly emptied the furnace could be deliberately taken out of production, rather than suddenly shut down. The wheel could fail, as could the head or tail race. Maintenance of the system was required.

For iron works that relied on water power the length of a campaign was also often dictated by the weather. For most of the British North American colonies winters were cold enough that millponds froze. Should this happen while the ironworks was still in operation, it shut off the blast and would cause the furnace to freeze. Rather than risk a loss of blast, it was common practice for colonial campaigns to begin in March and terminate around Christmas. Prior to the millpond freezing, ice formation on the wheel would decrease its efficiency. Ice formation in the tail race could damage the wheel as it broke up the ice.

Some losses of power could not be foreseen. The loss of power due to a dam blow out or a flood could not be anticipated. It was sudden and catastrophic. Neither was there any remedy. The dam had to be rebuilt and the pond refilled before the furnace could be blown in again. Floods could also carry away parts of the headrace, damage the wheel, or flood the furnace. If the later happened and the furnace was in blast it could explode.
Other Tuyere Related Problems

Although tuyeres rarely failed outright, they did erode under the intense heat and corrosive conditions inside a furnace. This was especially true after the introduction of hot blast in the 19th century. The erosion was gradual and took place at a predictable rate. The erosion was worst at the nose, or furnace end. As the tuyere got shorter and shorter the air blast did not extend as far into the furnace. This alters the distribution of heat in the furnace. In the most extreme cases cold spots developed and the descending metal and slag resolidified. This reduced the effectiveness of the furnace, not only because of the uneven heating of the descending charge, but also because the resolidified masses restricted the operating diameter of the stack. Replacement of the tuyere would restore the original heat distribution and over time remelt the solidified deposits.

Later furnaces used more than one tuyere. This had a number of benefits. It introduced redundancy. When there was only one tuyere, its loss was a serious problem, requiring immediate attention. With multiple tuyeres, the furnace could continue to operate. Multiple tuyeres also did a much better job of ensuring that the heat was more evenly distributed. This eliminated cold spots and the furnace ran more efficiently.

Breakouts

One of the governing factors on the length of campaigns was wear and tear on the furnace lining and hearth. The movement of tons of abrasive ore and flux down the stack, the high temperatures of the molten iron and slag, and the corrosive nature of the slag wore out the interior of a blast furnace. Where modern blast furnace operators have numerous monitoring devices to warn of
problems, the historic ironmaster relied on experience and each blast furnace was unique. New furnaces were not run flat out to failure, because failure could be catastrophic. The campaign length was gradually increased to allow the ironmaster determine the wear rates of the various components and determine how long it was safe to operate his furnace. Part of the yearly round of maintenance when the furnace was taken off blast was to repaired/rebuilt the stack and inspect the hearth and replace it if necessary. It was not uncommon for the hearth to be replaced every year.

Breakouts are an extremely serious failure of the furnace. They occur when the hearth fails and molten slag or iron exit the furnace uncontrollably. The major remedy for breakouts is to maintain/repair the hearth to prevent them. A slag breakout can often be stopped by cooling it rapidly with water and plugging the hole with fire clay, or some other refractory material. Even today there is very little that can be done about a metal breakout. Often the operator has to wait until the furnace is empty of iron.

Breakouts are serious for a number of reasons. As there are very few people who do well ankle deep in molten metal or slag, they often resulted in serious injury or even death of anyone working in the casting arch. In a metal breakout all of the metal is ruined, and the furnace must be blown out or banked until the hearth was rebuilt (Burgo 1999:745). In a colonial furnace, where hearth stones were not always available, this might mean the furnace was out of blast for the months required to bring a new hearth from England.

Scaffolding, Hanging, and Bridging

Scaffolding, hanging, and bridging- all three of these terms refer to variations of the same problem. Scaffolding is often used as a generic term for
any impediment to the smooth descent of the charge and heat distribution in the blast furnace (Burgo 1999:745; Greenwood 1902:142-143; Percy 1864:494-495; Stoughton 1908:44). In other sources, scaffolding is the term used for the build up of deposits on the lower furnace. When the charge catches and does not descend evenly it is said to be hanging. This usually occurs in the stack, rather than lower in the furnace. Should either problem become especially severe they can result in a mass bridging across the furnace.

Amongst the causes contributing to the formation of scaffolds are: 1°, faulty shape of the furnace; 2°, the production of an imperfectly fusible slag; 3°, introduction into the furnace of too large a proportion of refractory ore in the charge; 4°, bad fuel, such as a weak friable coke [or charcoal] which crumbles under the weight of the superincumbent materials; 5°, faulty charging, whereby the regular distribution of heat over the entire horizontal section is not maintained [Greenwood 1902:143]

Shape could contribute to scaffolding primarily in two ways. Too acute a bosh angle (Figure 35, top row) provided a shelf that could cause the charge to hang up, slowing its descent. But, the angle of the bosh also supplied some support for the burden. If the stack was too vertical (Figure 35, bottom row), it could cause the charge to crush or compact under its own weight. This was especially a problem with charcoal. Modern blast furnaces, using much stronger coke, have more nearly vertical walls. Stack height also contributed to crushing or compaction. The fragility of charcoal limited the height of a blast furnace.

Although, blast furnace technology was hundreds of years old by the time the Albemarle Iron Works was constructed, there was a great deal of variation in shape. In the absence of documents and since all that remains of the furnace is a pile of rock, attributing any of the problems to the shape of the interior of the furnace is rank speculation.

Slag irregularities will be discussed at length later (see Trace Elements: Effects and Remedies). "An imperfectly fusible slag" is one that is "sticky" or not
fully fluid. These problems only occur toward the bottom of the blast furnace, near the hearth. It is there that temperatures are hot enough to form a slag. Viscous or sticky slags are usually the result of a chemical imbalance or a cold furnace. Some elements (see Trace Elements: Effects and Remedies below) raise the melting (liquidus) temperature of the slag. This causes it to thicken, become viscous, at normal furnace temperatures. In rare instances elements will precipitate out and form a slurry (see Titaniferous Slag below). If the flow of gases is impeded sufficiently or the furnace is run too cold, the slag will thicken.

Whether the slag is viscous because the blast furnace is too cold or because of a chemical problem, the result is the same. The slag will adhere to the furnace wall, and over time the deposit will grow toward the center of the stack. As the deposit grows it will impede the descent of the burden and the upward flow of the hot gases. This later effect will cause the formation of additional cold spots above the scaffold and contribute to its growth.

A "refractory" ore can be the result of a number of problems. The ore may contain a large amount of material that reacts endothermically. This will chill the furnace and cause slag viscosity problems. The ore may also only react at especially high temperatures. Titaniferous ores have historically had a reputation for being "refractory". Charging a "refractory" ore will cause problems because the ore is slower to reduce and may descend almost to the hearth in lump form. This will encourage the formation of scaffolds or hanging where the furnace narrows between the bosh and the hearth.

Improper charging of the blast furnace, in terms of both how it is charged and what is charged can cause scaffolding. If the pieces of ore and flux are too large they may hang up in the stack rather than descending smoothly. Too much powder (fines), charcoal is especially susceptible, in the charge can also result in hanging. Here as the charge heats, the powder acts either as a cement or blocks
the flow of the hot gases. Improper loading can also be a problem. For instance, if not enough fuel is charged into one side of the furnace, uneven heating will occur and some of the ore may descend to the hearth unreacted. Another cause of scaffolding can be the redeposition of some material that vaporizes farther down the stack, such as lead or zinc. If an especially friable fuel is used, it may crush under the weight of the burden and form a plug.

Farther down, at the bosh, scaffolds are more likely to be caused by too much powder (fines) in the charge (charged or caused by crushing) or an incorrect chemical balance that causes the slag to thicken. In the first case the powdered material impedes the flow of hot gases up the stack and localized cooling of the burden. If a molten slag has already partially formed, it resolidifies and adheres to the furnace wall. A thickening of the slag due to a chemical imbalance can have the same result. The thickened slag adheres to the furnace wall. Over time the accretion grows in size.

If the condition is not remedied the scaffold will continue to grow and it effects the furnace in two ways. As it reduces the usable diameter of the furnace, the scaffold reduces production of iron. And because it deflects the movement of hot gases up the stack and the charge down it results in uneven heating and increases fuel consumption.

In extreme examples a scaffold may bridge the entire stack. This prevents most, or all, of the charge from continuing to move down the stack. Scaffolding, hanging, and bridging can also result in slips (see below).

Good furnace management will prevent the formation of most scaffolds, bridges, and hangs. In the event that one forms, there are a number of remedies. If the obstruction is small, increasing the blast and/or the ratio of fuel in the charge will drive up the furnace temperature and melt off the accretion. The furnace can be taken off blast, this reduces the air pressure in the space below the obstruction and may cause it to collapse. If the obstruction can be reached, it can be broken loose with iron bars (Burgo 1999:745; Percy 1864:494-495).
Figure 35. Blast Furnace Shapes (after Hasenfratz 1812:Pl 19-21)
Slips

Slips are caused by the collapse of a scaffold, bridge, or hang. As the obstruction halts the descent of the burden above it, a space forms below it. This is filled with hot gas. If the obstruction is not removed quickly this gap can become quite large. When the obstruction falls, slips, the results range from spectacular to disastrous.

The rapid heating of the raw materials as they cascade through the hot gas below them causes the instant volatilization of any water and the rapid expansion of any gases between the solid particles. In some cases the result is the forcible ejection of the burden above the obstruction out the top of the stack. If the force is great enough the top of the stack may also blow off. In extreme examples the entire blast furnace explodes. If the slip is farther down the stack, the slip may cause the forcible ejection of molten slag and iron from the hearth. A more serious slip can explosively destroy the hearth, spraying molten material. In both of these cases the metal in the hearth is ruined.

At the extremes slips range from amusing to deadly. There are numerous tales of people being pelted with fragments of rock, or wondering about the unusually large hail stones. At the other extreme are numerous cases like that reported by Percy (1864:521). In March of 1860 a falling scaffold ejected all of the molten material in the hearth of the furnace at the Dundyvan Iron-works (Scotland), engulfing three men and a boy working in the arch. They were severely burned over most of their bodies and died the next day. There are also many stories of death and dismemberment of entire furnace crews. A similar slip at the Vanvey Furnace in France, three men were injured, one later died (Percy 1864:525). In this later case there was clear evidence that the furnace had developed a scaffold (irregular descent of the charge, variable output).
A large slip that does not destroy the furnace may choke off the blast, freezing the stack. This is caused by the rapid chilling of the metal in the hearth or the total obstruction of the bottom of the furnace. The only way to avoid slips is to prevent the formation scaffolds, bridges, and hanging (Burgo 1999:745; Percy 1864:494-495).

**Gobbing Up**

Where scaffolding and hanging generally occur at the intersection of the charge and the furnace lining, gobbing up takes place in the charge. To some extent gobbing up is a free floating scaffold, and the causes are very similar. Too much particulate matter (fines), a fuel that crushes easily, or a chemical imbalance that causes the slag to thicken can all precipitate the problem. The consequences of gobbing up are also similar to scaffolding. Like scaffolding it blocks the free descent of the charge and the free ascent of hot gases. The hot gases are deflected and cold spots develop. Fuel consumption rises and production of iron falls.

Percy describes one incident in Seraing, Belgium that took 15 days to cure. During this time the furnace suffered multiple slips and produced very little iron.

There are a number of corrective measures for gobbing up, which vary depending on the cause. Changing the ore mix or increasing the fuel/ore ratio will usually increase the fluidity of the slag. Continuing the blast, while halting charging, will clear the problem out of the furnace so a normal charge can be restarted. Changing fuels to one that is less prone to disintegration/crushing or reducing the particulate matter charged, will restore the free circulation of hot gases (Percy 1864:495-496). If gobbing up is not corrected the furnace may freeze.
Channeling

For the furnace to operate efficiently, the hot gases must flow through the entire burden, evenly heating the entire burden. If the particle size in the charge is too variable, if there is too much particulate matter (fines), or if the raw materials are not evenly distributed in the furnace, channels may form. This occurs when the gases form channels (like chimneys) in the burden, bypassing other parts. This results in uneven heating and disrupts the reduction process. Channeling is more of a problem as the air pressure increases inside the stack. Although, it might occur in an 18th century blast furnace, it is much more likely in a modern high pressure system (Burgo 1999:745). Channeling can be prevented by insuring that the charge is broken into proper sized pieces and powdered raw material are not loaded into the furnace.

Freezing the Stack

Freezing the stack is the complete chilling of the contents of the furnace. It is usually caused by the involuntary cessation of blast activity. That is the blast is completely choked off and the furnace chills to the point that all of the once molten materials fuse. Short of the furnace blowing up, it is an ironmaster’s worst nightmare.

Freezing can be caused by uncorrectable gobbing up, a major slip, or extreme scaffolding. The only remedy is to dismantle the furnace and remove the solidified charge. During the colonial period this would have been done with pick axes, crow bars, sledgehammers, and chisels. Once the charge was removed the damaged portions of the furnace would have to be rebuilt. This would almost always involve replacing the hearth.
Trace Elements: Effects and Remedies

A number of different problems can occur in blast furnaces. Some are mechanic in nature and have already been discussed. But, most are related to the effect(s) of trace elements on the smelting process. Regardless of how iron is made, small amounts of other chemicals become incorporated in either the slag or the metal itself. These chemicals are present in the iron ore, fuel, flux, or furnace lining. Certain ones are reducible in the furnace, and if soluble in molten iron form an alloy. Some elements, such as aluminum (Al), calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) are not reducible and are incorporated into the slag. In some cases these elements have little or no effect on either the iron or the slag. Others can exert a powerful influence on the behavior of the iron or slag or the operation of the furnace. Sometimes the effects are benign, sometimes beneficial, others can spell disaster by either ruining the iron or halting the process.

A number of methods are available for determining trace elements. These include: thin section, PIXE (particle induced X-ray emission), SEM (scanning electron microscopy), XRD (X-ray diffraction), and XRF (X-ray fluorescence). Metal and slag samples should be sent to a lab for metallographic/petrographic, chemical, and spectrographic analysis. Although many labs have the equipment to perform the testing, only one with archaeometallurgical experience can fully explain the results to non-metallurgists.

Major alterations in the character of the iron can be caused by fairly small chemical differences. Steel and cast iron vary only in the amount of carbon alloyed with the iron. Other chemicals were added because they made the iron more fluid, harder, or conferred some other desirable quality. The use of a flux made a furnace more efficient, increased the fluidity of the slag, and lowered its
melting temperature. How the slag behaved, how the furnace operated, and the quality of the iron produced depended on the chemical composition of the ore, fuel, and flux and how much of each was charged into the furnace and how the furnace was managed.

It was not until the very end of the 18th century that ironmasters began to understand iron metallurgy. But even as late as 1848, John Tuomey wrote:

We have as yet no schools in which the practice and principles of metallurgy are taught; the consequence is, we have the principles without the practice, or more frequently the reverse. New establishments that commence with untried materials suffer most from this cause. What is called a "practical man" (by experience) is employed, who finds himself placed under new circumstance, with materials entirely different from those to which he is accustomed; his old processes are inapplicable and his want of knowledge of principles prevents the introduction of proper modifications. Alteration after alteration is made, often at vast expense, the profits of the company are swallowed up or their means exhausted, and the enterprise is mistrusted, if not abandoned. [Tuomey 1848:270-271]

Over time ironmasters used trial and error to develop recipes, mixes of ores and other materials, to achieve the desired result. A furnace produced the best iron it could with the available ore. The recipe would be used as long as it continued to produce "good" iron.

Today it is possible to minutely regulate the chemical makeup of a batch of iron and the slag. The effect of each chemical constituent is better understood and carefully monitored. This is done by controlling what is charged into the furnace and by manipulating conditions inside the furnace. Modern furnaces are computer controlled and continuously monitored. The operator has almost complete control of the final product. Once the iron is tapped out it is again analyzed and any required final adjustments made. The iron or steel produced can be chemically configured for specific applications. If a particular contract calls for iron with a carbon content of 3.07%, the process is monitored in the
furnace and during finishing the carbon content is adjusted. An 18th century founder was stuck with what was tapped out of his hearth. He even had to wait until it cooled to determine its performance characteristics. The standard test was to break a pig and examine the fracture.

In the 15th to 18th century some furnaces were known for their superior casting metal. Another furnace's pig iron had a reputation for being well suited for fining into bar iron. The price that iron brought on the market, depended on how it performed in the hands of the customers (blacksmiths, foundries, fineries, etc.). Iron was judged not only in terms of its performance under the hammer or in the foundry, but its also consistency. If the product of a furnace varied from month to month or year to year, it brought a lower price. No one wanted to have to test every pig prior to use. John Wightwick stressed the importance of both quality and consistency in a letter dated October 2, 1730 to John England, of Principio:

The Potomack piggs [Accokeek] will not reach 5£. 15s. they being cheap piggs are fittest for founderys... We have sold some of these last arrived, but the dealers complain they are too white, if they were grey they would go off much better... for we have pretty near an equal quantity of grey piggs mixed with the white which inclines me to think this must be some mismanagement of the Founder that they are not grey. I therefore hope you will consider and give directions to the Founder accordingly, and let the Hearths at both works be always set Burrow and not Transheer, for white piggs will do us great prejudice in the sales... there will be a difference of 10s p. ton in the sale betwixt grey & white...

In later years "Best Principio" became almost a grade of iron.

If problems did develop, the principal way of effecting them has remained the same, raise or lower the furnace operating temperature, increase or decrease the blast volume, or alter what is charged. The primary way to change the temperature in an historic blast furnace was to alter the amount of fuel charged. The more fuel that was added, the higher the operating temperature. This
technique is still available today, but it is far from all that is available. Where a 17th or 18th century founder had very little latitude on blast volume, today the range is very broad and even the chemical composition of the blast can be altered. For instance, 200 hundred years ago a blast of pure oxygen (oxygen lance) was not an option. As a result there are very few conditions that can occur inside a modern furnace that cannot be corrected before they become serious. Such was not the case 200 years ago.

The following is a examination of the most common trace elements in 16th to 18th century English iron. The source of each will be discussed. Effect(s) will be covered for inclusion in the slag, operation of the furnace, and as part of an iron alloy. Finally, any techniques developed for controlling the concentration of the chemical will be explained.

Aluminum

Small amounts of aluminum (Al) are present in many ores and some limestone. However, until the introduction of brick lined furnaces the amounts present were small enough that they did not have a significant effect on either the iron or slag. With the introduction of fire brick for hearths and the interior of blast furnaces, the amount of aluminum increased dramatically. Brick contains large amounts of aluminum and the liquid slag eroded the furnace lining.

Aluminum is very hard to reduce and requires high temperatures. As a result aluminum contamination of the iron was rarely a problem in cold blast furnaces. But, with the introduction of hot blast in the 1840s, aluminum contamination became more of a concern.

However, aluminum does increase the viscosity of the slag (Kato and Minowa 1969:37; Ohno and Ross 1963b:265; Rosenqvist 1983:311). If the slag
becomes too viscous it will have a number of adverse effects on furnace operation. The thicker slag will slow the descent of the charge, prolonging the process, increasing fuel consumption and decreasing iron production. High viscosity will also impede the movement of the hot carbon monoxide gas up the stack. This will slow the energy transfer and slow the reduction reaction, reducing iron production.

In order to tap out cast iron it must completely separate from the slag. Normally this is not a problem as the two materials have much different specific gravities and the iron passes readily through the molten slag to pool at the bottom of the hearth. But the rate at which the iron "settles" is largely dependent on the viscosity of the slag. Rostoker and Bronson (1990:81) have demonstrated that the time it takes for a droplet of molten cast iron to pass through 6 cm of liquid slag can vary from 12.5 minutes to over 7 hours. As the slag becomes thicker, more and more of the iron will be entrapped in the slag and tapped out with it, rather than pool in the hearth. So the slag viscosity effect on the settling rate can seriously decrease iron production by slowing the accumulation of iron in the hearth and by increasing the amount of iron discarded with the slag. High concentrations of aluminum may also make it more difficult to tap off the liquid slag. At the extreme this could lead to a frozen furnace.

There are a number of solutions to a high aluminum slag. The best way to avoid aluminum contamination is to not use ore or a lime source with a high aluminum content. The iron ores of Virginia are not particularly high in aluminum (see Chapter 4). Since fire bricks were not used in colonial blast furnaces, that source of aluminum contamination was not then a problem. Where aluminum contamination cannot be avoided, increasing the ratio of lime flux will decrease the viscosity (Rosenqvist 1983:311). Increasing the furnace temperature will also generally decrease viscosity. This can be accomplished by increasing the
fuel/ore ratio in the charge and/or the volume of air injected in the blast. As stated earlier, the blowing devices available in the 18th century, blowing tubs and bellows, did not allow much variation of blast volume.

**Carbon**

Carbon is the most important trace element in iron metallurgy. The amount that alloys with the iron has a profound effect on how it reacts in the hearth and its working characteristics. This has been covered in greater detail in the first chapter. The range of carbon content is relatively low, generally 0-4%.

Iron with a carbon content up to 0.15% is called wrought or bar iron. It melts around 1550°C and can be worked both hot and cold. It can be hammered or bent repeatedly without breaking.

Just a little more carbon results in steel (0.5-2.0%). The higher the carbon content, the lower the melting temperature and the harder the steel. Steel can be worked hot or cold and can also be hammered or bent, but may need to be heat treated to relieve brittleness. Steel holds an edge.

High carbon iron (2-4%) is called cast or pig iron. Its melting temperature declines as the carbon content increases, reaching a minimum of 1143°C at 4.3%. Cast iron can only be worked as a liquid. It cannot be hammered or bent. Depending on the conditions in the furnace and how the iron is cooled it forms gray, mottle, or white iron. Gray iron (see pages 18-19) is softer, can be filed, and contains flakes of graphite. White iron (see pages 18-19) is extremely hard.

**Manganese**

One of the few trace elements with only positive effects is manganese (Mn). Any manganese oxide that passes into the slag will replace iron oxide, act
as a flux, and increase the iron yield. This is particularly true in bloomeries, because they do not generally get hot enough to reduce manganese oxide (1500°C). Blast furnaces operate hot enough to reduce manganese. The amount of manganese reduced is temperature dependent, as a result manganese is a good indicator of internal furnace temperature (Burgo 1999:730-731).

Manganese is especially important in iron that is destined to be converted into steel by increasing its hardenability. Hardenability is the capacity "to harden deeply through quenching or to achieve full hardening at slower cooling rates". For instance a 15 cm thick bar of manganese steel will harden to the center in air. A similar piece of steel without the manganese will quench harden only a few millimeters (Rostoker and Bronson 1990:19).

The stücköfen of Carinthia and Styria produced a high manganese bloom steel that was highly prized (Rostoker and Bronson 1990:20). The 16th to 18th century Swedish furnaces of Dannemora produced a high manganese iron that was used to make steel "of the highest quality" in Sheffield and elsewhere (Percy 1864:198, 736).

**Phosphorus**

As is well known, practically all the phosphorus of the iron ores smelted in the blast-furnace passes into the pig-metal, increasing its fluidity, but diminishing its strength to such an extent that, if phosphorus exceeds a certain amount, the metal is only fit for fine castings, not required to resist strains, and it cannot be used for the ordinary purposes of good foundry-iron. [Rossi 1897:144]

"It is not necessary to search for phosphorus, most irons contain more than is needed, and the care should be to keep it within limits" (Turner 1900:204). Phosphorus (P) has four major effects on iron: increased hardness and strength, lower solidus temperature, increased fluidity, and cold shortness. For thousands of years Ironmasters have understood and used these effects to manipulate the
operating characteristics of iron. But if not carefully controlled, phosphorus can render iron unuseable.

Most Virginia iron ore contains some phosphorus. The limonite ores have 0.1 to 0.4%, while the fault deposits have up to 2% (Furchron 1935:81-108; Holden 1907:406). Bog ore often has a high phosphorus content (Gordon 1996:57). Unlike silicon and titanium, phosphorus is almost completely reduced in the blast furnace or bloomery. As a result most will alloy with the iron, rather than go into the slag (Burgo 1999:731; Rossi 1897:144).

The strength and hardness of iron increases with the concentration of phosphorus. Cold hammering can also harden high phosphorus iron. The hardening effect is true for any concentration of phosphorus. The more phosphorus, the harder the iron becomes and the more hammering can harden it. 0.05% phosphorus in wrought iron makes it as hard as medium carbon steel (Tylecote 1987:261). Modern steel makers can increase hardness by as much as 30%, without sacrificing shock resistance by maintaining phosphorus levels between 0.07 and 0.12%. Like manganese, phosphorus increases the depth of hardening due to quenching. But at the same time it decreases the solubility of carbon in iron at high temperatures. This would decrease its usefulness in making blister steel, where the speed and amount of carbon absorption is the overriding consideration (Rostoker and Bronson 1990:22-23). There is growing evidence that early ironsmiths understood and exploited the advantages of "phosphoric iron" (see pages 23-27). Relatively high phosphorus iron was selectively used to make items were steel would also have been appropriate, such as weapons and tools.

Careful control of phosphorus can be of great benefit in casting operations. Phosphorus depresses the liquidus temperature, allowing the iron to remain molten for longer and also increases fluidity. The addition of 1% can double the
distance molten iron will flow (Rostoker and Bronson 1990:22). The maximum effect, about 500°C, is achieved at a concentration of 10.2% (Rostoker and Bronson 1990:194). For general foundry work Turner felt the ideal iron had 0.2-0.55% phosphorus. The resulting iron filled molds with fewer voids and also shrank less, but was not too brittle. In the 19th century some producers of decorative cast iron used iron with up to 5% phosphorus. The extreme fluidity allowed them to make very complex and delicate castings. But, they could not be weight bearing, as they had no strength (Turner 1900:202-4).

The addition of phosphorus has a downside. At concentrations higher than 0.2% iron becomes increasingly cold short, or brittle at low temperatures. Cold short is especially important for bar iron. Although, bar iron is usually worked hot, its uses often require it to be tough, bendable, and resistant to shock at room temperature. A nail that shattered when hit with a hammer or a carriage wheel that broke when it hit a rock would not be marketable. High enough concentrations of phosphorus render any iron unusable (Rostoker and Bronson 1990:22).

The effects of cold shortness are magnified by temperature. Thus, a piece of iron that is perfectly serviceable in summer, might become brittle in winter. For instance some of the very wealthy of the Middle Ages may have had a high phosphorus sword for the summer campaign season and a low phosphorus sword for winter (Rostoker and Bronson 1990:22).

"The only means of controlling the phosphorus content of the hot metal [in a modern furnace] is by limiting the amount charged to the furnace" (Burgo 1999:731). There were two remedies for high phosphorus iron in historic furnaces. The oldest, and easiest, was avoidance. Blast furnaces avoided iron ore that produced cold short iron, because it was unmarketable. The second method involves oxidizing the phosphorus during the fining process by adding iron.
oxide. The problem is that since additional iron oxide must be added to the slag bath, it increases fuel costs. This technique is usually associated with puddling in the early 19th century, and may not have been previously understood. Isaac Zane, the owner of Marlboro Iron Works did not appear to know about it in 1772. There is good evidence that Zane’s early ore source had too much phosphorus. He abandoned it and built a new blast furnace once he found the ore banks at Marlboro. Given Zane’s reputation for keeping abreast of the latest developments, the technique was probably unknown to the ironmasters of Virginia and Pennsylvania.

Removing the phosphorus was accomplished by adding iron oxide to the slag in the form of bloomery slag or iron ore, or by allowing some of the pig iron to oxidize. In any case some of the iron oxidized. So although it was possible to produce virtually phosphorus free iron, the ironmaster did so at the expense of producing less bar iron.

Robert Gordon (1997) has proposed a means for testing whether or not this technique was used by a particular facility by analyzing the finery slag. If it has a very high FeO content as well as a high P, then the method was probably in use. A definitive answer can only achieved by testing the P content of the ore and pig iron produced. Samples collected at the Mount Riga, Connecticut complex (1810-55) indicate that the finers were actively reducing phosphorus. Metal drops in the blast furnace slag contain 0.15% P, while the slag has 0.4%. The finery tap slag contains 87% FeO and 0.71% P (Gordon 1997:9, 12, and 16-17).

Silicon

Silica (SiO2) is almost always present in iron ore. Most of it is slagged off during the smelting process. But, at temperatures above 1300°C some will be
reduced and form an alloy with the iron. The hotter the furnace, the more silicon will be present in the iron. The rate of the reaction is slow, but accelerates as the temperature increases. As a result the amount of silicon reduced, like manganese, is an excellent indicator of the interior temperature of the blast furnace (Burgo 1999:731). It is not uncommon to find up to 1.5% Si in European cast iron from the 16th to 18th centuries.

The major effect of silicon is that it promotes the formation of gray iron (see pages 18-19). Gray iron is less brittle and easier to finish than white iron. It was preferred for casting purposes for this reason. Turner (1900:192-7) reported that silicon also reduced shrinkage and the formation of blowholes, lowering the number of bad castings.

Brian Awty argued that high silicon gray cast iron was preferred not only for casting, but also for fining. "Its conversion into bar iron at the forge was also quicker and less complicated, so it could be fined at less expense both of labour and of charcoal than white cast iron" (Awty 1996:18). There are a number of problems with this statement. First is the assumption that gray cast iron has a high silicon content. Although silicon encourages the formation of gray iron, gray iron does not require silicon to form. The second is the claim that gray iron was cheaper to fine. This is based on a statement made by Schubert that white iron required a longer fining process "which required a greater consumption of fuel" (Schubert 1957:286) and Percy (1864:608-609). Schubert concludes that it is a longer and more costly process based on work by Karsten (1816:391). Heine, in a series of experiments published in 1951, demonstrated that just the opposite was true. During the fining process, the silicon must be removed first, because it blocks decarburization. At a temperature of 1300°C almost all of the silicon must be removed before any carbon is oxidized. At 1500°C the effect is significantly lessened (Heine 1951; Rostoker and Bronson 1990:140).
Slag

Slag is not the historic equivalent of fire cracked rock. Rather, it is the metallurgical analog of a prehistoric lithic scatter. Slag is often the first indicator of the presence of a metallurgical site and the last one to completely disappear. No matter what happens to a metallurgical site there will always be slag. Slag is diagnostic. It not only varies drastically depending on the metallurgical process that created it, but also contains important information about the process. Just as some stone tools required the manufacture of a blank or resulted in the creation of a core, slag was deliberately produced and was an integral part of the metallurgical process. Finally slag is site specific. Metallic artifacts may or may not have been manufactured on site, but slag is rarely transported. A rare U.S. exception is the Hopewell National Historic Site. Hopewell's slag was removed prior to the park's formation for road building. The National Park Service recreated Hopewell's slag pile by trucking in slag from the nearby Joanna Furnace. In some cases bloomery slag was reused as a raw material by blast furnaces. But, this was uncommon in the Americas. And in the rare instances where it occurred, the bloomery slag will be in discreet "ore" dumps, not lens deposits. Because of the potential information value of slag analysis, it should be included in any research of a metallurgical site. Slag should be recovered and submitted to a qualified laboratory for spectrographic and crystallographic analysis.

In the Americas iron smelting sites are historic. But, exact locations are seldom known even for historic sites. The names of water courses change and early land survey was anything but exact. Since most early American iron sites were water powered, the easiest way to locate a smelting site is to walk the
stream it was "located" on. Once slag is found follow the slag upstream to the site. This technique has been used in Britain to locate hundreds of hitherto unknown Roman era iron sites.

In some cases the difference between various slags is readily apparent to the naked eye. Glassy blast furnace slag is visually different from slags produced by bloomeries, fineries, smithies, and foundries. But, other important differences are not visually discernible. What to the naked eye appear to be relatively homogenous are in reality complex mixes of minerals with often complex crystalline structures. Many of these compounds occur or are formed under very restrictive physical conditions. As a result the careful study of slags can reveal a great deal about the operational parameters at a site. This includes: operating temperature, ore source, and whether or not a flux was used. For instance the ratio of magnetite (Fe₃O₄), wüstite (FeO), and metallic iron in a slag reveals the reducing conditions in a furnace and can be used to differentiate between blast furnace and bloomery/finery slags. The minerals present and crystalline phases, many of which form shortly after the slag is tapped out of the furnace coupled with the use of phase diagrams can be used to reconstruct the temperature gradients and chemical process in the furnace. The bulk composition of slags can also be used to determine viscosity at a particular temperature. The size of entrapped metallic prills is also an indicator of slag viscosity. As analytical techniques improve more and more data about the operation of historic smelters can be extracted (Bachmann 1980 and 1982; Craddock 1995:16-21; Craddock and Hughes 1985; Bottinga and Weill 1982; Gordon 1995 and 1997; Rostoker and Dvorak 1990; Starley 1999).

An ongoing project in Virginia is to replace the collection of slag made by T. T. Brady that was lost when he died. Lyle E. Browning is coordinating the efforts of members of the Archeological Society of Virginia, local volunteers, and
some professional archaeologists to collect slag samples from all of the known Virginia iron sites. These will then be subjected to detailed laboratory analysis. The ultimate objective is to produce an iron slag database. This can be used for a variety of purposes including identifying ore sources and the sources of unprovenanced iron artifacts.

Slag is a mixture of metal oxide, silicates, and other elements. Its exact composition depends on both the process that produced it (bloomery, blast furnace, foundry, or finery forge) and the chemical composition of the raw materials used. Different kinds of slag are produced at different stages in the production of iron (see Figures 8 and 9).

A primary difference between blast furnace slag and finery, forge, and bloomery slag is the amount of iron present. Although early blast furnaces that operated without deliberate fluxing could lose iron to the slag, they were still more efficient than bloomeries. This is because the bloomery uses iron as a fluxing agent. Straker and Tylecote found bloomery slags contained between 31 and 59% iron oxide, while blast furnace slag contained only 1-11% (Straker 1969:94-98; Tylecote 1962:286-303). By the mid 17th century it was generally understood that lime aided slag formation and increased blast furnace yields. By that time blast furnaces were able to convert over 90% of the available iron into metal (Gordon 1996:103).

**Bloomery Slag**

Bloomeries produce two different kinds of slag—tap slag (Figure 36) and skulls (or mossers). Tap slag is removed from the hearth as a liquid (around 1200°C) and then allowed to solidify before being discarded. While skulls or mossers are the bloomery equivalent of bears of salamanders and are removed as solids. A finery forge produced about the same volume of slag as the pig iron it
used (Gordon 2001:59-60)

Tap slag is primarily fayalite (Fe$_2$SiO$_4$ or 2FeO•SiO$_2$), a ferro-silicate. It is created by the fusion of silica (SiO$_2$), wüstite (FeO), and the other trace elements in the gangue. It can take a number of forms and colors. But, usually it is blue-black in color and has a nubbly, knuckley, or ropy texture. It may also be vermiform (worm shaped) or vesicular (containing many thin walled chambers). Tap slag has a specific gravity that varies from 2.31 to over 4 (Straker 1969:92).

Some of the fayalitic slag always becomes entrapped in the bloom as it forms. Although most of this is expelled during subsequent processing (hammering or rolling), some remains incorporated in the final wrought iron or merchant bar. Thin strings of fayalitic slag are characteristic of wrought iron.

The skull, or mosser, is the bloomery equivalent of a bear, horse, or salamander. It is an accreted mass of slag, charcoal, iron ore, and iron left over after the formation of the bloom. It is removed from the hearth after the bloom. These large masses are common at bloomery sites and are often incorporated in dams.

Slag has a number of effects on the performance characteristics of iron. Slag fibers contribute to the corrosion resistance of wrought iron (Gordon 1995:70, Rostoker and Bronson 1990:85, and Tylecote 1986:170). Slag may also function as a welding flux, protecting exposed surfaces of hot metal from oxidizing (Rostoker and Bronson 1990:85 and 167-8). But, slag can also seriously weaken bar iron. The best bar iron has a small amount of slag uniformly distributed in a matrix of iron. Strength is seriously degraded when the slag content is above 10%. The distribution of slag is especially significant in applications with a small cross section (wire, nails, gun barrels). A large slag inclusion can precipitate structural failure. Gordon and Smith found that iron from the 17th century bloomeries at Governor's Land, the New Haven ironworks, and Saugus all had a high percentage of slag (15-16%) and that it was poorly distributed (Gordon 1995:70-71).
Figure 36. Bloomery slag from Rowley/Boxford, MA. Photo by author.

Figure 37. Blast Furnace slag from Connecticut. Photo by author.
Furnace Slag

Furnace slag (Figure 37) is a byproduct of the blast furnace process. Vast quantities were and are produced during all phases of smelting and working iron. A rough rule of thumb is that a blast furnace produces about twice as much slag, by weight, and five to six times as much volumetrically as it produces iron (Egleston 1873:207). But, this is only about half of the volume of ore it charges (Gordon 2001:59). It is not normally present in cast or pig iron. Some can be incorporated if the founder is careless and allows tap slag to run out of the hearth with the iron.

Furnace slag is primarily a silica-lime glass. It is composed of silica (SiO2) and lime (CaO) and whatever other elements are present in the ore and the charge. It looks and acts like glass and is classed as a ceramic. Its physical appearance can be altered by how it is cooled and varies in appearance from bottle glass to a foamy brittle mass. Rapid cooling results in a glassy material that exhibits a good conchoidal fracture, is translucent in thin section, and has a shiny surface. Slower cooling will result in a more stone-like material, the fracture will be dull, and it will be opaque in section. If furnace slag is run onto wet sand or ground or tapped into water it will be dull and full of bubbles. The solid glassy variety has a specific gravity of around 2.86. While extremely bubble filled varieties can be as low as 1.42 (Straker 1969:98-99).

Furnace slag is generally gray, green, or gray green. But depending on its composition, other colors are possible. For instance, a high titanium slag is black, while manganese slag is blue. The silica (SiO2) in the slag comes primarily from the iron ore, but some may be from the fluxing agent. The calcium (Ca) is mostly from the flux, but some ores contain enough that they are self fluxing. While some aluminum is found in ores, most comes from the refractory (fire) bricks.
Brick lined furnaces, introduced in the late 18th century and common in the 19th and 20th centuries, resulted in slag containing 10-20% alumina (Al2O3). The alumina is from erosion of the furnace lining.

There is always some metallic iron in the slag in tap slag. This is because the iron must pass through the slag to get to the hearth. Slag floats on top of the molten iron because it is less dense. Depending on the slag viscosity it can take a considerable amount of time for an iron globule to pass through to the hearth. Experiments have shown that it takes from 12 minutes to almost 7 hours for iron droplets to pass through only 6 cm of slag. The viscosity of the slag must be carefully controlled as a very thick (viscous) slag can seriously decrease the production rate of a furnace (Rostoker and Bronson 1990:81, 199). There may also be some iron oxide in blast furnace slag.

**Sulfur**

Sulfur (S) is a frequent contaminant in coal and coke. It was the presence of sulfur that prevented the use of coal and coke in blast furnaces until 1709. Some sulfur could also be charged with the iron ore. Iron sulfide (pyrite, FeS2) is a common iron ore, with large deposits in Virginia (Figure 31). It is also present in small quantities in many other ores.

Sulfur dissolves readily in both liquid and solid iron at the temperatures used in iron smelting. The effects of even small amounts of sulfur are immediate, serious, and potentially catastrophic. The effects were so serious and so obvious that they were one of the first worked out by ironmakers. Sulfur causes iron to be red or hot short (Gordon 1996:7).

Hot short iron is brittle when hot. This was a serious problem as most iron was used as bar or wrought iron during the 17th and 18th century. Wrought iron
is shaped by repeated blows with a hammer while hot. A piece of hot short iron will crack, or even shatter, when struck with a hammer. When a piece of hot iron or steel cracks the exposed surface quickly oxidizes. This layer of oxide prevents the mending of the crack by welding. Large cracks cause the iron or steel to break up. Smaller cracks usually go undetected and can cause the object to fail during use. The degree of hot shortness is in direct proportion to the amount of sulfur present. Today iron with over 0.03% sulfur is avoided.

Hot short iron can be worked, but it must be worked at low temperatures. Working at lower temperatures requires more physical effort from the smith or forgerman because it must be struck more often and harder to achieve the same result. This is because the resistance of iron to deformation only begins to dramatically decrease above 750°C, cherry red (700 and 900°C). Because it is much easier to work hotter iron, most smiths prefer to wait until the iron has reached 1000°C (light yellow to white hot). A mildly sulfur contaminated bar could be worked, but it required a great deal more time and effort (Rostoker and Bronson 1990:5-6, 21).

Sulfur also lowers the melting (liquidus) temperature of iron. But the amount of sulfur needed is so great that it renders the iron unusable. The melting temperature drops only 150°C for concentrations up to 20%. Between 20 and 31% the melting temperature drops almost 400°C, reaching a low of 988°C (Rostoker and Bronson 1990:21 and 194). This can also have serious consequences in wrought iron. Wrought iron is not homogenous and the spot concentration of sulfur can be very high. Since a smith would prefer to forge iron above 1000°C, it is possible to liquify small pockets of iron within a forging. These pockets of liquid iron disrupt the fibrous structure of the iron, can cause minute cracks, and make it weaker and prone to failure. On the surface the piece of iron may look fine, but it will fail when used (Rostoker and Bronson 1990:21, 194).
Sulfur promotes the formation of white cast iron. As little as 0.5% can counteract the effects of slow cooling and a high silicon content (Rostoker and Bronson 1990:21). White cast iron is more brittle, but also harder. It was generally avoided, because it was difficult to work, except in China where high sulfur cast iron, some as high as 0.57%, made with coal and coke, was used to make bells and chimes (Rostoker et al. 1984:760). In the rest of the world a high sulfur cast iron could be used for making castings, but would make poor wrought iron. According to Turner (1900:200), good foundry iron should have less than 0.15% sulfur.

There are a number of remedies for sulfur contamination. The first, and the one most used in historic and prehistoric operations, was avoidance. If an ore resulted in hot short metal, another ore was found. Coal was not used in Europe (it was used in China) as a fuel for smelting because it contained sulfur and caused hot short iron. The Chinese were able to use coal largely because their demand for cast iron was much higher.

Sulfur can also be removed from ores by roasting and washing, both common practices. There is ample evidence that early metallurgists practiced both (Agricola 1950:287-348, 349-351, 274-279 [1556]; Biringuccio 1966 :141-142 [1540]; Tylecote 1986:155-156, 179-180, 204; 1987:53-65, 111-115). Roasting oxidizes sulfur to form sulfur dioxide (SO$_2$) which either escapes into the atmosphere or can be washed out. In warm climates it was possible to leave pyritic ore out in the rain. The combined action of rain, bacteria, and heat oxidize the sulfides to sulfates (FeSO$_4$), which are water soluble (Turner 1900:77). Natural weathering was also used in Sweden. The same process, at geological speed, results in the gossan limonites ores.

The importance attached to low sulfur iron is demonstrated by the consistently higher prices paid for the iron of Sweden, Russia, and Spain from
the 16th to 18th centuries. Today sulfur is no longer a problem. The modern remedy is the addition of manganese. Some historic iron displays elevated manganese levels. But most are well below the level needed to neutralize sulfur (Rostoker and Bronson 1990:21).

**Titanium**

The use of titaniferous ores in the blast-furnace has been the subject of much controversy for many years. Divers objections have been raised against them, and, for one cause or another, the verdict has been so unfavorable that they have been excluded from the practice of ironmasters" [Rossi 1893:832-33].

Many [magnetite] deposits, both in Sweden and in New York, are contaminated with titanium, and concentration cannot be regarded as successful unless this is eliminated. Titaniferous ores have been worked in small quantities for generations, but every attempt to employ them upon a large scale, especially in the manufacture of steel, has been a failure. [Campbell 1907:42]

It was long held that the presence of a small quantity of titanium rendered ore entirely unfit for use in the blast furnace, but the whole question has recently been attacked anew and methods will probably be found whereby it can be fluxed. There is much reason to believe that the former verdict against it was on insufficient grounds. [Johnson 1918:28]

Titanium was discovered in 1791 by British clergyman William Gregor in the mineral menachanite. He named it menachite. It was rediscovered in 1795 by German chemist Martin Klaproth, who named it titanium. Iron ores containing titanium are common throughout the world. They were used in the manufacture of iron in Europe, especially in Scandinavia during the 19th century. Often, because they were the only ore available. Plentiful titanium free deposits of iron ore in the United States enabled ironmasters to avoid the "titanic stigma" (Bowron 1883:159). Today they are used almost exclusively as a source of titanium, with iron as a byproduct (Bowron 1883; Forbes 1869; Francis 1940; Lankford 1985; Percy 1864; Rossi 1893; Poveromo 1999:570).
Titanium has no injurious effects on the quality of the pig iron as it passes into the slag. The objection to it is due to the fact that it raises the temperature of fusion of the slag, causes greater loss of iron in the slag, and causes accretions of nitrocyanide of titanium in the furnace hearth. These difficulties can in part be overcome by special methods. In general trade, however, an ore should not contain over one per cent. of titanium. [Singewald 1911:127]

Titanium, like other trace elements, can affect either the iron, the slag, or the overall smelting operation. Until the introduction of the high temperature electric furnace in the early 20th century, only small amounts of titanium could be reduced to metal. As a result the primary effects of titanium were seen in the slag. Modern metallurgical texts and historic works, show the use of titaniferous ores does not adversely affect the quality of iron. The controlling effects are in the slag, primarily due to the small amount of titanium that could be reduced prior to the introduction of high temperature electric furnaces in the early 20th century. There is a considerable body of information on titanium's effect on blast furnace slag, both historic records and modern metallurgical research. And there is data that it effected blast furnace operation.

An additional effect mentioned in some texts is that titanium may raise the melting (liquidus) temperature of cast iron and make it viscous (Lankford 1985:579; Burgo 1999:733). However, this only becomes a concern at the higher temperatures available after the introduction of hot blast in the 1840s.

Historical texts are in general agreement that the use of titaniferous ores should be avoided due to the slags produced. There are historic reports of furnace operations being adversely effected by increased scaffolding and other problems related to the slag. The use of titaniferous ores may also increase fuel consumption per ton of iron produced (Forbes 1869:70; Bowron 1883:). It was also reported that lower blast temperatures and slower "driving" were required.
Modern metallurgical texts are not as unanimous. There are conflicting experimental results on the effects of titanium on slag.

"Titanic Iron"

Titanium has no injurious effects on the quality of the pig iron as it passes into the slag. [Singewald 1911:127]

In order for titanium to effect the "quality" of the cast iron, it must be reduced to a metal and form an alloy with the iron. But, titanium dioxide (TiO₂, also called titania and titanic acid), like silica (SiO₂), reduces at higher temperatures than iron. Before the introduction of hot blast and steam powered blowing engines in the 1840s, it was impossible to achieve high enough temperatures in a blast furnace to reduce any appreciable quantities of titanium. Even after the widespread adoption of hot blast, numerous references to the difficulty of reducing titanium and the small quantities present in pig iron and steel persist. It was not until the advent of electric furnaces in the early 1900s that titanium alloys became practical (Francis 1940:285; Greenwood 1902:73 and 208; Stoughton 1908:419).

Robert Mushet received thirteen patents for the use of titanium to improve iron and steel during the period 1859 to 1861. John Percy (1864:163-168) reported a number of experiments with, and the results of testing Mushet's "titanic steel". Given the technology available in 1864, it was found virtually impossible to alloy titanium with iron and "analytical chemists of skill and repute declare that they have examined specimens of "titanic steel' without being able to detect any titanium in it" (Percy 1864:168). As late as the 1890s Bauerman wrote "Titanium may be present in pig iron to the extent of about 1 per cent. When a proportion of titaniferous ore is added to the charge" (Bauerman 1890:53).

Titanium frequently occurs in grey pig-ion [gray iron is frequently the
result of silicon and indicates a high furnace temperature], but in white iron it has always escaped detection, even when ores containing it have been added to the furnace charge, owing to the very high temperature required for its reduction ... [but it] does not appear to pass into the malleable iron produced from such pig. [Greenwood 1902:73 and 208]

Even as late as 1940 it was still difficult to reduce metallic titanium in a blast furnace designed to produce iron.

Titania is similar to silica, SiO₂, except that it is more difficult to reduce at temperatures attainable in the blast furnace, and all but traces of it, which are found in the iron, pass out with the slag. [Francis 1940:285]

It is not until the introduction of electric furnaces around 1900 that high enough temperatures could be achieved to produce titanium steel (Stoughton 1908:419).

A number of authors published papers and articles on the characteristics of "titanic iron", that is pig iron produced from titaniferous ores. Some of the earliest published American accounts are found in Forbes (1869) and Bowron (1883). Forbes wrote that the Scandinavian ore "yielded a very good iron (1869:70). Bowron that:

The iron will be white, or, at best, mottled, if there is much titanic acid to contend with. Titanic iron is essentially a forge iron. Foundry iron can only be produced when titanium is low... [Bowron 1883:163-164]

The iron produced by Bowron at Norton (Bowron's furnace) was "found to be extremely strong and was used in Europe for armor plates" (Rossi 1893:839). In 1874 Dr. Forbes wrote

Whatever may be the reason of this effect, what is known with a certainty is, that titaniferous ores in the United States, Canada, New Zealand, Sweden, and Norway are such that the metal produced from them is wonderfully good. [quoted in Rossi 1893:839]

Other late 19th century authors praised the quality of "titanic iron" (Bauerman 1890:53; Percy 1864:165-168; Rossi 1893:838-841).
The only potential downside to "titanic iron" was that, according to a number of late 19th century authors, it was not suitable for foundries (e.g. Bowron 1883:163-164). But even if the presence of small amounts of titanium limited its use to the forge, the demand for "forge iron" remained high throughout the 19th century. This would have been even less of a problem for the Albemarle Iron Works, as upwards of 90% of the iron produced in the 18th century was destined for the forge. American production of "titanic iron" was never more than a fraction of overall output, and could be easily absorbed by the market.

**Titaniferous Slag**

What are the effects of titanium on blast furnace slags and might the use of titaniferous ores effect the operation of a cold blast charcoal furnace? There are numerous reports on the effects of using titaniferous ores in blast furnaces. Both the historic texts and the iron and steel industry are in almost complete agreement that the use of titaniferous ores in blast furnaces causes an increase in the viscosity of slag, and the increased viscosity can result in operational problems. Experimental results have shown that titanium can increase or decrease viscosity, depending on the partial pressure of oxygen.

**In the Furnace**

The literature of iron making is full of accounts of the effects of titanium on slag. But, due to the general avoidance of titaniferous ores in the English speaking world much of the information is second hand like that of John Percy, who wrote:
I know nothing from my own experience of the effect of this acid [titania] on blast-furnace slags on the large scale, but I am assured by Swedish metallurgists, skilled in the smelting of iron in Sweden, that it, like magnesia, renders the slag difficultly fusible, and may be the cause of much trouble in consequence. [Percy 1864:507]

There are exceptions. Forbes (1869) and Bowron (1883) both worked with Scandinavian titaniferous ores. The use of titaniferous ores was rare in the United States during the 19th and 20th centuries. But, it was used and there are accounts of its effects. Rossi (1893 and 1896) wrote about the Tahawus, NY furnace's experience and his own laboratory experiments with titaniferous slags. Egleston (Rossi 1893:866) wrote that while testing New Jersey magnetite for phosphorus, he discovered that the ore contained 5 to 6 per cent titanium. A Pennsylvania blast furnace had been using it for years. The Bush River Iron Works (owned by John Lee Webster an early participant in the Albemarle venture), in Maryland, used a titaniferous hematite containing 18% TiO$_2$ during the 1830s. The "ore was used with good success, but required careful management" (Singewald 1911:161).

In spite of some limited success with the use of titaniferous ores, the general consensus (Burgo 1999:733; Dzermejko et al. 1999:239; Johnson 1918:27-28; Lankford 1985:579; Percy 1864:507; Singewald 1911:127; Stoughton 1908:15 and 419; Turner 1908) is that they "interfere with the blast furnace smelting by producing sticky [viscous] slags which are not easily handled" (Stoughton 1908:15). Another term that often appears in historic texts is "infusible". This means that it is difficult to form a fully liquid titaniferous slag. In the blast furnace titanium also raises the melting temperature (liquidus) of the slag. These problems were overcome through the manipulation of fluxing agents (Forbes 1869; Bowron 1883; Rossi 1893 and 1896) or the very high temperatures in electric furnaces (Stoughton 1908:419). The higher temperatures available with hot blast
were not apparently high enough to significantly reduce viscosity. As a result, Bowron tried the opposite approach. He found that reduced temperature, slow driving, was effective (1883:163).

Forbes wrote that titaniferous magnetite from the Gulluxrud Mine in Eger, Norway could only be used when mixed with other ores. "When smelted alone [it] was found to be refractory, and not to produce a liquid slag" (Forbes 1869:71). He also reported difficulty forming a slag with the titaniferous magnetite from the Cristine Mine, Krageroe, Norway. It was only after employing an unorthodox mixture of limestone and crushed quartz that it was possible to work the "ore cleanly and profitably" (Forbes 1869:70).

Although Bowron makes no mention of problems with the slag at the Norwegian Titanic Iron Company's Norton, England furnace, he did use an unorthodox flux similar to Forbes'. At Norton he used a combination of "limestone, basalt, old red bricks, or any similarly fusible silicate" (Bowron 1883:160). Although Rossi does not give details on the flux used at Tahawus, it is obvious from the ore and slag analysis that one high in silica was used (Rossi 1893:835-846).

For most blast furnace operations, higher temperatures resulted in a more fluid slag and cast iron. But in the case of titaniferous slags, higher temperatures could result in significant changes in the slag chemistry (see next section for detailed discussion of laboratory results). These include the formation of titanium carbide, carbonitrides, and nitro-cyanide of titanium (titanium-cyanonitride, Ti₅CN₄). All have limited solubility in iron and slag and are often found in the salamander or as deposits on the hearth wall (Burgo 1999:733; Greenwood 1902:142; Lankford 1985:579, Turner 1908). With a titaniferous ore, the deposits on the hearth wall can significantly reduce the volume of the hearth (Johnson 1918:27-28) and decrease iron production.
Titanium is sometimes deliberately added to the charge of modern European and Japanese furnaces to form a viscous slag. This slag adheres to the furnace hearth walls and prolongs the operating life of the furnace (Burgo 1999:733; Dzermjeiko et al. 1999:239). Morizane et al. (1999:29) advocate that "the addition of titania bearing materials should be optimized to form a protection layer on the refractories without causing possible operational problems".

**Experiments with Titaniferous Slag**

Laboratory experiments on the effects of titanium on iron slag appear somewhat contradictory. Some (Osborn and Gee 1969; Holmes and Banning 1968; DeVries et al. 1955) found that low concentrations of titanium decreased viscosity, increase fluidity, and lower the melting (liquidus) temperature. While other experiments found just the opposite (Fine and Arac 1980: 165-66; Morizane et al. 1999:29). To add to the confusion, some studies found that Ti both decreased and increased slag viscosity and melting (liquidus) temperature (Handfield and Charette 1971; Ohno and Ross 1963a and 1963b; Rosenqvist 1983:302 and 312). However, careful scrutiny of the experimental data, shows that when the experiments were conducted under blast furnace conditions the use of titaniferous ores resulted in sticky or viscous slags.

The contradictory experimental results are due to a number of factors. Primarily that there appear to be three reactions that are causing the changes in viscosity and melting temperature. These depend on the temperature and atmosphere in which the experiments were conducted. At higher temperatures, like those found in modern blast furnaces, the titanium forms titanium carbide, nitride, or carbonitride. These are so insoluble that the slag may become a slurry (Fine and Arac 1980:165-66; Morizane et al. 1999:29; Lankford 1985:579; E. T.
Turkdogan, personal communication 1999; Burgo 1999:733, Handfield and Charette 1971). While this explains the behavior of some high temperature titaniferous slags, it does not explain either the lowered viscosity and melting temperatures noted by numerous scientists, or the increased viscosity and melting temperature under low temperature conditions.

The contradictory results appear due to the differential behavior of titanium based on the presence or absence of oxygen. When tested in air, dry nitrogen, or argon TiO$_2$ breaks down into Ti$^{4+}$ and O$^{2-}$ ions. The initial decrease in viscosity appears to be due to the liberation of O$^{2-}$ ions which break up the silicate matrix. What Ohno and Ross referred to as the polymerization of orthosilicate ions (Ohno and Ross 1963b:272). However, as the partial pressure of oxygen drops, more and more of the titanium forms Ti$^{2+}$ and Ti$^{3+}$ ions. These form suboxides; which like titanium carbide, nitride, and carbonitride; have very limited solubility and form solid phases in the slag. It is possible that in modern high temperature blast furnaces suboxides as well as titanium carbides, nitrides, and carbonitrides are precipitating out and contributing to the higher viscosity and melting temperatures of titaniferous slags.

Handfield and Charette (1971) found that small amounts of TiO$_2$ decreased slag viscosity. But continued addition of TiO$_2$ resulted in increased bulk viscosity due to the formation of carbonitride particles in the slag.

Ohno and Ross (1963a and 1963b) conducted extensive experiments to find both the effect of titania on lime-titania-alumina-silica slags (viscosity and liquidus) and determine the primary phase and an optimal slag for blast furnace operations. They found that adding TiO$_2$ "decreased the original slag viscosity" (1963b:272-274 and 264-268). And that this effect could be used to significantly reduce the viscosity of slags containing 10-20% alumina (Al$_2$O$_3$). For instance at 1500°C a slag that was 30% lime, 50% silica, and 20% alumina had a poise of 29.0.
By adding 20% titania and maintaining the lime-silica ratio the poise was reduced to 12.5. 30% titania brought that down to a marginally fluid poise of 5.0 (Ohno and Ross 1963b:264-268).

They then took the slags and held them in graphite crucibles at a constant temperature. This simulated the environment in a modern blast furnace, where slag is held in the hearth for up to four hours in the presence of hot carbon (charcoal, coke, anthracite) before being tapped. Ohno and Ross found that the viscosity increased gradually over time, but the chemistry had to be carefully managed to maintain a free flowing slag beyond two hours (Ohno and Ross 1963b:269-275). Because the viscosity is a function of dwell time in the hearth, the effect would be even more pronounced in an 18th century furnace which was probably only tapped every 8 to 12 hours. What effect would this be, explicate.

A slag containing 50% Ti showed a gradual rise in viscosity when held at a specific temperature of 1450-1600°C. But the slag experienced a sudden increase in viscosity between 36 and 60 minutes, sometimes solidifying (Ohno and Ross 1963b:269-270). The mechanism for the thickening was not fully understood and was to be the subject of a future paper. However, it was theorized that it was caused either by the precipitation of titanium carbonitride or the polymerization of orthosilicate ions (Ohno and Ross 1963b:272).

Rosenqvist wrote that "the viscosity of a lime-silicate [blast furnace] slag is decreased by the addition of TiO2" (Rosenqvist 1983:312). But, he also wrote that "it is known that titania-rich slags on heating under strongly reducing conditions will thicken with the precipitation of solid phases" (Rosenqvist 1983:302).

Careful study of the other experimental results reveals that, like the Rosenqvist data, all the studies where titanium decreased viscosity and lowered the melting temperature were done in air (high oxygen potential) or in dry
nitrogen or argon. While all of the testing done under low oxygen potential conditions, like the reducing atmosphere in a blast furnace, found that as the concentration of titanium increased so did the viscosity and the melting (liquidus) temperature of the slag (Fine and Arac 1980: 165-66; Morizane et al. 1999:29; Rosenqvist 1983:302). Fine and Arac found that the melting temperature of a slag with 2% TiO₂ under reducing conditions, was as much as 100°C higher than predicted by the data determined in air or dried nitrogen or argon (Fine and Arac 1980: 165).

The mechanism for the changes in viscosity are still not entirely understood. While in modern furnaces the increase in viscosity is caused by the formation, and precipitation, of titanium carbonitride, carbide, and nitride; these compounds do not appear in 18th century blast furnaces. The high temperatures required, do not occur prior to the American introduction of hot blast furnaces in the 1840s. The Albemarle slag exhibits none of the characteristic bright copper colored titanium carbonitride crystals. A better explanation, especially in a cold blast charcoal furnace like Albemarle’s, is the differential behavior of titanium in air and under reducing conditions.

Under oxidizing conditions (in air) some of the TiO₂ breaks down into Ti⁴⁺ and O²⁻ ions. The addition of O²⁻ ions partially breaks up the silicate network and decreases the slag viscosity. But as the partial pressure of oxygen is reduced, more and more of the titanium appears as Ti²⁺ and Ti³⁺ ions and less O²⁻ ions are available. This effect is particularly pronounced in the presence of hot carbon (like Ohno and Ross’ graphite crucible), as would be the case in the vicinity of the tuyere(s) in a blast furnace. The rate of thickening was increased by the addition of titanium (Ohno and Ross 1963b:278). At an O₂ partial pressure of 10⁻¹⁵ atm most of the titanium will be Ti²⁺ and Ti³⁺ ions. These form lower or suboxides- TiO, Ti₂O₃, or Ti₃O₅, which are not as soluble as "normal" titanium.
compounds and form solid phases (Fine and Arac 1980:165-66; Rosenqvist 1983:302 and 312). This behavior may also explain the sudden increase in viscosity discovered by Ohno and Ross (1968:269-270). The slag slowly thickens because some precipitation of suboxides occurs from the beginning. But at the point the solution becomes supersaturated there is a sudden increase in the formation of solid phases and a corresponding rapid rise in viscosity and increase in melting temperature.

Dr. Christopher Salter, Oxford University, has identified at least five crystalline phases in the Albemarle slag that he has never before seen in iron slag. Part of the ongoing testing at Oxford is to determine the composition of the crystalline phases present in the Albemarle slag. Some of the compounds that cause problems in modern furnaces may not form in a cold blast charcoal furnace because of the lower hearth temperature. There may be others that do not form in modern blast furnaces.

**Titanium and Blast Furnace Operation**

These changes in the slag properties are not favorable for a blast furnace operation, since gas and liquid permeabilities inside the furnace are important aspects in the furnace operation, and since any difficulties in tapping the molten metal and slag out of the furnace could cause serious operational problems. Thus, the addition of titania bearing materials should be optimized to form a protection layer on the refractories without causing possible operational problems. [Morizane et al. 1999:29]

The use of titaniferous ore in a blast furnace can have both good and bad effects. On the one hand, titaniferous slag is deliberately created in Japan and Europe to increase hearth life (Burgo 1999:733; Dzermejko et al. 1999:239). However, even small quantities of titanium (over 1%) inhibits the operation of a blast furnace (Holden 1907: 405-407; E. T. Turkdogan, personal communication 1999) by altering the behavioral characteristics of the slag. Titaniferous slags have
been cited as the cause of scaffolding, bridging, hanging, slips, channeling, and gobbing up. If not controlled a highly viscous titaniferous slag will impede blast furnace operations. The immediate effect of using a titaniferous ore in a cold blast furnace is to reduce production by slowing down the process. It may also be difficult to tap and may increase fuel consumption. At the extreme, titaniferous slag can halt production, forcing the dismantling of the blast furnace, or even result in the destruction of the furnace.

In order for a blast furnace to produce cast iron the ore must be reduced to fluid metallic iron and it must pass through the slag bath so that it can be tapped out of the furnace. A viscous slag effects the reduction reaction through a number of mechanisms. The reduction reaction requires heat and a reducing agent (Chapter 3, pages 54-58 and 81-86). In the 18th century blast furnace both are provided by carbon monoxide gas (some reduction may occur through contact with hot charcoal) that forms in the vicinity of the tuyere(s). The hot carbon monoxide gas both heats and reduces the iron ore as it moves up the stack. Anything that impedes this flow slows the reaction, moves the reaction lower in the furnace stack, and slows the decent of the charge.

Because it drains out of the charge more slowly, a viscous slag plugs up the interstices and impedes the flow of hot gases up the stack. This slows the heat transfer and reduction reaction. Because the reaction is slowed, the reaction occurs farther down the stack. This can reduce the efficiency of the furnace because the ore is not reduced for as long. Some of the ore may reach the hearth unreacted.

The slag can also adhere to the furnace walls, redirecting the flow of gases causing channeling (page 181) or causing portions of the charge to stick to the wall. Both of these conditions promote scaffolding, hanging, or bridging (pages 174-180), and gobbing up (pages 180-181). All of these slow the descent of the
charge, and if not corrected the furnace will stop working or a slip (pages 179-180) will occur. Although not always catastrophic, a large slip can result in the forcible ejection of liquid iron and slag through the working arch or cause the furnace to explode. Both of these result in serious injuries or fatalities among the crew, production delays, costly repairs, and lost profit.

If the slag became so viscous that it would not tap or collected faster than it could be drained, it would eventually block the tuyere(s). This would choke off the blast and extinguish the furnace.

In order for the iron to be run out of the furnace, it first has to pass through the slag bath. The rate molten iron moves through the slag is dependent on its viscosity. Rostoker and Bronson demonstrated experimentally that it can take between 12 minutes and 7 hours for a droplet to move through 6 cm of slag (Rostoker and Bronson 1990:81). As the slag thickens, more and more iron is trapped and discarded when the slag is tapped. This decreases production.

If the slag is viscous enough, the blast furnace will stop working or freeze (page 181). Dr. E. T. Turkdogan thinks this is what happened at the Albemarle Iron Works during the winter of 1771-72. He feels a slag with the titanium concentrations at Albemarle could "not form a molten slag... and chokes up the entire operation" (E. T. Turkdogan, personal communication 1999). The only remedy for a frozen furnace is to let it completely cool off and then manually empty it with pickaxes, sledgehammers, and chisels. In some cases the stack must be torn down and entirely rebuilt.

The claim that titaniferous ores required uneconomical quantities of fuel is based on articles by David Forbes and William Bowron. Forbes reported that "The experience of the Scandinavian ironmasters has shown that the only objection to the use of titaniferous ores is... they require so much larger an amount of charcoal to smelt them as not to render their employment profitable in
a country where other ores, free from titanium, can be obtained at a reasonable rate" (Forbes 1869:70; and quoted in Bowron 1883:162-63). Bowron's paper was based on his own personal experience as a chemist for the Norwegian Titanic Iron Company (Norton, England).

The process, regarded as a process, was a perfect success; but the enormous quantity of fuel required, the small quantity of iron in the ore, and the cost and uncertainty of importation [the Norton furnace imported Norwegian ore] militated against its commercial success, and a few years saw the attempt abandoned. [Bowron 1883:159]

Two factors caused an increase in fuel consumption. The first was that

The whole secret of working these ores successfully and continuously is to keep the heat so low as to just reduce the iron and not reduce the titanic acid. [Bowron 1883:163].

Heating the air used to provide the blast in a blast furnace was a major contributor to fuel efficiency. The hotter the blast, the less fuel was consumed by the blast furnace. Operating at a reduced temperature meant an increase in fuel consumption.

However, the overriding cause of the high fuel cost in both Scandinavia (Forbes 1869) and at Norton (Bowron 1883) was not the titanium in the ore but the paucity of iron in the ore.

The poorer ores, such as contain so little as 35 per cent Fe, while the titanic acid [TiO2] reaches 38 to 40 per cent, in fact the ores which were smelted successfully at Norton, England (see Mr. Bowron's paper, Trans., xi, 159), might be fairly rejected on account of their leaness, as incapable of being treated with commercial success, at least in this country. But this judgment might be independent of any question of TiO2; an equal amount of silica [SiO2] taking its place would make the ores unacceptable to any ironmaster here.... at Norton, he used lean ores containing 35 to 36 per cent of Fe and, under these conditions, the consumption of fuel per ton of iron produced could not very well be attributed, at least not solely, to the presence of TiO2, but rather to the absence of iron. [Rossi 1893:840-841]
Any ore with this little iron, would require large amounts of fuel per ton of iron produced (Bowron 1883:159; Rossi 1893:840-841). This is the case because of the large amount of gangue that had to be heated to extract the iron.

In both instances the increased fuel requirement may have been the result of the low iron content (below 40% Fe) of the ore used. There is very little evidence that where two ores with equal iron content, but different amounts of titanium were smelted that the later required more fuel.

The consequences of using titaniferous ore were, at the least, decreased iron production. More serious problems could include lost production due to scaffolds or gobbing up, or the cessation of production by freezing the stack. The worst possible consequence, would be a major slip that caused crew fatalities or the explosive destruction of the furnace.

**Titanium and Bloomeries**

Because of the significant differences in the chemistry of bloomery and blast furnaces, titanium does not appear to significantly inhibit the operation of bloomeries. There are numerous examples from around the world of bloomeries successfully using titaniferous ores. Titaniferous sands were successfully smelted in Canada during the 19th century using the "American Bloomery" method (Greenwood 1902:224-225). Sands were also successfully smelted in Macedonia (Photos et al. 1984:113-120). According to Dr. David J. Killick, University of Arizona, there are numerous examples of African bloomeries successfully working titaniferous ores (personal communication 1999-2000 and van der Merwe and Killick 1979:89-93). Dr. Ingo Keesman, Johannes Gutenberg-Universitaet Mainz, has provided similar information concerning bloomeries in Sri Lanka and Settefilia, Spain. Dr. Keesman did note that the titaniferous slags
exhibited fairly high viscosities due to "crystalline phases in the melt even under the highest reducing conditions and normal temperatures somewhere around 900-1100 degrees" (personal communication 1999-2000). Closer to home, David Harvey's reconstruction bloomery in Williamsburg used a titaniferous bog ore (personal communication 1999).

**Remedies**

Iron making was not a science in the 18th century. Problems were solved by trying variations on known solutions until it worked. There was very little innovation. It was partially for this reason that it took so long for the use of coke, anthracite, and hot blast to replace the tried and true cold blast charcoal furnace. Even though the 18th century ironmaster was severely limited in his options, a number of remedies for the problems associated with titaniferous ores were available. These included avoidance, varying furnace heat, and changing the mix of raw materials charged into the blast furnace.

The most obvious remedy was to avoid using titaniferous ores. This was the preferred solution in England and the United States. Very few furnaces during the 19th and 20th centuries chose to use titaniferous ores. It was this avoidance of titaniferous ores that prompted William Bowron (1883) and Auguste Rossi (1893) to write their papers. They felt that a large amount of valuable ore was needlessly excluded by the iron industry.

But, if titaniferous ores could not be avoided, what actions could be taken to remedy the preceding conditions? One option was to alter the operating temperature of the furnace. The behavior of slags is largely temperature dependent. By the 18th century it was understood that higher temperatures
make a slag more fluid and cooler temperatures makes it thicker.

The temperature inside a modern blast furnace can be varied through a number of techniques (fuel ratio, blast volume, injection of fuel, or an oxygen lance). Not all of these were available in the 18th century. Pure oxygen was unavailable for the oxygen lance. Likewise the technique of injecting natural gas or a liquid fuel was not developed until much later. An 18th century ironmaster could only vary the ratio of fuel in the charge or manipulate the volume of air injected in the blast. The amount of control he had and the amount of change he could achieve was relatively minor. 18th century blast furnaces were low pressure so an ironmaster could not significantly increasing the volume of air injected in the blast. As a result the difference in temperature was probably less than 200°C. Fine and Arac found that concentrations of as little as 1% titanium raised the melting temperature of blast furnace slag by 100°C (Fine and Arac 1980:166). The Albemarle slag exhibited TiO₂ levels an order of magnitude higher.

Increasing the ration of charcoal charged into the furnace also raised the temperature. But again the temperature gains possible in a cold blast furnace are not very great. Stoughton (1908:419) did not think that high enough temperatures were possible to overcome the slag problem until the introduction of the electric furnace in the 1st quarter of the 20th century.

Another potential problem stems from the law of unintended consequences. While generally speaking raising the operating temperature of a blast furnace increases slag fluidity, it can also alter the chemical composition of the slag and even of the iron produced. In the case of titaniferous slags, higher temperatures reduce more titanium and promote the formation of lower oxides. The metallic titanium readily combines with the iron. However, the titanium compounds can rapidly saturate the slag and begin to precipitate out. This has
little effect on the quality of the iron, but turns the slag into a highly viscous slurry. Higher temperatures also cause the formation of nitro-cyanide of titanium which builds up in the hearth and decreases iron output. Again there is no evidence that a cold blast charcoal furnace can achieve high enough temperatures to reduce significant amounts of titanium or form nitro-cyanide of titanium. However, Dr. Christopher Salter, Oxford University, has identified at least five crystalline phases in the Albemarle slag which he has never seen in an iron slag. Until testing is completed, exactly what these are remains unknown.

Where these ores have been tried in furnaces that were smelting other ores of a non-titaniferous character, and difficulties have been caused by their hanging and beginning to build on, relief has usually been sought by increasing the heat, and, after considerably annoyance, the ore has been discarded. The whole secret of working these ores successfully and continuously is to keep the heat so low as to just reduce the iron and not reduce the titanic acid. [Bowron 1883:163]

William Bowron addresses two issues in this quote. The first is that as late as 1883, ironmasters are still trying to work through problems by the tried and true methods. So when confronted by the problems caused by titaniferous slags, they immediately raised the blast furnace temperature. The second point is that increased heat doesn't work. In most cases, ironmasters then abandoned the ore. Bowron, and a small number of other ironmasters, found that "the whole secret of working these ores" required them to abandon the traditional solutions. The technique he advocated was called "slow driving" (a furnace that was pushed to maximize production was driven "hard"). While this might have worked, it was diametrically opposed to furnace practice of the day, self interest, and common sense. Also many ironworkers were paid by the ton. Deliberately slowing the furnace down would have decreased their pay. William Twaddell's job was to produce as much iron as possible, there was no reason for him to gamble that slowing the furnace down would achieve the desired result. It made no sense.
In a trial and error system it is rare for someone to do the opposite of accepted practice. A classic example of this was the resistance to and slow acceptance of hot blast. Everyone knew that blast furnaces operated better in winter. Everyone also knew this was because the air was colder. So hot blast couldn't possibly work. But the real reason that furnaces work better in winter is because of the lower moisture content of the air, not its temperature.

The final way to effect the operation of the furnace was to vary the mix of raw materials charged. Changing the ratio of fuel (charcoal) has already been discussed. The only other alternative was to alter the flux, either in terms of quantity or the type used. Here again an 18th century ironmaster had a limited number of options. By the 1770s it was understood that a blast furnace needed a source of lime to work properly. A variety of materials were used including limestone, dolomite, marble, gabbro, shells, and burned lime. Confronted with a sticky slag, the first response would be to increase the amount of flux charged. If that didn't work, an ironmaster might try decreasing it, or changing to a different lime source. In fact when confronted with slag viscosity problems this is exactly what Forbes tried. He "used lime as a flux, and probably went to the other extreme [increased amounts], with the object of slagging off the titanic acid as titanate of lime" (Forbes quoted in Bowron 1883:163). It didn't work.

It is extremely unlikely that any 18th century ironmaster would have tried the unorthodox fluxes developed by Forbes, Bowron, Rossi, and the Tahawus furnace. Their flux solutions were the subject of papers in the 1880s and 90s because they were unorthodox. They solved a problem, the use of titaniferous ore, that had been a concern of the iron industry for years.

In all three cases additional silica was charged as well as lime. David Forbes developed a flux that included not only limestone, but also stamped quartz. "This was found to give very satisfactory results in practice, and when
the amount of titanium in the ore did not exceed 8 per cent" (Forbes 1869:70). In the 1870s William Bowron charged his hot blast furnace in Norton, England with ore, limestone, coke, red bricks, and basalt (Bowron 1883:160). The Tahawus Furnace (1840 to 1856) used an ore that had only 1% silica content. But, slag taken from the site contained 27% silica. Clearly, like Forbes and Bowron, Tahawus charged its furnace with something high in silica (Rossi 1893:835-46). Interestingly, the Tahawus slag is visually very similar to that found at Albemarle (personal communication 2001 Dr. Gordon Pollard, SUNY Plattsburgh).

Rossi performed a series of experiments which he published in 1893. He found that fully fluid titaniferous slags could be achieved through chemical manipulation. Additions of alumina, magnesia (MgO₂), and silica were used (Rossi 1893:846-64). Although these unorthodox fluxes were available to William Twaddell, given prevailing furnace practice in the 1770s, there was no reason for him to suspect that they offered a solution. They went against everything 18th century ironmasters knew about how to properly operate a blast furnace.

Today titaniferous ore is smelted not for iron, but for titanium. It is worked by companies that specialize in titanium, not iron and steel companies. Iron is a byproduct. Interestingly TiO₂ or titanium is sometimes deliberately added to a blast furnace charge to create a sticky slag. This slag coats the walls of the furnace and increases furnace life by decreasing erosion due to smelting operations (Dzermejko et al. 1999:239).
Figure 38. Albemarle slag, exterior. Photo by author.
Figure 39. Albemarle slag, interior. Photo by author.

Figure 40. Albemarle slag, interior showing iron prills. Photo by author.
CHAPTER 8: Albemarle Slag Analysis

Slag analysis played a central role in the two primary goals of this paper—showing that titanium was responsible for the failure of the Albemarle Iron Works and that the ore came from the Martin Mine. In order to do this it was necessary to prove that the furnace used a titaniferous ore, and that the amount of titanium present would have adversely effected the operation of the furnace, and that the ore came from the Martin Mine. This was accomplished by collecting samples of slag from the furnace site, subjecting them to detailed elemental analysis, determining the effect this would have had on the blast furnace’s operation, and comparing the elemental analysis to Dagenhart and Maddox’s 1977 chemical analysis of the ore.

Three samples were collected from the bed of the creek adjacent to the ruined furnace stack. They were subjected to PIXE (particle-induced x-ray emission) at the University of Delaware, SEM (scanning electron microscope energy dispersive X-ray) analysis at the University of Bradford (UK), and two thin sections are undergoing analysis at Oxford University (UK).

Blast furnaces normally produce a glassy slag (Chapter 7, pages 193-199). Repeated searches of the Albemarle site by the author, T. T. Brady, and William Reynolds turned up no glassy furnace slag. In the creek, at the foot of the remains of the furnace stack, are two 3' diameter salamanders or bears. These were created at the end of a blast. A Salamander is made up of any iron and slag that could not be tapped and any remaining partially reacted portions of the charge. The creek, extending from the furnace ruins downstream for 500', is full of accreted masses of slag, ore, charcoal, and metal.

Although blast furnace slags appear relatively homogenous, they are somewhat variable. Visual examination of the slag piles associated with 18th and
early 19th century blast furnaces shows a wide variety of colors and textures. However, with a few exceptions, most of the slag is "glassy". And while careful searching of a slag heap usually reveals a variety of colors, most of the slag at a given furnace will be one color. This is not true of the three samples from the Albemarle Iron Works (Figures 40, 41, and 42). The wild divergence; in terms of color, texture, and iron inclusions; supports the argument that something was wrong with the process at the Albemarle Iron Works.

Table 6. PIXE Analysis of Albemarle Slag

| Sample # | 1 | 2 | 1a | 1b | 1c | 2 | 7 | 8 |
| Ref #     | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| glassy     | glassy | matte | matte | matte | matte | matte | grey | grey |

| MgO   | 0.76 | 1.29 | 1.04 | 0.92 | 1.39 | 1.14 | 0.96 | 1.54 |
| Al₂O₃ | 2.16 | 3.84 | 2.64 | 1.97 | 2.99 | 2.98 | 3.11 | 4.18 |
| SiO₂  | 20.37| 32.47| 22.48| 19.22| 23.15| 22.68| 27.11| 36.36 |
| P₂O₅  | <0.15| 0.17 | 0.23 | <0.13| <0.20| <0.16| <0.15| <0.21 |
| SO₃   | 0.69 | 0.16 | 0.81 | 0.33 | 0.12 | 0.08 | 0.08 | 0.21 |
| K₂O   | 2.16 | 2.06 | 2.17 | 1.79 | 1.59 | 2.59 | 2.48 | 2.49 |
| CaO   | 24.69| 18.65| 256.52| 30.62| 30.18| 29.78| 24.06| 21.43 |
| TiO₂  | 27.07| 35.86| 28.27| 18.25| 28.15| 27.99| 37.35| 36.34 |
| MnO   | 0.60 | 0.51 | 0.17 | 0.54 | 0.45 | 0.37 | 0.82 | 0.55 |
| Fe    | 20.89| 4.53 | 15.39| 24.40| 9.17 | 11.28| 3.30 | 3.21 |
| CuO   | 0.12 | <0.01| 0.12 | 0.17 | 0.17 | 0.01 | 0.14 | <0.01 |
| ZnO   | 0.02 | trace | 0.12 | 0.17 | 0.17 | 0.01 | 0.14 | <0.01 |
| Rb₂O  | trace| 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| SrO   | 0.09 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| Y₂O₃  | 0.10 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| ZrO₂  | 0.24 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |

Total 100.0 100.0 100.0 100.0 100.0 100.0 100.0 100.0
Normalized as oxides, % by weight. Iron is present as metallic prills.

Although indicative of problems, visual macro examination could not establish the chemical composition of the Albemarle slag. The three slag samples
(Figures 40, 41, and 42) were analyzed by Dr. Charles P. Swann of the Bartol Research Institute at the University of Delaware, Newark using PIXE (particle-induced x-ray emission) spectrometry. Nine runs were performed on the three specimens. Eight were conducted on the slag matrix and contained between 18 and 37% titania (TiO2). The ninth run was on a prill of metallic iron (Tables and Figure 40).

PIXE spectroscopy at Bartol makes use of an in-air (or helium) system which allows for the analysis of objects of almost any size or shape. The analysis is non-destructive, but a clean surface is required. The sample is bombarded by a stream of protons generated by an HVEC AN 2000 Van de Graaff accelerator. The energetic charged particles remove electrons from the atomic configuration of each element present. As the electrons return to fill vacancies, photons are produced. The highest energy of which are characteristic of the element involved. For the study of iron two measurements are made. The first at a proton energy of 1.3 MeV. A flow of helium surrounds the beam extraction hole (500um), the sample under study, and the entrance window of the cryogenically cooled Silicon (Lithium) x-ray detector. This allows analysis of the elements from magnesium to iron. The second measurement makes use of a 2.0 MeV proton beam and an x-ray filter of vanadium backed by aluminum. The non-linear character of the absorption of this filter drastically reduces the intensity of the iron x-rays. This allows for a large increase in the proton beam current for the observation of the x-rays resulting from the heavier elements. These include Cu, Zn, Zr and Pb. PIXE cannot discern molecular structure, only the elements present. It is also unable to detect carbon, which is important in iron analysis.

Dr. Gerry McDonnell of Bradford University's Ancient Metallurgy Research Group performed SEM (scanning electron microscope energy dispersive X-ray) analysis on samples one and two. Ten runs were performed on
two samples (Table 7) and three on metallic prills of iron (Table 8). The results again showed high concentrations of titania (TiO2) in the slag (8.0-95.3%). The 95.3% result is probably from a crystalline form of titanium like rutile.

Table 7. SEM Analysis of Albemarle Slag

<table>
<thead>
<tr>
<th>Sample #</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>2</th>
<th>2</th>
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<td>15</td>
<td>16</td>
<td>18</td>
<td>19</td>
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<tr>
<td>Na2O</td>
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<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.1</td>
<td>0.8</td>
<td>1.5</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>MgO</td>
<td>3.0</td>
<td>2.9</td>
<td>3.5</td>
<td>3.1</td>
<td>0.6</td>
<td>2.5</td>
<td>3.7</td>
<td>4.1</td>
<td>3.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Al2O3</td>
<td>5.9</td>
<td>5.8</td>
<td>8.8</td>
<td>6.4</td>
<td>0.7</td>
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Additional analysis is being performed on two thin sections by Dr. Geoff Grime and Dr. Christopher Salter of Oxford University's (UK) Materials Science-Based Archaeology Group using a variety of instruments including PIXE and the JXA-8800 Superprobe. This analysis is incomplete, but has already produced important results. The Oxford team has determined that almost all of the iron is present as metallic prills. SEM showed that less than 0.3% is an oxide and that may well be an artifact of post smelting oxidation of metallic prills. One narrow beam PIXE run showed approximately 20% TiO2, but only 0.2% Fe. This, and other data, confirms that the slag is from a blast furnace. The extreme reducing conditions indicated were not possible in either a bloomery or finery forge. Using Rutherford Backscatter (RBS), Oxford has confirmed the Bradford data, the iron
prills contain carbon in concentrations consistent with cast iron (2-4%). They have also identified prills of gray cast iron with the characteristic graphite flakes (Figure 41). Dr. Salter has also identified at least five different crystalline phases that do not normally occur in iron slag. Their chemical makeup and the melting temperature of the slag are goals of future analysis.

There are differences between the data generated by PIXE and SEM. For instance PIXE shows TiO₂ concentrations of 18-37%, while the SEM found 8-95%. The iron content in the PIXE runs performed at Delaware show 3.21-24.4% Fe, while the Bradford SEM and Oxford PIXE showed under 3.6%. The data variance between SEM and PIXE is normal and is due primarily to differences in the two sampling techniques. It was also not possible, given the distance between the labs, to get the same spot on each sample analyzed. The results do not, and should not, match. The Albemarle slag, like most iron slags, is not homogenous and varies considerably even within a given sample. SEM uses a fairly narrow beam and can sample discrete spots, whereas PIXE uses a wider beam (up to 1mm) and is sampling all the components of the slag. The SEM TiO₂ reading of 95.3% was a TiO₂ crystal. PIXE shows more Fe (iron) because the beam width made it impossible to avoid the prills of metallic iron scattered throughout the samples. Another factor is that SEM samples only the surface, where PIXE can detect iron and titanium at depths of up to 50um. Again this increased the amount of iron picked up by PIXE.

The slag analysis confirms most of the predicted behavior of titaniferous ores. As expected, most of the titanium was incorporated into the slag (Francis 1940:285; Greenwood 1902:73 and 208; Morizane et al. 1999:29). While the slag matrix shows TiO₂ concentrations of 8-95.3%, the metal prills have less than 1% Ti. The opposite is true for phosphorus (P), most being taken up by the iron in the prills. The slag matrix shows 0.3% or less, while the iron has concentrations of 1.0-2.6% P.
Figure 41. Electron micrograph of Albemarle Iron Works' gray cast iron. Courtesy of Dr. Christopher Salter, Oxford University.
Table 8. Analysis of Iron Prills

<table>
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<tr>
<th>Sample #</th>
<th>Description</th>
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</tr>
</tbody>
</table>

Carbon (C) could not be measured by PIXE

The high viscosity of the slag should have slowed the descent of the cast iron through the slag bath, entrapping more of it as prills (Rostoker and Bronson 1991:). This was confirmed both on the macro (Figure 40) and micro (Figure 41) level. The slags contain abnormally large number of metallic prills. Finally there is an excellent match between the elemental analysis of the slag and that performed by Dagenhart and Maddox (1977) on the Martin Mine ore. The Martin Mine ore contained eight primary minerals (Table 4, page 143): magnetite (Fe₂O₄), ilmenite (FeTiO₃), Apatite (the source of the phosphorus), biotite, hornblend, zircon, and garnet. The apatite also contained up to 3.5% rare earths. The analysis of the slag showed the presence of all of the elements present in these eight minerals except fluorine (F). PIXE cannot detect fluorine (F) because it is blocked by the detector window. Also fluorine will form F₂O, a gas, which is exhausted up the furnace stack during smelting. PIXE did detect sodium (Na), but it was below the detection limits and was eliminated when the data was normalized. The slag also contained yttrium (Y), a rare earth; and between 8 and
95.3% titania (TiO₂).

The Martin Mine is the only known source of highly titaniferous ore in the area. Coupled with the trace element match between the ore analysis and the PIXE and SEM, it is virtually impossible for the slag found at the Albemarle Iron Works to have been produced from any other ore.

The slag analysis reveals other information about the operation of the furnace and conditions in it. Silicon (Si) reduces at a temperature between that of iron and titanium and is a good indicator of hearth temperature (Burgo 1999:731). Albemarle's silicon level, and therefore hearth temperature, is comparable (0.5-1.3%) to a series of analysis on European cast iron from 1547-1702 (Awty 1996:18). It is below those reported by Percy in the 1860s for titaniferous pig (1.86-3.55%, Percy 1864:532-551) and considerably below the 3-5% Si reported by Campbell in the early 1900s (Campbell 1907:81). This data clearly indicates that the Albemarle blast furnace operated at "normal" temperatures. Theoretically, this would preclude the formation of nitro-cyanide of titanium and other titanium compounds.

While bloomery slags can be as much as 70% iron oxide, there is very little iron (0.1-21%) in the Albemarle Iron Works slag (Tables 6 and 7). The ongoing analysis at Oxford has already confirmed that all of the iron is present in the metallic prills. What little iron oxide is present, appears to be due to post smelting oxidation of the prills. It is not present as fayalite. This confirms that the slag is from a blast furnace and that the conditions within the furnace were highly reducing.
CONCLUSION

The Albemarle Iron Works was "stopd" (Wilkinson 1792) in May of 1772. On June 4th the partners met at Blenheim, Edward Carter's home, and agreed to shut down the iron works (Wilkinson 1774a, 1792). Wilkinson was retained to run the mills, and did so for a number of years.

Why was the Albemarle Iron Works Albemarle "carried on at a very great expense and never produced any profit" (Walker 1791)? Although Rev. Woods, Dagenhart, Maddox, and Reynolds all correctly identified titanium in the ore as the reason for the Albemarle Iron Works failure, none understood the mechanism. Woods simply proposed that some "foreign ingredient" was responsible (1901 and 1932:56-57). Dagenhart and Maddox concluded:

Smelting titaniferous ore requires much more wood and charcoal to charge the furnace than pure iron ore, and the resulting iron-titanium alloy is very difficult to work. [Dagenhart and Maddox 1977:362]

But, wood is not used in smelting and the higher fuel requirements for titaniferous ores are not due to the titanium. Any ore with a similar iron content would require the same amount of fuel. And contrary to their statement, historic documents show that there was no stigma attached to titanic iron. In fact it was sought after and garnered praise for its high quality. It is clear that Reynolds was not a metallurgist and accepted Dagenhart and Maddox's argument on the role titanium played in Albemarle's failure. He wrote:

The latter [titanium] made the magnetite difficult to smelt successfully, requiring large amounts of charcoal and flux. The resulting pig iron was difficult to work and would have not found a ready market. [Reynolds 1992:56]

From the existing documents it is apparent that the Albemarle Iron Works
had problems. But, beyond the references to money shortages in Twadell’s two letters, the cause of the companies' failure was not spelled out. The failure of the company and the ensuing protracted lawsuit resulted in a great deal of name-calling and finger pointing, but the documents were short on specifics.

Two common threads, however, were shortages of money and managerial skill. Assuming the owners were justified in replacing Wilkinson, three managers and two ironmasters in less than a year had to adversely affected operations. But, was money and management the entire story?

What part, if any, did site selection play in the failure? John Wilkinson and John Old took seven years to settle on the furnace site. How well or how poorly did they understand the selection criteria? The company had a number of obvious potentially serious problems. These included: management turmoil, the partners' tight monetary policy, lack of blast furnace experience, ore with a high phosphorus content, and titaniferous ore. Each and every one of these problems exacerbated the Albemarle Iron Works' operational difficulties. But, was the collapse precipitated by any one factor? Or was it caused by the confluence of problems?

**Site Selection**

A great deal of effort went into the discovery and evaluation of potential furnace sites. The essential elements required for a successful ironworks were understood and this knowledge was applied to the Albemarle Iron Works site selection process (see Chapter 5). The seven years that John Old and John Wilkinson devoted to site selection was not excessive. It is clear from the care they exercised in both site selection and forming the Albemarle Iron Works partnership that they understood that in order for the furnace to succeed they
had to ensure the availability of raw materials (iron ore, flux, and charcoal), sufficient water power, and access to markets. How well they did this could have a profound effect on the viability of their company and their personal fortunes.

Although the Albemarle site was not perfect, it does not appear that Old and Wilkinson made any fatal site selection decisions. There were ample quantities of raw materials (iron ore, flux, and charcoal) available to operate the furnace for years. The water power available from the South Fork of the Hardware River was more than adequate to power the blast furnace and exceeded the flow available at most of Virginia's 18th century iron works. And although not ideally placed, the Albemarle Iron works should have been able to access both the local and distant markets through a network of roads and via the James River. Site selection did not cause the failure of the blast furnace.

Leadership Problems

As stated earlier (Chapter 4, pages 100-112), documentary evidence shows that the Albemarle Iron Works had up to four managers in less than a year. Initially John Wilkinson, one of the partners, was charged with repairing the mills and building the iron works. He was replaced on 18 July 1771 by John Swan, but possibly only to manage finances. William Twaddell took over on 17 September, probably finished the blast furnace, and operated the works until he was let go in May of 1772. After the partners agreed to permanently shut down the furnace on 4 June, Wilkinson was again placed in charge of the mills. He continued to operate the mills until at least 3 August 1788.

This kind of turmoil at the top must have adversely effected the operation of the Albemarle Iron Works and its milling operations. But, was it the proximate cause of the blast furnace's failure?
Very seldom does a company transition seamlessly from one management team, or leader, to another. Every change of leadership initiates a period of turbulence. Most companies weather the storm and continue to operate. But, in some instances changes in management prove fatal.

The amount of disruption ranges from minor and short term to catastrophic, and is often directly related to the amount of "change" the new leader represents. The least disruption usually occurs with planned transitions. The successor is from inside the company and is "groomed" for the job by the outgoing leader. Here, although the leadership "style" may be different, the new leader is already part of the company and well acquainted with the "company way". A "groomed" replacement is also likely to have a similar corporate philosophy or "vision".

The forced replacement of a company's leadership is always disruptive. The new leader has a much steeper learning curve as s/he does not know the company, the workers, etc. Unless the company has been so badly mismanaged that there is no loyalty to the outgoing leader, there will also be residual loyalty and worker resentment to overcome.

The worst possible situation is that where the head of a company is forced out, but remains on site. Here not only does the new manager have to learn the ropes and return the company to functionality, but also contend with the active interference of the old leader. This was what happened at the Albemarle Iron Works. Although John Wilkinson was removed as manager of day to day operations, as a partner he was still very much present. If his affidavit (Wilkinson 1792) accurately portrays events, Wilkinson was not silent during William Twaddell's tenure as ironmaster. The implication of the affidavit is that Wilkinson was not only opposed to his replacement by Twaddell, but also was not shy about expressing his low opinion of his replacement. In the absence of
documents, one can only speculate on the effect this had on Twaddell's ability to run the iron works. The relationship with Wilkinson was certainly not cordial and the active opposition of one of the partners must have had an adverse effect on operations.

Although they certainly exacerbated the company's problems, leadership problems were unlikely to have precipitated Albemarle's failure. One compelling reason being that the blast furnace was only in operation under one of the managers, Twaddell. If neither Swan nor Wilkinson operated the blast furnace, they cannot be held responsible for its failure. It is possible that interference by Wilkinson aggravated the company's problems. But, the two surviving letters from Twaddell mention a number of issues, none of them named John Wilkinson. Had Wilkinson been a significant thorn in William Twadell's side, he should be mentioned. However, where leadership turmoil may not have caused the company to fail, the lack of blast furnace experience on the part of the company's leadership may have played a role. This has already been discussed in Chapter 4 (pages 96-97 and 103-112) and its effect on furnace operations is discussed below.

**Monetary Policy**

A blast furnace, in terms of both initial investment and operating expenses, was one of the most expensive undertakings of the colonial era. An iron works cost thousands of pounds to build and thousands more to operate. It consumed tons of raw materials every day and had a large crew. Each and everyone of whom required food, clothing, shelter, and pay. The use of slave labor, common throughout the British North American Colonies, decreased the payroll, but increased the start-up cost of a blast furnace complex. Albemarle
used slaves (see Twaddell’s 1772). All of this required money or goods to barter. By the late 18th century because of the amount of money required to operate a blast furnace, it was not uncommon for the man in charge to be a business manager rather than an expert on iron making. For instance Cornwall Furnace in Pennsylvania frequently had a manager (ironmaster), company clerk, and two founders who actually ran the furnace (Miller 1951:94-100).

Initially John Wilkinson managed both operations and finances for the Albemarle Iron Works. After only six and a half months the other partners hired John Swan to transact all business for the company. Two months later, in September 1771, the company hired William Twaddell as ironmaster and, based on the information in his two letters, to manage the both the mills and the iron works.

However, it is clear from his two letters that the partners kept him on a tight financial leash. He complained about "the want of Money at the Works" in both. In the October letter (Twaddell 1771) reported that he ran out of beef for the workers and got seventeen head of cattle with a draft on one of the owners. He also reported that "we are in great want of some to pay for Several Articles now wanted". In the January 1772 letter (Twaddell 1772) he was primarily concerned with the mill and sawmill, but mentions that he was still "very much in want of some [money]."

There is no way to know what the "Several Articles now wanted" at the furnace in October 1771 were, or why Twaddell needed money in January 1772. It could have been additional material needed to complete the furnace or the mills or raw materials to put the furnace in blast. In an event, the tight money policies of the owners clearly impeded Twaddell’s ability to efficiently manage the works. Delaying the initial blast because of a shortage of material or not running the mills meant that the company was not producing products and was
not making money. Starting and stopping the blast furnace would also lower the company’s profitability. But, unless the works were more out of production than in as a result, neither would cause the company to fail.

Furnace Experience

A problem that may have contributed to the company’s failure was a lack of blast furnace experience. With the exception of John Old and John Wilkinson, none of the partners were from iron families, they were merchants and planters.

The surviving records indicate that Wilkinson, Old, and the man hired to manage the furnace, William Twaddell were associated with or worked in forges, not blast furnaces. This is not to say that they were totally ignorant of blast furnace operations. Finery forges relied on blast furnaces for the pig iron they fined, and all of these men knew blast furnace operators and had business dealings with them.

However, Wilkinson must have known something about blast furnaces. Because the partners put him in charge of construction and managing Albemarle's furnace when it was completed. It may be that the other partners found more than just his financial skills wanting, because he was replaced first by Swan and then Twaddell. The company must also have had some reason to expect Twaddell to be able to manage the blast furnace, or they would not have hired him.

Given the dearth of documentation, an evaluation of Twaddell’s abilities as a founder and ironmaster cannot rest solely on documented expertise. The evidence of the 16 January 1772 letter is more compelling. Releasing the woodcutters after they had cut only 155 cords of wood (Twaddell 1772) demonstrates that Twaddell thought like a forgeman and not a founder. This
amount of wood, while enough to run a forge for a year, would fire a blast furnace for only a couple of weeks. An experienced ironmaster would have cut more wood.

Wilkinson, Old, and Twaddell must have though they had the requisite experience to operate a blast furnace. And if the Albemarle furnace had not encountered problems, they may have been correct. But, with the slag as a silent witness, they did have serious problems. There is no glassy blast furnace slag on the site. This is clear evidence that the furnace never operated properly. When things went wrong Twaddell tried to fix them, but failed. It may be that given the limitations of 18th century cold blast furnace technology, that there was no solution. It may be that if Twaddell, Wilkinson, or Old had more blast furnace experience they might have found a solution.

**Phosphorus and Cold Short Iron**

Dagenhart and Maddox identified substantial amounts of apatite, which contains phosphorus, in the Martin Mine ore. They concluded that the phosphorus contributed to the failure of the Albemarle Iron Works and later Andrew Hunter's iron mine.

Analysis of the entrapped iron prills, conducted by the University of Bradford and University of Delaware (Table 8), shows that they contained 1.0-2.6% phosphorus. Only one of the Oxford runs was performed on a metal prill. While it showed a lower level of phosphorus, it still showed 0.68%.

Phosphorus is beneficial in foundry irons (pages 188-191). But, anything above 0.2% causes the iron to become increasingly cold short (brittle at room temperature). Based on the analysis of the prills in the slag, the iron produced at Albemarle would have been acceptable for casting decorative ironwork. But that
market did not develop until well into the 1800s, and the blast furnace at South Garden was built primarily to provide pig iron for fining into wrought iron. Assuming the limited test regime conducted on the Albemarle slag is representative what the furnace could have produced, the high levels of phosphorus would have made Albemarle's iron so brittle that it would have been useless as wrought iron. Any finery purchasing Albemarle iron, or a blacksmith or forge purchasing wrought iron made from Albemarle pig, would not have made the same mistake twice.

The importance of phosphorus was well understood by the time Andrew Hunter reopened the mine after the Civil War. Very few iron works would have been interested in buying a high phosphorus ore. But the phosphorus was contained in apatite which was a constituent of the biotite-nelsonite. By the 1870s it may have been possible to segregate this mineral and avoid most of the titanium and phosphorus contamination. Today magnetic separation of the ore, and other techniques, would allow the removal of all of the unwanted impurities.

But to say, as did Dagenhart and Maddox, that the phosphorus content of the ore was a factor in the failure of the Albemarle Iron Works and Hunter's mine presupposes that Albemarle made iron and that Hunter made a serious effort to sell the ore and that the geologists he used could not tell magnetite from ilmenite or biotite-nelsonite. Admittedly the documentary record is limited, but there is no evidence of either. No documents, found to date, show that Albemarle had problems with iron quality or even produced any iron. And Hunter in his 1873 letter clearly indicated that high transportation costs were his primary problem. His preferred solution was to build a blast furnace at the mine. It is reasonable to assume that the mine's failure was due not to ore quality, but to Hunter's inability to raise enough money to build an iron works in North Garden and the
high cost of transporting the ore to other furnaces.

However, had the Albemarle Iron works been able to produce iron in the 1770s, they would have had considerable difficulty selling it because of the phosphorus. If Andrew Hunter built a blast furnace and was unable to segregate the magnetite, the iron produced would only have been good for castings. In both cases the high phosphorus content would have rendered the iron unacceptably brittle.

However, it is possible that given 19th century advances in both metallurgy and geology that Hunter might have been able to produce low phosphorus iron. The phosphorus in the Martin Mine was present as apatite in the biotite-nelsonite. Recognition of this could have resulted in a sorting process that eliminated the phosphorus bearing ore.

**Titanium, the Ruination of the Albemarle Iron Works**

The PIXE and SEM analysis of the Albemarle slag proved the blast furnace used a titaniferous ore. It also confirmed that the ore could only have come from the Martin Mine (see Tables ). While most of Virginia's iron ores contain trace amounts of titanium, higher concentrations are usually very localized (Watson and Taber 1913). The ore at the Martin Mine contains 6.53% TiO₂ (Bowron 1883:162, Pumpelly 1886:263), meeting both Rossi's (1893:842) definition of a "highly titaniferous" ore (at least 6% TiO₂, titania) and Poveromo's (1999:570) of a titaniferous magnetite (exceeds 2% titanium). The Martin Mine is the only known source of titaniferous ore in the vicinity of the Albemarle Iron Works. The amount of titanium in the slag, and the structure of the slag demonstrate that it had a high viscosity and caused the failure of the furnace. The only solutions available to alleviate the high viscosity, high temperature or high silica flux, were
either not available to an 18th century blast furnace or unlikely to be discovered.

Earlier authors identified that the Albemarle Iron Works’ and Andrew Hunter’s problems stemmed from "some foreign ingredient [in the ore] which impairs its utility" (Woods 1901 and 1932:57). Dagenhart and Maddox concluded that it was titanium in the ore that was the problem.

the titanium and phosphorus impurities in the ore have precluded extensive production. [Dagenhart and Maddox 1977:360].

titanium is not so innocuous. Smelting titaniferous ore requires much more wood and charcoal to charge the furnace than pure iron ore, and the resulting iron-titanium alloy is very difficult to work. [Dagenhart and Maddox 1977:362]

Reynolds wrote:

The Cook Mountain ore used in the Albemarle Iron Works furnace was magnetite containing high levels of titanium. The latter made the magnetite difficult to smelt successfully, requiring large amounts of charcoal and flux. The resulting pig iron was difficult to work and would have not found a ready market. It is therefore likely that the efforts of Twaddle, Wilkinson, and Old were unsuccessful commercially due to the poor quality of the ore. [Reynolds 1992:56-57]

While they identified the cause of the problem, they did not understand the mechanism. In fairness, none are metallurgists. Dagenhart and Maddox were geology students, while Reynolds is an historian. All were trying to explain why the Albemarle Iron Works could not deal with the titanium in the ore (W. Reynolds, personal communication 2001). To a large extent Reynolds was following Dagenhart and Maddox’s lead.

Both conclusions appear to be a misreading of Forbes (as quoted in Bowron) and Bowron (1883). Forbes wrote:

and if much titanium is present they require so much larger an amount of charcoal to smelt them as not to render their employment profitable in a country where other ores, free from titanium, can be obtained at a reasonable rate. [Bowron 1883:162-163]
The key to this passage is that the higher fuel cost was not due to the titanium, but to the low concentration of iron in the ore. This is much clearer in Rossi (Bowron 1883:162; Rossi 1893:840-841). Any ore with this little iron would have required a similar amount of fuel. While the Martin Mine ore was not "pure" iron ore, it had as much or more iron (52.5%) as many other Virginia ores (pages 130-148). As a result, the problem at Albemarle was not due to abnormally high fuel consumption.

Bowron never wrote that titanic iron was difficult to work. He wrote that "Titanic iron is essentially a forge iron. Foundry iron can only be produced when titanium is low..." (Bowron 1883:163-164). Dagenhart and Maddox took this statement and the modern knowledge that titanium-steel is extremely hard and appear to have extrapolated that an iron-titanium alloy must also be extremely hard and difficult to work. But 18th century blast furnace technology did not allow for the high temperatures necessary to reduce titanium in quantities that would have had any effect on the iron. The PIXE and SEM analysis shows that both titanium and silicon made up less than 1% of the composition of the metallic prills (Table 8), confirming the low temperatures in the Albemarle blast furnace. Similar amounts of titanium were noted by numerous late 19th century authors in iron that garnered almost universal praise for its quality (Bauerman 1890:53; Forbes 1869:70; Percy 1864:165-168; Rossi 1893:838-841).

It is not claimed that the iron smelted from titaniferous ores is of inferior quality. Whenever (as in Europe, Canada, or New York) such ores have been smelted, the iron has been found excellent. Those who make the most serious objections to the use of such ores are willing to concede this point. [Rossi 1893:838-839]

Dagenhart, Maddox, and Reynolds also misunderstood the changing demands of the iron market. While it is true that wrought (forge) iron is a
minuscule part of today's iron market, over the course of the 19th century the iron market changed dramatically from one dominated by wrought (forge) iron to one dominated by cast iron. By 1883, when Bowron wrote, an iron that was unusable in foundry work would have been at a disadvantage. But, in the 18th century it made up less than 10% of the market. The important point is that titanic iron was praised as a forge iron.

Titanium, therefore, had little or no effect on either the quality of the cast iron produced at Albemarle, or its marketability. But, it could, and did dramatically effect the operation of the blast furnace. This is clearly indicated in the Albemarle slag. The slag normally associated with blast furnaces, called "furnace slag" is glassy in appearance. The slag found at the Albemarle furnace site is full of accreted masses of slag, ore, charcoal, and prills of metallic iron and more closely resembles bloomery slag. It is not glassy in appearance and it is a visual indicator that the furnace was not operating normally.

Both the SEM and PIXE analysis showed high concentrations of titanium (8-95%) in the slag. Microscopic examination at Oxford has revealed at least five crystalline phases not normally associated with iron slag.

Theory says that as the concentration of titanium climbed the slag would become increasingly viscous or sticky. As the slag became more viscous it retarded the production of iron. This would have been the result of two mechanisms: high viscosity slowed the overall reduction reaction and the total quantity of iron produced, and it also entrapped more iron in the slag. The later is confirmed by the unusually high number and size of iron prills entrapped in the slag (Figures 42 and 43). It may be, as proposed by E. T. Turkdogan (personal communication 1999), that the slag became saturated and some of the titanium compounds precipitated out, forming a highly viscous slurry. Without documentation it is impossible to know whether the blast furnace failed due to
scaffolding, freezing, or simply didn't work well enough to produce commercial quantities of pig iron.

Slag analysis, performed by Dr. Charles Swann at the University of Delaware, Dr. Gerry McDonnell at Bradford University, and Dr. Christopher Salter and Dr. Geoff Grime at Oxford University established the titaniferous nature of the ore used at the Albemarle Iron Works. The close elemental match between the slag and the Martin Mine ore confirmed that it was the ore used at the blast furnace. Research into the effects of titanium on blast furnace slags and blast furnace operations demonstrated that the high concentrations of titanium found in the slag would have resulted in the furnace's failure. Given the technology available in the late 18th century the Albemarle Iron Works could not have worked with ore from the Martin Mine. The extreme nature of the titanium related problems resulted in the furnace's abandonment after one campaign. All of the indications are that the stack froze. At least in the 18th century, there appear to be good reasons for the "titanic stigma" and the avoidance of titaniferous ores by American iron makers (Bowron 1883:159).

There were numerous attempts to restart the furnace, mostly at the instigation of John Wilkinson or John Old, prior to the final dissolution of the partnership. None were successful.

Just as advances in geology might have allowed Andrew Hunter to use ore from the Martin Mine and not produce high phosphorus pig iron, 19th century advances in geology and iron making might have eliminated titanium as a problem as well. One of the problems faced by the Albemarle Iron Works was that the ilmenite at the Martin Mine bore a strong visual resemblance to the magnetite (Dagenhart and Maddox 1977:362; Watson 1907:232). It is likely that the ilmenite was mistaken for magnetite. By the 1870s, better geology might have allowed Hunter to avoid the ilmenite. Use of magnetic separation, a technique
introduced in the late 1800s, would have quickly segregated the magnetite from the ilmenite fractions in the ore. Leaving behind a very pure magnetite. Given the localized nature of most titanium deposits in Virginia, it is possible that the Albemarle Iron Works might have prospered if it had used one of its other ore deposits.

The purpose of this thesis was to establish the cause of the failure of the Albemarle Iron Works. All aspects of the operation of the blast furnace were studied, using a combination of archival research and the latest scientific techniques (SEM, PIXE, etc.), to determine how they might have been involved. Another goal was to determine the role played by the Martin Mine’s ore. It is now possible to state that the titanium present in the Martin Mine ore caused the failure. 18th century technology was not able to handle the extremely viscous slags that resulted from the highly titaniferous ore. The Albemarle blast furnace choked on titanium.
Appendix A: A Note On English

England and America are two countries separated by a common language
(attributed to George Bernard Shaw)

Great care must be exercised when dealing with sources in another language or a variation/dialect of one's own. This is especially true when dealing with sources from another era. Languages change over time and space. New words are created, old words fall out of use. Often the words remain, but the meanings change. We do not speak the Queen's English, neither did the Jamestown settlers speak either 20th century English or American. To further confuse the issue ironmasters and workers developed a technical jargon all their own.

All industries have a technical jargon. The evolution of some terms relating to the manufacture of iron and inherent ambiguity of others will continue to plague historians and archaeologists alike. Most of these problems can be avoided through a thorough understanding of iron making technology. It is the responsibility of each researcher to ensure that they fully understand and accurately report what went on at the sites they are studying. Even such basic terms as coal, charcoal, furnace, foundry, and forge can trip up the unwary. Since many of the researchers working on the iron industry are not metallurgists it is also essential that every effort be made to be consistent and concise in the use of technical terms. Blast furnaces should not be referred to as furnaces. Neither should bloomeries or fineries be called forges, because many people do not know the difference.

The terms coal and charcoal are somewhat interchangeable in 12-19th century English. What today we think of as coal is more correctly termed
mineral, pit, or sea coal in 17-18th century English. Coaling was either the process of converting wood to charcoal or the act of putting (charging) coal or charcoal into something (like a blast furnace or a ship). A collier either mined mineral coal or made charcoal in a hearth, colliers hearth (Oxford English Dictionary 1989:626), charcoal pit, pit, coaling pit, forest clamp, forest kiln, or meiler. In recent years some Virginia archaeologists have used the term collier/collier's pit as a synonym for a charcoal pit (Barber and Wittkofski 1999; Russ et al. 1993, 1995, 1997; Russ and McDaniel 1994; Katherine Stroh 1998 ASV Annual Convention, 2000 Uplands). Dr. John McDaniel said that the term was taken directly from USGS maps (personal communication 2000). According to numerous people in the cartographic sections of USGS; Stanley Johnson, Virginia State Geologist; and Michael Upchurch (personal communication 8 March 2000), a geologist for Virginia, the term collier/collier's/colliers pit has never appeared on any maps of Virginia. They also said that it is very unlikely that a charcoal pit would be mapped. They are too small and they are not mineral deposits. The terms colliery and pits appear on some maps from the mid 1800s, but they refer to coal mines/shafts. While no term for the place charcoal was manufactured is perfect, of the terms used in the United States, meiler, charcoal pit, or charcoal hearth are probably the least ambiguous, historically valid, terms.

The least precise term associated with the iron industry, and most often used, is forge. The Virginia landscape is littered with "forges". But there were at least five different kinds. A finery forge converted pig iron into bar iron through decarburization. Before the 19th century this process was usually performed in finery and chafery hearths, but both were housed in a "forge" building. In the 18th and early 19th century a forge could also be a large blacksmith shop (such as Anderson Forge in Williamsburg). A forge, from the 19th century on, was also a large industrial plant where forgings were made. A forge was also the generic
term for any iron works other than a blast furnace or foundry and can represent either a specific building or a complex of buildings. "Forge" could also be a truncated form of "bloomery forge" or "finery forge". Thus a forge could be a building that housed an iron process, an iron works, a finery, a bloomery, a large blacksmithy, or an industrial forge. In which case it could function as either a bloomery or a forge, or both. Use of either the compound term (bloomery forge or finery forge) or just bloomery or finery is preferred. This minimizes the chance of confusion on the part of the reader. The term "forge" by itself should be avoided except where it is part of the name of an historic iron works, such as Buffalo Forge or Anderson Forge.

This problem is not confined to Virginia, nor to the United States. In the *Iron Industry of the Weald*, Cleere and Crossley wrote:

> The major difficulty is to find out what the works described as 'forges' in the years before 1550 actually produced, as the term could be used for a bloomery or for a finery converting pig iron to bar. Also, the bloomery was both laid out and equipped in ways which made rebuilding as a finery forge possible. Each required a water-driven hammer and two hearths with water-powered bellows. The bloom-hearth could be replaced with a finery, and the string-hearth where the bloom was reheated had its counterpart in the chafery. [Cleere et al. 1995:108]

A bloomery usually was a facility used to convert raw materials into blooms of wrought iron. But, the term bloomery furnace was often used interchangeably with blast furnace in England. Adding further confusion, it was common practice to build a bloomery first to try the ore, modern geologists and labs not being available, and to initiate an income stream. Once a blast furnace had been built, the old bloomery was often used as a forge or finery forge. The same site, and even the same hearth could be both a bloomery, finery, and a forge. The only way to distinguish which was which is to carefully examine the
documentary and/or artifactual evidence, paying special attention to the raw materials used, the slag found at the site, and intermediate and finished products. Even this does not always help as both bloomeries and finery forges produced blooms and bar iron. It is, unfortunately, not uncommon to refer to the decarburized mass of iron produced at a finery forge as a bloom. The slag is chemically and visually similar, but can be differentiated by an expert archaeometallurgist.

Unfortunately, it was, and is, common practice to refer to any facility that converted raw materials to metal or melted metal as a furnace. Thus, a reference to a furnace, in either an historic or modern context is not necessarily to a blast furnace, but could also be to a bloomery, BOF (basic oxygen furnace), open hearth furnace, Bessemer converter, or any number of other structures. For example Alexander Spotswood’s Massaponax furnace is often incorrectly assumed to be a blast furnace. It was an air furnace, a type of foundry. It did not make iron, it remelted pig iron made at Spotswood’s Tubal Furnace and cast it into usable forms. At least in European and American contexts only the bloomery and blast furnace were in common use for the production of iron. Numerous other "furnace" types were used throughout the rest of the world.

The terms Fine and refine can also cause problems. Prior to the invention of puddling by Cort in 1783 the terms were used interchangeably for the removal of carbon from pig iron in a finery forge. After 1783 refine was used for the removal of silicon from pig iron using coke prior to puddling or fining. Unfortunately, it continued to be used as a synonym for fining. John Percy addressed this problem in his 1864 book on iron and steel. Percy used fine for decarburization and refine for the removal of silicon. In order to avoid confusion, it behooves us to follow Dr. Percy’s lead.

King James I chartered two “Companies” for the settlement and
exploitation of "Virginia". They are the London and Plymouth Companies of Virginia. As the Plymouth Company went on to found the Plymouth Colony and settle what became New England, it has come to be known as The Plymouth Company. The London Company is also referred to as The Virginia Company. I have followed this convention.

The Bloomery Furnace in Bloomery, West Virginia exemplifies how confusing this can be. From its name, this site should contain a bloomery. But, the structure in the wayside park is clearly a blast furnace (Figure 42). It is called the Bloomery Furnace because it is in Bloomery, WV. Presumably the town is named for an earlier ironworks, which was a bloomery.

Working with historic documents is a little like archaeology. Someone without proper training and field experience is unlikely to properly excavate and decipher an archaeological site. Historic documents also need interpretation and sometimes more than a little translation. When writing a report or paper, modern authors have a responsibility to write in a clear and concise way and use modern terminology. Ambiguous terms must be avoided and just because a term was used historically is not a justification for using it today. Unless you are writing a period novel.
BLOOMERY IRON FURNACE

The furnace was built in 1858 by Thomas Purdy and later was owned by Lewis Pasmore. He placed a Mr. Cornwall in charge who operated it until 1848, when it was sold to S.A. Pascoe. He and his heirs operated it until 1875 when the furnace was closed down. It was operated for a short time in 1860-1861. Annual capacity was 8500 tons. The iron was carried on rafts and flatboats down the Cacapon River.

Figure 42. Bloomery Furnace, Bloomery, WV. Photo by author.
Appendix B: GLOSSARY

The definitions listed in the glossary are taken from a number of sources. These include: Robert Gordon (1996, primarily pp. 307-311), Rostoker and Bronson (1990, primarily pp. 211-217), Straker (1969:xii-xiv), Tiemann (1933), and Gale (1971). Where a definition was found in only one source, the specific source is cited. All highlighted terms have entries.

**Air Furnace**- A reverberatory furnace. A type of foundry. An air furnace, like the double air furnace at Massaponax, is usually built to make very large castings, like cannons.

**Alloy**- A substance made by combining two or more metals or a metal and other elements. Provides characteristics that are different than a pure metal. Stainless steel is an alloy of iron, carbon, and chromium.

**Ancony**- What results when a bloom is worked in a finery.

**Anneal** - A method used to soften stressed metal by heating and then slowly cooling to reduce brittleness.

**Austenite**- High temperature form of pure iron or iron-carbide solid solution.

Decomposes at 723°C into ferrite and cementite.

**Bay (UK)**- The dam used to form a pond for a mill or furnace.

**Bar Iron**- The iron produced in a forge or chafery. Iron composed of ferrite with slag inclusions, with less than 0.15% carbon and a melting temperature around 1,534°C.

**Bear**- English term for a salamander or horse.

**Blast** - The air blown into the hearth by a blowing engine, blowing machine, bellows, or other device. A blast furnace is "in blast" when it is in
operation and producing cast iron. It is out of blast when it is out of service after being blown out.

**Blast Furnace**- A shaft furnace with an injected air blast that converts raw materials (ore, flux, charcoal, etc.) into molten metallic (pig) iron.

**Blister Steel**- Steel made by heating wrought iron packed into crucibles with powdered charcoal. The surface of the iron absorbs carbon and blisters form.

**Bloom**- A spongy mass of metallic iron and slag. Produced in a bloomery.

**Bloom Iron**- The iron produced in a bloomery. Term is often used interchangeably with bar iron (see) or wrought iron (see).

**Bloomery**- An iron smelter that converts raw materials into a solid bloom of iron and liquid slag.

**Bloomery Furnace**- Same as a bloomery.

**Blow(n) In**- Lighting a furnace, either for the first time or at the beginning of a campaign.

**Blow(n) Out**- Shutting down a blast furnace at the end of a campaign.

**Blowing Engine/Machine**- The device that provides the air blast for a furnace, forge, or bloomery. A term usually used after the 18th century and connoting something other than a bellows.

**Blowing tub(s)**- Consisted of two wooden pistons, replaced bellows to provide the blast for a furnace.

**Bog Ore**- A form of limonite formed in wetlands through bacterial action.

**Bosh (boshes)**- The widest part of a furnace, the point at which it begins to taper in to the hearth.

**Burden**- The charge in a furnace stack.

**Brown Hematite**- An obsolete term for limonite or goethite.

**Calcining**- Roasting.
Campaign- The total elapsed time a blast furnace is in continuous operation, from the time it is blown in to when it is blown out.

Carburizing- Adding carbon to iron to form a higher carbon alloy.

Case Hardening - Hardening the surface of iron by heating it with carbon and then quenching. The surface is converted into steel.

Cast Iron- Iron containing between 2 and 4.5% carbon (also Pig Iron).

Cementite- Iron carbide (Fe₃C). What makes white iron so hard.

Chafery- or Chafery Hearth A hearth used to reheat a bloom of iron during hammering at a finery forge (Walloon method). When only one hearth is used (German method) the chafery is used for both decarburizing and reheating the bloom.

Charcoal- An almost pure form of carbon made by controlled burning of wood.

Charcoal Burner- see collier.

Charcoal Burning- Converting wood to charcoal (coaling or charking).

Charcoal Hearth- A pit kiln, charcoal pit, pit, meiler, or forest kiln. A pile of wood covered with charcoal, leaves, and dirt burned to make charcoal.

Charcoal pit- A pit kiln, charcoal hearth, pit, meiler, or forest kiln. A pile of wood covered with charcoal, leaves, and dirt burned to make charcoal.

Charking- Converting wood to charcoal (coaling or charring).

Charring- Converting wood to charcoal.

Cinder- Slag (also sinder or cynder).

Charge- To load raw materials into a furnace. Or the raw materials themselves (charcoal, flux, ore, etc.).

Coal- In a pre 20th century context, charcoal. In the 20th century a mineral formed by applying heat and pressure to rotting plant remains. Also referred to as mineral or sea coal (also cole).

Coaling- Making charcoal (charking) or charging coal/charcoal into a furnace.
Coke- A high carbon porous fuel made by driving off all of the volatiles in bituminous coal.

Cold Short- The tendency for iron to crack when hammered at room temperature. Usually caused by phosphorus.

Collier- A coal miner or someone who converts wood to charcoal.

Collier Pit- A term used by the U.S. Forest Service and associated archeological firms primarily in Western Virginia. A charcoal pit, Meiler, charcoal hearth, forest kiln, or pit kiln.

Cord- A standard measurement of wood. A pile of wood either 14’ long, by 3’ wide, by 3’2” tall (133 cubic feet) or 8’ long, by 4’ wide, by 4’ high (128 cubic feet, used more often in U.S.).

Crucible Steel- Steel made in a crucible by melting blister steel or wrought and pig iron.

Decarburizing- Removing carbon from iron to form a lower carbon alloy. The process used to make wrought iron from pig iron in a finery.

Direct Process- Process of making wrought iron or steel directly from ore.

Driving Hard- Working a blast furnace to achieve maximum production.

Ductility- Property of metal allowing it to undergo plastic deformation without fracturing. A very ductile material can be hammered, twisted, drawn, or bent without breaking.

Faggotting- A method used to improve the working characteristics of bar iron after fining or puddling. The bars are stacked and bound with wire into bundles that resemble bundles of sticks (faggots). Then they are heated and forged into a bar. This process is repeated as desired. The resulting bar iron has smaller slag inclusions and a more homogenous composition.

Fayalite- Fe₅SiO₄, a primary component of bloomery slag.

Ferrite - Low-temperature form of pure iron. Converts to austenite at 910°C.
Finer's Bar- Iron forged directly from a bloom of fined iron. Has a high slag content and is usually further processed by faggotting, piling, or pile welding prior to use by a blacksmith.

Finery or Finery Forge- An ironworks used to convert pig iron to wrought iron by decarburizing it.

Finery Hearth- A hearth used to decarburize pig iron in a finery, finery forge, or forge.

Fining- The conversion of pig iron to bar iron by decarburizing it. Performed in a finery, finery forge, or forge.

Flux- Material added to a charge to help form a slag.

Forest Kiln- A pit kiln, charcoal hearth, charcoal pit, pit, meiler, or forest kiln. A pile of wood covered with charcoal, leaves, and dirt burned to make charcoal. Usually found in British documents.

Forge- A facility consisting of a finery and chafery used to convert pig iron to bar iron. Also a bloomery forge, or from the 18th century on can be a large blacksmithy. A facility that makes forgings. To shape a piece of metal by hammering or make forgings, see Forging.

Forge Welding- Combining two pieces of metal usually by hammering them while they are hot, but not liquid. The surfaces fuse together.

Forging- Working metal, usually hot, or changing its shape by striking it with a hammer or other instrument. Can also be further differentiated by using compound terms such as: hand forging, hammer forging, drop forging, or hydraulic forging. See also Forge Welding and Forge.

Founder- Person in charge of a foundry or blast furnace.

Foundry- A facility that remelts pig iron and casts it into usable forms. Today many blast furnaces are referred to as foundries. More than half of the iron produced today is made from scrap and not ore.
Furnace- Any facility that converts (smelts) raw materials (ore, flux, charcoal, etc.) into metallic iron or melts metal. Usually used interchangeably with blast furnace.

Gangue- Non-metallic and non-volatile components of an ore.

German Method- finery process using only one hearth.

Goethite- The modern term for limonite.

Gossan- A form of limonite formed by the weathering of iron pyrite (FeS2). This type of ore was used by many of the early furnaces in Virginia. Copper ore is usually found near the water table in the same deposits.

Graphite- A form of carbon.

Gray Iron- Cast iron containing graphite flakes.

Hammer- The site of a powered hammer (a bloomery, forge, finery, or chafery).

Hardness- The resistance of a piece of metal to dents and scratches.

Hammer Welding- See Forge Welding.

Haute Fourneau- French for high furnace. A blast furnace (see).

Head- The height water falls at a dam or wheel.

Hearth- The lowest section of a blast furnace or the bottom of a finery or reverberatory furnace, where metallurgical processes take place.

Helve- The haft of a water powered tilt hammer. The helve is lifted by a cam on a rotating shaft connected to the water wheel.

Helve Hammer- Large power driven cast iron hammer used to consolidate a bloom or loup of iron.

Hematite- Iron ore (Fe2O3).

Hematite, Brown- An obsolete term for limonite or goethite (see).

High Bloomery- A bloomery with a tall stack. Stückofen

Hochofen- German for high furnace. A blast furnace.
**Horse**- Another term for a **salamander** or bear (see). Could also form in the stack, rather than in the hearth. (Greenwood 1902:142, 1907:127)

**Hot Blast**- Preheating the air prior to injecting it into a furnace through the **tuyere**. Invented by Neilson in 1828. Significantly reduces fuel consumption. Raises the temperature of the hearth and speeds up the smelting reaction.

**Hot Short**- The tendency for iron to crack when hammered at forging temperatures. Usually caused by sulfur.

**Indirect Process**- Process for making wrought iron or steel by first making cast iron and then fining (decarburizing) it.

**Keeper**- Ironworker in charge of actions at the casting arch. Responsible for tapping slag and iron.

**Lake Ore**- A form of **limonite** found at the bottom of ponds and lakes.

**Limonite**- A hydrated iron ore. $2\text{Fe}_2\text{O}_3\cdot3\text{H}_2\text{O}$.

**Liquidous** - The temperature at which all of a material is molten.

**Loup**- A bloom of iron.

**Meiler** - A pit kiln, charcoal hearth, pit, charcoal pit, or forest kiln. A pile of wood covered with charcoal, leaves, and dirt burned to make charcoal. (from German).

**Magnetite** - Iron ore ($\text{Fe}_3\text{O}_4$).

**Martensite**- A form of iron formed by rapid cooling (**quenching**). It has a feathery appearance when looked at under a microscope.

**Mine (myne)**- an English term for iron ore.

**Mosser**- an English term for a skull. Called this because moss frequently grows on them.

**Mottled Iron**- Cast iron composed of a mix of white and gray iron.
**Muck Bar** - Iron forged directly from a *bloom* of *puddled* iron. Has a high slag content and usually must be *faggotted, piled, or pile welded* prior to use by a blacksmith.

**Oxidation** - The chemical process that bonds oxygen into a compound. Two common examples are: burning \((C + O_2 \rightarrow CO_2)\) or rusting \((2Fe + O_2 \rightarrow 2FeO)\).

**Pearlite** - A form of iron found in steel and cast iron consisting of plates of *cementite* in a *ferrite* matrix.

**Pig Iron or Pigs** - The most common form of *Cast iron* as it comes from the *blast furnace*. The name comes from the practice of tapping the furnace into a series of open molds connected by a central channel. This reminded early ironworkers of a *sow* suckling piglets.

**Pile Welding or Piling** - A general term for all of the techniques for *welding* together bundles or piles of iron bars or plates. These are used to homogenize the structure and also can produce decorative effects.

**Faggotting**.

**Pit** - A *meiler, charcoal pit, charcoal hearth*, or *pit kiln*. A pile of wood covered with charcoal, leaves, and dirt burned to make charcoal.

**Pit Kiln** - A *charcoal pit, charcoal hearth, pit, meiler*, or *forest kiln*. Term used primarily in British sources.

**Puddling** - Decarburizing *pig iron* in a *reverberatory furnace* using an *oxidizing* agent.

**Pyrite** - FeS\(_2\). A brass or gold colored mineral. Also known as Fool's Gold. Used to make sulfuric acid.

**Pyrrhotite** - FeS. A brownish-bronze, weakly magnetic iron ore. Usually used to make sulfuric acid.
**Quench**- Rapid cooling of hot steel by plunging it into a cold liquid. Causes the steel to become much harder, but also more brittle.

**Red Short**- See **Hot Short**.

**Reduction**- The chemical process of removing oxygen from a compound. A crucial step in making iron (FeO + CO → Fe + CO₂).

**Refinery Hearth** used to remove silicon from pig iron in preparation for fining or puddling. Often uses coke.

**Refining**- Removing silicon from pig iron using coke in preparation for fining or puddling. Often used, as a synonym for fining.

**Reverberatory Furnace**- A furnace in which the fuel and the charge are separated. The heat is radiated or reflected from the roof onto the charge.

**Roasting**- Calcining. Heating ore in air prior to smelting. This drives off volatiles, makes the ore more porous, and decomposes carbonates, hydroxides, sulfates, and sulfides.

**Run Out**- To tap the iron in a furnace.

**Salamander**- A mass of metal, slag, and furnace lining found in the bottom of a blast furnace after it is blown out. Can also form as the result of accidents, when the iron freezes before it can be run out. Also called a **horse** or **bear** (see)

**Sesquioxide of Iron**- Obsolete term for **magnetite** (Fe₃O₄).

**Shear Steel**- Steel made by **hammer welding** or **piling** bundles of blister steel.

**Shingling** - The first forging of a **bloom** from a **bloomery**, **finery**, or **puddling**. Shingling consolidates the metal and drives out most of the slag. It results in a **muck bar**.

**Siderite**- Iron ore (FeCO₃)

**Skull**- The bloomery equivalent of a **salamander**. A solidified mass of fayalitic slag, ore, charcoal, and iron left in the bottom of a bloomery hearth after
the bloom is removed. Called a skull because the bottom is curved like the top of a skull. Steel or cast iron that solidifies in a runner or ladle. Also called a scull or mosser.

**Slag**- A ceramic or glass made up of gangue and metal oxides from the ore, fuel ash, fluxes, and portions of the furnace lining. The primary industrial waste found at iron sites.

**Solidus**- The temperature at which a compound becomes a solid.

**Sow or Sow Iron**- A large piece of pig iron. Early furnaces could cast an entire day’s production as a single piece. As furnaces became larger, so too did the sows. Until they became too large to handle and founders began casting pigs instead.

**String Hearth**- Hearth used to reheat blooms for hammer consolidation.

**Stückofen** - German for stack furnace or high bloomery. Considered by many to be ancestral to the blast furnace.

**Temper**- Reheating steel to render it softer and less brittle after quenching.

**Tensile Strength**- Force needed to break a piece of metal.

**Tilt Hammer**- A large hammer, mounted on a horizontal shaft, used to shape iron.

**Toughness**- Resistance to cracking.

**Trompe**- A form of air pump often associated with Catalan forges. The blast is powered by air being pulled down a tube by the action of falling water. It has no moving parts, but can only be used where there is a large constant head.

**Tuyere, Twyer**- A nozzle used to inject air into a furnace or hearth.

**Walloon Method**- Finery process developed in Wallonia and used in Great Britain and the United States. Walloon process uses two hearths (chafery and finery) and a powered hammer.
**Weld**- Joining together two pieces of metal.

**White Iron**- A very hard cast iron made up primarily of cementite.

**Wrought Iron**- Bar iron.

**Wüstit**e- An iron oxide (FeO). Rarely found in nature, but very important in smelting operations.
## Appendix C- Albemarle Iron Works Land Acquisitions
(Albemarle County)

<table>
<thead>
<tr>
<th>Date of Deed</th>
<th>Citation</th>
<th>Grantor</th>
<th>Grantee</th>
<th>Acres</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 20 February 1769</td>
<td>DB5:80</td>
<td>White</td>
<td>Old, Wilkinson</td>
<td>98</td>
<td>&quot;west side of Hardware River&quot;. Possible mine tract for a bloomery. &quot;Forge tract in &quot;ragged mountains&quot;. Probably on Cook Mtn. Possible mine tract</td>
</tr>
<tr>
<td>2 21 February 1769</td>
<td>DB5:65</td>
<td>Cook</td>
<td>Old, Wilkinson</td>
<td>5.75</td>
<td>Purchase agreement dated 7 November 1767. Ore lands on Cook Mtn. (Martin Mine)</td>
</tr>
<tr>
<td>3 21 February 1769</td>
<td>DB5:135</td>
<td>Gillum</td>
<td>Wilkinson,Giles, Webster</td>
<td>10</td>
<td>&quot;both sides of Micheaux creek of the South fork of Hardware... Beginning... on the top of a mountain&quot;. Crest of Fan Mtns for charcoal</td>
</tr>
<tr>
<td>4 12 May 1770</td>
<td>PB38:886</td>
<td>Wilkinson</td>
<td></td>
<td>39</td>
<td>&quot;North waters of the south Fork of Hardware River and on one of the Ragged mountains called Fitz's&quot; Crest of Appleberry Mtn. for charcoal</td>
</tr>
<tr>
<td>7 12 May 1770</td>
<td>PB38:889</td>
<td>Wilkinson</td>
<td></td>
<td>400</td>
<td>&quot;ragged mountains, on the waters of the south fork of the iron works.</td>
</tr>
<tr>
<td>8 12 May 1770</td>
<td>PB38:890</td>
<td>Wilkinson</td>
<td></td>
<td>400</td>
<td>Forest land for charcoal. Forge Tract.</td>
</tr>
<tr>
<td>10 12 May 1770</td>
<td>PB38:892</td>
<td>Wilkinson</td>
<td></td>
<td>395</td>
<td>&quot;ragged mountains, on the waters of the south fork of the iron works.</td>
</tr>
<tr>
<td>No.</td>
<td>Date</td>
<td>DB/PB</td>
<td>Last Name</td>
<td>Company</td>
<td>Acres</td>
</tr>
<tr>
<td>-----</td>
<td>---------------</td>
<td>-------</td>
<td>-------------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>11</td>
<td>10 January 1771</td>
<td>DB5:300</td>
<td>Fitzpatrick</td>
<td>AIW Partners</td>
<td>145</td>
</tr>
<tr>
<td>12</td>
<td>10 January 1771</td>
<td>DB5:304</td>
<td>Coles</td>
<td>AIW Partners</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>10 January 1771</td>
<td>DB5:306</td>
<td>Moon</td>
<td>AIW Partners</td>
<td>153</td>
</tr>
<tr>
<td>14</td>
<td>10 May 1771</td>
<td>DB5:317</td>
<td>Martin</td>
<td>AIW Partners</td>
<td>240</td>
</tr>
<tr>
<td>15</td>
<td>10 May 1771</td>
<td>DB5:317</td>
<td>Ramsey</td>
<td>AIW Partners</td>
<td>200</td>
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<tr>
<td>3</td>
<td>November 1771</td>
<td>DB5:416</td>
<td>Terrell</td>
<td>AIW Partners</td>
<td>25.5</td>
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<tr>
<td>16</td>
<td>20 June 1772</td>
<td>PB40:709</td>
<td>Walker</td>
<td></td>
<td>332</td>
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<tr>
<td>17</td>
<td>1 August 1772</td>
<td>PB40:780</td>
<td>Walker</td>
<td></td>
<td>226</td>
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</table>

**TOTAL** 3772.25

DB (Albemarle County Deed Books), PB (Royal Patent Books), quotes from The (Richmond) Enquirer Vol 11, Number 12, 18 June 1814.
Bibliography

Archives and Repositories

LC       Library of Congress. Washington, DC.


SWEM     University Manuscripts and Rare Books Department, Swem Library, College of William and Mary. Williamsburg, Virginia.

UVA      Special Collections, Alderman Library, University of Virginia. Charlottesville, Virginia.

VHS      Virginia Historical Society. Richmond, Virginia.

VSL      Virginia State Library. Richmond, Virginia.

References

Adams, M. E.

1884 The Pyrite Deposits of Louisa County, Va. Transactions of the American Institute of Mining Engineers, XII(June 1883-February 1884):527-535.

1892 The First Iron Blast-Furnaces in America. Transactions of the American Institute of Mining Engineers XX (June 1891 to October 1891):196-215.

Adams, W. N.


Ågren, Maria


Agricola, Georgius

Albemarle County  
Deed Book V. Albemarle County Court House and the VSL Microfilm Collection.

Arber, Edward (ed.)  
1910  

Armstrong, Lyn  
1978  

Ashton, Thomas Southcliffe  
1924  

Åström, Sven-Erik  
1982  

Awty, Brian G.  
1987  

Bachmann, Hans-Gert  
1980  

Bacon, Sir Francis  
1625  
Of Plantations. London.

Barber, Michael B. and J. Mark Wittkofski  
1999  

Barraclough, Kenneth C.  
1976  
Bartholomaeus Anglicus

Bauerman, H.

Bell, I. Lowthian

Bergstrom, Peter V.

Bining, Arthur Cecil

Biringuccio, Vannoccio

Birkinbine, John
1893 The Influence of Location Upon the Pig-Iron Industry. *Transactions of the American Industrial Mining Engineers* XXI (February 1892 to February 1893): 473-91.

Bishop, John Leander
1966 [1868] *A History of American Manufactures from 1608 to 1860: Exhibiting The Origin And Growth Of The Principal Mechanic Arts And Manufactures, From The Earliest Colonial Period To The Adoption Of The Constitution: And Comprising Annals Of The Industry Of The United States In Machinery, Manufactures, And Useful Arts, With A

Blick, C. R. (ed)

Bohm, Ivar

Bottinga, Y. and Weill, D.

Bowron, William M.
1883 The Practical Metallurgy of Titaniferous Ores. Transactions of the American Industrial Mining Engineers XI(May 1882 to February 1883):159-164.

Boyd, C. R.
1884 The Ores of Cripple Creek, Virginia. Transactions of the American Institute of Mining Engineers XII (June 1883-February 1884):27-40.

Brady, T. T.
1979 Field Notes on Albemarle IW. Available from author.
ND Field Notes.
various VHS Mss B7297a.Fa2.

Bridenbaugh, Carl

Brown, Alexander
1890 The Genesis of the United States; a narrative of the movement in England, 1605-1616, which resulted in the plantation of North America by Englishmen, disclosing the contest between England and Spain for the possession of the soil now occupied by the United States of America; set forth through a series of historical manuscripts now first printed, together with a reissue of rare contemporaneous tracts, accompanied by bibliographical memoranda, notes, and brief biographies, collected, arranged, and edited by Alexander Brown; with 100 portraits, maps, and plans. In two volumes. Houghton, Mifflin and Company,
Boston.


Brown, Peter J.

Bruce, Kathleen
1927 The Manufacture of Ordnance in Virginia During the American Revolution, Part II. Army Ordnance VII (41, Mar-Apr 1927).

Burgo, J. A.

Byrd, William

Cabell, William
1771 16 September 1771, Transfer of John Wilkinson's bond from Old to Cabell. Cabell Family Papers (65 C12), Box II, Folder 1. SWEM.
1777 Articles of Agreement between John Old and Wm. Cabell. Cabell Family Papers (65 C12), Box II, Folder 7. SWEM.
1778 Commonplace Book. VHS MSS 5:5C 1117:7
Campbell, Harry Huse

Carter, Edward
1771 Sale of 1/2 of interest in Albemarle Iron Works to John Old, dated September 21, 1771. Walker-Page Manuscripts (Mss #3098). UVA.

Chandler, Alfred

Charles, James A.

Cleere, Henry, David Crossley, Bernard Worssam, and The Wealden Iron Research Group

Coles, John
1770-1807 Ledger of John Coles, 1770-1807. Accession #9533, UVA.

Condit, William W.

Cotter, John Lambert

Craddock, Paul T.
1995 *Early Metal Mining and Production.* Washington, D.C., Smithsonian Institution Press.

Craddock, Paul T. and Hughes, M. J. (ed)

Cremers, Estelle

Crossley, David
1990 *Post-Medieval Archaeology in Britain.* Leicester University Press, Leicester.

Crossley, David and Denis Ashurst

Crossley, David; Jean Cass Neville Flavell; and Colin Turner (eds)
1989 *Water Power on the Sheffield Rivers.* Sheffield Trades Historical Society and the University of Sheffield Division of Continuing Education, Sheffield.

Dagenhart, Thomas V., Jr. and Gary L. Maddox

de la Ware, Lord Thomas, Sir Thomas Smith, Sir Walter Cope, Master Waterson
Dermody, Larry D.

DeVries, R. C., R. Roy, and E. F. Osborn

Dew, Charles B

Diderot, Denis

Dietrick, Richard V.

Disbrow, Natalie J.


Eggert, Gerald G.

Egleston, T.
1873 Uses of Blast-Furnace Slags. Transactions of the American Institute of
England, John

Enquirer, The
Richmond Virginia. VHS and VSL.

Evans, Oliver

Evans-Sibert Family Papers
1873 A List of balance due to labourers in mine. 30 September 1873. Evans-Sibert Family Papers, 1849-1900. VSL Collection 27770.
1874 Commissioners Sale Broadside. Evans-Sibert Family Papers, 1849-1900. VSL Collection 27770.

Evelyn, John

Fairbairn, William

Fine, H. A. and S. Arac

Flinn, M. W.

Forbes, David

Forbes, Robert James.
1950 Man, the Maker; A History of Technology and Engineering. Schuman, New York.
Force, Peter (ed.)


Fackenthal, B. F. Jr.
1890 *Filling and blowing in at the Durham Blast-Furnace. Transactions of the American Institute of Mining Engineers* 11(May 1882 to February 1883):159-164.

Francis, C.B.

Froehling & Robertson, Inc.

Furchron, A. S.

Gale, W. K. V.


Gee, Joshua


Gies, Frances and Joseph

Gilmour, Brian
1999 Ironworking in ancient China: a review of two recent

Gilmer, Jeremy Francis
1864 Albemarle County, 1864. The Confederate Engineers' Maps. Jeremy Francis Gilmer Collection. VHS.

Gjerloff, A. K. and H. Sørensen

Gordon, Robert B.

Gordon, Robert B. and Patrick M. Malone

Gordon, Robert B. and Terry S. Reynolds

Greenwood, William Henry

Hammersley, G.
Handfield, G. and G. G. Charette

Harris, J. R.

Hartley, Edward Neal

Hartwell, R. M.

Harvey, David

Hassenfratz, J. H.

Hay, Thomas
Heine, R. J.

Heite, Edward F.

Hermelin, Samuel Gustav

Hildebrand, K. G.

Hodges, Graham Russell

Holden, R. J.

Holmes, W. T. and L. H. Banning
1968 Production of Nominal Slag Compositions. U. S. Bureau of Mines

Horne, Lee

House of Lords Record Office (HLRO)
1750 An Account of the quantity of Iron Imported from the British Colonies in America from Christmas 1710 to Christmas 1749 distinguishing each year and the Quantity Imported from each Colony & distinguishing how much in Piggs & how much in Barrs. House of Lords Record Office, London.

Howell, Charles and Allan Keller

Huntley, Jacqui. P.

Hyde, Charles K.

ICCROM

Ince, Laurence

Jockenhovel, Albrecht
Jefferson, Thomas

Johnson, J. E.

Johnson, Keach

Johnson, Robert
1609 *Nova Britania: Offering Most Excellent fruits by Planting In Virginia. Exciting all such as be well affected to futher the same*. Samuel Macham, London. In Vol. I (1836) of *Tracts and Other Papers, Relating Principally to the Origin, Settlement, and Progress of the Colonies in North America, From the Discovery of the Country to the Year 1776*. Peter Force (ed.). Peter Force, Washington.

Jones, Geoffrey and David L. Maki
1999 *A Geophysical Investigation at the Falling Creek Iron works (44CF7)*. Submitted to Chesterfield County. Copies available at VDHR and Chesterfield County.

Kaminski, Jaime

Karsten, C. J. B.
1816 *Handbuch der Eisenhüttenkunde*. Halle.

Kato, Makoto and Susumu Minowa

Kelley, D.W.
Kelly, Jennifer Olsen and J. Lawrence Angel

Kemp, Richard L.

Kemper, Jackson III

Kingsbury, Susan Myra,

Lankford, William T., Jr.

Leffel, James

Lesley, J. Peter

Lewis, Lynne G.
1992 Presentation at 6th Council of Virginia Archaeologists Symposium (COVA): 18th Century at the University of Virginia.

Lewis, Lynne G., Larry D. Dermody
1990 *Archaeology on Ice: The Tempietto/Ice House at Montpelier*. Manuscript on file at Montpelier.

Lewis, Ronald Loran
1978 Slave Families at Early Chesapeake Ironworks. *Virginia Magazine*
of History and Biography 86:169-180.

Macpherson, David
1805 Annals of commerce, manufactures, fisheries, and navigation, with brief notices of the arts and sciences connected with them. Containing the commercial transactions of the British Empire and other countries, from the earliest accounts to the meeting of the Union Parliament in January, 1801; and comprehending the most valuable part of the late Mr. Anderson’s History of commerce ... with a large appendix ... Nichols, London.

Magnusson, Gert

Markell, Ann B.

May, Earl Chapin

McCusker, John J, and Russell R. Menard

Miller, Frederick K.

Mitchell, Richard S.

Morizane, Y., B. Ozturk and R. J. Fruehan
Moxham, Edgar C.  
1893 The "Great Gossan Lead" of Virginia. *Transactions of the American Institute of Mining Engineers* 21(February 1892 to February 1893):133-38.

Mulholland, James A.  

Needham, Joseph  

Nelson, Wilbur A.  

Noël Hume, Ivor  

Nørbach, Lars Chr. (editor)  

Nørbach, Lars Chr.  

Ohno, Atsumi and H. U. Ross  
Photos, E; H. Koukouli-Chrysanthaki and G. Gialoglou

Pierce, Arthur D.

Pigott, Vincent C.

Poveromo, J. J.

Prugh, Byron J., Jr. and Clairience G. Humphrey

Pumppelly, Raphael (Special Agent)


Rehder, J.E.

Reynolds, William W.
1990a Field Notes on Albemarle IW. Available from William Reynolds and author.


Riden, Philip


Riden, Philip and John G. Owen


Robbins, Michael


Rosenqvist, Terkel


Rossi, Auguste J.


Rostoker, William and Bennet Bronson


Rostoker, William, Bennet Bronson, and James Dvorak


Rothenberg, B. and A. Blanco-Freijeiro

Russ, Kurt C. and John M. McDaniel

Russ, Kurt C., John M. McDaniel, Kristen Rawlings, Burke Willard
1997 Archaeological Investigations Of The Longdale Iron Mining Complex In Allegheny County, Virginia. Manuscript on file at Laboratory of Anthropology and Department of Sociology and Anthropology Washington and Lee University. Lexington, Virginia

Russ, Kurt C., John M. McDaniel, and Thomas C. Upchurch

Russ, Kurt C., John M. McDaniel, and Katherine T. Wood

Sanford, Douglas W.

Schallenberg, Richard H. and David A. Ault

Schenck, Helen
1992 The Upper Forge at Valley Forge. IA, The Journal of the Society for
Schenck, Helen R. and R. Knox, Jr.  
1985  Wrought Iron Manufacture at Valley Forge. MASCA Journal 3(5):132-.  

Schubert, H. R.  

Scrivenor, Harry  

Singewald, Joseph T., Jr.  

Skipton, H. P. K.  

Smith, Cyril Stanley  

Smith, Captain John  
1910 [1608]  A True Relation of such occurrences and accidents of noate as hath hapned in Virginia since the first planting of that Collony, which is no resident in the South part thereof, till the last returne from thence. John Tappe, London. Reprinted in Travels and Works of Captain John Smith.: President of Virginia, and Admiral of New England 1580-1631. Edward Arber (ed.). John Grant, Edinburgh.  

Spears, David B. and Michael L. Upchurch

Spring Forge Journal
1765-67    PHS.

Starley, David

Stoughton, Bradley

Straker, Ernest

Strachey, William

Sutherland, Hunter C.

Svedelius, G

Swank, James M.

Tarleton, LTC Banastre

Temin, Peter
Tholander, Erik

Tholander, Erik and Stig Blomgren

Thomas, Brinley

Tiemann, Hugh P.

Troup, Charles G., Arthur G. Barnes, and Norman F. Barka

Truran, William
1855  The Iron Manufacture of Great Britain Theoretically and Practically Considered, Including: Descriptive Details of the Ores, and Fluxes Employed; the Preliminary Operation of Calcination; the Blast, Refining, Puddling, and Balling Furnaces, Engines, and Machinery; and the Various Processes in Union; Statements of the Quantities of Materia; Period of Time, and Amount of Power Consumed in the Successive Stages; cost of Raising Minerals; and Manufacturing Crude and Finished Iron; and Analytical Researches into the Causes Affecting the Economy of Fuel in Blast Furnaces. E. & F. N. Spon, London.

Tuomey, Michael
Turkdogan, E. T. and R. J. Fruehan  
1999  

Turner, Thomas  
1900  

Twadell, William  
1771  
Letter from Wm. Twadell to Wm. Cabell, dated 16 October 1771. Cabell Family Papers (65 C12). Box II, Folder 1. SWEM.  
1772  
Letter from Wm. Twadell to Thomas Walker, dated 16 January 1772. Walker-Page Manuscripts (Mss #3098). UVA.

Tylecote, R. F.  
1962  
1976  
1986  
1987  

Tylecote, R. F. and Joan Day (editors)  
1991  
The Industrial Revolution in Metals, The Institute of Metals, London.

U.S. Bureau of the Census  
1960  

van der Merwe, Nikolaas J. and David J. Killick  
1979  

Vogel, Robert M.  
1985  

Wagner, Donald B.  
1993  
Early iron in China, Korea, and Japan. Paper presented at "Korean
excavations of iron armour: Political and technological implications for protohistoric East Asia, Los Angeles. Available on the web at:
http://staff.hum.ku.dk/dbwagner/KoreanFe/KoreanFe.html.

http://staff.hum.ku.dk/dbwagner/Fate/Fate.html.

http://staff.hum.ku.dk/dbwagner/EARFE/EARFE.html.


Walker, Joseph E.

Walker, E. N.

Walker-Page Manuscripts (Mss #3098).
1769 Account Book. 8 September 1769. UVA.
1770a Account Book. 25 January 1770. UVA.
1770b Articles of Agreement, 28 December 1770. UVA.
1771 Sale of 1/2 of interest in Albemarle Iron Works to John Old, dated September 21, 1771. UVA.
nd (1771-2) Account of Sums paid Furnace. UVA.
1772 Inventory of Albemarle IW. UVA.

Walker, Thomas
1791 Affidavit dated 25 February 1791. Walker-Page Manuscripts (Mss #3098). UVA.

Watson, Thomas Leonard
1907 Mineral Resources of Virginia. P. J. Bell Co Printers & Binders, Lynchburg, VA.

Webster, John Lee
1766-1773 Account Books of John Lee Webster, 1747-1793, Ledger B [Webster LC B]. MMC 1068. LC.
Wertime, Theodore A.
1962 *The Coming of the Age of Steel*. The University of Chicago Press, Chicago and The University of Toronto, Toronto.

Wertime, Theodore A. and James D. Muhly (editors)

Whisonant, Robert C.

Whitaker, Alexander
1613 *Good newes from Virginia. Sent to the Counsell and Company of Virginia, resident of England. From Alexander Whitaker, the minister of Henrico Virginia. Wherein is a narration of the present state of that countrey, and our colonies there. Perused and published by direction from that Counsell. And a preface prefixed of some matters touching that plantation, very requisite to be made knowne*. Felix. Kyngston for William Welby, London.

Whitely, William G.

Wilkinson, John
1769 30 January 1769, John Wilkinson Bond to John Old. *Cabell Family Papers* (65 C12), Box II, Folder 1. SWEM.
1774a Letter Wilkinson to Thomas Walker, dated June 7, 1774. Walker-Page Manuscripts (Mss #3098). UVA.
1774b Letter Wilkinson to Thomas Walker, dated June 28, 1774. Walker-Page Manuscripts (Mss #3098). UVA.
1792 Affidavit dated 7 April 1792. Walker-Page Manuscripts (Mss #3098). UVA.

Woods, Rev. Edgar
1901 *Albemarle County in Virginia; giving some account of what it was by*
nature, of what it was made by man, and of some of the men who made it. Michie Co., Printers, Charlottesville.

1932

*Albemarle County in Virginia*. The Green Bookman, Bridgewater.

Wright, Louis B.
1965


Young, Suzanne M. M., A. Mark Pollard, Paul Budd and Robert A. Ixer (ed)
1999


Zouch, Sir John
1904 [1636]

Vita

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Life Member of the Archeological Society of Virginia, member of the Board of Directors (2001), and past Editor of the Quarterly Bulletin. Archaeological advisor to the Falling Creek Iron Works Foundation. Presented a number of papers and posters on the early iron industry or Albemarle Iron Works at various conferences (Uplands 2000, Ironmasters 2000, Pioneer America Society 2000, Archeological Society of Virginia 2000, and Society for Historical Archaeology 2001, Society for Industrial Archaeology 2001). The SHA paper was co-authored with Dr. Charles Swann of the University of Delaware. Co-authored a paper with Dr. Swann presented at the International Conference on Nuclear Microprobe Technology and Applications (September 2000), Bordeaux, France. Co-authored a paper with Dr. Swann and Dr. Geoff Grime (Oxford University) at the IX International Conference on Particle-Induced X-Ray Emission and its
Analytical Applications (PIXE 2001), Guelph, Canada (paper has been accepted for publication).

Archaeological experience, both paid (York Archaeological Trust; Nene Valley Research Committee; Valentine Museum; Lost River Museum; Grey & Pape, Inc.; Educational Consultants; Department of Archaeological Research, Colonial Williamsburg Foundation; and Browning and Assoc., Ltd.). and as a volunteer (Archeological Society of Virginia and Falling Creek Iron Works Foundation), includes work in both the United States and Great Britain on a variety of sites, projects, and time periods. These include:

Orton Flail Farm (UK), a Roman and Saxon farm
Wroxeter (UK), a Roman town
Upper Bishop’s Hill (UK), medieval English industrial site
Cactus Hill, VA pre-Paleo site
Ft. Trenholm, Civil War earthen fort outside Charleston, SC
Pamplin Park, Petersburg, VA Civil War encampment
Geophysical Survey of the Falling Creek Iron Works (Chesterfield County, VA)
Maymont Canal Boats (Richmond, VA)