Chapter 1

The Nature of Ironmaking

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1.1 Introduction

The term ironmaking inevitably conjures a picture of man wresting glowing liquid hot metal from a giant reactor using methods steeped in history, more art than science. Understanding of the processes taking place, however, has expanded dramatically over the past few decades, bringing science to the operation, while retaining some of the art for future explanation. Our knowledge has increased significantly even since the publication of the 10th edition of *The Making, Shaping and Treating of Steel* in 1985, and it is the intention of this volume to present this information, together with the previous understanding of the process.[1]

While the production of molten iron from the blast furnace has held the predominant position to the present day as the method of supplying virgin iron units for oxygen steelmaking, it remains dependent on the availability of suitable coals for making coke. Alternative processes have proliferated in recent years to take advantage of lower cost raw materials and lower capital cost for smaller scale equipment. Some are coal-based, some are gas-based. Some use lump iron ore, some use iron ore fines. All are properly included in this volume on ironmaking, which presents the basic principles, operating practices and equipment used in separating iron from its naturally occurring oxide state.

1.2 Structure of this Volume

This introductory chapter is largely devoted to the history of ironmaking, bringing the reader from the earliest records to present day developments in blast furnace technology and equipment. Following this chapter, Chapter 2 presents a review of the fundamental basic physical chemistry and kinetics of iron and steelmaking, including the critical thermodynamic data and other data on the properties of iron–carbon alloys and slags relevant to ironmaking. The next four chapters deal with materials of significance used in ironmaking, their production and use. These include a general section on steel plant refractories, a chapter on refractories specific to ironmaking, followed by the production and use of industrial gases, and fuels and water requirements.

Chapters 7 and 8 deal with ironmaking raw materials, namely the manufacture of metallurgical coke, and iron ores and their beneficiation. Chapters 9 and 10 present in detail the latest advances in blast furnace equipment and construction, and a concise explanation of the practices and techniques used in the manufacture of pig iron in the blast furnace.

Chapter 11 on direct reduction and smelting processes concludes the volume with a considerably expanded review of the alternative processes to the blast furnace. The extent to which these will succeed will depend upon local conditions. Whether they succeed in promoting electric furnace steelmaking (or perhaps some other process) to a dominant position vis-a-vis the basic oxygen furnace, and whether the ironmaking blast furnace finds continued life, perhaps as a major supplier of raw material to these other steelmaking steps, will no doubt be subjects for discussion in the next edition of *The Making, Shaping and Treating of Steel*.

1.3 The History of Ironmaking

1.3.1 Prologue

Iron is a metallic element, a metal of transition group VIII of the periodic table, with the symbol Fe from the Latin word ferrum. Iron has an atomic number of 26, an atomic weight of 55.847 and melting point of about 1535°C (2975°F) or lower depending on the purity of the metal. Iron has the property of uniting chemically, also known as alloying, with numerous other elements which may improve its properties or have a deleterious effect. Iron makes up 5% of the earth's crust, second in abundance to aluminum among the metals and fourth in abundance behind oxygen, silicon and aluminum among the elements. Nowhere does iron occur as a usable metal. It is always found as an iron ore, which needs complicated processing before becoming a recognizable iron product.

All iron ores are basically oxides, which mean iron is chemically united with the element oxygen. These ores also contain small amounts of other elements such as manganese or phosphorus and are mixed physically with earthy materials such as sand, rock and clay. Ironmaking depends on eliminating the unwanted elements and foreign matter from the ore and controlling the amount of those elements which are beneficial.

Because iron has a natural affinity to unite with other elements, it can take many forms but it is possible to divide it into three major categories: wrought iron, cast iron and steel. Today steel is by far the most important form but cast iron is still commercially produced and wrought iron has been resigned to ornamental applications. Wrought iron is the oldest iron product dating back at least four thousand years. It is the commercially pure form of iron and has a fibrous structure. It is strong in tension, that is it resists forces tending to stretch it, but it can be shaped by hammering, squeezing or rolling.

Cast iron, which dates from the fourteenth century, is crystalline and relatively weak in tension. It cannot be shaped by hammering but it can be melted and poured into a mold, the shape of which it will retain after it cools and solidifies. Cast iron is an alloy of iron and carbon, which may contain up to about 5% of the latter element.

Steel is the most widely used and versatile form of iron. It can be of a simple composition chemically or it can become a complex alloy containing a number of other elements, which control the desired properties of the finished product. Bulk steel manufacturing only became possible after the invention of the Bessemer process in 1856, although small quantities of a simple form of steel were made hundreds of years earlier.

Now that this introduction is complete, the history of ironmaking will be presented in more detail with a chronological listing of its migration from the cradle of civilization, and a description of the evolution to modern production technology.

1.3.2 Ancient Ironmaking

The origin of the first smelting of iron is veiled in the unrecorded history of human civilization. The first evidence of iron implements actually transmitted to us from ancient times comes from Egypt where an iron tool was found in a joint between two stones in a pyramid. The origin of many prehistoric iron implements was probably meteoric iron. This iron was called *parzillu* by the Assyrians and Babylonians, *barsa* by the Sumerians and Chaldeans, *barzel* by the Hebrews and *ba-en-pet* by the Egyptians. The popular translation of these ancient terms is “metal from heaven.” Meteoric iron contains 5-26% nickel while smelted iron contains only traces of nickel, therefore iron artifacts made from meteors can be differentiated from manmade iron objects. It was in the great pyramid of Giza built circa 2900 B.C. that the earliest authenticated find of nickel-free iron was made. Another piece of smelted iron was found in a grave at Abydos, Egypt dating from approximately 2600 B.C.

Other prehistoric iron objects were also found around the Mediterranean Sea. A cube of iron was found in an 1800 B.C. grave at Knossos in Crete. Tombs at Pylos in the Peloponnesian peninsula of Greece contained iron finger rings dating from around 1550 B.C. What was probably an iron dagger was found at the site of Ur of the Chaldees in Iraq and is believed to date from 3100 B.C. Tools and weapons were discovered at Gerar, near Gaza in biblical Palestine, and some of the iron knives found there are believed to go back to 1350 B.C. Remains of iron working furnaces from about 1200 B.C. were also unearthed at this site. The Hittites, who were ancient Syrians, are credited with developing a commercial iron smelting process in 1200 B.C. that spread north and west into lower European countries. The dates given here are only approximations as archeological research is continually discovering new evidence that necessitates revision of chronology.

How did man learn to extract iron from ores? Archeological evidence indicates that a knowledge of how to obtain copper from its ores existed long before iron was made by man. Mixtures of copper and tin that formed bronze, and of copper and zinc that formed brass, provided the ancients with metals that found widespread usage. The origins of the methods used by early man for extracting iron from iron ore is unknown but some have suggested that men learned the method accidentally. This may have occurred when fires were built by chance on crude hearths built of iron-bearing rock, especially if the fire was in a location where a strong natural draft caused it to burn fiercely. This is a possibility, since what could happen under such circumstances would meet the conditions now known to be required for extracting iron from its ores. These conditions are that iron-bearing ore should be heated strongly in contact with hot carbon, out of contact with oxygen, which would result in the reduction of iron oxide to iron known as smelting. It may be assumed that such chance production of iron occurred often enough in the experience of one individual or group of people to attract attention and eventually to create a desire to reproduce the process at will. The resulting product would have been a lump of sponge iron that could not be cast into its final form like bronze or brass but instead would have to be hammered into a tool, implement or weapon.

The first recorded depiction of a smelting process was found on the wall of an Egyptian tomb dating to about 1500 B.C. , Fig. 1.1. This process was a simple pit with ore and unknown fuel that had the fire intensified through the use of foot-operated bellows.

The first written mention of ironmaking is found in the Bible, Genesis 4: 22, which names Tubal-Cain as “…an instructor of every artificer in brass and iron.” Other significant writings referring to iron have been found in Babylon where in the sixth century B.C., Nebuchadnezzar declares

Fig. 1.1 Egyptian smelting, circa 1500 B.C

"with pillars and beams plated with copper and strengthened with iron, I built up its gates." Herodotus, in the fifth century B.C., speaks of the "Chalybians, a people of iron workers." Homer makes references to manmade iron as a prize at the funeral games of Patroclus, being "a mass of iron shapeless from the forge." Sophocles who died in 406 B.C. speaks of the tempering of iron in water. The writer Daimachus, a contemporary of Alexander the Great, describes four different kinds of steel and their uses. Iron and steel weapons began to displace those of bronze in the Mediterranean countries soon after the battle of Marathon fought in 490 B.C. Ironworking technology spread from the eastern end of the Mediterranean sea from Greece to Rome around 300 B.C. and finally to Spain about 200 B.C.

The history of the ironmaking process in Africa was never written down but passed by word of mouth for generations from approximately 600 B.C. An early ironmaking site has been excavated near Lake Victoria in Northwest Tanzania. The excavations in conjunction with oral history passed to current living members of the Haya tribe have resulted in a detailed description of the ironmaking process in Africa. The raw materials consisted of roasted iron ore and charcoal made from the Muchweizi tree. The ore was roasted in a smoldering fire to drive out the moisture and increase its surface area for improved chemical reactions by causing the ore to crack. The charcoal was produced in open pits and carried to the smelting area on the backs of the workers. A pit approximately 0.91 m (3 ft) in diameter was dug in the ground in the shape of a bowl and lined with mud made from termite mounds. The mud was dried by burning swamp grass in the pit. Blowpipes used to convey air from manually operated goatskin bellows were produced by packing mud around a straight stick, then withdrawing the stick after the mud had dried out in the sun. These blowpipes, which are approximately 48 cm (19 in.) long were placed around the bowl at ground level with their ends sticking deeply in toward the center of the pit. Then a cone shaped shaft approximately 1.5 m (5 ft) high was constructed out of pieces of old refractory slag and termite mound earth, Fig. 1.2. The shaft was then filled with charcoal and iron ore. The smelt was then started with the ignition of the charcoal and blast was provided by several two-chambered goat skin bellows that were designed to let the operator compress each chamber with a stick attached to the goat skin. Each of these sticks was placed in one hand and the operator's arms were moved up and down vertically in a pumping, reciprocating motion which compressed the air in the bellows chamber through the clay blowpipe and into the smelting bowl. Because the ends of the blowpipes were being heated inside the pit, the blast was being preheated and the temperatures in the pit reached approximately 1802°C (3275°F). The smelt lasted about twelve hours with the shaft continually being recharged with charcoal and ore. The product was a liquid slag and pieces of sponge iron in front of each blowpipe about the size of a human fist. This sponge iron was similar to a mild steel with a carbon content of 0.2-0.6%. At the end of the smelt the shaft of the furnace was demolished and the chunks of sponge iron removed. The pieces of iron were then reheated and hammered by a blacksmith to remove slag inclusions and to form the iron into its final shape.

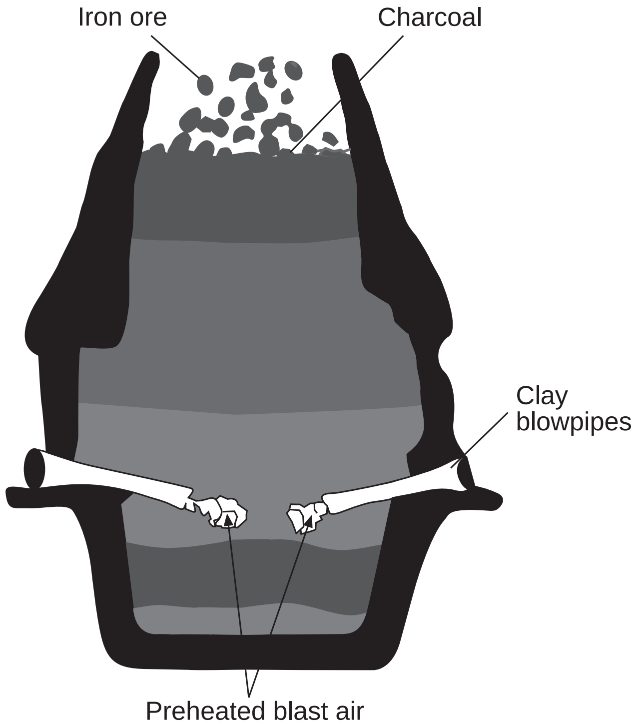

Fig. 1.2 African smelting pot.

Similar smelting holes were used throughout the Mediterranean countries. Improvements in this first ironmaking

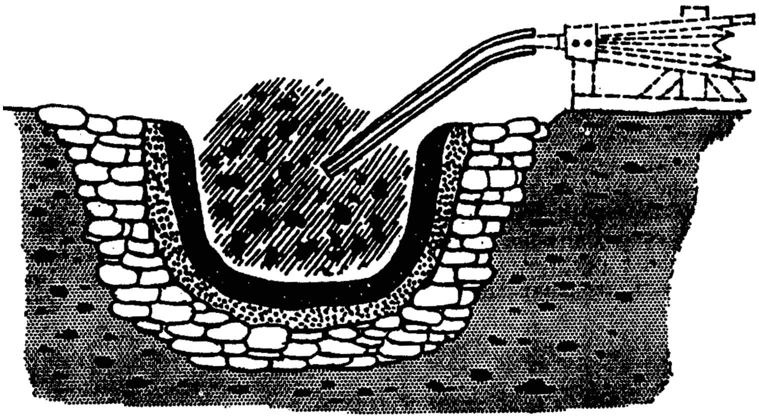

Fig. 1.3 Early smelting hole.

process were made by lining the smelting hole with stones as well as mud and using bellows made of wood and leather, Fig. 1.3. Elsewhere in the world, iron smelting had been evolving independent of events in the Mediterranean. In China, the use of iron appeared about 600 B.C., spreading widely during the course of the Warring States Period (403-222 B.C.). The Chinese developed superior ironmaking technology and liquid iron was produced as early as 200 B.C. based upon the discovery of cast iron utensils. Ancient writings in both China and India refer to iron smelting. Other artifacts include swords, axes, sickles and hoes. By A.D. 310 a sufficient quantity of iron could be produced to allow the erection of the famous iron pillars of Delhi and Dhar in India. The wrought iron pillar in Delhi is 18 m (60 ft) tall, 41 cm (16 in.) in diameter and weighs 17 tons.

In Japan, the traditional iron and steelmaking process known as *Tatara* was not fully developed until the seventeenth century after Christ.

In North America, South America and Australia, iron smelting was not known to the ancient inhabitants. Ironmaking technology was brought to these countries by the Europeans.

1.3.3 The Spread and Evolution of Ironmaking in Europe

The ironmaking process developed around the Mediterranean Sea spreading northward through Europe. Historians state Phoenicians, Celts and Romans all help spread ironmaking technology. One of the ironmaking techniques spread by the Romans as far north as Great Britain was the early bowl or shaft furnace, Fig. 1.4.

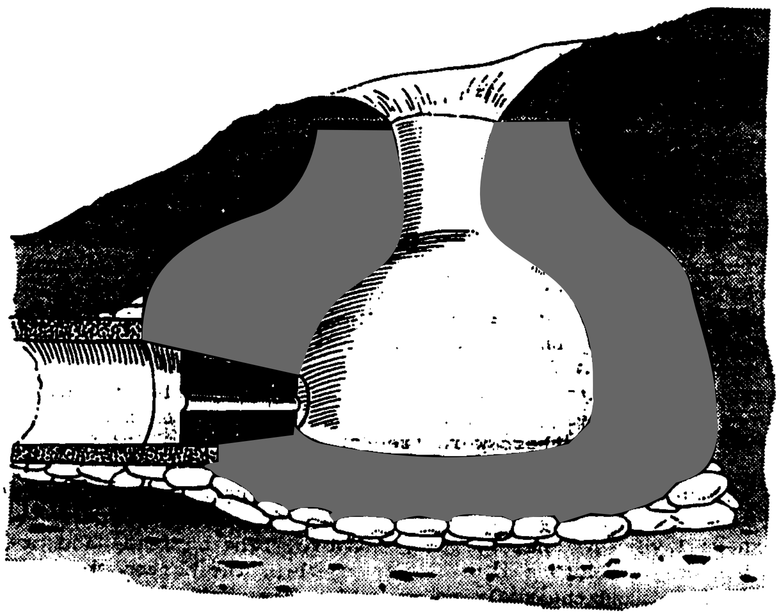

Fig. 1.4 Natural draft furnace.

This furnace consisted of a bowl-shaped vessel or a cylindrical shaft 2 m (6.6 ft) high being built into the side of a hill. The air used to fan the fire inside the furnace was provided by an opening built near the bottom of the bowl which faced into the prevailing wind. The furnace was filled through the top opening with layers of charcoal and iron ore that were ignited through the lower opening. There are two theories on how the iron smelting was driven, one that the wind blasted in through the bottom opening providing air which heated the process and the other that the wind blew over the open top, creating a low pressure area

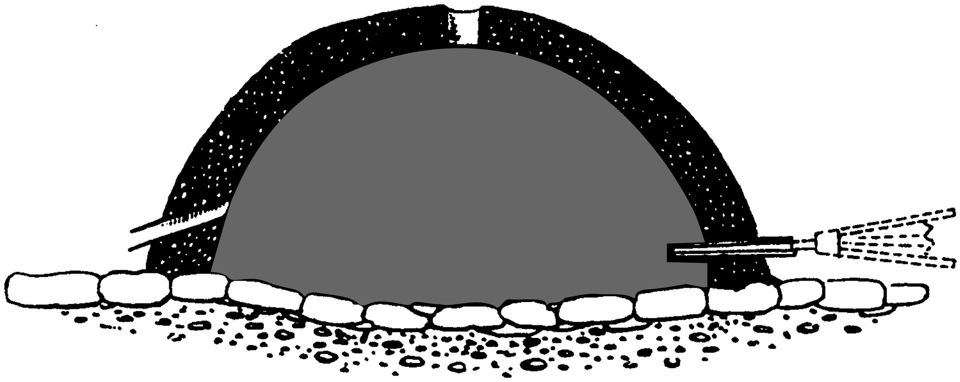

Fig. 1.5 Beehive furnace.

along the inside front wall which sucked air in through the lower opening. In either case, the process was dependent on wind and was not reliable throughout the year. The product was once again a mass of sponge iron, which was removed through the lower opening and then hammered into its final form.

Another type of early iron smelter was the beehive furnace, Fig. 1.5. This furnace resembles a beehive coke oven and was constructed on flat ground by piling alternate layers of charcoal and iron ore. The mound was covered with a thick layer of clay and blowpipes connected to bellows were inserted through the lower side walls. The bottom layer of charcoal was ignited and compressed air was provided by the bellows. At the end of this batch type smelt, the clay dome collapsed. The sponge iron produced was dug out of the demolished beehive furnace and taken to the blacksmith. Once again, the production was small lumps of iron and the smelting furnace had to be demolished and rebuilt after each production run.

These types of ironmaking processes were used for several hundred years into the modern era without much improvement. Then approximately during the eighth century, a small forge operating in the mountains of Catalonia in northeastern Spain represented one of the early significant metallurgical advances in ironmaking. The early Catalan forge had a stone-built cup called a hearth, about 0.91 m (3 ft) high and 0.76 m (2.5 ft) in diameter, Fig. 1.6. A short distance above the front of the base was a small opening that allowed a nozzle known as a tuyere to be installed. The tuyere nozzle was connected to a bellows to supply air. The hearth was filled to the tuyere level with lumps of coal. Then iron ore was placed above the tuyere and more charcoal was layered on top of the ore. The charcoal was lit and air from the bellows forced hot carbon monoxide over the iron ore which reduced the ore to a hot, lumpy mass of iron. The mass of iron known as a bloom, (Saxon word bloma) could weigh up to 160 kg (350 lbs) and could be removed from the hearth of the forge with tongs without destroying the stone structure. This quantity of iron could be generated in five hours while previous technologies could only produce about 23 kg (50 lbs) in five hours.

The Catalan forge was increased in size over the next two hundred years and its use spread into France, Belgium, England and Germany. The sizes of the hearth increased to 1 m (3.25 ft) square and were built out of rectangular stone blocks, Fig. 1.7. The amount of air delivered through the tuyere was also increased through the use of an air aspirator known as a *trompe*. As water falls through the trompe column, air is drawn into the tube and then expelled at the bottom of the box. When this device, Fig. 1.8, was incorporated into the Catalan Forge the pressure of the blast through the tuyere was 10–14 kPa (1.5–2.0 psi) which is considerably more than a hand or foot bellows could produce. This additional blast pressure accelerated the smelting process and slightly increased the bloom production.

From the tenth century through the fourteenth century, the Catalan forge underwent further evolution. Hand or foot-operated bellows were replaced with waterwheel-operated bellows which increased the volume and pressure of the air blast, Fig. 1.9. Next, someone attempted to capture

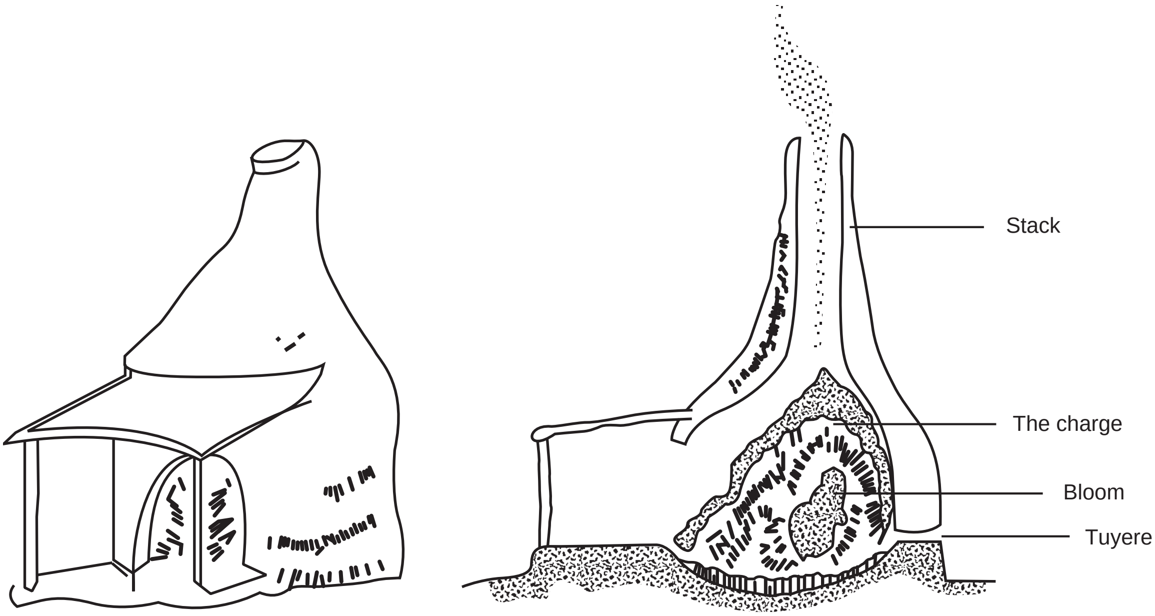

Fig. 1.6 Early Catalan forge.

the waste heat from the stack of the forge by increasing the height of the stack and charging iron ore and charcoal from the top of the stack so the ore could be preheated. The *wolf oven* or *wolf furnace* had a stack made of stone masonry that was about 1.8 m (6 ft) high. The *Blasofen* of Germany and the *Osmund* furnace of Sweden had a stack of 2.4 m (8 ft) high. Finally, the *Stuckofen* or *High Bloomery* common along the Rhine River had a stone shaft 3–4.8 m (10–16 ft) high. The only reason stack heights and the subsequent heights of the raw material charge could increase was due to the higher pressure of the blast which could be forced up these stacks from the waterwheel and bellows system.

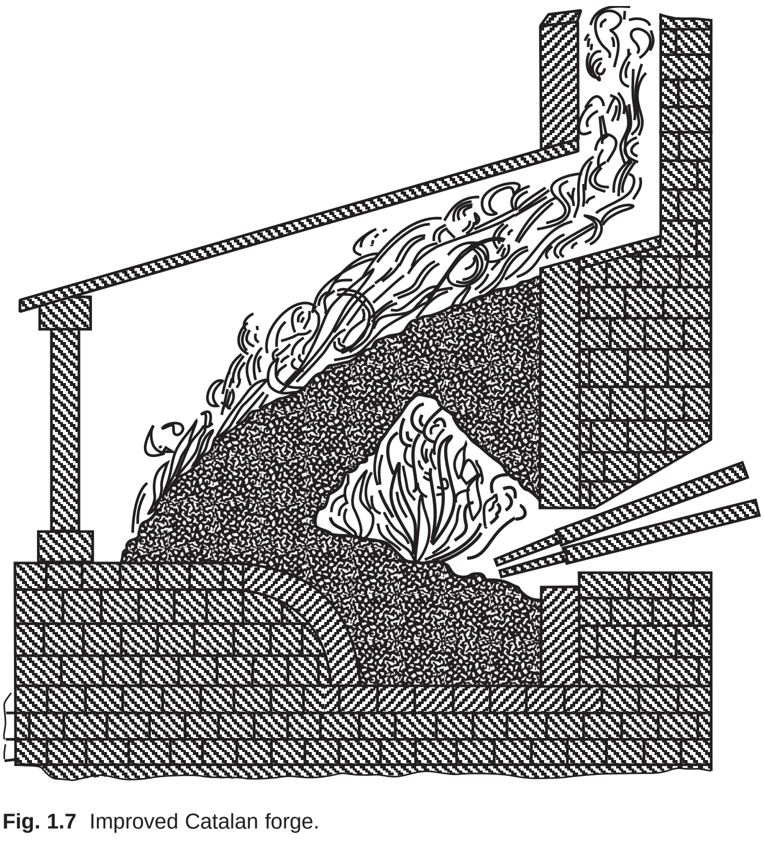

Fig. 1.7 Improved Catalan forge.

The Stuckofen not only had a higher stack but a change in stack geometry, Fig. 1.10. The furnace took the shape of two truncated cones connected at the widest diameter. Two tuyeres became the standard since the waterwheel drove two bellows with one of them constantly being compressed to deliver blast. There was an opening at the bottom of the furnace to draw off slag but stone work had to be removed to extract the final product which was still a bloom of iron

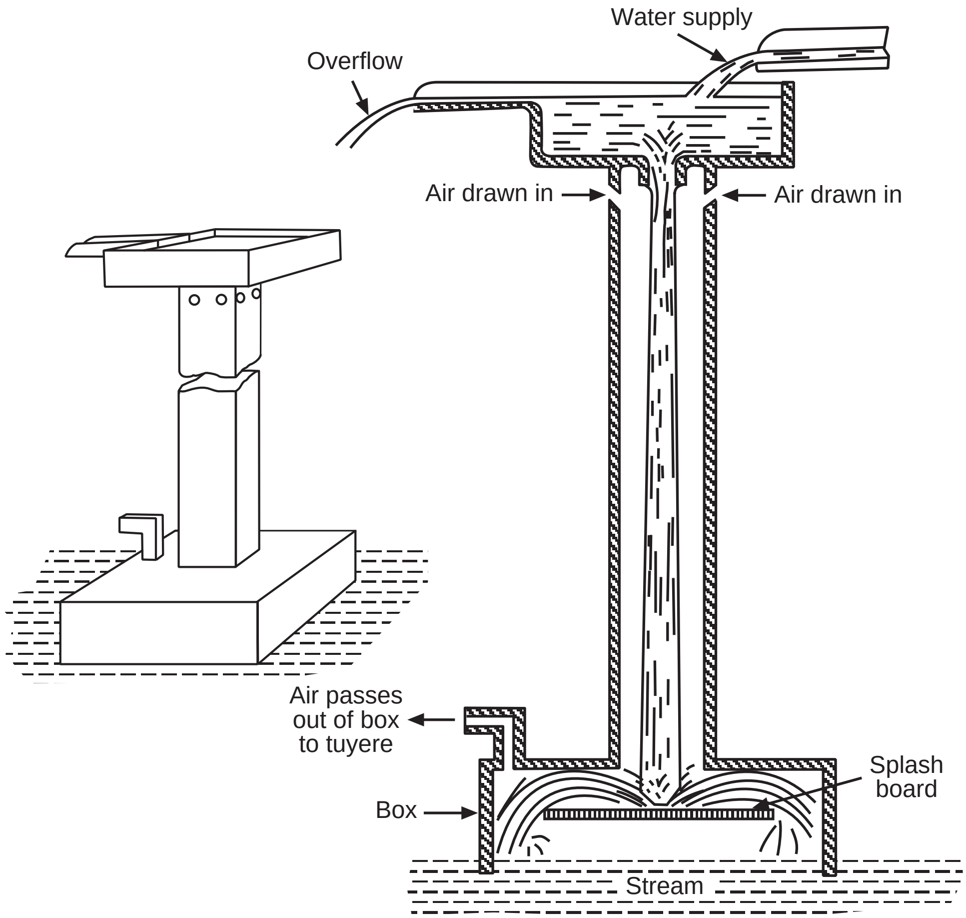

Fig. 1.8 Sketch of a trompe, used to increase the amount of air supplied to the tuyeres in a Catalan forge, circa A.D. 800–1000.

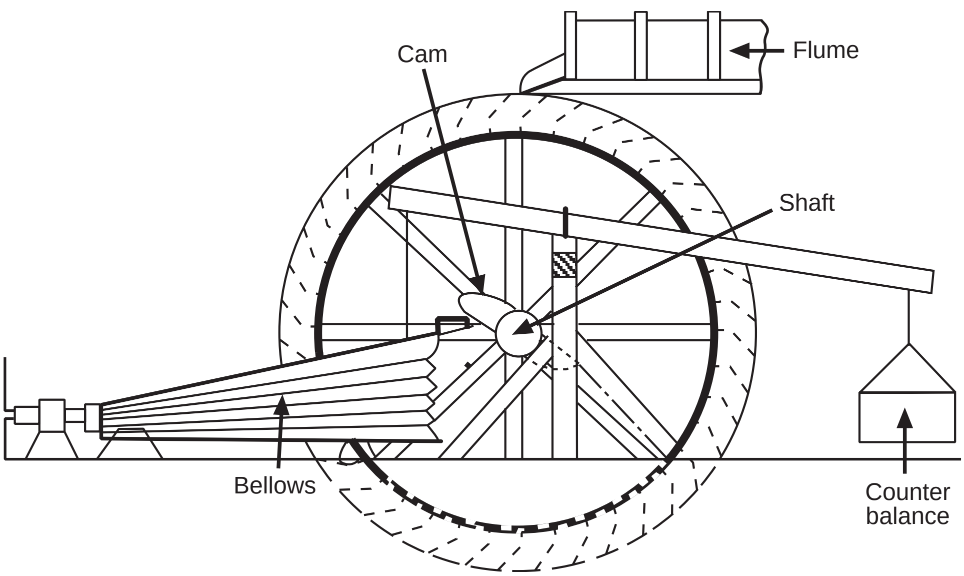

Fig. 1.9 Waterwheel-operated bellows.

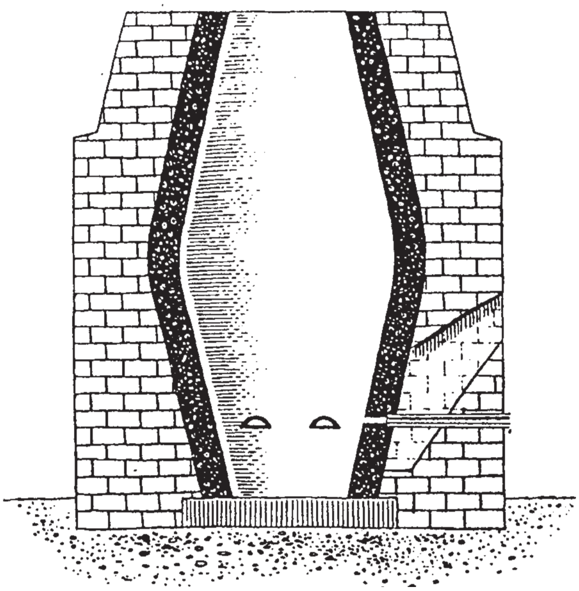

Fig. 1.10 Typical Stuckofen furnace design

which weighed 318 kg (700 lbs). The Stuckofen could produce 100 to 150 tons per year surpassing the production capability of a Catalan forge. One byproduct of the Stuckofen was liquid iron. Because the iron ore had a longer residence time in the furnace to undergo chemical reactions and be exposed to higher temperatures, the iron could absorb more carbon which lowered the melting point. When the bloom was removed from the furnace, this liquid iron was also removed. At first it was considered a detriment since it was too brittle to be worked with the hammer. In some cases, it was recharged into the furnace or even thrown away as waste. The Stuckofen may be considered the forerunner of the modern blast furnace. It was further modified into the *Blauofen* (blow oven) which was capable of producing either liquid iron or forging grade sponge iron at the ironmakers' discretion. This change in desired products was accomplished by changing the amount of fuel charged by 10 to 15% and by lowering the position of the tuyeres by 5 cm (2 in.) and pushing them deeper into the furnace. In the sixteenth century these furnaces were 6.7 m (22 ft) high and could produce 1814 kg (4000 lbs) of iron per day with a fuel rate of 114 kg (250 lbs) of charcoal per 45 kg (100 lbs) of iron produced. These furnaces had a low life expectancy of approximately 45 days.

The final step in furnace design to produce liquid iron all of the time was the *Flussofen* (Flow Oven). The development of the Flussofen or first blast furnace was in the fourteenth century in the Rhine River Valley and adjacent areas of France, Belgium and Germany. The city of Solingen, famous from the twelfth century for its swords, was an ironmaking center. However, with a change in the technology of warfare as well as of ironmaking, the casting of cannons from molten iron became the dominant industry rather than the forging of swords from sponge iron. As early as A.D. 1300, ironmakers actively sought to produce molten iron to cast guns. The first reliable documentation of a known blast furnace is in A.D. 1340 when the furnace at Marche Les Dames, in Belgium was built. In A.D.1377, cast iron cannons were made near Erfurt in Thuringia, Germany. The spread of the Flussofen or blast furnace was relatively slow, as indicated by the absence of any reference to it by Agricola in his book *De Re Metallica* written in 1530, although he describes the Stuckofen. The continental nations of Europe are entitled to the credit of having fully developed the blast furnace from the primitive method of producing iron blooms in a Catalan forge. The modern blast furnace is a shaft furnace that gradually evolved from the Stuckofen and Flussofen. In its early days, it was called a high furnace and today retains this name in Germany, *Hochofen* and France, *Haut Fourneaux*.

1.3.4 The Evolution of the Charcoal Blast Furnace

The charcoal blast furnaces developed in Continental Europe soon spread to Great Britain where the next evolution in ironmaking technology would occur. A blast furnace built in Monmouthshire, England in A.D. 1565 was the first furnace built in the forest of Dean which became a major ironmaking center. This furnace was 4.6 m (15 ft) high and 1.8 m (6 ft) at the bosh, which is the widest point inside the furnace where the two truncated cones meet. By 1615 there were 800 furnaces, forges or iron mills in Great Britain. Out of these 800 ironmaking facilities, 300 were blast furnaces averaging fifteen tons per week per furnace. The rate of growth was so fast that deforestation for charcoal production almost totally cleared the land. During the 1600s, laws were past to protect remaining forests and many blast furnaces were shut down. It was at the same time that

England encouraged the production of iron in its North American colonies, which had abundant supplies of wood and iron ore.

The first blast furnace built in North America was at Falling Creek, Virginia in 1622. This furnace was never put into production because native Americans massacred all of the ironworkers and the ironworks was destroyed. The first successful charcoal blast furnace in The New World was in Saugus, Massachusetts, outside of Boston, starting in 1645. This blast furnace, known as Hammersmith, can be used to describe a typical blast furnace in operation during the 1600s.

The furnace stack was 7.9 m (26 ft) square at the base and 6.4 m (21 ft) high with the outer walls sloping inward as they rose, Fig. 1.11. Made of granite and other local stone bonded with a clay mortar, it rested on level ground into which a subterranean drainage system had been cut to guard against the dampness to which the water that drove its big bellows wheel made it peculiarly susceptible. In the interior of the stack, which was roughly egg shaped, the maximum diameter known as the top of the bosh was 1.8 m (6 ft). The bosh, which slopes downward, supports the charge of ore, flux and charcoal. Below the bottom of the bosh was a square crucible also called the hearth which was lined with sandstone. Between the inner lining and outer masonry ran an inner wall with sand, clay and rubble which acted as a cushion for expansion and contraction during heating and cooling cycles. Two of the outer walls had large and deep arches. Through the smaller arch passed the noses of the two 5.5 m (18 ft) bellows and the two tuyeres, which delivered blast into the furnace. Under the larger arch was the working area of the hearth and casting floor.

The crucible or hearth acted as the reservoir for molten iron. The hearth was 46 cm (18 in.) square at the base but broadened out to 53 cm (21 in.) as it reached its full height of 1.1 m (3.5 ft). A pro-

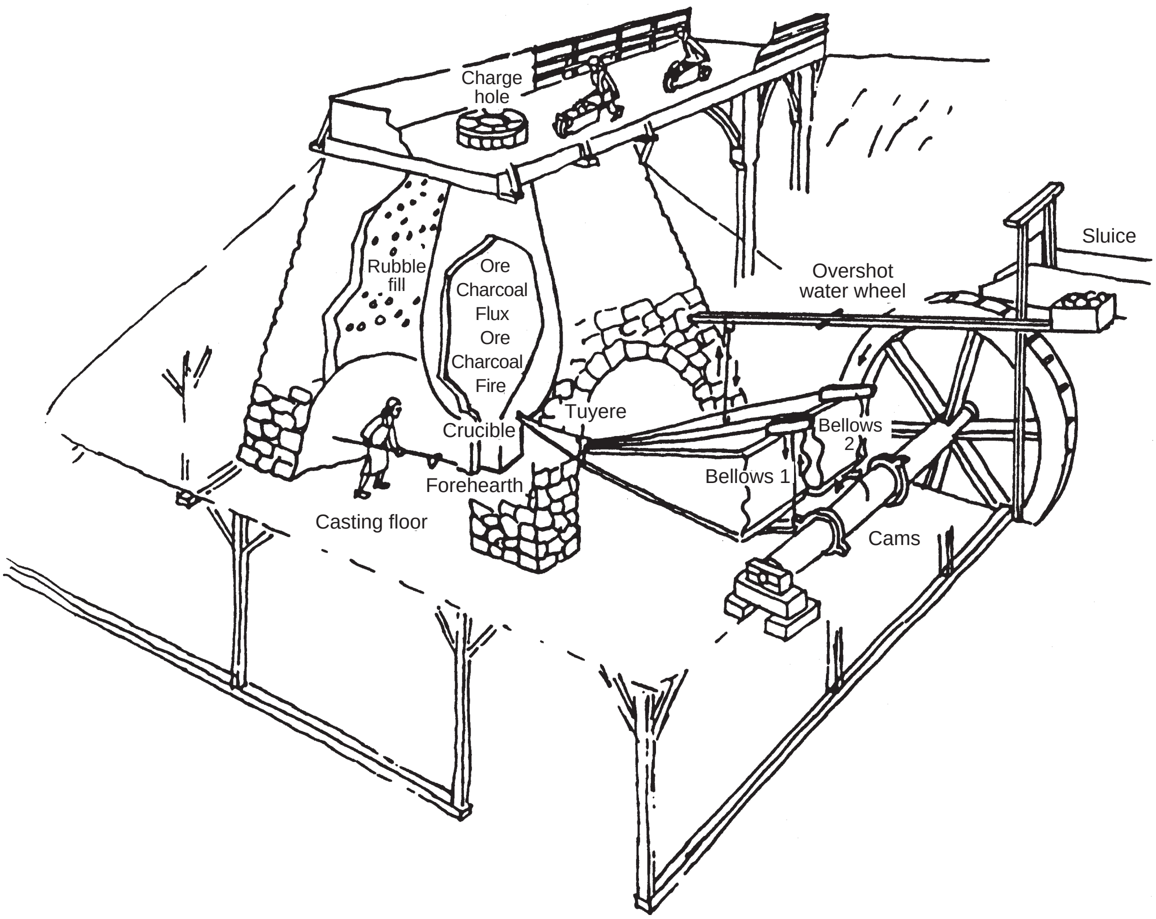

Fig. 1.11 Charcoal furnace from the 1600s.

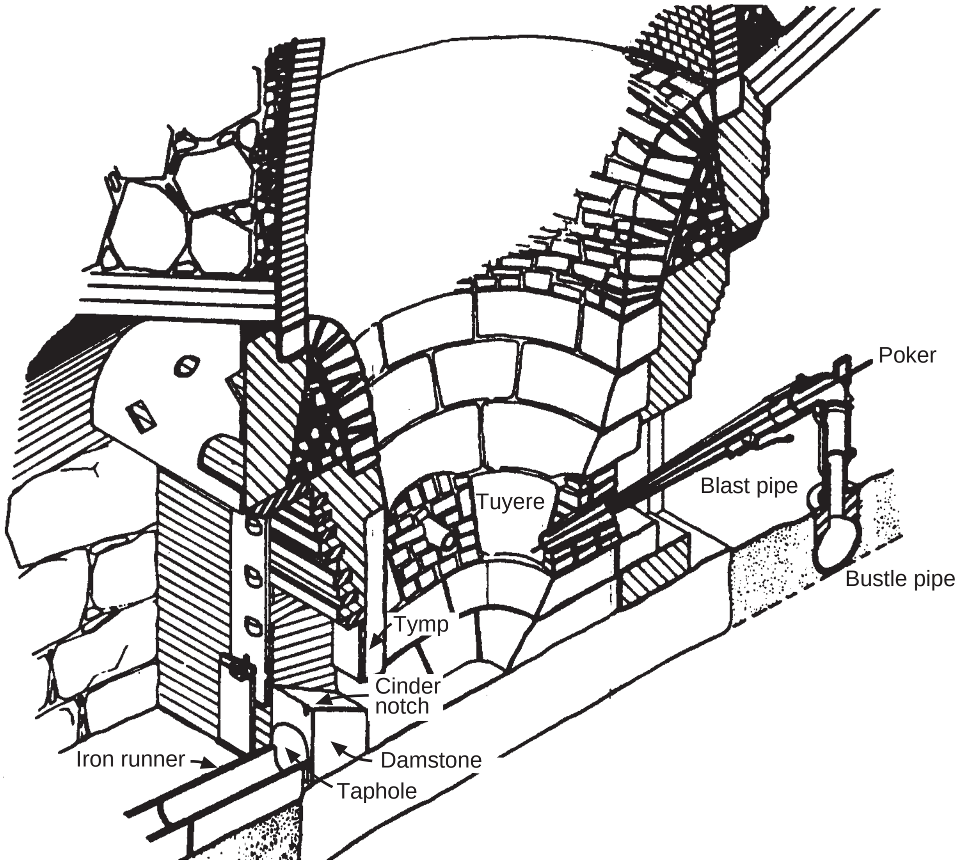

Fig. 1.12 Detail of a charcoal furnace hearth.

jection of its lower portion, called the forehearth, consisted of two walls and a forestone or dam. Above, and set back from the dam, was a stone curtain wall, called the tymp, whose bottom edge came down lower than the top of the dam, Fig. 1.12. Through the opening between the tymp and dam, a workman ladled off the iron for mold casting and with an iron bar, called a ringer, pried away slag that stuck to the walls or accumulated around the tuyere nose. For protection against wear and tear of such operations, both the tymp and dam were sheathed with iron plates. Slag removal was accomplished by raking the molten material over the dam stone at a location called the cinder notch. To tap the iron however, required the breaking out of a clay plug inserted in a narrow space, called the taphole, between one of the forehearth side walls and one end of the dam.

Besides all this reasonably complicated masonry, erection of the blast furnace involved work in timber and in leather. Between the furnace top and the adjacent bluff ran a heavy timber structure called the charging bridge. Raw materials were taken in wheelbarrows from their stockpiles on the bluff, across the charging bridge to the furnace top. On three sides of the furnace top were wooden wind screens, set up to provide some safe shelter for the men pouring raw materials into the charging hole that belched smoke, sparks and occasionally flames. The stack of the furnace at ground level was wrapped on two sides by a wooden lean-to structure called the casting house. This shelter provided cover for the trench and mold casting area as well as the bellows. The two bellows were driven in reciprocating fashion by a cam shaft connected to an overshoot waterwheel. The bellows were deflated by the cams on the main shaft and were inflated by counterweights which were wooden boxes filled with stones and mounted on the moving beams that extended beyond the casting house roof through holes cut to accommodate them.

The furnace consumed 3.0 tons of iron ore, 2.0 tons of flux stone and 2.6 tons of charcoal for every ton of iron produced. The taphole was opened twice a day and 454 kg (1000 lbs) of liquid

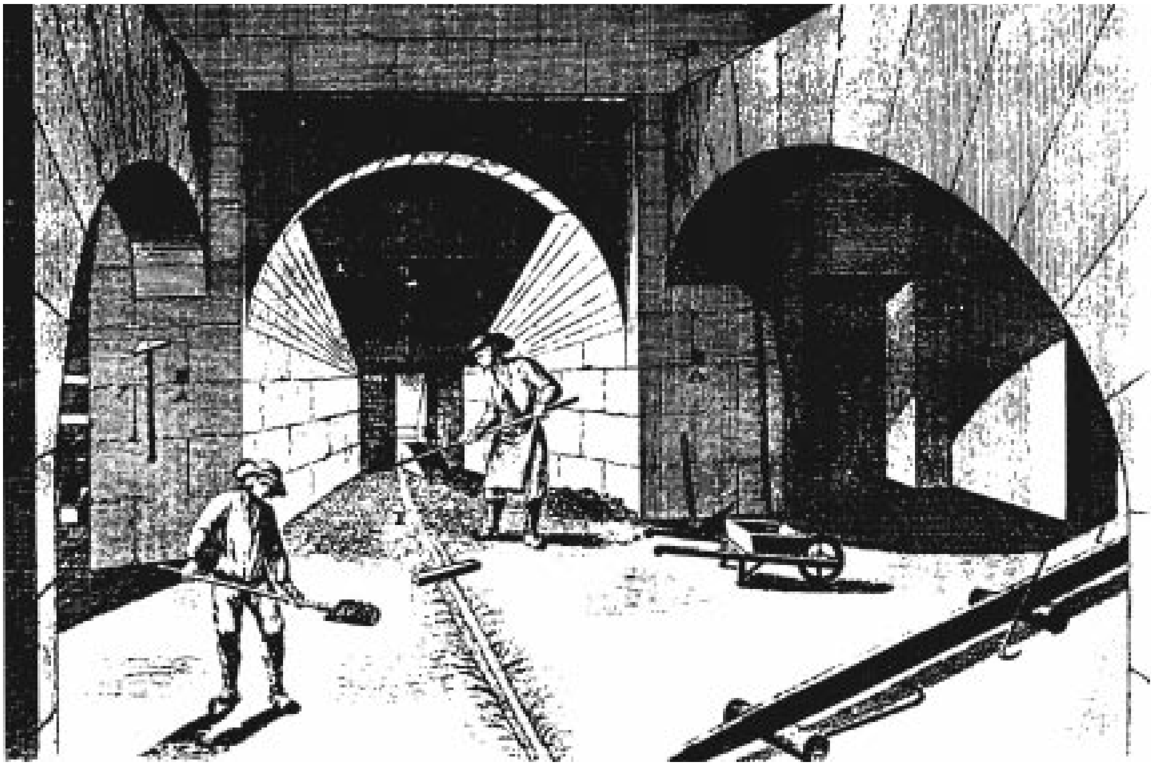

Fig. 1.13 Tapping a blast furnace in the 1600s.

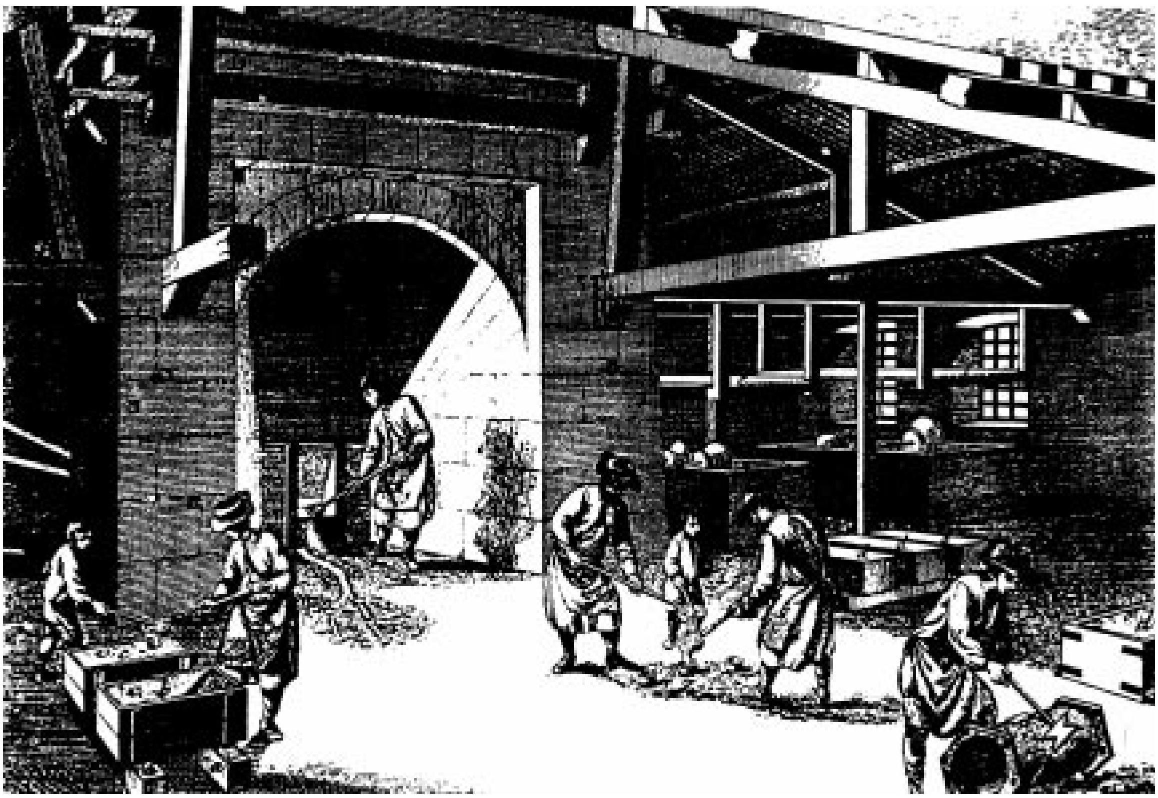

Fig. 1.14 Producing iron castings from a blast furnace in the 1600s.

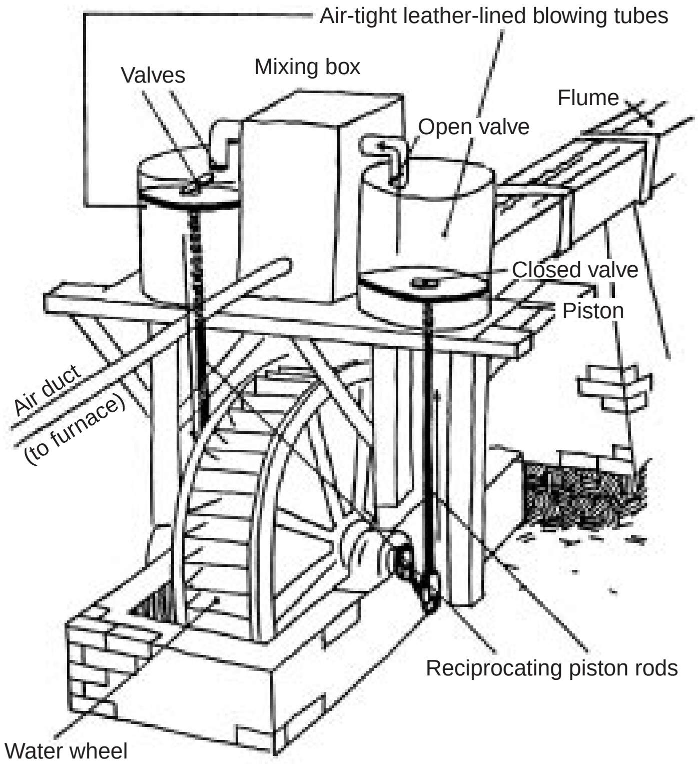

Fig. 1.15 Waterwheel and blowing tubs utilized to increase blast pressure.

iron was removed during each cast. The hot metal was drawn into a single trench, Fig. 1.13, or ladled into sand molds, Fig. 1.14, to produce pots, pans, stove plates and other domestic commodities.

The previous description of charcoal ironmaking changed only slightly over the next 100 years into the 1700s. The blast furnace stacks increased in size and improvements were made in blowing equipment. The 1700s also saw the first blast furnace constructed in Canada at St. Maurice, three miles west of Trois Rivieries in 1737. A typical charcoal blast furnace of the 1700s saw an increase in size to 9.1 m (30 ft) in height and a bosh diameter of 2.4 m (8 ft). The increase in furnace size was permissible only through improvements in the wind delivery equipment that resulted in higher blast pressures. The first improvement in blast systems was the invention of wooden blowing tubs. These tubs could be square or round. The tubs were similar to wooden barrels held together with external steel hoops. An eccentric crank on the waterwheel would have a reciprocating piston rod and blowing tub on each side, Fig. 1.15. The piston inside the tub was fitted with leather to form a seal. As one piston was ascending to compress air in one tub, the other piston was descending in the other tub. At the top of each tub was an outlet pipe connected to a common mixing box that was always under pressure. The mixing box fed compressed air to an air duct or blast main which led to the furnace tuyeres. A typical blowing tub was 1.8 m (6 ft) in diameter and 1.8 m (6 ft) high, producing 14 kPa (2 psi) of blast pressure.

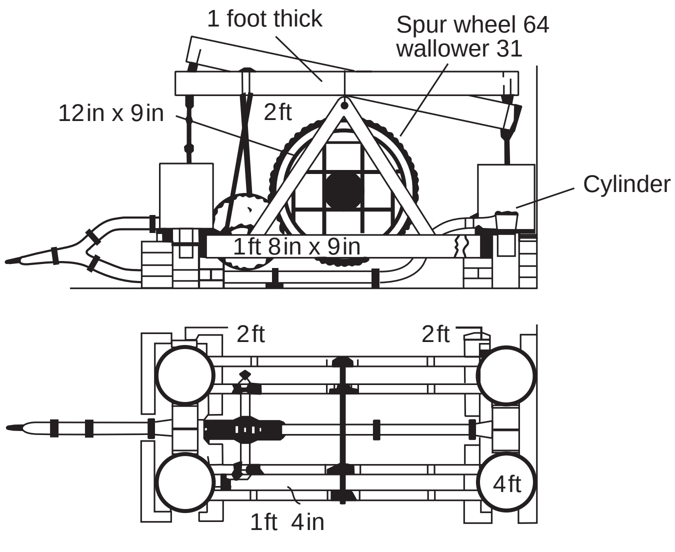

Fig. 1.16 Vertical blowing cylinders powered either by waterwheel or a steam engine.

The concept of wooden blowing tubs was carried one step further by John Smeaton in England in 1760. He converted the wooden tubs into cast iron tubs driven first by a waterwheel and then in 1769 by a steam engine, Fig. 1.16. The first blast furnace to use the steam driven blowing engines was built at the Carron Works in Scotland in 1769. It was the invention of steam driven blowing engines and the resulting higher blast pressures that would allow further use of mineral fuels such as coke and coal.

As a result of improvements in the 1700s, the blast furnace production increased from the one ton per day in the previous century to 3–5 tons/day by the late 1700s. The introduction of better blowing equipment and the use of mineral fuels caused a rapid decline in the number of charcoal furnaces in Great Britain and Europe, although charcoal iron capacity increased in North America as the populations moved west into a seemingly unlimited supply of wood.

In the 1800s, charcoal iron production peaked and then declined in the United States and the rest of the world. Many of the technological innovations applied to charcoal furnaces were also applied to anthracite furnaces and coke furnaces, therefore the remaining discussion of charcoal furnaces will focus on cold blast charcoal furnaces of North America.

In the middle of the 1800s, high quality iron ores were discovered in Pennsylvania and the Upper Peninsula of Michigan. As these locations also had dense virgin forests, newly built charcoal furnaces would be the biggest and best equipped in history. These furnaces were equipped with steam-driven blowing engines that allowed another increase in furnace height and volume. Typical stacks rose to 13.7 m (45 ft) with bosh diameters of 2.9 m (9.5 ft). The number of tuyeres increased from two to three, which were distributed equally around three sides of the furnace while the taphole remained on the fourth side. The blowing equipment was usually horizontal blowing cylinders with typical diameters up to 127 cm (50 in.) and strokes of 1.5 m (5 ft), Fig. 1.17. Elevator-type platform hoists replaced charging bridges, Fig. 1.18, and all iron ores and fluxes were weighed as part of a standard charge. Charcoal was still charged by the volume of a large wheelbarrow. Iron shell plates slowly replaced the masonry stone stacks and natural stone linings were upgraded to alumina bricks.

One of the major technological improvements installed on these charcoal furnaces was charging equipment. Originally, raw materials were dumped into an open-mouthed stack through the *tunnel head*. Blast furnace operators realized that an open top furnace had two disadvantages, first the flammable gas exiting the stack could not be captured to fire boilers and second, the distribution of raw materials was causing furnace operating inefficiencies. The first efforts to capture the gas in 1832 in Germany resulted in changes that were made at the top of the furnace. A hinged lid, Fig. 1.19, was installed over the charging hole and was only opened as raw materials were dumped from the wheelbarrows. An opening was also placed in the side of the furnace located at the upper stack. This opening was fitted with a pipe known as a downcomer that carried the blast furnace gas to the

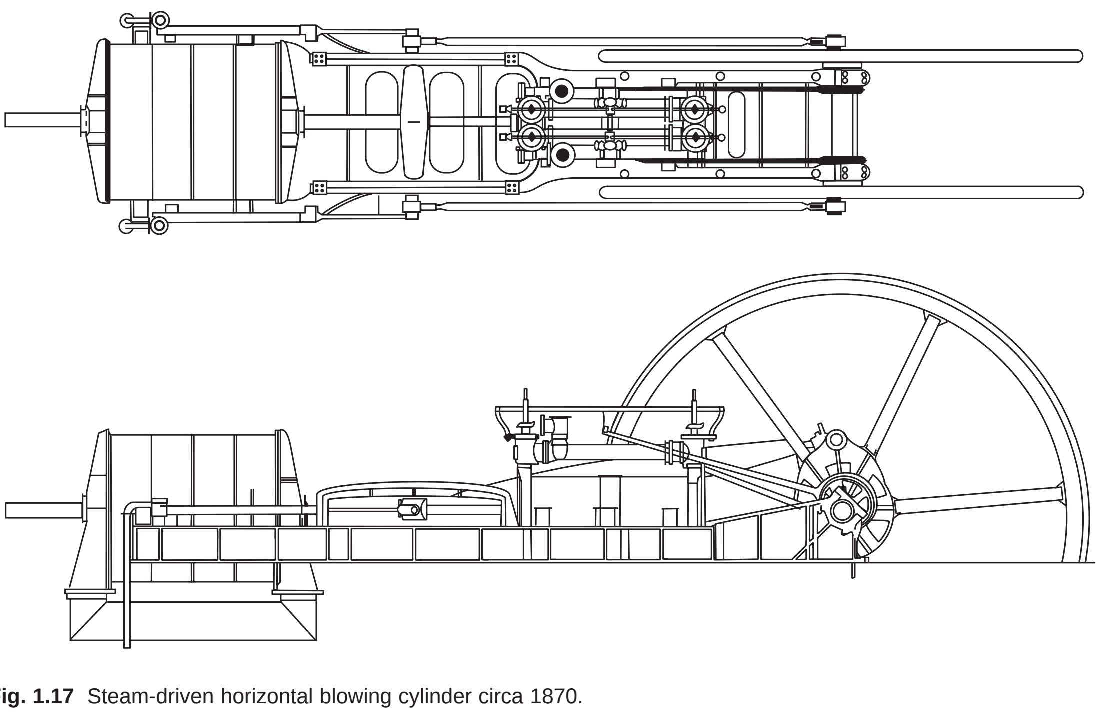

Fig. 1.17 Steam-driven horizontal blowing cylinder circa 1870.

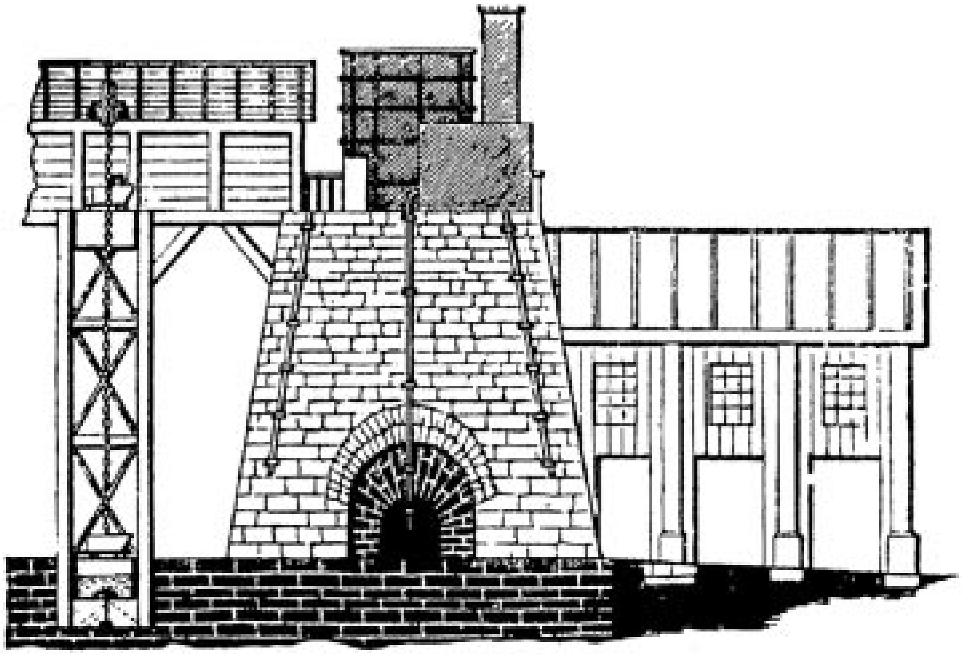

Fig. 1.18 Water-driven hoist from the 1800s.

ground level to be burned in auxiliary equipment. The issue of furnace inefficiency due to raw material placement required a more complicated solution that evolved in several steps. The cause of this inefficient operation, characterized by high fuel rates, was that fine material dumped through the charging hole in the center of the furnace stayed at the center of the heap while coarse particles rolled down to the furnace walls. This resulted in the wall area having higher permeability and so most of the gas and heat ran up the walls. This was detrimental to the furnace operation as the material at the center of the furnace arrived unprepared for melting in the bosh area and excessive gas flow at the wall would accelerate the lining wear. The first attempt to solve this burden distribution problem was a charging apparatus known as a cup and cone. It consisted of an inverted conical cast iron funnel fixed to the top of the furnace feeding the charging hole, Fig. 1.20. This cone was approximately one-half the diameter of the throat. Inside the cone would sit a cast iron cup, which was suspended on a fulcrum beam opposite a counterweight. The cup was raised manually by using a winch connected to the counterweight. This system was successful in capturing the gas but too much coarse material still rolled to the wall. The next modification to the cup and cone equipment was to hang a cast iron truncated cone, Fig. 1.21, inside the furnace that would result in moving the peak of raw materials closer to the wall so coarse particles could now also roll to the center of the furnace resulting in more central permeability and gas flow.

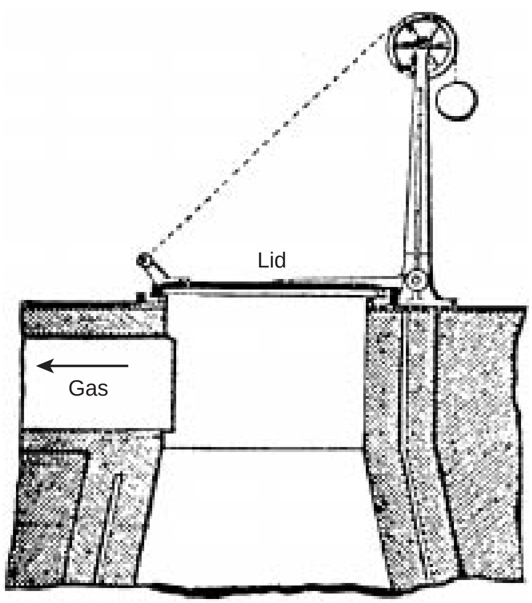

Fig. 1.19 Charging hole lid, circa 1830.

The next evolutionary step in charging was to eliminate the cup and cone completely and hang an inverted cone that opened downward into the furnace. This was the first bell-type top, Fig. 1.22. This bell was successful in pushing the peak of

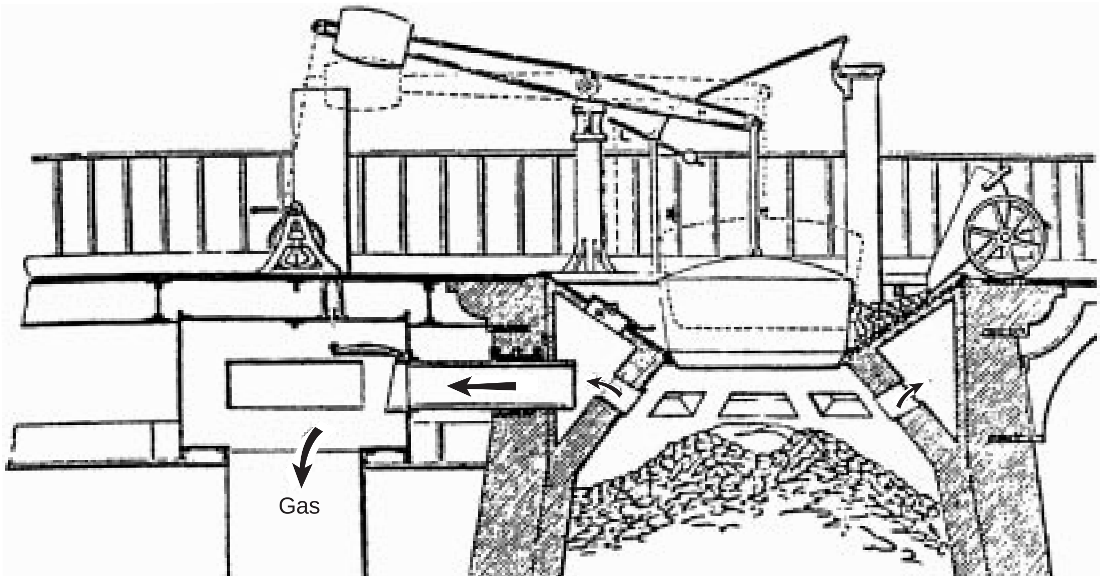

Fig. 1.20 Cup and cone filling, circa 1880.

raw materials further toward the wall which reduced gas flow around the periphery and increased gas flow in the center, but blast furnace gas escaped from the stack with each bell dump. The solution to this was to have a bell and a charging hole lid, Fig. 1.23. When material was dumped out of the wheelbarrow, the lid was up but the bell was closed keeping the gas in the furnace. Then the lid was closed and the bell was dumped which also kept the gas in the furnace and at the same time yielded the proper burden distribution. The results of these improvements were better physical and chemical reaction efficiency inside the furnace which reduced fuel requirements, increased productivity and decreased refractory lining wear.

As production increased due to the many blast furnace design improvements, removing the molten products of iron and slag became an issue. Charcoal furnace production had increased over the from one ton to 25 tons per day. This higher tonnage

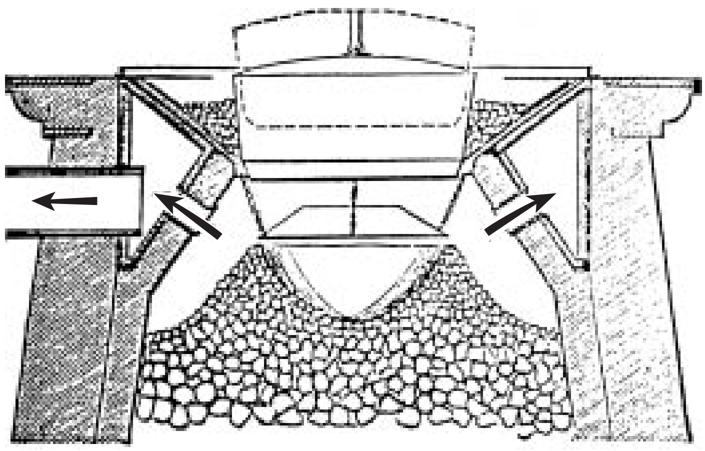

Fig. 1.21 Cup and cone filling with a bell suspended from chains, circa 1880.

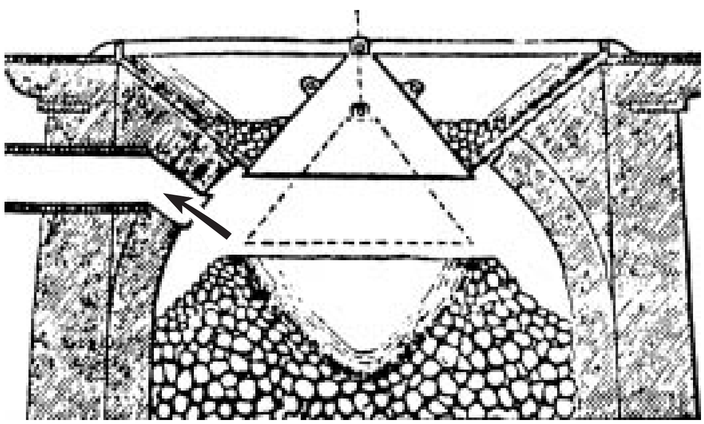

Fig. 1.22 Simple one bell top, circa 1880s.

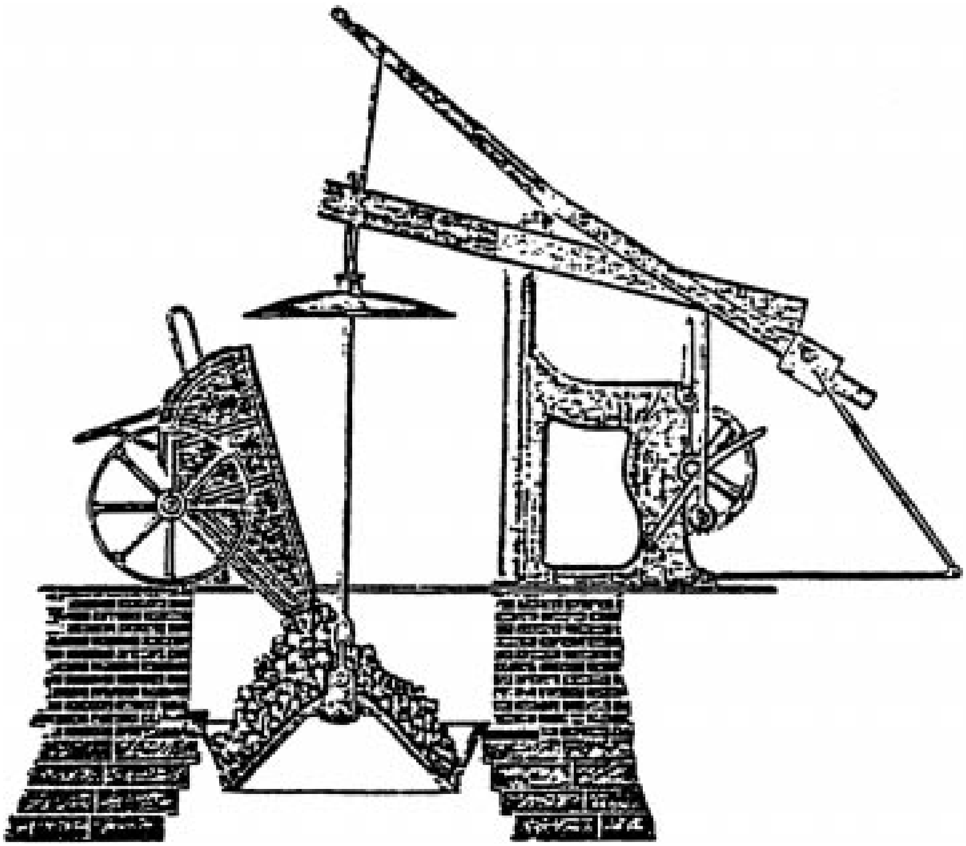

Fig. 1.23 Single bell with a charging hole lid, circa 1880s.

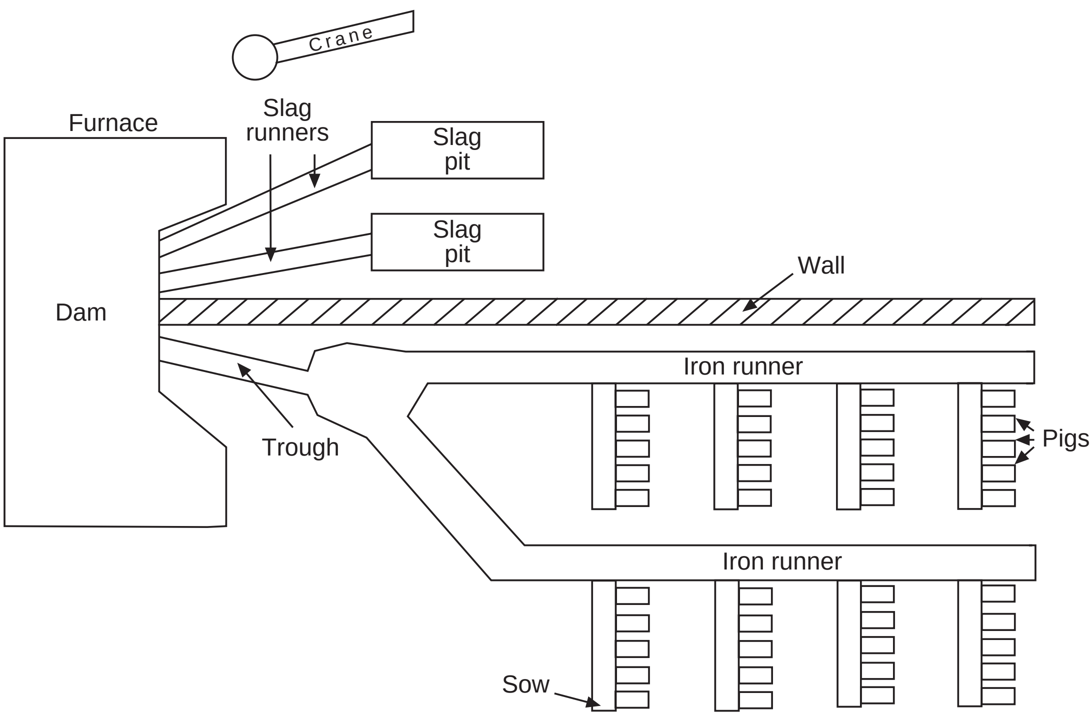

Fig. 1.24 Casthouse layout for pig iron production in the 1800s.

could not be handled with two casts per day through a single trench in front of the taphole. The size of the casthouse building increased to approximately 12.1 m (40 ft) wide and 21.2 m (70 ft) long. The casthouse contained separate areas for iron casting and slag removal, Fig. 1.24.

The side for iron removal consisted of a large trench called a trough that sloped downward from the front of the furnace into the sand filled casthouse floor. It then spilt into two runner systems. A main runner on each system ran parallel with the length of the casthouse. As this runner sloped downhill, a series of dams were made at regular intervals. At a right angle before each dam a smaller runner called a *sow* was formed in the sand. Then off of this sow were numerous cavities called *pigs*. These names were applied as this system looked like a line of piglets suckling their mother. There were several parallel rows of sows and pigs produced by pushing D-shaped wooden forms in the moist sand on the casthouse floor. During the cast, as each sow and its pigs were filled with liquid iron, the sand dam on the main runner was knocked out with a bar and the molten metal ran downhill to the next sow and pig bed. There were two complete systems which allowed the furnace to be cast more frequently. As one side was filled with molten metal, the other side had its pigs removed and beds reformed.

The other side of the casthouse was used for slag removal. Slag was constantly running over the front of the dam down a slag runner and into a slag pit. The slag dam at the front of the furnace was divided into two halves with each half feeding a separate slag runner and slag pit. The slag pit was a large depression in the sand with ridges in the bottom. These ridges acted as fracture points when it was time to remove the solidified slag. In some casthouses, a jib type wooden crane was used to lift large pieces of slag. If the casthouse men saw the slag layer getting too thick, they would place a bar in the center of the liquid slag. Then when the slag froze around the bar, a rope or chain could be wrapped around it and the large pieces of slag were hoisted by the crane. Once again, there were two complete slag systems so that while one was being used, the other could be cleaned and prepared.

The origin of the word *casting* is believed to be from the perception that the iron was *cast out* or thrown from the furnace. The casting operation consisted of two parts. First, while liquid slag was formed in the furnace, it would float on top of the iron until it reached a high enough level to flow between the tymp and dam into the slag runner and ultimately the pit. The second part of the casting operation was the liquid iron removal from the hearth of the furnace. This began by shutting off the blast and then driving a pointed bar into the taphole with a sledgehammer. The iron ran down the trough into each consecutive sow and its pigs. When the iron stopped flowing, the taphole was manually plugged with a moist mixture of sand and fireclay or sand and coal. The blast was then returned to the furnace. After cast, the casthouse crew removed the solidified iron from the pig beds. This was done by using pry bars and sledgehammers. The casthouse men wore wooden clogs on their shoes to protect their feet from the heat. When the pigs were cool enough to handle, they were loaded onto carts, wagons or railroad cars. This cycle of events happened six times per day, with four to six tons being produced each cast. The iron produced was classified into different grades which had different prices. Charcoal iron had a low sulfur value which resulted in a tough gray cast iron which was used to produce railroad track and railcar wheels needed to support the expanding railroads of the 1800s.

By the end of the Charcoal Era in the late 1800s, the production costs were no longer competitive with mineral-based ironmaking processes. Even though charcoal furnaces could be easily built near local iron ore deposits, the high fuel rates of 115 bushels per ton (907 kg or 2000 lb) had virtually wiped out virgin forests and enough wood to convert into charcoal was not available. The last charcoal furnace in North America was shut down in 1945 in Newberry, Michigan. However, modern charcoal furnaces are still being operated in South America due to its abundant forests.

1.3.5 Mineral-Based Ironmaking in the 1700s and 1800s

Due to the depletion of virgin forests required to sustain charcoal iron, the iron masters were forced to look for alternative fuel sources. This alternative fuel came in the form of bituminous coal, anthracite coal, coke and even peat. The development of coke and anthracite ironmaking paralleled each other and coexisted with charcoal production during the 1700s and 1800s. The use of bituminous coal and peat was limited and never became a major ironmaking fuel. Because deforestation due to charcoal production first occurred in England and Scotland, this was the birthplace of mineral fuel use in ironmaking.

In 1708, Abraham Darby leased a small charcoal blast furnace in Coalbrookdale, Shropshire and by 1709 he was producing coke. Over the next ten years, coke was mixed with charcoal in ever increasing proportions until 1718 when iron was produced from 100% coke as a fuel. Darby did not try to keep the use of the new fuel a secret, but he didn't publicize it either. Up until 1750, the only ironworks using coke on a regular basis were two furnaces at Coalbrookdale and one at Willey, all operated by the Darby family. Finally, during the period from 1750 to 1771, the use of coke spread with a total of 27 coke furnaces in production. The use of coke increased iron production because it was stronger than charcoal. It could support the weight of more raw materials and thus furnace size was increased. Coke also improved permeability in the furnace, allowing a larger volume of wind to pass through the furnace. This larger volume of compressed air was provided by the steam engine and blowing cylinders discussed earlier.

In continental Europe the use of coke did not become common until later. Coke was used in Le Creussot, France in 1785, Gewitz, Silesia in 1796, Seraing, Belgium in 1826, Mulheim, Germany in 1849, Donete, Russia in 1871 and Bilbao, Spain in 1880.

In North America, the first attempt to use coke as 100% of the fuel was in the Mary Ann furnace of Huntington, Pennsylvania in 1835. However, as early as 1797, coke was mixed with other fuels in U.S. blast furnaces.

The efficient use of coke and anthracite in producing iron was accelerated not only by the use of steam-driven blowing equipment but also by the invention of hot blast equipment which preheated air entering the blast furnace. At the beginning of the 19th century, ironmakers believed using cold blast improved both the quality and quantity of pig iron produced. They had observed that the blast furnaces produced greater tonnages in winter than in summer and erroneously concluded that the lower blast temperature was the reason. In fact, the furnace performance improved during the winter months because the air was drier (lower humidity) so that more combustion of fuel would be supported by a given volume of air delivered into the furnace.

In 1828, James Neilson conducted experiments on several Scottish furnaces with preheated blast being delivered to the tuyeres. In the same year he patented his invention which was a simple wrought iron box, 1.2 m (4 ft) × 0.9 m (3 ft) × 0.6 m (2 ft) which was externally heated. The maximum wind temperature was only 93°C (200°F) with this first hot blast equipment and one oven was required for each tuyere, Fig. 1.25. In 1832, Neilson improved his invention by constructing a larger oven by joined flanges, formed a continuous length of 30 m (100 ft) and provided a heating surface of 22.3 m^2 (240 ft^2). This oven, which was fired with solid fuel, produced a hot blast temperature of 140°C (285°F). Other iron masters continued to modify and improve hot blast ovens and by 1831, Dixon of the Calder IronWorks had developed a taller oven with U-shaped pipes that delivered hot blast at 315°C (600°F). By 1840, Neilson had issued 71 licenses to various iron masters and roughly 55% of British pig iron output was produced with hot blast. As the hot blast temperature increased, the quantity of fuel decreased and production increased.

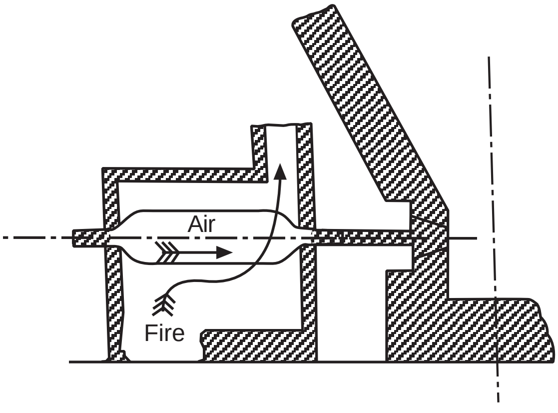

Fig. 1.25 Neilson's first hot blast equipment, dated 1828.

Even though hot blast improved furnace operation, the equipment required much maintenance. The cast iron pipes supported within a brick oven had different expansion characteristics, which resulted in numerous cracked pipes. Another issue was that the cold blast delivery equipment, which consisted of solid tuyeres and flexible leather joints between pipes, could not withstand the high temperatures. The final issue with the original hot blast systems was the increased cost of solid fuel to heat the ovens. All of these issues forced further improvements in hot blast equipment. First, solid fuel used to heat the hot blast ovens was replaced with blast furnace gas. Primitive heat exchanger type hot blast equipment was built on top of the furnace, Fig. 1.26, and simply used the waste heat to preheat the cold blast running through the cast iron pipes. Then the waste gas from the furnace top was conveyed to the hot blast oven where it was burned to generate heat, Fig. 1.27. This type of hot blast oven became quite complex with numerous rows of vertical pipes, Fig. 1.28. The second issue of cast iron pipes cracking was addressed by eliminating the pipes and using refractory. To use this method, from two to four stoves were installed for each blast furnace. As one stove was being heated by the burning blast furnace gas, another was being drained of its heat. As cold blast entered the stove, it was warmed

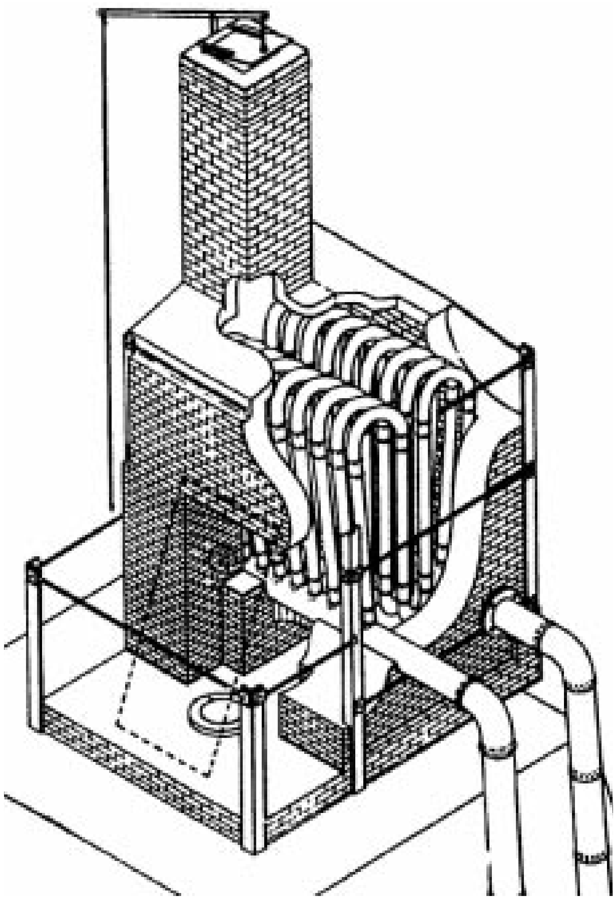

Fig. 1.26 Primitive hot blast heat exchanger situated on the top of the furnace.

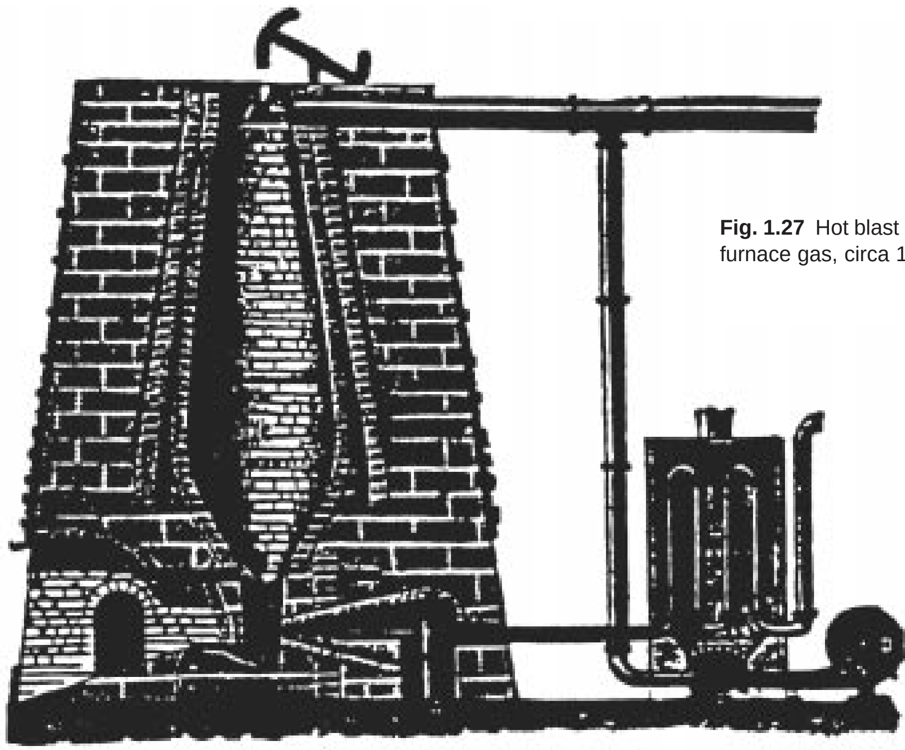

Fig. 1.27 Hot blast oven heated by blast furnace gas, circa 1800s.

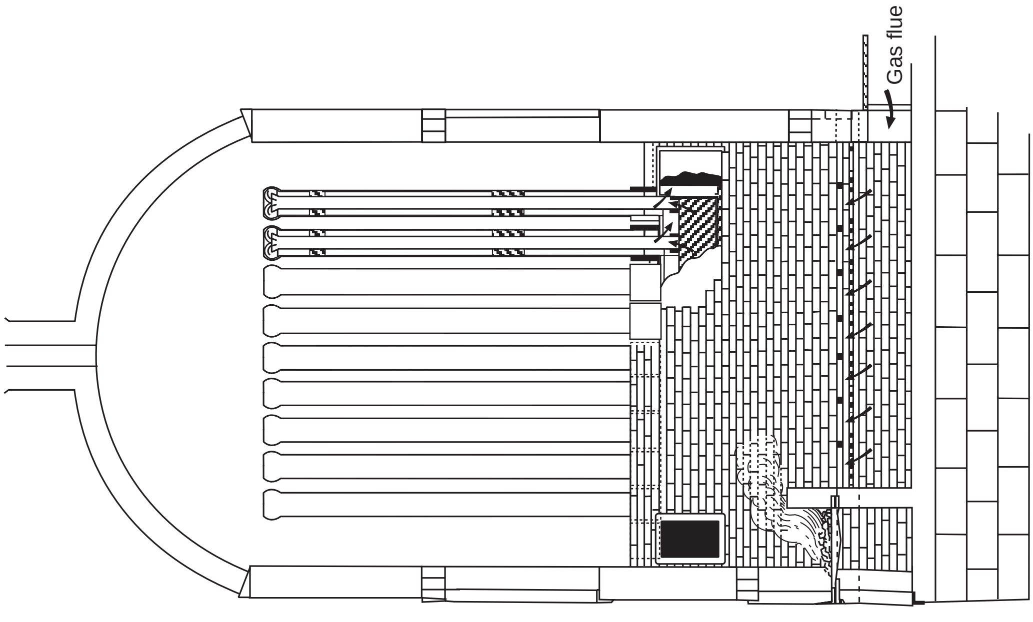

Fig. 1.28 Pipe-type hot blast oven.

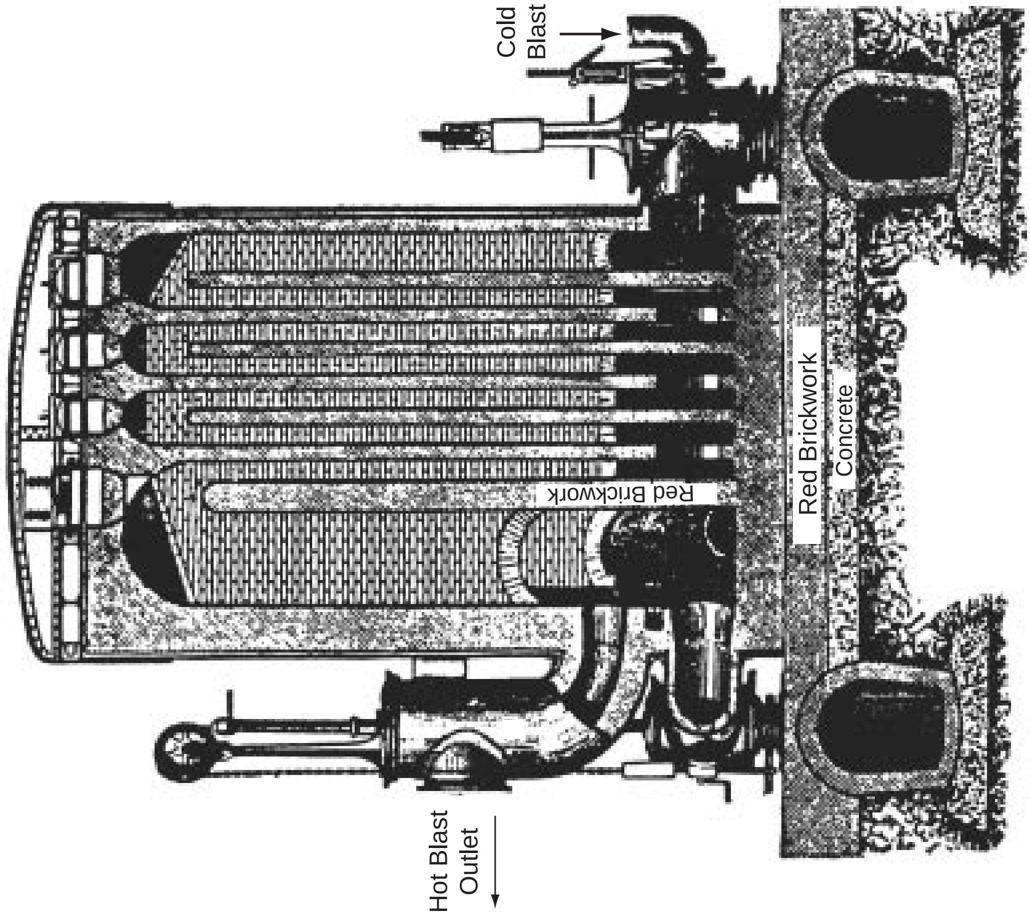

Fig. 1.29 Regenerative hot blast stove, circa 1870s.

by the hot bricks and finally exited the stove as hot blast. In 1854, the Cambria Iron Works was the first company to use regenerative stoves in the United States. These stoves were representative of those produced by Cowper and Whitwell. The stoves were constructed of iron shells, internally lined with refractory and containing refractories with multiple passages for the blast, Fig. 1.29. A typical stove of this design had 186–232 m^2 (2000–2500 ft^2) of heating surface.

The Whitwell stoves erected at the Cedar Point Iron Co., Port Henry, New York, and at the Rising Fawn furnace in Dade County, Georgia in 1875 were 6.7 m (22 ft) in diameter, 9.1 m (30 ft) high and had a total heat surface of 8546 m^2 (92,000 ft^2), Fig. 1.30. These were the first stoves to use hexagonal refractory checkers, cast iron checker supports, and a semi-elliptical combustion chamber to improve distribution of gas through the checkers. These stoves could deliver from 454°C (850°F) to 566°C (1050°F) hot blast temperature to the furnace. This stove design has remained basically the same with minor modifications in refractory type, checker shape and stove size.

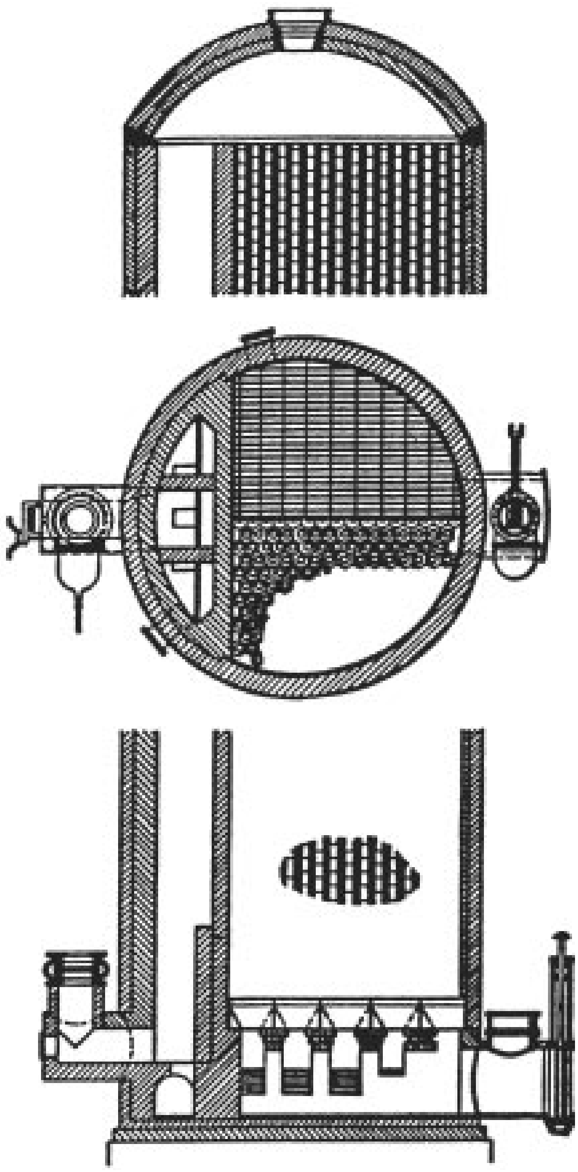

Fig. 1.30 Checker brick stove, circa 1890.

The final improvement in equipment required by the use of hot blast was the design of the tuyeres and the tuyere stock. The solid cast iron or cast copper tuyeres used on cold blast furnaces were replaced by water cooled tuyeres which were hollow, conical shaped castings which had water circulating through their interior. The pipes from the blowing engines to the tuyeres, which were jointed with leather on cold blast furnaces, had to be redesigned with metal-to-metal seats. As hot blast temperatures increased the inside of these blast mains and tuyere stock had to be lined with refractory, which required an overall increase in size, Fig. 1.31.

The use of hot blast was applied to both coke and anthracite furnaces. The evolution of coke ironmaking and anthracite ironmaking paralleled each other in the United States during the 1800s. The first attempt to use anthracite coal in a cold blast furnace was in 1826–27 in eastern France. This attempt failed as the ignited anthracite broke up into small pieces and blocked the blast from entering the furnace. As blast pressure increased with new blowing engines, both European and American iron masters found that anthracite could be charged with charcoal to improve productivity. In 1826, the Lehigh Coal and Navigation Co. erected a small furnace in Mauch Chunk, Pennsylvania to operate exclusively on anthracite coal. This practice was unsuccessful both there and at other places in the United States. Then in 1833, Dr. Frederick Geissenhainer of New York City successfully used hot blast in experiments to smelt iron with anthracite coal. In 1836 the Valley furnace near Pottsville, Pennsylvania used 100% anthracite and in 1837, George Crane produced 36 tons/week of anthracite iron from one of his furnaces at Yniscedwin, South Wales.

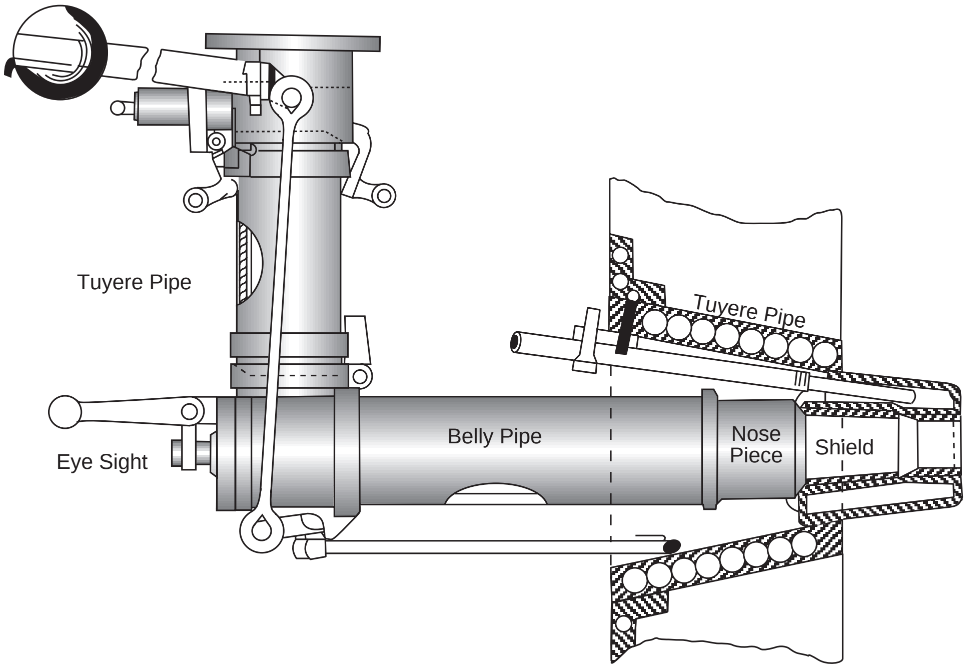

Fig. 1.31 Early tuyere stock from the 1870s.

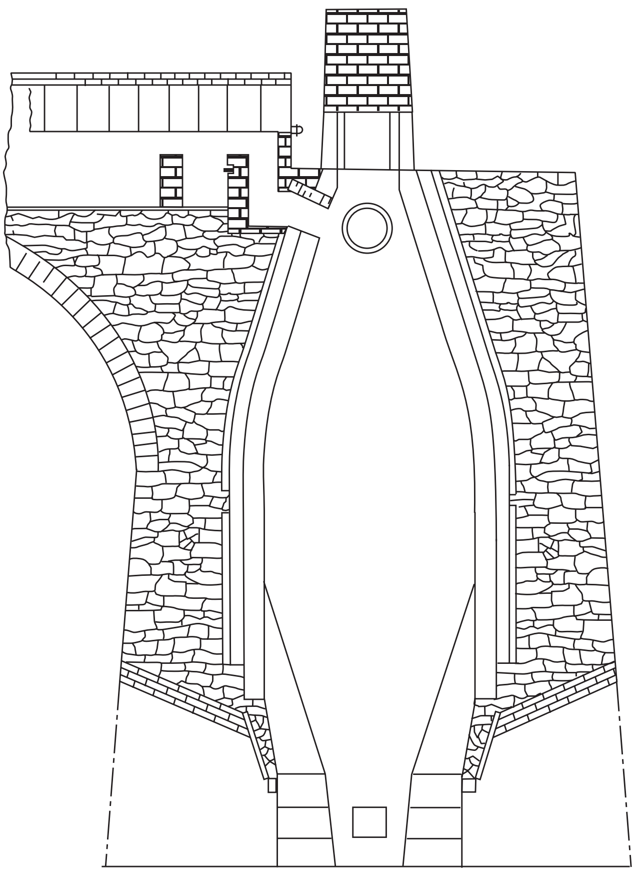

Fig. 1.32 Anthracite furnace with a stone stack, circa 1840s.

The individual most instrumental in the success of the anthracite blast furnace was David Thomas who had worked with Crane in South Wales. In 1838 he came to the United States to work for Lehigh Crane Iron Co. and built the Catasauqua blast furnace in 1840. The furnace was 10.7 m (35 ft) square at the base with a 3.6 m (12 ft) bosh and a height of 13.7 m (45 ft), Fig. 1.32. The hot blast stoves, fired with coal, were capable of heating the blast to 315°C (600°F). As the furnace operation was successfully producing 50 tons of good foundry iron per week, this furnace was used as a model for the construction of not only the four other furnaces built from 1842 to 1850 at the Lehigh Crane Iron Co., but also for the entire anthracite industry. By 1856 there were 121 anthracite furnaces in operation in the United States.

Other raw material fuels were also used in ironmaking. These were peat and bituminous coal. Peat furnaces were similar to charcoal furnaces and typically were no higher than 6.7 m (22 ft). Because the peat was physically weak, the use of these furnaces was local to peak bogs and they never played a major role in ironmaking evolution. Bituminous coal had been used to supplement charcoal prior to the introduction of hot blast. In the 1830s, splint coal was used in Scottish hot blast furnaces. In 1856, there were six furnaces in Pennsylvania and thirteen in Ohio using bituminous block coal. Numerous small furnaces were later operated with raw coal in southern Illinois and Indiana in the coal producing areas, but the bituminous coal era of ironmaking was essentially finished by 1895. This method of ironmaking never became a major force because the coal broke up into small pieces as furnaces were made larger and used higher blast pressure.

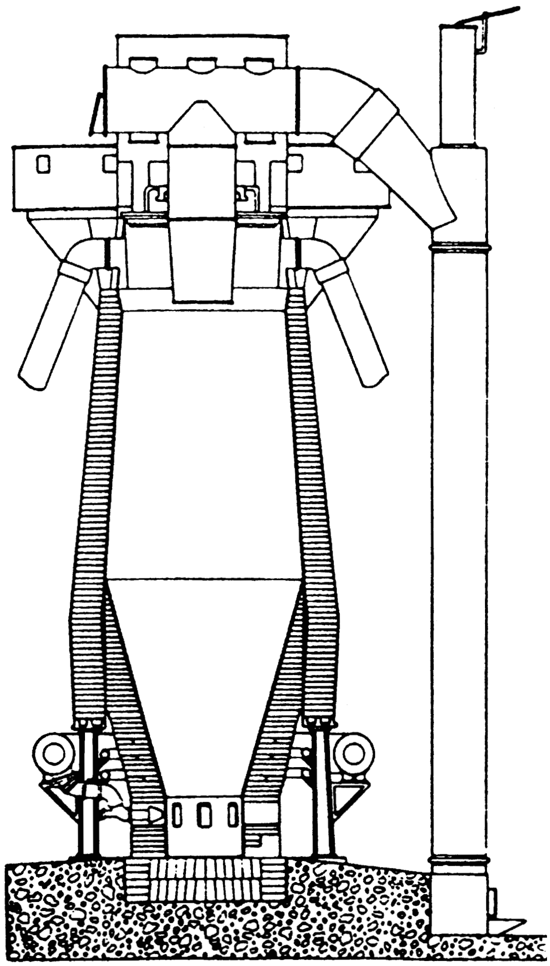

Fig. 1.33 Early coke furnace, circa 1880s.

With coke being the strongest and most available fuel, the evolution of 100% coke furnaces continued. As mentioned earlier, the first all-coke operation in the United States was in 1835 in Huntington County, Pennsylvania. The force behind this experiment was William Firmstone who had previously managed an ironworks in England. His knowledge in the use of coke and hot blast resulted in the Mary Ann furnace becoming one of the first furnaces to use hot blast in the United States. However, the experiment was not successful probably due to low strength coke. By the 1840s coke quality had improved through the use of beehive ovens, particularly from the Connellsville area of Pennsylvania. In 1856 there were 21 coke furnaces in Pennsylvania and three in Maryland. Coke consumption for ironmaking continued to increase. In 1867, the 'Monster' blast furnace at John Player's Ironworks at Norton, England was built. This coke furnace was 25.9 m (85 ft) high, 7.6 m (25 ft) across the bosh and had a working volume of 735 m^3 (26,000 ft^3). An example of a large coke furnace in the United States in 1884 was the Etna furnace located near Pittsburgh. This furnace was 21.3 m (70 ft) high, 6.1 m (20 ft) in diameter at the bosh, 3.4 m (11 ft) in diameter at the hearth and had seven 7 in. tuyeres, three Whitwell stoves and three blowing cylinders that were 2.1 m (7 ft) in diameter. This furnace produced 115 tons/day in 1881, 161 tons/day in 1882 and 182 tons/day in 1883. The coke furnace design at this time was very similar to the anthracite furnaces of the same era, Fig. 1.33.

1.3.6 Coke Furnace Evolution from the Late 1800s to Today

The evolution of blast furnaces using 100% coke continued with major steps being made in the Pittsburgh area between 1872 and 1913. The Carnegie Steel Co. and its predecessor firms developed a set of technological process improvements at its Monongahela Valley ironmaking furnaces that ultimately made it possible for the United States to take over worldwide leadership in iron production. It was centered on the hard-driving blast furnace practice of using more powerful blowing engines, higher blast temperatures, bigger furnaces, better charging equipment, improved raw material storage and production of clean blast furnace gas. These experiments and improvements started at the Lucy furnaces and continued at the Edgar Thomson Works, Duquesne Works and the Carrie furnaces. The many equipment and process improvements rooted in this era and improved upon in the 20th century will be reviewed.

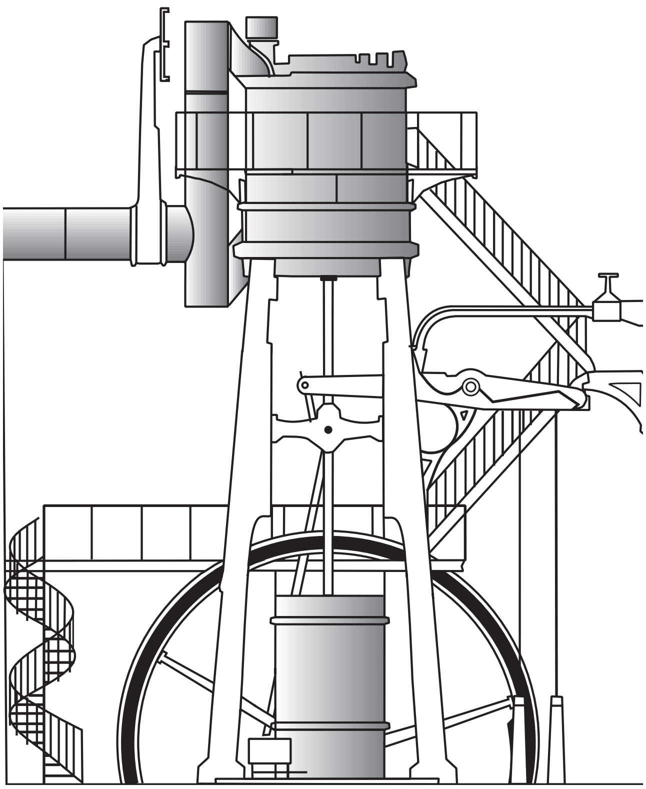

Fig. 1.34 Steam blowing engine for generation of larger blast volume and higher blast pressure, circa 1850s.

Blowing engine design and capacity was a major step to higher production, hard-driving furnaces. Blowing cylinders were replaced with large steam reciprocating blowing engines capable of providing a greater volume of blast air at a significantly higher blast pressure. These blowing engines were of the walking beam, steam condensing type, Fig. 1.34. The steam cylinder's piston rod was connected to a gallows beam and then by a crank to a heavy, large diameter flywheel. The blowing cylinder's piston rod was connected to the other end of the gallows beam and each stroke of the steam cylinder would provide a corresponding stroke of the blowing cylinder. Cold blast pipes were fitted to each end of the vertically positioned blowing cylinder so that air was compressed on both directions of the stroke. The flywheel provided momentum for the return stroke of the steam cylinder. The air that was compressed in this manner exited the cold blast pipes and entered the cold blast main which connected to the hot blast stoves. Prior to this type of blowing engine the normal blast volume was 3.5 m^3/sec (7,500 ft^3/min) at a blast pressure of 28 kPa (4psi). The Lucy furnace blowing engine could produce 7.6 m^3/sec (16,000 ft^3/min) at a blast pressure of 63 kPa (9 psi). Then in 1910, the final major step in blowing engine improvement was implemented in the form of a turbo blower. The first turbo blower was installed on No. 2 furnace of the Empire Steel Co. in Oxford, New Jersey and was capable of delivering 10.6 m^3/sec (22,500 ft^3/min) of wind. This is the direct ancestor of the modern turbo blower which can deliver up to 125 m^3/sec (266,000 ft^3/min) of blast volume at 400 kPa (58 psi) of blast pressure.

Another major improvement in high productivity blast furnaces was to increase the charging capacity. In the 1870s both Lucy and Isabella furnaces were equipped with a water driven elevator. In 1883, the first skip hoists were installed on the Carnegie Steel Co. furnaces. Skips have become larger and faster into the 20th century and existed as both buckets and cars mounted on wheels. In the early 1960s some skip charging systems were replaced with large conveyor belts.

The improvements in furnace charging capacity also included automatic coke charging systems, scale cars in the stockhouse, two bell tops and the rotating distributor, Fig. 1.35. Automatic stockline measurement was invented in 1901 by David Baker and it was installed in South Works of Illinois Steel Co. In 1903, J. E. Johnson also began to measure top gas temperature and its analysis.

Attempts to improve burden distribution occurred in the early 1990s with the McKee rotating top. After each skip of material was charged onto the small bell, the small bell hopper was rotated to 60°, 180°, 240°, 300°, or 0°. This prevented a peak of raw material directly below the skip bridge which would have resulted in uneven gas distribution and uneven lining wear. The next attempt to improve burden distribution was done in Germany in the late 1960s. This was accomplished by installing movable panels at the throat of the furnace that could be set at different angles for ore or coke. This movable armor has been installed on numerous furnaces throughout the world. The next burden distribution leap in technology came with the introduction of the bell-less top. This equipment uses airtight material hoppers that feed a rotating raw material delivery chute that can be set at numerous angles during the hopper discharge into the furnace. The result is the almost unlimited placement of each material anywhere on the burden surface which allows the operator to achieve maximum fuel efficiency.

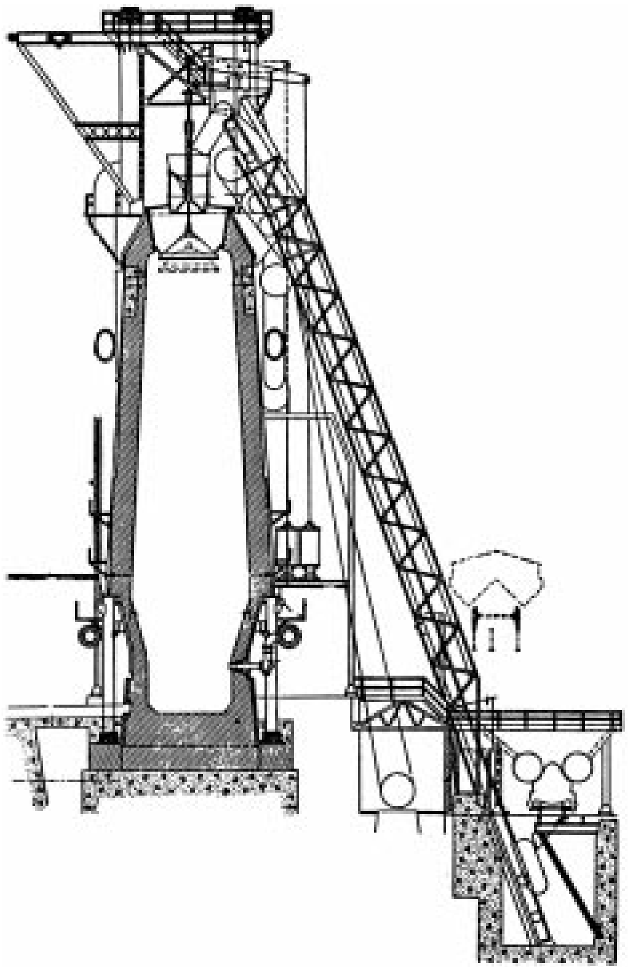

Fig. 1.35 Two bell top with rotating distributor, early 1900s

The next step in continuous improvement of the Monongahela Valley furnaces as a necessity to increased production was improved gas cleaning. As blast volume and pressure increased at the tuyeres, the velocity and volume of gas exiting the top also increased. More flue dust was then carried by this waste gas and if it was not removed, it began to plug up stove checkers which subsequently restricted blast volumes to the furnace. The first step in gas cleaning was the introduction of the dustcatcher in the 1880s, Fig. 1.36. With the introduction of the soft Minnesota Mesabi Range ores in 1892, the dry-type dustcatcher was not sufficient. In 1909, Ambrose N. Diehl, Superintendent of Duquesne Works' blast furnaces introduced a wet gas cleaning system. It consisted of a series of nine high-pressure spray towers and a set of four rotary washers. From 1914 to 1924, several types of tower washers equipped with multiple banks of sprays and baffles were tried at various furnaces. Gas disintegrators which contained high speed rotary drums were also tested in 1907. In 1929 electrostatic precipitators were used successfully at South Works of U.S. Steel. Today, combinations of tower-type gas washers, Venturi scrubbers and mist eliminators are the most common types of gas cleaning equipment.

The newest wet gas cleaning equipment is an annular gap scrubber which cleans the gas as well as controls top pressure. The final result of all these gas cleaning improvements was a decrease in stove checker brick hole diameter with an increase in stove size because plugging with dirt had been virtually eliminated. The resulting increase in stove heating surfaces has ultimately allowed modern stoves to deliver up to 1270°C (2318°F) hot blast temperature. The associated top pressure control allowed by modern gas cleaning equipment has resulted in furnace top pressures up to 230 kPa (33 psi). This higher top pressure in turn increases the density of gases, decreases gas velocity and increases gas retention time in the furnace, yielding better gas-solid reactions, improved reducing gas utilization and lower fuel rates.

The quest for higher production rates in the late 1870s and onward forced changes in furnace size and configuration. In the 1870s, the Isabella and Lucy furnaces were 22.9 m (75 ft) high. In 1880, the B blast furnace of Edgar Thomson Works was blown-in and it was 24.7 m (80 ft) high, had a 6.1 m (20 ft) bosh diameter and a 3.4 m (11 ft) hearth diameter. It produced 120 tons/day with a 1574 kg/tonne (3149 lb/ton) coke rate. Just ten years later, in 1890, H furnace was constructed with a stack 28.0 m (92 ft) high and with a 6.7 m (22 ft) bosh. It produced 325 tons/day. Then in another 10 years, in 1901, D furnace was started with similar stack and bosh dimensions as H furnace but

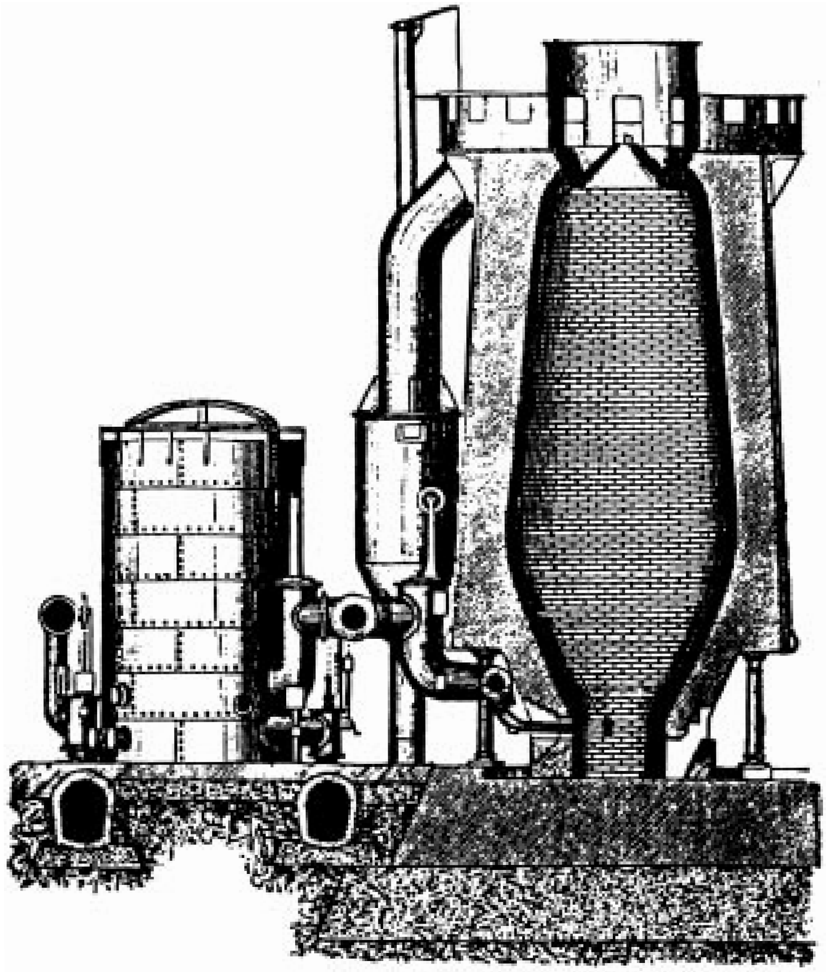

Fig. 1.36 Early dustcatchers, circa 1880s.

the hearth diameter was increased to 4.4 m (14.5 ft). This furnace produced 463 tons/day at 1113 kg/tonne (2227 lb/ton) coke rate, Fig. 1.37. The other subtle change with these size increases was the lowering of the bosh/stack bend line and the steepening of the bosh angle. This change was detrimental as the furnaces saw poor burden descent and slipping with these bosh angles. To eliminate these problems, the hearth diameter of these size furnaces was increased up to 6.7 m (22 ft) as evidenced in U.S. Steel's Gary No. 9 furnace in 1927. This bigger hearth furnace produced 880 tons/day at a coke rate of 922 kg/tonne (1845 lb/ton). The first 1000 ton/day furnace was Ohio Works No. 2 furnace in 1929. This furnace was equipped with a hearth diameter of 7.6 m (25 ft). In 1955, Great Lakes' A furnace was the largest in the world with a 9.2 m (30.25 ft) hearth and 24 tuyeres. The next leap in blast furnace size increase occurred during the 1960s as Japan rebuilt their outdated steel plants. Today, furnaces with 15 m (50 ft) hearth diameter, 40 tuyeres and four tapholes, are common in Europe and Asia.

Along with the larger furnaces, higher blast temperatures and increasing driving rates came the need for better blast furnace refractory lining and cooling systems. In the 1880s a high duty fireclay brick with approximately 40% alumina and 46% silica was typical. However, carbon refractories were used in German blast furnaces since 1886. While refractory technology was relatively unknown at this time, methods to cool the lining seemed to be the answer to the wear problem. Beginning about 1880, there were simultaneous developments in efforts to maintain furnace linings by means of pipe coils around the bosh or by cooling plates embedded in the brick. One of the first uses of a bronze bosh plate is believed to be an installation made by Julian Kennedy at one of

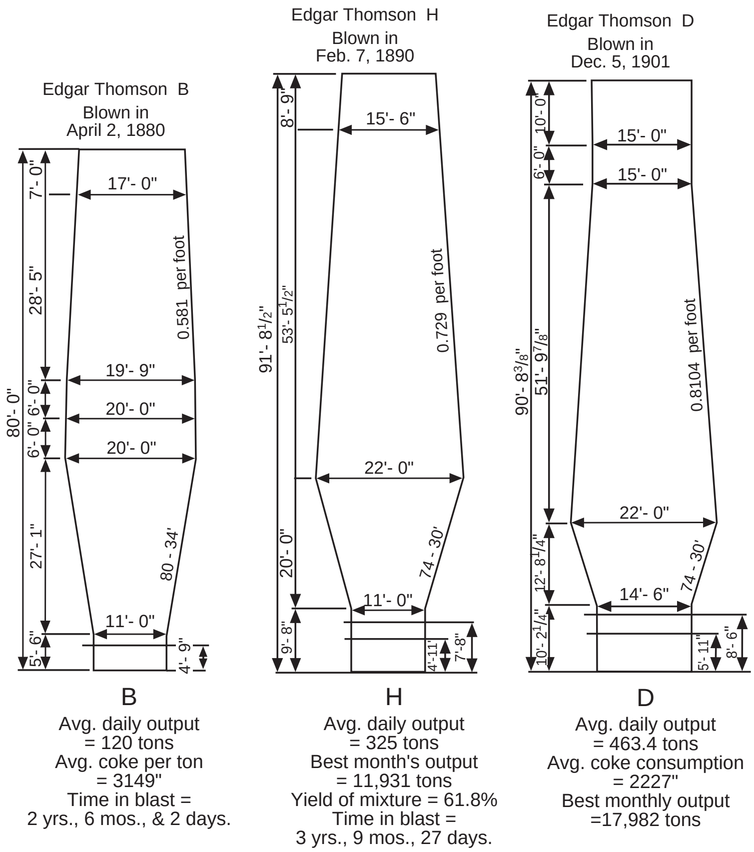

Fig. 1.37 Carnegie Steel Co. furnace lines from 1880 to 1901.

the Lucy furnaces, probably in 1883. High pressure feed water was supplied to cooling plates in about 1890. An early reference to the use of water-cooled hearth jackets is on the furnace blown in at Edgar Thomson Works in 1882. At this time, cooling of the hearth sidewalls and bosh was the concern and stack cooling was not felt to be necessary. The higher charging rates were also wearing out the throat of the furnace faster. In 1872, iron or steel armor was built into the brickwork of the furnace throat at a furnace of the Glendon Ironworks in Easton, Pennsylvania. Since that time, various types of armor have been used in the stockline area.

The first important developments in brick making technology did not occur until the 1900s. In 1917, the first machine-made brick was introduced with its resulting increase in density and strength. In 1935, vacuum pressed bricks further improved brick quality. In 1939, super-duty alumina brick containing up to 60% alumina was first available. In the 1930s, carbon blocks were used in German furnace hearths but were not used in the United States until 1945. Today many varieties of alumina, carbon, and silicon carbide refractories are available for blast furnace lining. The improvements in furnace cooling and lining have increased typical campaign lengths from two years in the 1880s to more than ten years in the 1990s.

Another area of the blast furnace which was forced to change with increased production was the casting operation. The old style tymp and dam open front of the furnace was no longer adequate. In 1867, the Lurman front was patented to eliminate the tymp and dam. It consisted of a cast iron panel which was water cooled and had separate openings for iron removal (still known as a taphole) and for slag removal (known as the cinder notch), Fig. 1.38.

This design was changed by the 1880s by rotating the cinder notch ninety degrees from the taphole. Both the taphole panel and cinder notch panel were water cooled. By separating these two

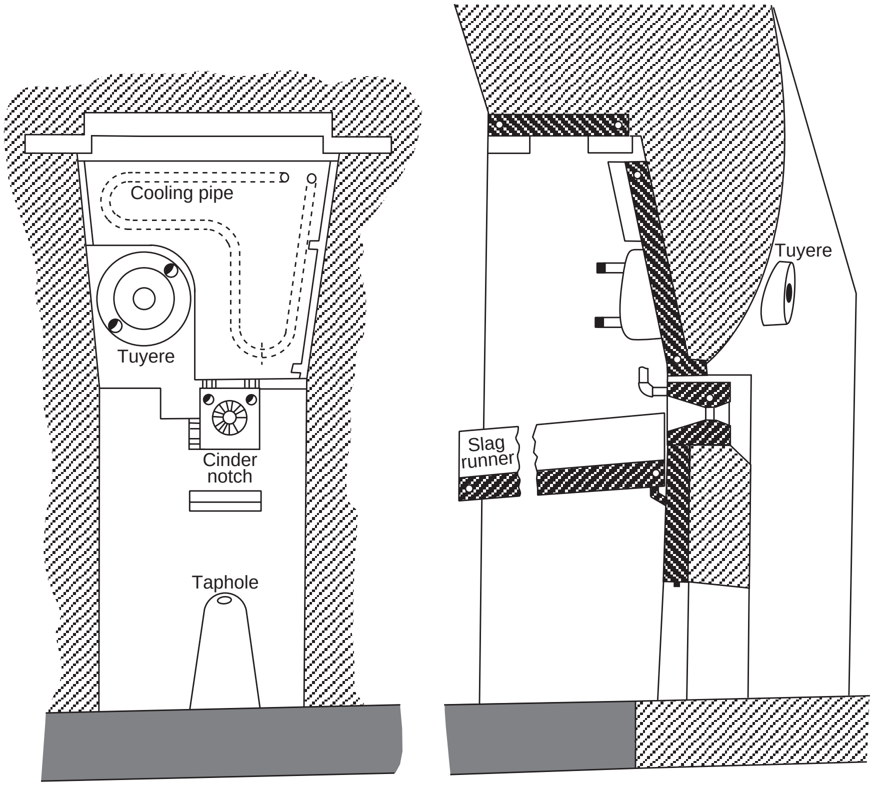

Fig. 1.38 Taphole and cinder notch patented by Lurman in 1867.

liquid tapping points, more room was available to set up the furnace for the increasing number of casts required at higher production rates. The area in front of the taphole was completely available for pig beds while the slag pits were moved around to the side of the furnace, Fig. 1.39. During normal operation, the cinder notch was opened with a bar as the liquid slag level approached the tuyeres. The slag was flushed into pits or special slag cars, Fig. 1.40. When the cinder notch blew wind out of the opening, it was closed with a manual stopper. By tapping the slag or cinder off between iron taps, a greater volume of the hearth was available for liquid iron which resulted in larger cast tonnages. The iron casting process in the 1880s did not change much from previous operations but pig beds were bigger and in 1909 a slag skimmer was installed at the Edgar Thomson Works to skim the floating slag off of the iron as it flowed down the trough. In 1896, the installation of a pig casting machine invented by E. A. Uehling at the Lucy furnaces finally brought about the complete elimination of the pig bed in the casthouse. Next came the advent of open-top brick lined ladles. These ladles carried approximately 10–75 tons of hot metal and required the furnace and casthouse to be elevated above ground level so the ladles could be placed under the casthouse floor. The pig beds were gone but troughs and runners remained and spouts going into the ladles were added to the casthouse. In 1915, Jones and Laughlin Steel Corp. first used torpedo-type ladles at their Pittsburgh Works. These railroad mounted ladles carried 90 tons but were increased to 150 tons by 1925. Today, the iron ladle design is similar but capacities up to 400 tons are available. In Europe, open-type Kling ladles mounted on flat cars are still used today. Prior to 1890, the taphole was opened with a bar and sledge hammer. Then in 1890 the first pneumatic rock drill was used at the Sparrows Point plant of the Maryland Steel Co. The taphole was manually stopped with wind off the furnace until 1914 when H. A. Berg, at the Carrie furnaces in Rankin, Pennsylvania, developed the remote controlled mudgun which pushed a clay plug into the furnace with a wind on. In 1906, the first oxygen lancing was used to melt skulls in the taphole. Modern furnaces have evolved to include remote controlled taphole drills, hydraulic mudguns, slag granulation units and iron tilting spouts to feed an unlimited number of iron ladles. Furnaces may also have from one to five tapholes and two to six slag pits depending on their size. Removing the bottleneck in the casthouse allowed the first 1000 ton/day operation in 1929 and led to 1990s production levels of 12,000 ton/day

A parallel line of improvement activities which rapidly evolved starting in the late 1800s was iron ore preparation. Iron ore used in ironmaking consists of many geological forms such as red hematite, specular hematite, magnetite, limonite, fossil ores, bog ores and carbonates. The metallic iron content of these ores ranges from approximately 30% in the bog ores to 72% in some hematites. All iron ores are mixed with other compounds in the earth which are undesirable in the smelting process. Beginning in the 1700s, iron ore was roasted with charcoal in open pits or enclosed kilns. The object of roasting or calcining was to liberate all volatile constituents, such as water, carbonic acid or bituminous substances, and to soften and crack the ores, making them more permeable to reducing gases. In the 1800s, iron ore screening was introduced to more closely size the ore for improved gas permeability inside the furnace. At first, hand screening equipment was used but, by the 1870s, steam-driven ore washers consisted of one or two drums that were perforated with holes or slots for the fine material to exit with the washwater while the final sized and washed ore exited the inside of the drum into a wheelbarrow or stockpile.

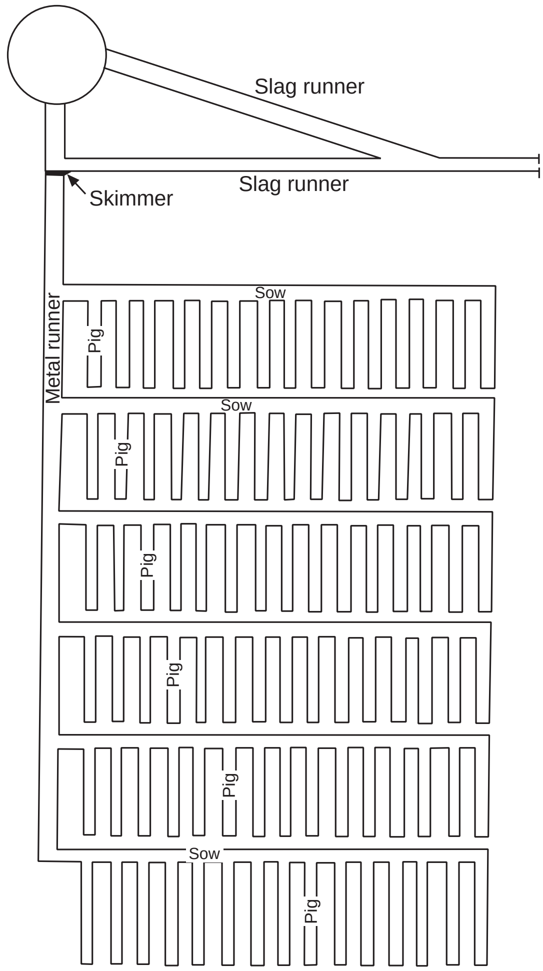

Fig. 1.39 Schematic of a casthouse with the cinder notch and taphole located 90∞ apart. The trough has a skimmer and a slag runner, circa 1909.

As iron production increased, the purest iron ores were depleted in many areas so lower grade ores had to be mined. These ores had undesirable impurities and methods to concentrate these ores to higher iron percentages were required. In 1880, Thomas A. Edison obtained a patent for an electromagnetic separator. A demonstration plant was built on the Marquette Iron Range of Michigan and produced 893 tons of magnetic concentrate in 1889. Edison also attempted to make and market iron ore briquettes but this venture failed due to the discovery of ore on the Mesabi Iron Range in Minnesota in 1893. In 1911, A. G. Anderson applied for a Swedish patent for drum-rolled balls which, subsequently, were fired for hardening. In 1931, a pilot plant at Rheinhauser, Germany tried a similar process patented by C. A. Brackelsberg. In the 1940s, C. V. Firth, E. W. Davis and their associates at the Mines Experiment Station at the University of Minnesota evolved the idea of firing iron ore balls made from moist concentrates in a shaft furnace. Pilot plants to pelletize taconite concentrates were built at Ashland, Kentucky and Aurora, Minnesota in 1948. By 1956, two commercial-scale taconite mining and processing operations were producing pellets in Minnesota. The first straight grate pellet machine was used at the Eagle Mills plant in Michigan in 1956 and the first grate-kiln pellet machine was put into operation in 1960 at the Humbolt Mine also in the Upper Peninsula of Michigan. Pelletizing technology spread throughout the world from the northern Midwest regions of the United States. The newest development in pelletizing was the introduction of raw limestone, dolomite or olivine into the pellet to improve its metallurgical properties which, in turn, improved blast furnace productivity and fuel rates.

Iron ore agglomeration also took a separate route from pelletizing earlier in the 1900s. Sintering, as we know it today, originated in the nonferrous industry as a batch process in the late 19th century. In

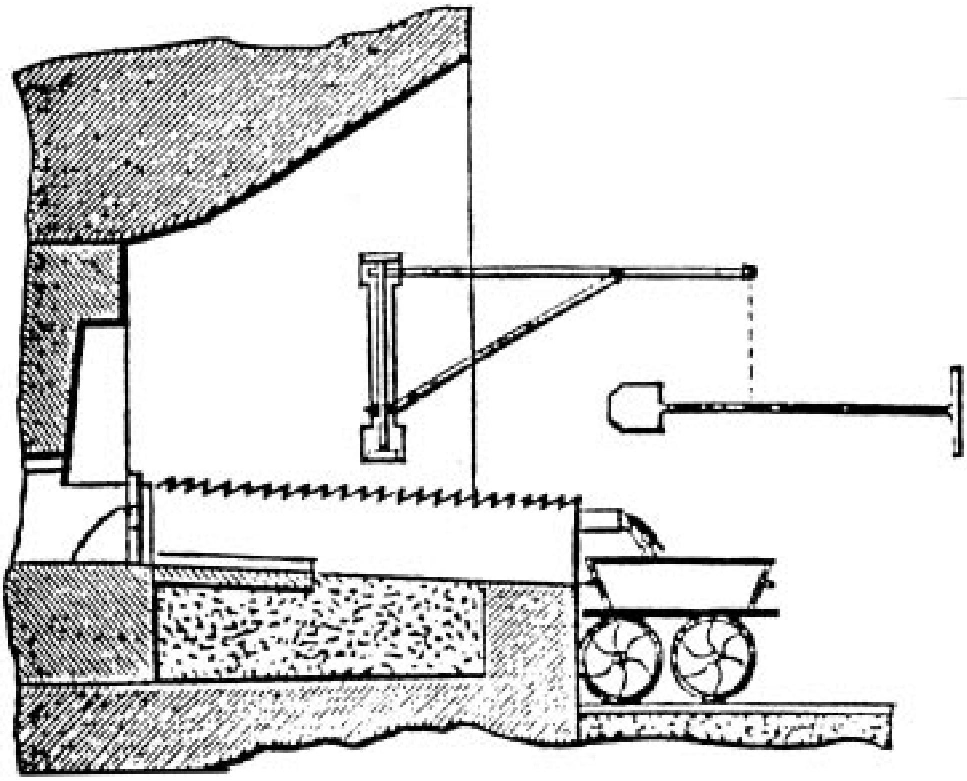

Fig. 1.40 Cinder notch with a stopper and a slag cart from the late 1800s.

June 1906, Dwight and Lloyd built the first continuous sintering machine, a chain grate design, which was installed in Cannanea, Mexico for sintering copper and lead sulfide ores. The first installation for the ferrous industry was made at Birdsboro, Pennsylvania in 1910. This was a machine 107 cm (42 in.) wide by 7.8 m (25.5 ft) long and produced about 140 tons/day when processing blast furnace flue dust. In 1925, the first 1.8 m (6 ft) wide machine was built and by World War II the 4.0 m (13 ft) wide machine was typical. Up to the 1950s, most sinter had a base/acid ratio less than 1.0. However, over the next fifteen years, operators realized that a basic sinter with a base/acid ratio more than 1.0 brought a precalcined flux source into the blast furnace which resulted in a fuel rate savings.

One of the final technological improvements in ironmaking over the last 100 years has been tuyere level injectants. The first recorded use of injectant was in 1871 in the state of Michigan when an iron master suffered a frozen hearth on the Morgan charcoal furnace. Because blast could not enter the tuyeres due to frozen material, a hole was punched through the furnace wall above the salamander and a large tuyere was installed. Coal oil was then forced under pressure into the tuyere from a pipe running from the top of the furnace. Six days and seven barrels of oil later the salamander had been melted and the furnace was running smoothly. In the first decade of the 1900s early tests with oxygen injection were run in the small Ougree blast furnace in Belgium. The first large scale oxygen enriched blast was used by National Steel in 1951. The benefits of pure oxygen injection are increased furnace production due to increased fuel burning capacity and an ability to use more hydrocarbon tuyere injectants. The evolution of hydrocarbon injectant occurred in the 1940s and 1950s. In 1944, William L. Pogue, the owner of the Bellefonte furnace in Ashland, Kentucky, submitted a patent for the use of coal injection. Then in 1953, natural gas injection was implemented by Lone Star Steel in Texas. In the early 1960s, injection of oil and tar through lances was developed at numerous steel companies after substantial coke savings were proven by testing in an experimental blast furnace in 1959. By 1967, half of the blast furnaces in the U.S. were using some form of fuel injection. Today, fuel injectants compose up to one third of the fuel in world class furnaces. The final tuyere injectant, which evolved concurrently with fuel injection, was moisture injection. Historically, hot blast temperatures were limited as excessively high temperature combustion zones resulted in poor burden descent. The injection of moisture consumed coke more rapidly than air alone and produced a gas that was both richer in carbon monoxide and hydrogen and was less dense. These factors improved the rate of heat transfer between gases and solids and the rate of reduction of the burden in the furnace stack, which resulted in a smooth running furnace. The combination of moisture injection, fuel injection and oxygen injection permitted the increase of hot blast temperature and the use of all of these tuyere level variables further improved productivity and reduced fuel rates in modern blast furnaces.

1.3.7 The Science of Ironmaking

Historically, ironmaking was more an art than a science. Early iron masters learned their trade through years of training from the previous generation of iron masters. Many improvements in ironmaking practice were based on instinct or pure luck. However, by the mid-nineteenth century, science was creeping into the developments in iron smelting.

One of the earliest researchers of chemical and physical phenomena occurring inside a blast furnace was Charles Schinz of Germany. Schinz attempted to make quantitative mass and energy balances of a blast furnace operation but was severely limited by the lack of accurate thermodynamic data. He conducted laboratory experiments to determine heat capacity and heats of formation and was apparently the first to determine the reducibility of iron ore. More importantly, Schinz defined different zones of the blast furnace and the major chemical reactions taking place in each zone. The results of his work were compiled in a book that was published in 1868.

Many of the principles recognized today by ironmakers were first postulated by Sir Lothian Bell, a well-educated scientist and ironmaker who worked during the late 1800s in England. His book, *Chemical Phenomena of Iron Smelting*, was published in 1872 and is recognized as the first text on blast furnace ironmaking. In 1884, he was apparently the first to document the function of the different slag components and their effect on melting temperature. He also observed that there was a range of slag compositions which resulted in good fluid properties and good desulfurizing capability and that blast furnace slags were complex structures. Probably the most important of Bell's many contributions was his understanding of chemical reactions. He recognized the importance of CO and CO_2, and was the first to start defining equilibrium in the Fe–O C system. Bell was not only a theoretician and scientist but also a practicing ironmaker. In his second book, Bell discussed preheating and pre-reduction of iron ores and the importance of the furnace stack where these reactions occurred. He also made carbon, oxygen and nitrogen balances of his blast furnace operations and showed that some of the charged carbon was consumed in the stack by carbon dioxide in the *solution loss* reaction.

A contemporary of Bell was M. L. Gruner, a professor of metallurgy in France. Gruner further expanded Bell's methods of determining blast furnace heat balances by comparing many different furnace operations. Gruner, like Bell, believed that the minimum fuel rate for blast furnaces would be achieved when solution loss was eliminated.

The first American scientist to explore the blast furnace process was J. E. Johnson, Jr. In the early 1900s he published two books on blast furnace design and operation. Johnson was the first scientist to apply the first and second laws of thermodynamics to ironmaking. He explained how fuel rate was impacted by blast temperature and postulated that there was a critical furnace temperature above which a minimum amount of heat is required. This minimum amount of heat he called *hearth heat*. In his book, *The Manufacture of Pig Iron*, published in 1913, Johnson produced a diagram showing chemical reactions and isotherms in the blast furnace. Possibly more important than the specific explanations provided by Johnson's thermal equations was the fact that the application of his critical temperature and hearth heat concepts further convinced furnace men that their process was rational and as a result, predictable.

During the period from 1920 to 1930, the flow of solids and gases in the blast furnace was studied extensively by a group of workers at the U.S. Bureau of Mines. This group, composed of P. H. Royster, S. P. Kinney, C. C. Furnas, and T. L. Joseph, was interested in physical and chemical phenomena occurring in blast furnaces and in order to understand these phenomena they felt it was necessary to sample and probe operating furnaces. Their work started with a small experimental blast furnace at Minneapolis and spread to commercial furnaces. The results of their studies showed that the flow of gases and solids was not uniform across any horizontal plane in the blast furnace and that improving gas-solid contact in the stack of the furnace could significantly increase the efficiency of the ironmaking process. Furnas and Joseph continued this work and determined that raw material size and reducibility was critical in gas-solid reactions. This important work led to understanding burden distribution and the optimization of iron ore sizing as it impacts both reducibility and permeability.

In 1962, R. L. Stephenson was the first to understand the role of solution loss. Previously, it had been thought the production of carbon monoxide by reacting carbon dioxide and carbon was a waste of fuel. Stephenson pointed out that iron oxide reduction is a combination of indirect reduction and direct reduction and that indirect reduction followed by solution loss is direct reduction. Using these considerations to determine carbon rates for all combinations of these two reduction routes as a function of solution loss, results can be plotted on the *carbon-direct reduction diagram*.

In the 1960s and early 1970s, the best applications of these blast furnace theories were put into practice in Japan. Currently, the Japanese improvements have spread in the form of large, highly automated blast furnaces to every continent of the earth.

1.3.8 Summary

The theory and practice of iron smelting technology have come a long way in the last four thousand years. The transition from sponge iron produced in forges to molten iron produced in blast furnaces in the 1300s was the first major step in advancing ironmaking technology. Then came the change from cold blast, charcoal furnaces to hot blast, coke furnaces in the mid-1800s which brought ironmaking into the modern era. The better understanding of ironmaking reactions and improved equipment evolved into the hard-driving furnace operation centered around Pittsburgh, Pennsylvania in the 1880s to 1900s. Finally, the revolution in scientific applications to iron smelting, the installation of more sophisticated equipment, and the advent of electronically controlled systems has accelerated blast furnace ironmaking into the current state as demonstrated by the operation of 11,000 tonnes/day (12,0000 tons/day) blast furnaces with fuel rates less than 460 kg/tonne (920 lb/ton) found around the world. The products of ironmaking operations have allowed mankind to evolve from an agrarian to an industrial society and to enjoy modern conveniences and comforts unknown and inconceivable at the beginning of the Iron Age. Joseph Glanvill, a member of the Royal Society, best sums up the importance of iron in this 1650 quotation:

> *"Iron seemeth a simple metal but in its nature are many mysteries⁄and men who bend to them their minds, shall, in arriving days gather therefrom great profit not to themselves alone but to all mankind."*

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