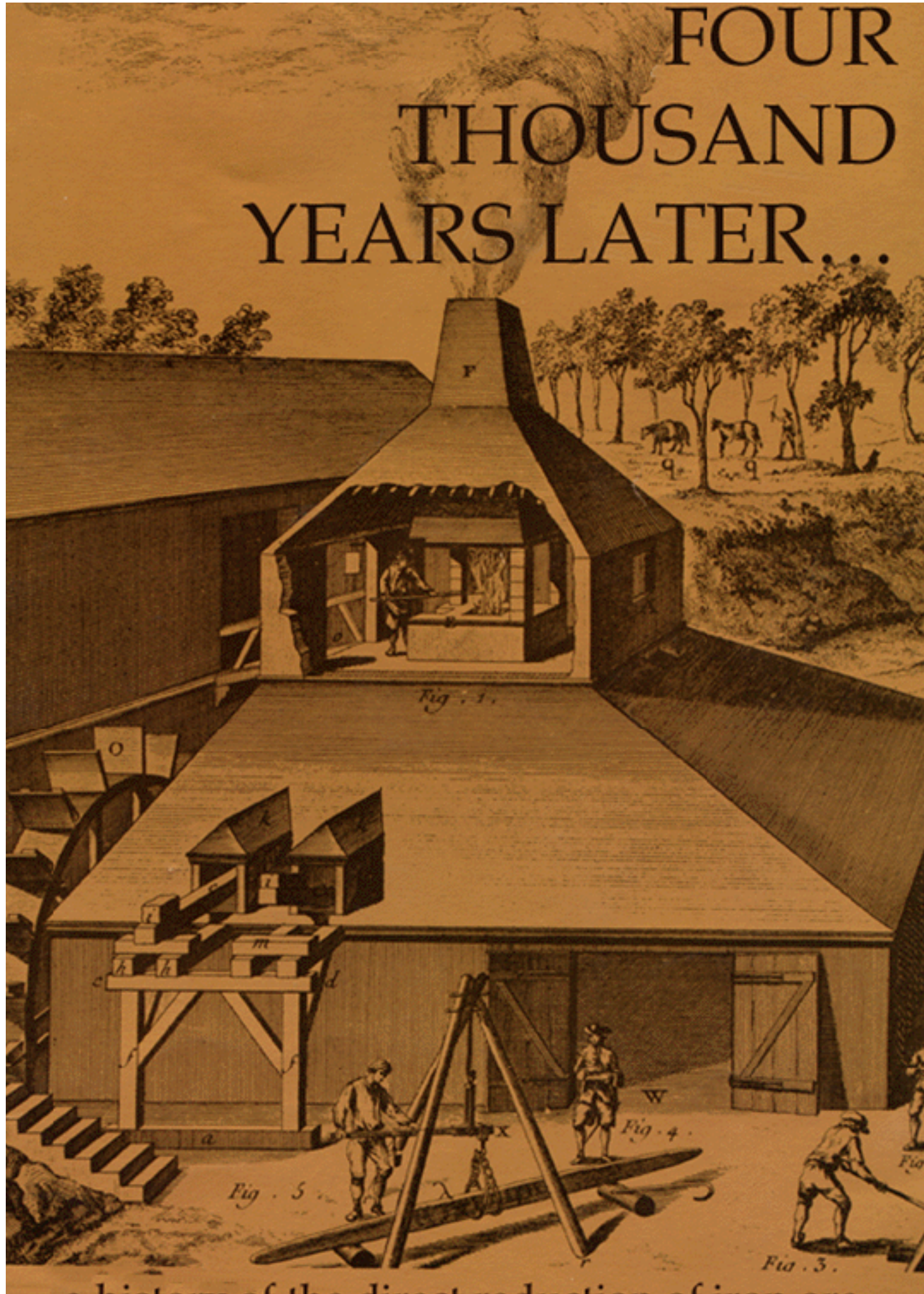


FOUR THOUSAND YEARS LATER...



A history of the direct reduction of iron ore

**4000 Years Later...
a history of the direct reduction of iron ore**

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Preface

The modern era of direct reduction began on December 5, 1957 when the Hylsa 1M HYL Process plant first started production. Back then, total world steel production amounted to just under 300 million tons. The electric arc furnace share of the market was barely 8%, or about 24 million tons. And of course none of that involved use of direct reduced iron. At least, not until the last month of that year.

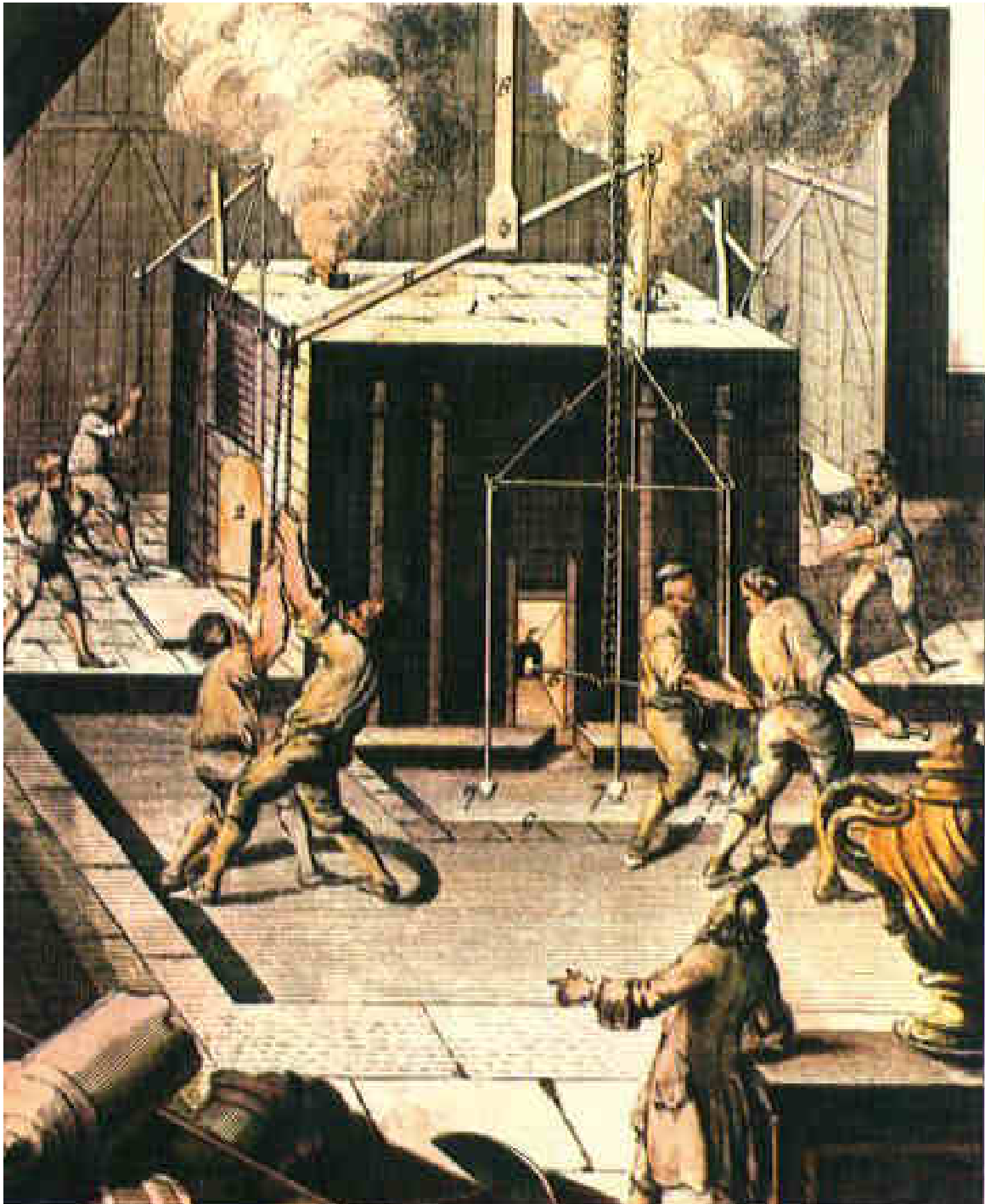
Forty years of history have been written since then and the industry has changed enormously as a result. World steel output now exceeds 750 million tons, of which over a third now comes from electric furnace mills. Forty years hence, the iron units charged to those electric furnaces (and to several integrated mills) include over 36 million tons of DRI and HBI.

With three more years to go before the start of the new millenium, our industry appears to already be making strong headway into the 21st century. The steel industry continues its modernization and growth and, at least for now, shows no signs of weakening. New technology already in place and newer technologies on the horizon will help keep steel a vital part of the world economy. Direct reduction technology will continue to be an important part of that growth and development, as the new steel technologies continue to require higher quality iron units. New direct reduction technologies and updates of existing technologies will be developed to keep up with the challenge.

HYL is proud to have been a participant in the development and growth of the direct reduction industry, and will continue to be a participant in its future. Current research and development efforts show great promise for the coming years, as we continue to improve both technological and economic aspects of HYL Process technologies.

Two decades ago, to mark the 20th anniversary of the 1M plant, this book (originally entitled *4000 Years Later - The story of the iron ore direct reduction process*) was edited and distributed by Hylsa. The book traced ironmaking from its prehistoric origins up to the onset of modern direct reduction. Now, after having concluded 40 years in the direct reduction business, we offer this updated version of the original book *4000 Years Later - The story of the iron ore direct reduction process*, which we hope you will find to be both educational and informative.

Editor



Encyclopedia of Trades and Industry. Denis Diderot.

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"Vulcano's Forge". Diego Velázquez. Del Prado Museum.

Four Thousand years later... a history of the direct reduction of iron ore.

A group of men are seated around a bonfire, burning within a crude circle formed by rocks which they have gathered nearby. They gaze in wonderment at something new to them: a strange, dark something has appeared from the rocks over the embers of their fire.

What these men are looking at is a chunk of iron.

It is the first piece of iron created directly, though involuntarily, by a human being. It is different from that which, at times, falls to earth from the heavens...

The men who gazed at that first fragment of iron died some four thousand years ago. Yet, unknowingly, they had begun what would become a long journey in man's progress.

Forty centuries later, following the same basic process which man, through the development of other techniques had slowly abandoned, a new, precise and industrially economic process was born.

This book is dedicated to our colleagues who, four thousand years ago, gazed for the first time and wondered at this phenomenon—the way in which iron ore, fire and air are transformed into pure iron.

The Spinal Column

If the world had been provided with a backbone, it would not be made of bone, nor of cement; nor would it be plastic or rock; It would be made of steel.

The very skeleton of modern civilization, the structure of our world, is forged in iron and in steel.

Virtually everything that moves contains steel. What rises to the heavens contains steel and steel makes what sails across the seas.

Machines, trains, tracks, buildings, aircraft & spacecraft

Below the ground, miles upon miles of steel tubes and pipes carry water and contain and protect telephone and electric power cables.

In our homes, iron and steel is ever present. The moment modern man takes note of his surroundings, iron and steel urgently come to his attention. Without them, our world, our civilization not only would be different, but infinitely worse. Our present as well as the foundations for our future are built upon that backbone of steel. And this strength that carries all, acquires, too, the significance of a liberating phenomenon. The advantages of an integral and autonomous industrialization are such that they allow a nation to pass from dependency to freedom.



Iron in Nature

Iron is the most widespread and abundant heavy metal on the face of the earth. Because of the ease with which it reacts, it is rarely found in the form of pure iron. The small amounts which have been found are surely extraterrestrial in origin (meteorites which have fallen to the earth, or meteoric iron) and are always associated with other metals. Pure iron presents itself in the form of a silvery metal, very tough and flexible, elastic and malleable.

Iron is found in almost all living beings. The adult male has from 3 to 5 grams of iron in his body, of which more than half forms part of his hemoglobin. The rest is found in the mioglobin (muscles) and in some cellular respiratory enzymes. A reserve of this metal is found in the liver of the human organism, as well



as in the spleen and bone marrow, in the form of certain compounds such as ferritin and hemosiderin. Normally, man absorbs iron in his food and a specific mechanism regulates its absorption, according to his needs. The lack of iron in the organism results in a lowering of hemoglobin which in turn gives origin to ferroponic anemia which often is found in women and children.

Because of its avidity for oxygen, iron is found in nature in the form of mineral ores composed mainly by oxides. Of these minerals, the ones most used industrially for extraction of the metal are: hematite, limonite, magnetite and siderite. Hematite is an oxide (Fe_2O_3) which, when pure, contains 70% iron; however it generally varies between 40 and 60%. Limonite ($\text{Fe}_2\text{O}_3 \times \text{H}_2\text{O}$) is another oxide, but contains variable quantities of water and is derived from the alteration of the other fer-



rous minerals; its metal content varies from one deposit to the next but generally does not surpass 50%. Chemically, magnetite is an oxide (Fe_3O_4) and is the mineral that contains the most iron. In its pure form it should contain 72.4%.

Siderite is a carbonate (FeCO_3) which in its pure state contains 48.3% metal, but it is rarely used in the production of iron and steel.

In order to extract the metallic iron from these mineral ores, it is necessary to separate the oxygen, which is combined with the iron that forms the oxides, as well as the major part of the impurities which are present in the ore.



DE RE METALICA. AGRICOLA.

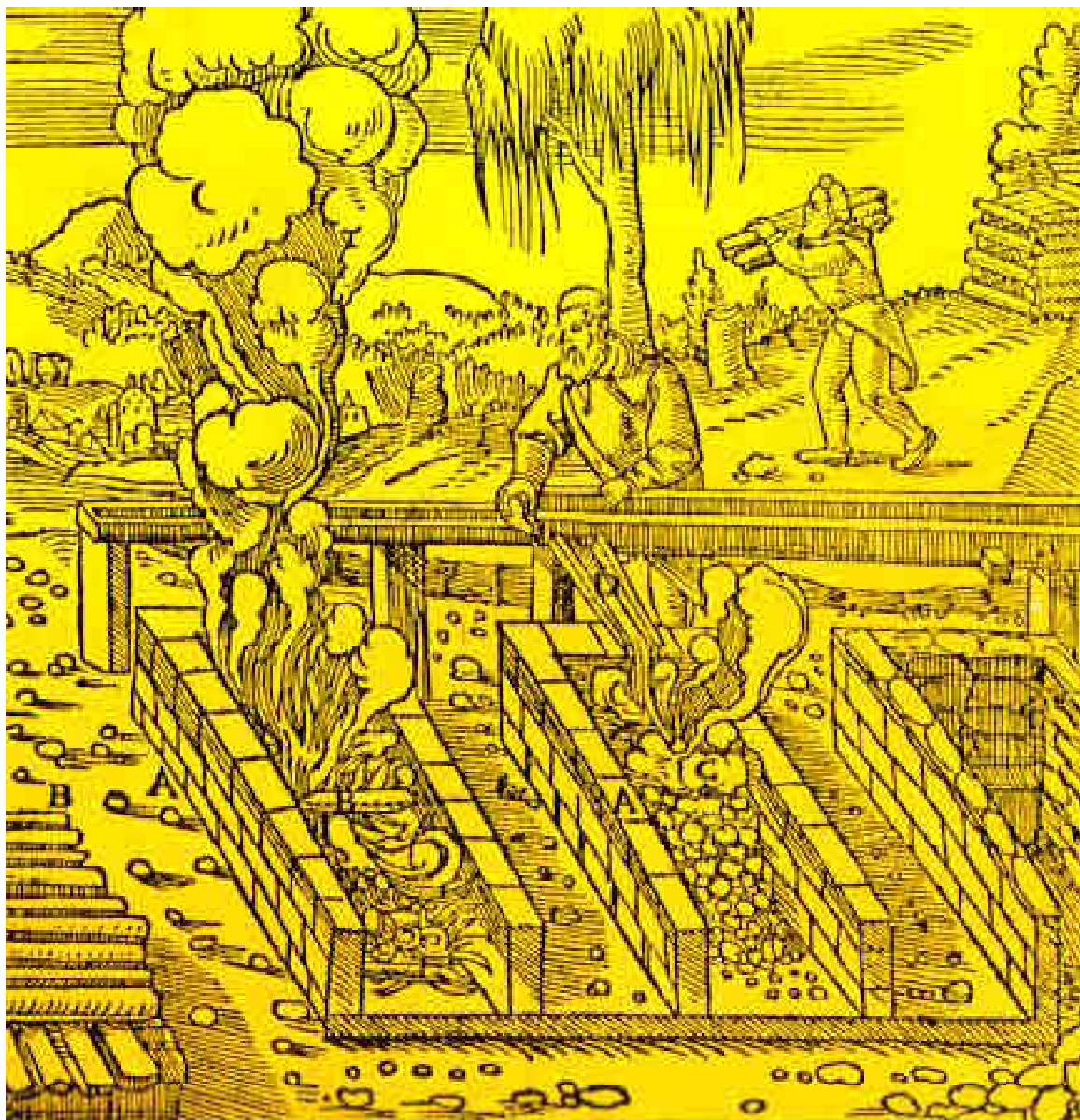
Ways of beneficiating iron ore

Metallic iron is found in nature chemically combined with other elements, mainly as an oxide mixed mechanically with a certain amount of substances (principally sand or clay) in large deposits known as ore bodies.

Iron ore can be concentrated magnetically. The most common ways of preparing it are grinding, pulverizing, screening, agglomerating or sinterizing.

What is meant by direct reduced iron?

Technically, direct reduced iron (DRI) is usually defined as iron ore or ferrous oxide which has been reduced to metal without melting it. In other words, a direct reduced iron making process is one in which the solid particles of metallic iron are obtained directly from particles of solid ore without subjecting either the ore or the metal to fusion.



DE RE METALICA. AGRICOLA.



"Iron Arised From Ancient Times", Timken Series.

A Bit of History

It is thought that the first iron objects made by man were created from materials whose origin was non-terrestrial. Fragments from meteorites were transformed into various objects or ornaments. The strange material of unusual hardness had come from heaven and it followed that heaven should be the recipient of a gift of gratitude through worship.

This hypothesis may be confirmed by looking at the names which were given to iron back in ancient times. When translated, regardless of their culture of origin, they all revolve around the same meaning: The stone that comes from heaven, Metal from the stars and many more.

The most ancient iron objects known today are two pieces that were found in Egypt: one in the Great Pyramid (built approximately in 2900 B.C.) and the other in a tomb in Abydos (2600 B.C.). An iron cube, also taken from a tomb, was found in Knossos, Crete. It dates back to the year 1800 B.C.

Many years had to pass before the metal from the stars became, too, the metal from the earth.

The origin of the methods employed by primitive man to extract iron from its ores is unknown. The earthy, granular or rocky aspect of the ores did not reveal their true essence nor their valuable content.

The accident could have been produced when man discovered that by

repeating certain conditions, he could obtain the same product that he got when he built a fire on rocks that contained iron in its mineral form. When the blowing wind made the temperature of the fire rise, the result was a chunk of iron.

Such a process does not reveal to mere observation its simple phenomenon: the oxygen contained by the ferrous oxide in the ore combines with the glowing coals of the fire, thus releasing the iron metal.

In modern language, it is said that the iron has been **reduced** from its oxides. Iron produced in this manner by primitive man, would have the appearance of a not-too-coherent, or spongy mass, with metallic granules and containing many impurities in its pores. Basically, the process was the same as that used today in the production of iron!



The decisive step would be to transform those dirty rocks into a bright and resistant material. The discovery probably came about when primitive man realized that if he hammered the spongy mass with a hard object while it was still hot, the blows would make it possible for the impurities to fall away and a hard metal would result. If he then reheated the metal and continued to hammer it, the product improved even more and the metal, finally, could be shaped and turned into useful objects.

Toward the XIII century B.C., metallurgy of iron had developed spectacularly in Anatolia, in Asia Minor, with the introduction of iron for military use, instead of bronze.

The Hittites had located iron ore deposits which they exploited on a grand scale. They devised forges, transformed their armament and created an empire. Their knowledge of metallurgy permitted them to build a mercantile economy which went well beyond mere bartering, when they introduced silver ingots on the exchange market.

Their monopoly was broken toward the years 1270-50 B.C., when the Hittite king, Hattussil, made a gift of several iron implements of war to the Egyptian Pharaoh Ramses II, providing him as well with some artisans who were experts in the manufacture of those implements. In 1150 B.C. the Doric tribes conquered Greece with the knowledge of iron and its



DE RE METALICA. AGRICOLA.

application for military implements.

The men who emerged from the mythical Trojan horse did so armed with iron and fire.

In 400 B.C. an iron culture emerged in Northern and Central Europe, also known as the Halstatt culture. The smoke from their forges rose above their fortified villages. Their women adorned themselves with iron buckles and brooches.

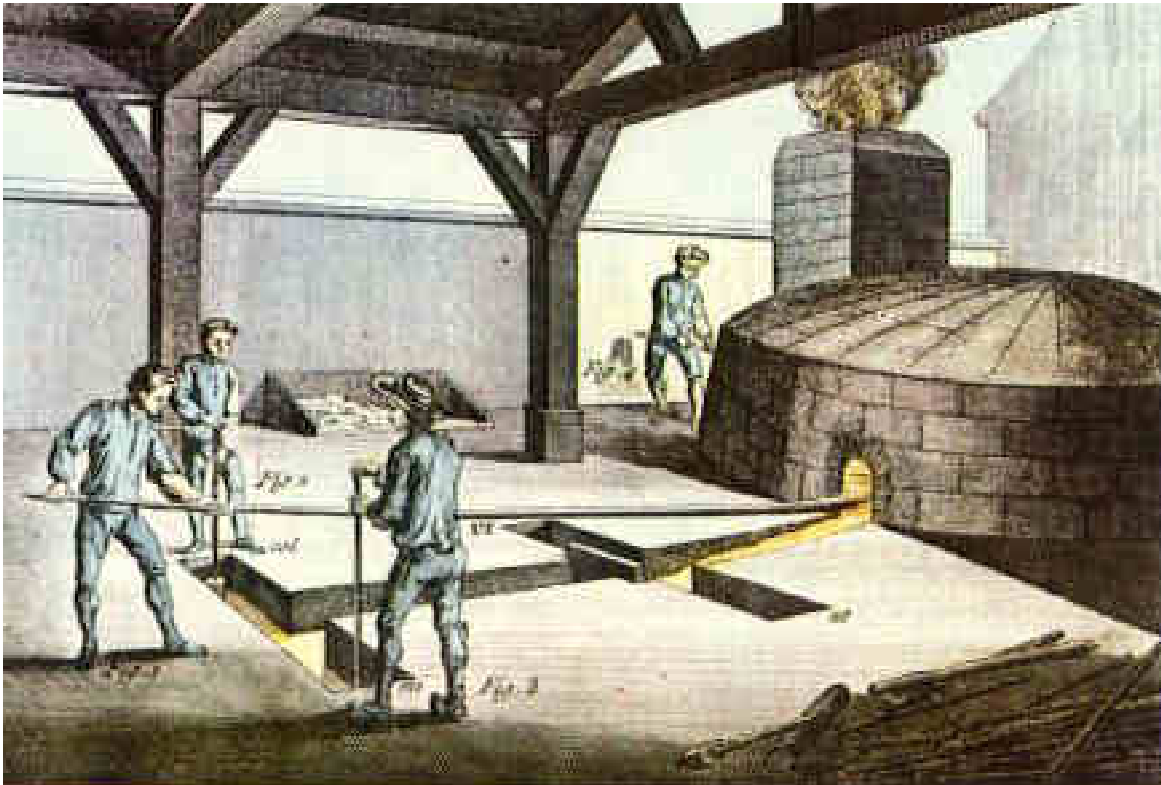
The first Chinese empire was constituted by the Ch'ü dynasty in 221 B.C. and was able to dominate the peripheral kingdoms thanks to their knowledge of iron production.

The presence of iron had altered the course of history.



When the smelting of iron was developed among the more advanced cultures, the primitive iron workers had some knowledge in the art of metallurgy. They knew how to smelt gold, copper and lead and how to produce bronze. They could mold the metals and had developed the technique of blowing through tubes and devised bellows made from animal skins, with the object of raising temperature through air injection.

For a long period, the Catalan forges—which consisted of one, two and even three smelting furnaces fed with charcoal, one or more air ducts and one, or various hammers of great weight operated by a hydraulic wheel—constituted the universal technical process for the smelting of iron and the production of steel. This process was followed by the introduction of blast furnaces which made possible a more impressive yield.



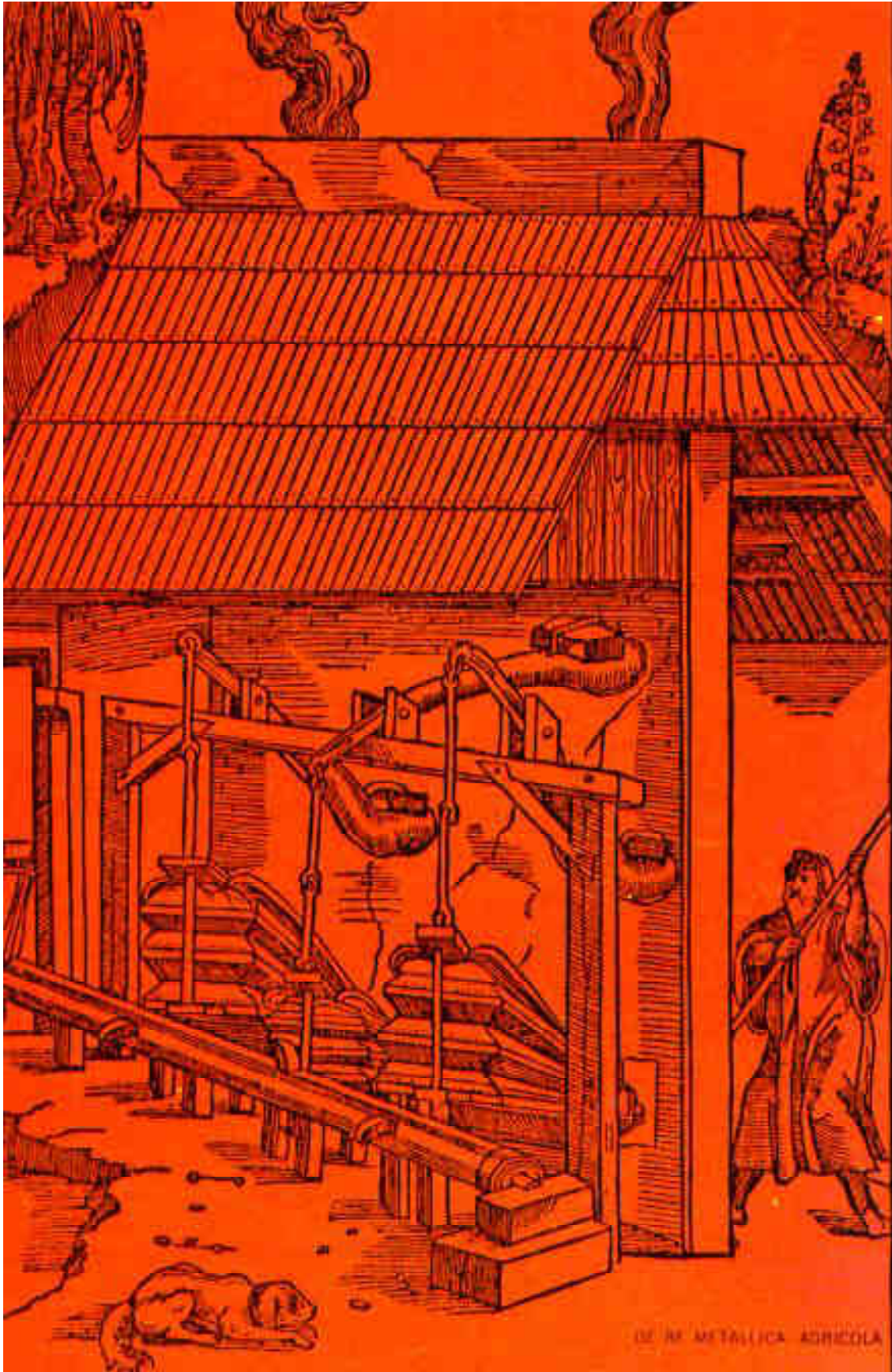
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DE RE METALLICA AGRICOLA



“The Discovery Of The Process In Crucible”, Timken Series.

Steel

Steel, man's most useful metal, is essentially a combination of iron and carbon. Pure iron metal does not possess sufficient resistance or hardness for tools, machines, sheets, bars, beams, pipes, rails, and other products which must be made of a strong and hard material.

When iron is combined with small quantities of carbon (usually less than 1.5 per cent) it changes into an extremely useful metal called **carbon steel**. The properties of carbon steel depend, mainly, on its carbon content. Up to certain limits, the more carbon it contains, the stronger and harder it will be. In addition to iron and carbon, carbon steel contains small quantities of other elements. Part of them can be added deliberately during the manufacturing process; another part proceeds inevitably from the raw materials used in manufacturing the steel. By changing the proportions of the different elements, it is possible to produce carbon steel, adequate for many important industrial uses.

But carbon, by itself, cannot endow steel with all the special properties that modern industry requires, among which are its ability to harden to a great degree or to resist rust and corrosion. Certain elements must be added to molten steel in order to give it those special properties.



Actually, the term **steels** is a generic name representing thousands of products encompassing a great variety of compositions, shapes and qualities. The creation of ferrous alloys endowed with special chemical and mechanical characteristics has spectacularly widened the field for the application of iron.

Stainless steels, using nickel or chromium as their essential alloying constituents, are employed for the construction of products ranging from corrosion resistant machinery to kitchenware for home use. Extremely hard manganese steels are used for the manufacture of gearing and safes.

High-speed tungsten steel and vanadium steel are employed to manufacture various types of high-speed tools. These are, however, but a few of the special steels that this specialized technology prepares and perfects continually to meet the most diverse demands.

Even so, it becomes quite evident after a moment of reflection, that the uses for iron are so numerous and varied that, without it, it would be impossible to conceive of our civilization. To describe its applications fully would entail enumerating practically every phase of human activity.



Description of the Processes for the Manufacture of Steel

“SPONGE IRON”

The method by which the first iron workers in ancient times produced a spongy and incoherent mass by reducing the iron ore with the hot coals of their small bonfires has already been described. Because of its appearance, and with the passing of time, man came to call it *sponge iron*.¹ This product contained metallic iron, ferrous oxide which had not been reduced, slag and impurities and only traces of carbon. Later, through beating and reheating successively, it lost a good part of the impurities and slag and turned into iron that was stronger and more useful for the making of weapons and utensils. In this way, sponge iron was the principal source of supply for iron and steel for many centuries until, around the year 1300 A.D., a process was developed whose impact and importance to civilization are well known and which was called the Blast Furnace.

THE BLAST FURNACE PROCESS

This is the traditional process by which iron and steel have been produced for more than 600 years.

The blast furnace has been used mainly for the reduction and smelting

of metals such as iron, lead and copper.

But, undoubtedly, it has reached its highest degree of development in the iron and steel industry. In the blast furnace, iron is separated from the oxygen with which it is combined in the ore, as well as from other compounds which are considered impurities. It is obtained, however, with a large quantity of carbon in solution, introduced during the reactions of combustion and reduction. This iron, which is obtained from the blast furnace in a molten state and which contains carbon in solution in more or less high percentage (3.5%), is called pig iron.

The blast furnace is designed so that its top section is used for feeding into it the charge of iron ore and coke—a previously prepared form of mineral coal which serves as an excellent fuel—as well as other fusing elements such as limestone and dolomite which act as fluxes. That is, these help the smelting process and aid in trapping the impurities in the ore and other materials which form a mass of lesser density than the iron, called slag.



¹The term sponge iron was common until the early 1980s when the more correct name “direct reduced iron” became generalized. Sponge iron is still used today, although the term has largely been abandoned, since it conflicts with another material which is problematic because of its toxicity.

Preheated air under pressure is blown in through blast pipes into the lower part of the furnace. Its oxygen content causes the coke to burn and form carbon monoxide, which serves to reduce the iron ore.

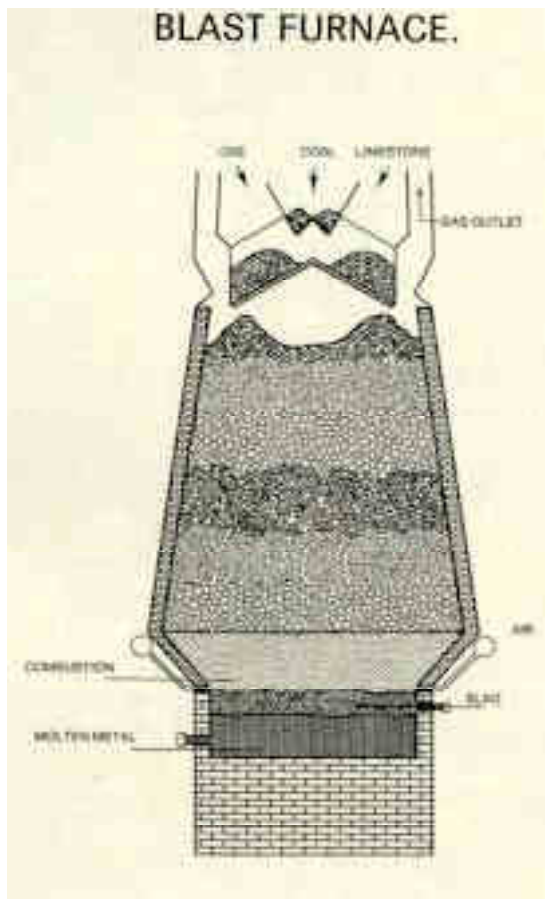
The heat of combustion raises the temperature of the coke to incandescence, drives the carbon dioxide out of the fluxes and dries the ore in the upper zones of the furnace. The rising carbon monoxide reduces some of the ore to iron and some of it to iron monoxide, and escapes from the top of the furnace as top gas. In the bosh, direct reduction with the glowing hot carbon in the coke, converts



all the ore into metallic iron, which absorbs 3-4% of carbon as it trickles down to the hearth. As the solid charge descends slowly, it separates into molten metal and slag which later will be discharged through the tap hole in the lower part of blast furnace.

The blast furnace is lined with refractory materials surrounded by a strong steel shell. It is divided into five sections which, starting from the bottom are: the hearth bottom, the hearth, the bosh, the shaft and the throat. The hearth bottom and the hearth contain the molten metal and slag until a sufficient quantity of pig iron has collected there for discharging through the tap hole into ladles. The bosh, situated directly above the hearth bottom and hearth, is the hottest part of the furnace. The preheated air is blown in through tuyeres or blast pipes spaced out around the base of the bosh. This air has been preheated in hot blast stoves and on entering the bosh causes the coke to burn.

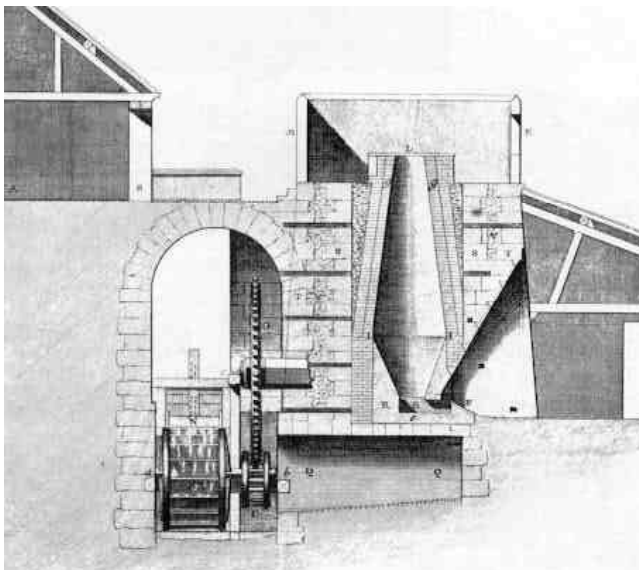
The shaft contains the charge which, as it descends slowly, is reduced chemically by the ascending gases, which cool as they pass through it.



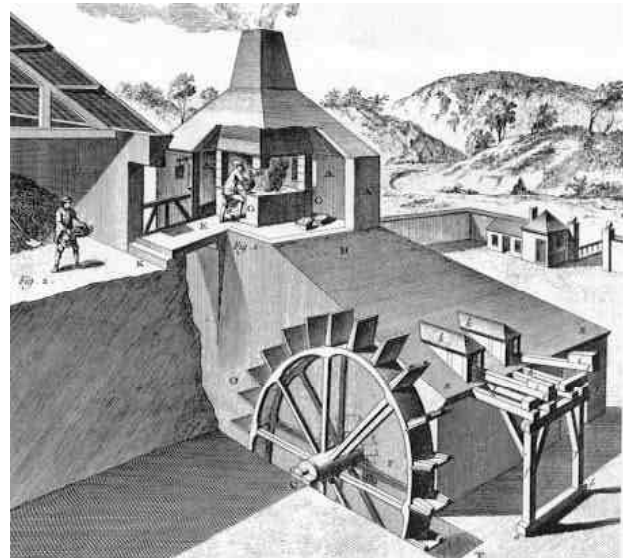
The charge is fed to the blast furnace through the throat. The fixtures and equipment used to regulate the feeding process are situated in the upper part of the blast furnace.

In addition to the furnace itself, a blast furnace plant must include the following:

1. A large yard for storing the iron ore and limestone.
2. A plant for the agglomeration of the ore.
3. A coking plant for the conversion of coking coal into coke.
4. Equipment to weigh the raw materials and transport them to the furnace.
5. Blowers or turbines for forcing air into the furnace.
6. Teeming equipment and ladle or mold cars for transporting pig iron to the steel mill.
7. Pollution control equipment.



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8. Hot blast stoves or preheaters for heating the air that is injected into the furnace.

The operation of a blast furnace is a highly technical and complex process. The operator must try to obtain pig iron of a predetermined chemical composition and extract the maximum amount of metallic iron from the ore with a minimum consumption of fuel and fluxes.

The pig iron, which is the direct product of the blast furnace, then goes on to either be refined or converted into steel. This is accomplished with different types of furnaces: the open hearth furnace, electric furnaces and different types of converters of which the most commonly used today, because of its efficiency, is the blown oxygen converter also known as a BOF (Basic Oxygen Furnace).

Direct Reduction Processes

The processes for extracting low-carbon iron directly from the ore have been called Direct Reduction processes to distinguish them from the indirect processes through which, as a first step, high-carbon iron is obtained. That means that the iron is mixed with a high amount of carbon. The next step consists in refining the iron to lower its carbon content or to produce steel.

Early Investigations (1837-1950)

It is believed that the earliest known efforts to produce sponge iron as an alternate process to the production of steel in a blast furnace were carried out in England in 1837, at which time iron was utilized in processes to obtain copper.

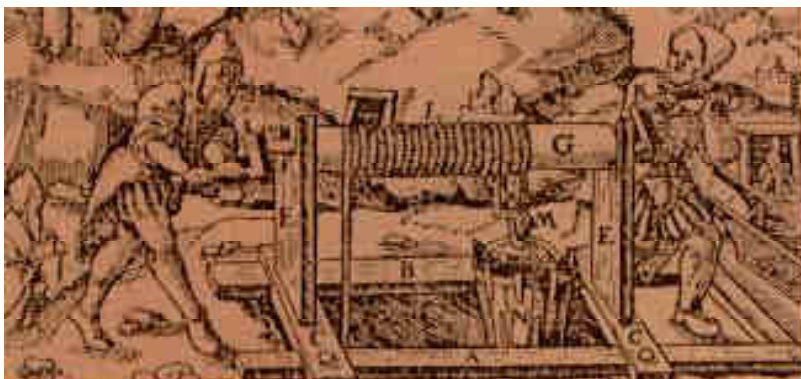
During these early undertakings many types of furnaces were proposed for the production of sponge iron. The most generalized, however, was the reverbatory furnace which was charged with coal mixed with iron ore. During the reduction of the ore with the coal the charge was turned

over 2 or 3 times and, finally, the reduced material was discharged into air-tight boxes made of sheet metal.

After these first attempts, a large number of processes were patented and tried out in various countries for a period of almost 100 years. Some of them were designed to produce sponge iron for use in the processes for extracting copper, but the purpose of most was to obtain a product for the manufacture of steel.

Two types of processes were important: those that utilized coal as a reductor of iron ore and others that used reductor gases, for lack of coal.

Within each of the two types, the processes used can be identified according to the type of furnace utilized to obtain reduction of the ore. The types of furnaces mainly used were the following:



RETORT TYPE FURNACES

In the United States, many attempts were made between 1870 and 1918 to utilize the vertical retort furnaces which were externally heated. In the continuous processes, the furnace was fed at its upper section with a charge consisting of iron ore and carboniferous material. The reduced iron, mixed with residual carbon and gangue, was discharged at the lower part of the furnace.

The heat necessary to preheat the charge and to produce the reduction reactions was generated by burning gas, oil or coal around the external part of the retort and was transmitted to the charge by conduction through the walls.

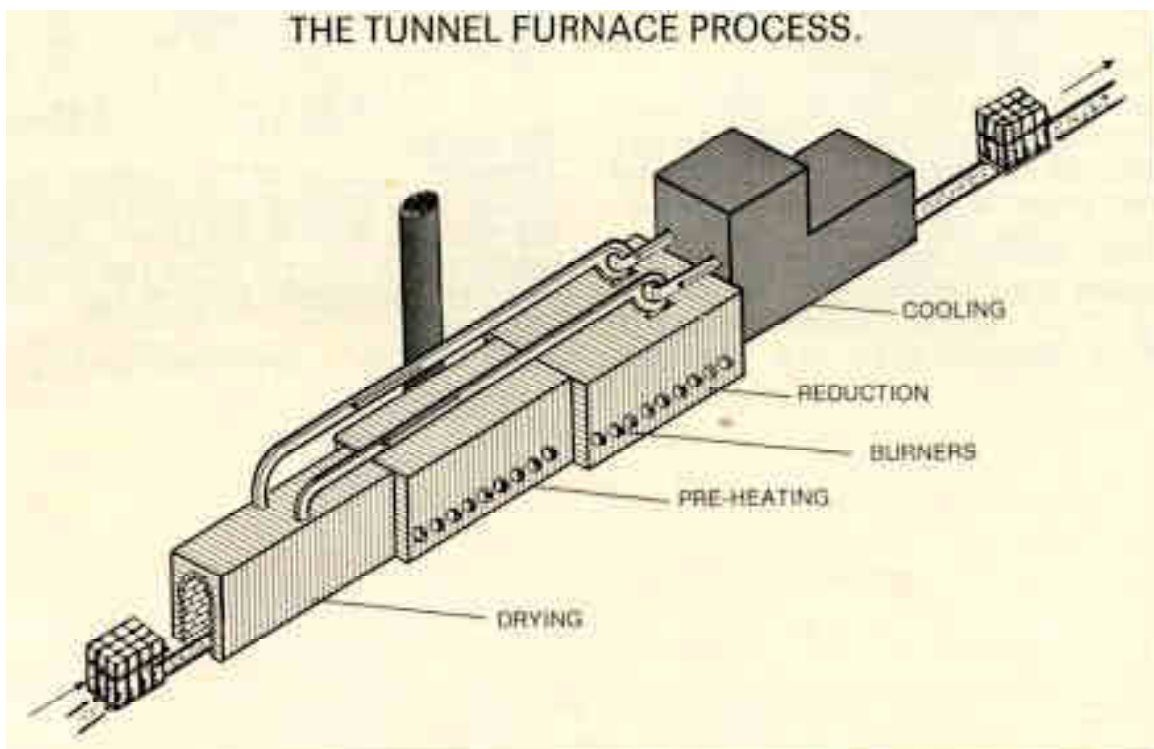


These processes had the disadvantage of the high thermal gradient between the external walls of the retort and the center of the charge, which resulted in a very high reduction time. The process was slow.

From 1920 onward, experiments were carried out with this same type of furnaces by changing from the early fuels to reductor gases.

LEHR FURNACES

In Sweden, a process was developed in 1909 in which the iron ore,



lime and coal were distributed in layers placed inside small containers. These containers were transported on cars into the tunnel-shaped furnace where they were heated by the combustion gases of Swedish coal.

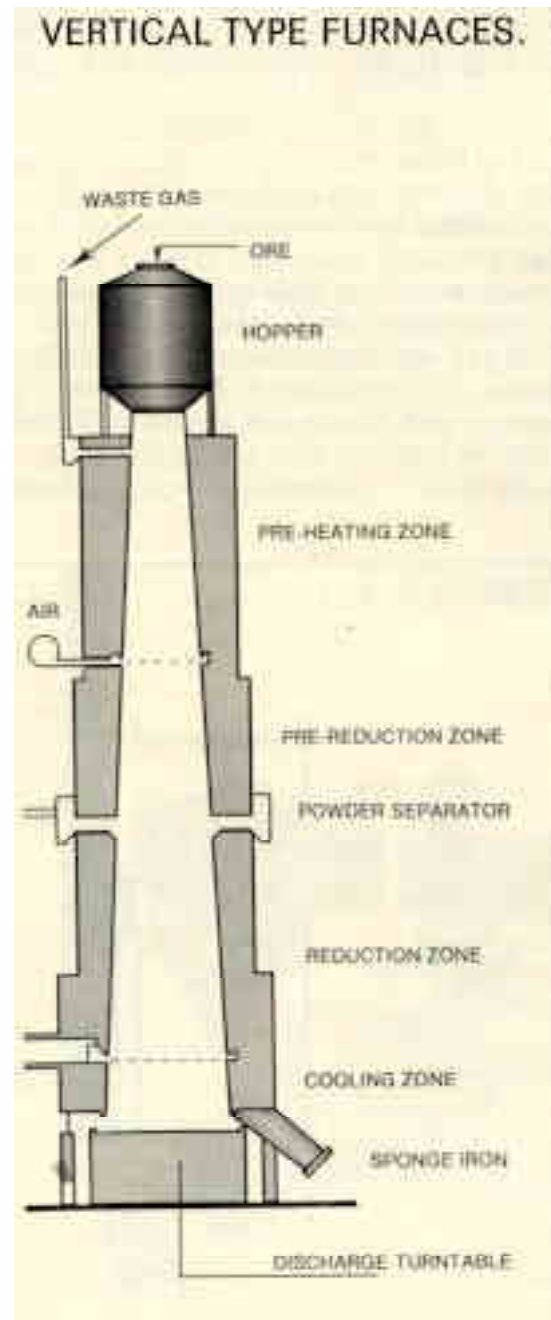
By 1930, the production capacity of these furnaces was 10,000 tons per year. Some industrial plants continued to operate until the early 1980s.

ROTARY KILN

From the years 1907 to 1912, numerous attempts were made to reduce iron ore in rotary kilns.

The usual type was a horizontal kiln of cylindrical shape, with steel walls lined with bricks and slightly inclined. This kiln could be used to heat charges in a continuous or intermittent operation. A mixture of ore and coal was fed into it through the upper part and it was heated with burners that used oil, gas or pulverized coal as fuel. The rotation of the kiln mixed the charge, exposing it to the reductor gases present in the kiln and caused the cooler parts of the charge to be heated more quickly as they came in contact with the hot walls of the kiln.

Due to the great demand for steel during the Second World War, numerous rotary kilns were installed in Germany, Japan, Korea, Manchuria and Czechoslovakia. These kilns were subjected to relatively long periods of operation. Today, several commercial plants are operating with this process.



VERTICAL TYPE (SHAFT) FURNACES

During these first years of direct reduction, several investigators obtained experimental results with these furnaces that showed promise. The reductor gases produced by a gas generator or through incomplete combustion of natural gas, were passed through the bed of iron ore which descended slowly in the furnace. In some cases auxiliary exterior heating was utilized.



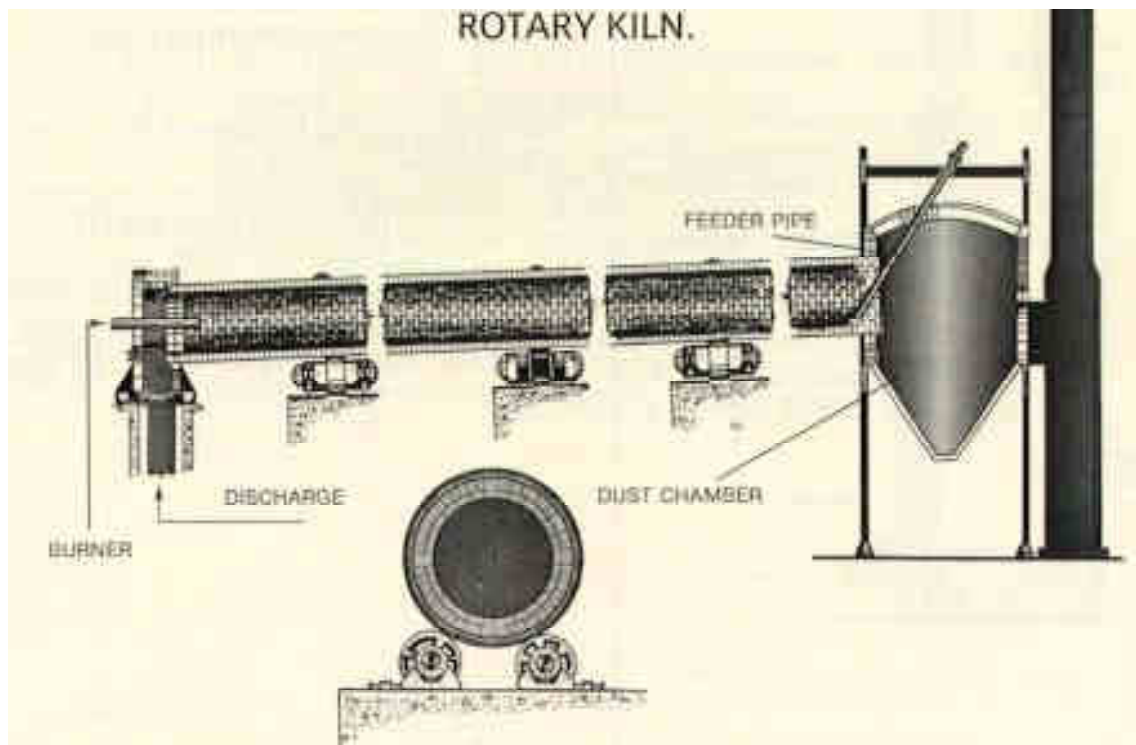
Study and experimentation continued with this type of furnaces until, in modern times, it has become the predominant method for producing direct reduced iron. The majority of industrial plants in operation use this method via different technologies with excellent production levels.

OTHER TYPES OF FURNACES

Many other types of furnaces continued under investigation and experimentation. Among them the following should be mentioned: rotary hearth furnaces, multiple hearth fur-

naces, lateral discharge rotary kilns D-shaped retorts, reverberatory and open hearth furnaces.

During an additional period of nearly 20 years, research and attempts continued to try to find a direct reduction process that was industrially feasible. By the year 1951, the United States Patent Office alone, had granted more than 240 patents for direct reduction processes.





Industrial Development (1950- 1970)

During the next 20 years, approximately from 1950 to 1970, some of the initial processes continued to operate with relatively small yields. Others disappeared completely and new processes were born. Some developed in such a positive manner that they soon reached industrial production scales and prolonged periods of uninterrupted operation.

A classification, at this point, to determine the order of importance of the types of direct reduction processes, will show which of them survived, were born or developed during that twenty year period.

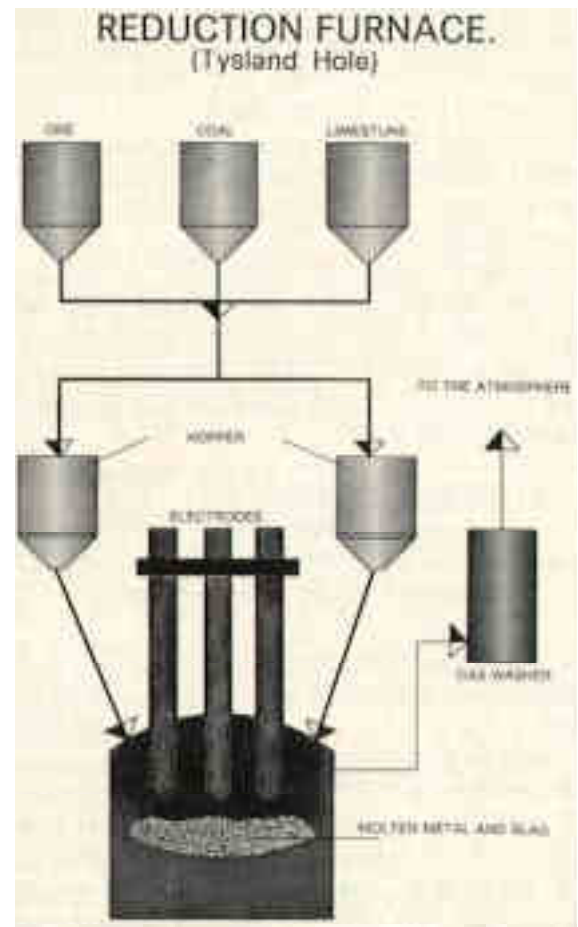
Processes That Use A Solid Reductor

ROTARY KILN PROCESSES

In this type of processes, continuous feeding is accomplished at one end of the rotary kiln. The charge consists of ore in the form of small granules or of pellets, with an appropriate amount of bituminous coal or coke, and with the addition, in some cases, of limestone. To heat the charge, pulverized coal, oil or gas are burned at one end of the furnace and the combustion gases are passed through the charge.

The product that is taken from the kiln consists of granules, formed by the agglomeration of the reduced iron, with a good amount of slag and a small excess of coal. The product is cooled and then pulverized for magnetic separation of the iron, which can later be compacted in the form of briquettes to facilitate its use in a furnace for the manufacture of steel.

These type of processes have been developed mainly in Germany, Norway, Denmark and Great Britain and some of them, despite their being pioneering processes, had continued to develop and operate until the early 1980s.



LEHR FURNACE PROCESSES

Of these processes, the most significant one was developed and introduced in Sweden in 1909.

In this process, alternate layers of high iron content ore, coke breeze and limestone were placed within cylindrical ceramic containers. These were heated inside a tunnel-shaped furnace. Low calorific power gas was burned to heat the furnace. The containers were cooled in the oven, after which they were taken out and the reduced iron was then separated and cleaned.

The major part of the reduced iron produced was refined and sold as powdered iron.

ELECTRIC FURNACE REDUCTION PROCESSES

In most cases, these processes consist in feeding iron ore, coke and limestone into an electric furnace which has 3 or more electrodes for heating and smelting the charge. Their product consists mainly of slag, that is, iron with a high carbon content which is later refined and turned into steel. These processes should be considered as **indirect**, in view of the fact that high carbon content iron is first produced and is then refined. They are, nevertheless, considered to be part of the direct reduction processes, in that

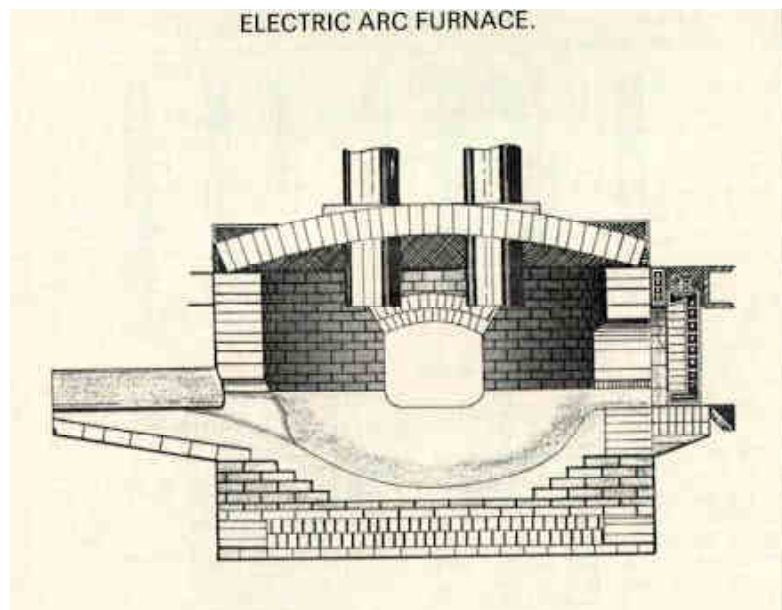


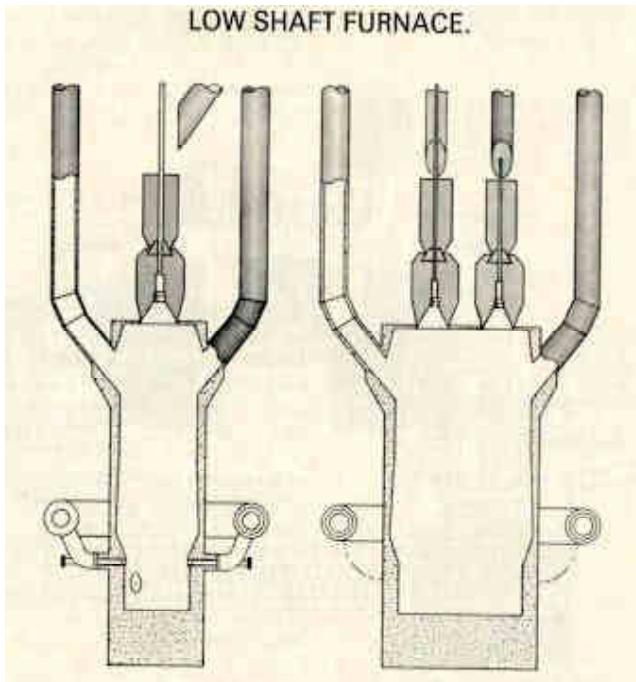
they differ from the blast furnace process.

Processes That Use Gaseous Reductor Agents

ROTARY KILNS

This type of processes utilize a rotary kiln in which the iron ore is reduced through the use of reductor gases which mainly contain hydrogen and carbon monoxide. They are obtained through the partial combustion of natural gas, through the reformation of this gas or of other fuels or as a by-product of the coking plants. These kilns are generally operated in a continuous manner.





VERTICAL TYPE (SHAFT) FURNACES

In vertical type or shaft furnaces, feeding of the ore is accomplished through the upper section of the furnace and the charge descends slowly, to be discharged through the lower section, with the use of different types of fixtures as required by the process being utilized. The reductor gases, which generally are made up of mixtures whose principal components are hydrogen and carbon monoxide, are fed into the furnace.

Depending on the process, the gases are fed through the upper section, the lower section, or at various heights of the furnace.

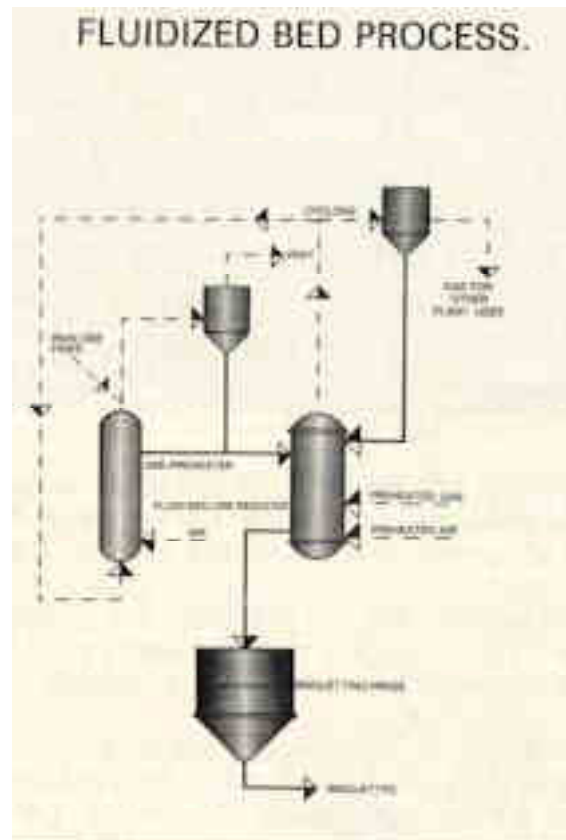
The reductor gases are obtained from different sources: through reformation or partial combustion of natural gas, or from other fluid or gaseous fuels. In some instances, gases from coal gasifiers can also be used, as can pure hydrogen or gases from coking plants.

In some processes, the iron product is cooled before taking it out of

the furnace and in others it is cooled after being taken out.

FLUIDIZED BED PROCESSES

These processes are so called because in them, the iron ore is used in pulverized form and is transported and reduced supported by a reductor gas which is high in hydrogen. In this type of processes, reduction is accomplished in several stages. They include continuous and intermittent techniques. The sponge iron, obtained in the form of fines, contains a high percentage of metallic iron and is quickly agglomerated by means of mechanical pressure (sintering) in different shapes called briquettes, which later will be used to manufacture steel.

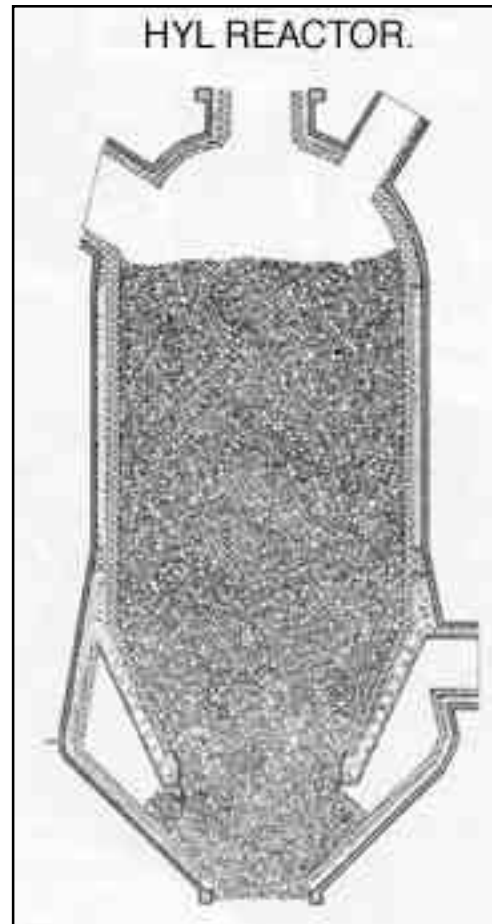


FIXED BED REACTOR FURNACES

The reactor employed in these processes consists of a vessel which is charged with iron ore in bulk or agglomerated in the form of spheres known as pellets. A mixture of hot reductor gases is passed through the ore bed. Their principal components are hydrogen and carbon monoxide. These gases first reduce the iron oxides and, during a later stage when they are cold, they carburize and cool the reduced iron product.

Once the reduced iron reaches an adequate temperature that will keep it from reoxidizing, it is discharged from the reactor which then is ready for a new reduction.

Before being fed into the reactor, the reductor gases are preheated, indirectly at first in a furnace, and later through partial combustion with hot air. They are used in several stages in order to take full advantage of their capacity as reductors.

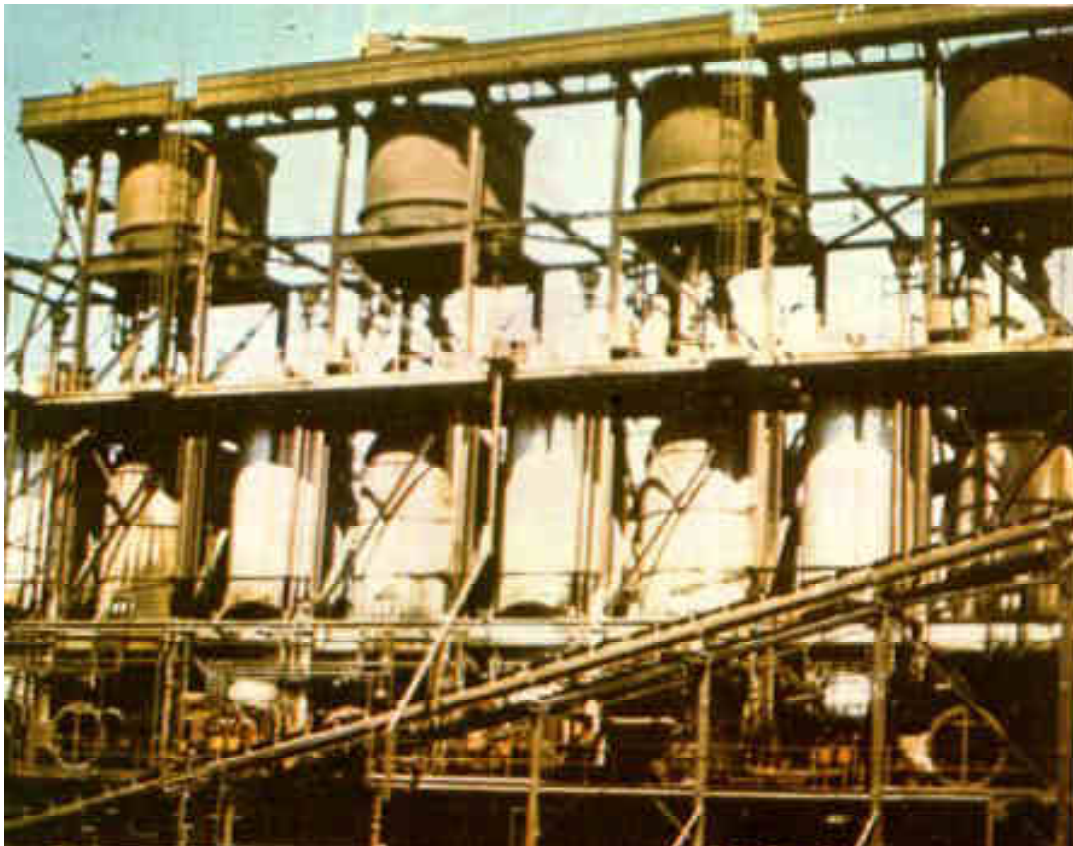


Many other direct reduction processes were studied, tried and were granted patents during the years in question. However, those processes which attained importance then, and continue operating successfully today, are among the types herein mentioned. The most important Direct Reduction Processes for sponge iron production were the SL/RN, FIOR, HIB, KRUPP, MIDREX and HYL processes.



HYL Plant 1M, Hylsa Monterrey. 1957.

HYL Plant 2M, Hylsa Monterrey. 1960.



The Problem and the Solution

The HYL Direct Reduction Process was the fruition of research efforts begun by Hojalata y Lmina, S.A., at the beginning of the 1950s.

These efforts arose from the pressing need to obtain raw material of adequate quality and at stable prices for the production of sheet steel, in order to assure the operation of its non-integrated steel plant in Monterrey, Mexico, which was having difficulties with its operation based on scrap iron. The growing demands for quality on the part of consumers, as a consequence of the general economic and technological development in Mexico were making it increasingly difficult to meet the required specifications, because of the use of a raw material of such variable quality as scrap iron. It was in response to this situation that study and exploration was begun in the field of ore reduction, in order to find a way to substitute the scrap iron for virgin iron. This led to the conclusion that the installation of a blast furnace was not a solution, since the smallest economic size of such a furnace was one that produced far more than the plant's need for iron, which at that time was turning out less than 100,000 tons per year of steel ingots. Furthermore, such a solution would have brought with it the obsolescence of steelmaking based on electric furnaces.

It became necessary to investigate the application of other processes to obtain iron in metallic form, starting with iron ore. Several direct reduction processes already existed in the world at that time, but few operated on a commercial scale.

Hojalata y Lmina, S.A. (now known as Hylsa) began to investigate the application of some of these processes to extract iron from the ore and thus obtain a raw material that would replace the scrap iron and have greater uniformity with regard to supply, quality and cost.

However, of all of the processes considered, only a few were found, at first, sufficiently attractive to risk trying them out in a pilot plant. After an initial evaluation, it was decided to install a process using a Lehr or tunnel furnace; several runs were undertaken by simulating the tunnel furnace process.

The first batch was made by using an ancient furnace (that had been built to heat plate) on the 5th of July, 1950. One part of crushed ore, ranging in size from 1/2" to 1", was mixed with 40% coke breeze and 15% limestone of the same granulometry as the ore. This mixture was put into clay crucibles and into 2 iron pipes, each one with a diameter of 4" and a length of 1 meter. This batch produced 20 kilograms of DRI and, appreciatively, its quality was good.

After this quite modest initial step, three tons of DRI were produced in the same furnace and the first steel batch was produced in an electric arc furnace (type Q Electromelt) with very good success.

Later, other batches were made, reaffirming the decision to install a tunnel furnace. The tunnel furnace began operating in March of 1952, using a Modified Hgans process. This furnace had a length of 100 meters and a transversal section of 1.50 m by 1.50 m. A mixture of ore and coal, similar to that used for the previous tests, was placed in refractory crucibles called saggars, which were then put aboard 48 cars that traveled through the length of the tunnel in 44 hours, passing through the heating, reduction and cooling zones of the furnace. Later, the refractory clay crucibles were replaced by steel alloy crucibles. For the design, construction and start-up of this installation, technical assistance was provided by the Ontario Research Foundation from Canada. The direct reduced iron that resulted had an acceptable degree of metallization, but with an excessive cost for the production of ordinary steels. For this reason, the operation of this furnace was stopped in 1954.

The possibility for replacing scrap iron with direct reduced iron had been demonstrated. However, it was necessary to find a process which was sufficiently economical for commercial operation. With this objective in



mind, Hylsa contacted Mr. Julius Madaras, of Longview, Texas, who claimed to be routinely reducing preheated iron ore by means of a pulsating flow of reductor gases obtained from the partial combustion of natural gas with preheated air. A contract was drawn up with Mr. Madaras which provided for an exploitation license as well as for his technical services to build and operate a plant using his process.

The plant, with a design capacity of 50 tons per day, was unable to reach acceptable levels of metallization. During the 18 months that it was in operation, it underwent several changes, including the installation of a natural gas reformer with the object of improving the reducing gas.

Finally, its operation was suspended during the first semester of 1955.

Faced with such discouraging results, obtained with the two patented processes which claimed to be able to reduce iron ore at competitive costs, the company decided to carry on research with its own resources and with new directives. The study and investigation of the reduction of iron ore on the basis of natural gas continued and numerous experiments were

carried out during several months, exploring the following aspects:

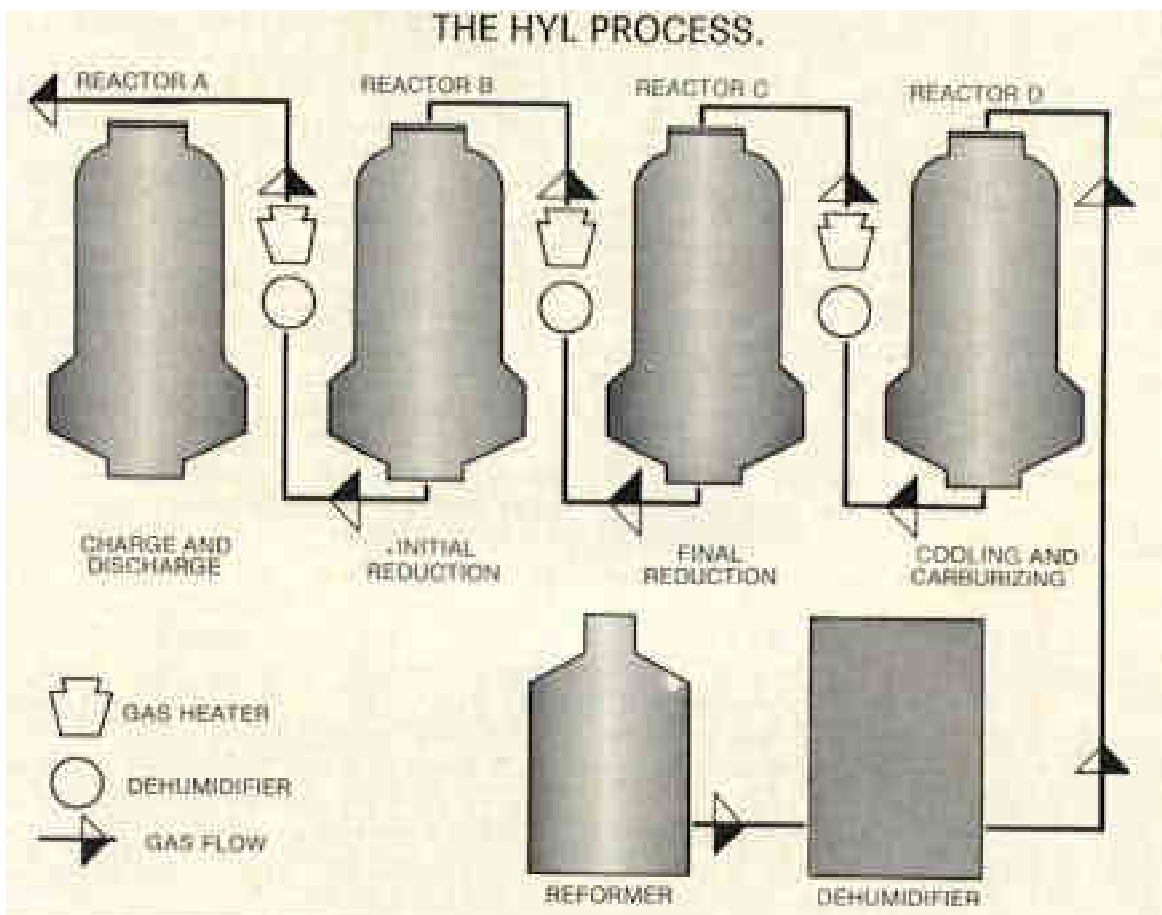
1. Different compositions of reducing gas were tried and the one that was found to be most adequate, technically as well as economically, was the one produced through the catalytic reformation of natural gas with steam.

2. Experiments were carried out with different reduction temperatures to determine their effect on the kinetics of the reactions. Since it wasn't possible to obtain the high temperatures required by the reduction process through indirect means, an ingenious procedure was devised: to inject

air into the flowing reduction gases, and by means of the combustion of a small fraction of these, to elevate the temperature to the required levels so that the process would be efficient and economical.

3. Many other aspects were studied, among them the importance of operating a simultaneous heating and reduction regime with which an increased reduction speed is obtained.

Furnaces, vessels, instruments and so forth were available. They had been used to carry out the previous tests. With them, a pilot plant was assembled to put the new ideas to the test. When this experimental plant



was put into operation, it started to successfully produce good quality reduced iron at a rate of 30 tons per day. It soon reached a systematic production of almost 60 tons daily.

By the end of 1955, after this pilot plant had produced the first 3,000 tons of direct reduced iron with the gas-based HYL direct reduction process, studies were begun for the design of the first commercial plant with a daily capacity of 230 tons of DRI.

The first industrial scale direct reduction plant was put into operation on December 5, 1957. The Hylsa Monterrey 1-M plant, a fixed-bed reactor or batch process, had an initial capacity of 75,000 metric tons per year of DRI. It remained in continuous operation until 1991, just short of a full 35 years of production. The plant averaged over 85,000 tons per



Plaque commemorating the HYL Plant 1M, Hylsa Monterrey, as an historical landmark in the iron and steel industry. The designation was made by the American Society For Metals in 1978.

year of DRI production, and produced in excess of 100,000 tpy during 10 different years.

In 1978, the American Society for Metals designated Hylsa's HYL Process Plant 1-M an historical landmark for having been the first successful industrial implementation of direct reduced ironmaking technology.



HYL Plant 1M, Hylsa Monterrey. 1957.

The Modern Era (1970 - present)

By the end of 1970, world direct reduction capacity consisted of four HYL process plants, an SL/RN and a Purofer facility and the first Midrex plant which had just started up. Total DRI output for 1970 reached 790,000 tons, 680,000 tons of which was produced in HYL process plants. The mid to late 1970s saw substantial growth in the number of D.R. plants installed, primarily due to the increase in state-owned steel industries in gas-rich developing nations. These were universally based on the electric arc furnace and, because scrap in a non-industrialized nation tends to be an imported commodity, on-site direct reduction became the preferred

HYL Pilot D.R., HYTEMP and EAF facilities.



method for obtaining iron units for the meltshop.

In 1980, twenty-three years after the success of its first HYL plant, Hylsa began operations using its new continuous shaft furnace process, which was called HYL III.² Three years prior, Hylsa set up a new operating division for the purpose of formally developing and commercializing their direct reduction technologies. While several HYL plants had been sold worldwide, Hylsa's main focus in the development of its direct reduction process had always been for internal application. The onset of the Midrex and other processes as commercial ventures brought needed competition

and the new HYL III technology was taken successfully to the marketplace.

As steel experienced a recession during the 1980s, so did demand for direct reduction plants. Scrap prices dropped to very low levels, making it reasonable to produce DRI only where natural gas and iron ore prices were well below international price levels. However, the modernization of steelmaking after the

² The name "HYL III" was chosen, representing the third generation of HYL technology. The second generation (HYL II) was basically a modification of the original fixed-bed process designed to improve efficiency and reduce natural gas consumption. The appearance of the HYL III process offered significant advantages and the HYL II process was never commercialized.



First HYL III Process Plant (Hylsa 2M-5), 1980, Monterrey, Mexico.

recession brought new technological developments in electric furnace steelmaking. Larger, more powerful furnaces using oxygen injection, and steelmaking advances such as continuous casting and thin slab casting, opened the doors for the new mini-mills to produce better grades of steel.

Although Hylsa had been producing flat steels in the EAF for decades, the typical scrap-based electric furnace shop produced only commercial grades of steel such as construction bar and rod. By adding quantities of virgin iron to the melt, it be-

came possible for EAF producers to compete against the larger integrated mills with products which had previously been technically unfeasible using only a scrap charge. Suddenly, the demand for direct reduced iron boomed and with it, the installation of new plants. Many of the new plants were installed as merchant producers—located in areas where raw materials costs were low and shipping DRI to consumer mills at distant locations.

The boom in demand for DRI, coupled with problems experienced with overseas shipments due to improper handling of the product, brought about the development of hot briquetted iron (HBI) as a more easily handled product form. By discharging the reduced material hot into briquetting machines, a product could be formed having a smaller surface area than the more porous DRI pellets. These pillow-shaped briquettes were more easily handled and many of the merchant plants employed this technology.





Hylsa 4M plant using reformerless HYL III technology with HYTEMP Pneumatic Transport System tied to the EAF minimill.

For EAF mills with the capability for installing their own captive direct reduction plants, a new product form was developed by HYL. Termed the HYTEMP System, this technology involves the pneumatic transportation of DRI, discharged hot from the reduction furnace, to a holding bin above the EAF and then gravity fed to the furnace at temperatures above 600°C. This product option represents significant energy savings in the electric furnace and promises to reduce the per ton cost of steel even

further.

By 1990, the direct reduction industry could be said to have entered its maturity stage. Steelmakers were learning about the benefits of using DRI and HBI and new plants and projects continued to develop.

While 90% of all DRI and HBI was produced by Midrex and HYL technologies, the burgeoning interest in alternate iron sources opened the doors for new process developments. Some of the technologies which were or are being developed include: Circofer, Circored, Comet, Fastmet, Finmet, Ghaem, Inmetco/ Mannesmann, Iron Carbide, Spirex, Sumitomo and the Zia processes. Time will tell which of these technologies could prove to be economically viable, or whether yet other technology developments will supersede them.



Impact of Direct Reduction Throughout the World

Throughout this historical essay, we have tried to present how, through forty centuries, one of civilization's most basic industries --steel-- has known and come to use a fundamental process, Direct Reduction.

We have also tried to show the reasons why this process was set aside some centuries ago by the blast furnace.

During the last decades, other scientific and technical areas have enjoyed an enormous advance while, at the same time, social and economic world conditions have encouraged new studies into Direct Reduction thereby making this process very attractive vis-a-vis the blast furnace.

An example of these conditions which, in changing, have modified past thinking, is the electric arc furnace's voracious need for iron and its rapidly evolving technology. Nor-

mally obtained from scrap, the EAF suddenly became faced with a situation in which the available iron units became too variable in cost, availability and in quality, for the reliable production of low cost quality steel products. The major significance in the use of DRI or HBI is measured, finally, in the cost of liquid steel. No longer can these iron products be compared in terms of ton-per-ton cost with steel scrap. The **value** of DRI and HBI must be measured as a function of the benefits they apportion to the steelmaking process. Steelmakers are learning that the overall reduction in residuals and the quality of steel produced by blending DRI and scrap, reduces the final cost of steel and thus more correctly states the value of using DRI or HBI.

Developing countries, in urgent need of steel and with inadequate coal resources for blast furnace use, presented another situation where Direct Reduction became very attractive.

Of course, most Direct Reduction processes have major advantages over the blast furnace because of their modularity, more rapid start-up times and smaller unit investment.

This confluence of technical and socioeconomic factors has renewed this old process and has enabled it to evolve from an obsolete technique into a modern one. Direct reduction has become, more and more, an ad-



vanced base for the modern steel industry. To illustrate this market acceptance we need only look at some historical production figures: In 1957 only one plant was in commercial operation (Hylsa I-M). Its capacity was only 75,000 tons per year. By the end of 1970 there were still only a

world D.R. capacity were optimistic, with estimates of 20 million annual tons by 1980 being common. Obviously, for numerous reasons, these projections exceeded the mark. Market conditions today and the highly evolved methods in use for electric furnace steel production, have virtu-



few Direct Reduction plants operating worldwide, with a total production of just under 800,000 annual tons. Production grew to over 7 million tons by 1980, 17.7 million tons by 1990 and, by the end of 1997, world DRI production amounted to 35 million tons per year.

Twenty years ago, predictions for

ally mandated a continuing growth curve for the direct reduction industry. Taking into account plants under construction, negotiation or in planning stages, it would not be unreasonable to expect world D.R. capacity to reach 55 million tons by the year 2000, and from 70 to 100 million tons by 2005.

Epilog

In this brief span we have seen the development of a technology. A technology which arose accidentally 4000 years ago, and that, in the last 40 years has been renewed and modernized, becoming a veritable spearhead of world steel making.

Notwithstanding the contributions of modern technology, we hereby recognize and acknowledge our age-old debt to those iron makers of four millenia ago who trapped the star metal for mankind's use.



Timken Series.



Direct Reduction Terms and Definitions

1. **Basicity:** Given by the ratio of the percent content of the alkaline oxides and the alkaline-earth oxides to the other nonferrous oxides, quantified by the ratio:

$$B = \frac{\% \text{ CaO} + \% \text{ MgO} + \% \text{ OX}}{\% \text{ SiO}_2 + \% \text{ Al}_2\text{O}_3 + \% \text{ OX}}$$

OX: Other representative oxides.

2. **Capacity:** The amount of metric tons of direct reduced iron, duly specified, produced in one year by a direct reduction plant from a given material, taking into consideration the effect of delays and equipment shut-downs for maintenance.
3. **Commercial Process:** The processes which have fulfilled the industrial production stage and comply with the established requirements and characteristics of the D.R. plant.
4. **Decrepitation:** The degrading and rupture experienced by certain oxidized minerals which produce iron ore fines, as an effect of the water of crystallization release and/or thermal effects in any kind of atmosphere in a heating cycle up to 750°C.
5. **Degradation:** The fragmentation or breakage with the production of fines, which the materials may experience by abrasion, handling, transportation, etc.
6. **Degradation Index:** The total degradation percentage in terms of weight, experienced by the material due to mechanical, abrasion, handling, reduction and other means, during the direct reduction process.
7. **Degree of Metallization:** (M°) The amount of metallic iron, expressed in

terms of percentage of total Fe contained in the direct reduced iron.

It is calculated by dividing the amount of metallic iron that the direct reduced iron contains by the total amount of iron this product contains and multiplying the results by one hundred.

$$\% M = \frac{\text{Metallic Iron}}{\text{Total Amount of Iron}} \times 100$$

8. **Degree of Reduction:** The amount of oxygen removed from the ore, expressed as a percentage of the initial amount of oxygen in the iron ore. It is calculated as follows:

$$\% R = \frac{\text{O}_2 \text{ removed}}{\text{O}_2 \text{ initial}} \times 100$$
9. **Degree of Reoxidation:** The increase of iron oxides as a result of the metallization loss and of the reoxidation of the wustite present in the direct reduced iron.
10. **Density, Apparent:** The ratio of the weight of a particle to its volume. It includes the porosity of the particle. It is expressed in Gm/Cml.
11. **Density, Bulk:** The ratio between the total weight of the particles and the volume they occupy, including the porosity of the bed and the porosity of the particles. It is expressed in Kg./M³.
12. **Density, True:** The ratio of the weight of the particle to its respective volume without including particle porosity. It is expressed in Gms/Cm³.



13. **Direct Reduced Iron (DRI):** A solid, porous and metallized material product of a direct reduction process.
14. **Direct Reduced Iron Fines:** Those particles which due to their size, cause handling problems in conventional equipment and are generated by degradation or are the result of a direct reduction process whether it uses fine iron ore or not.
15. **Direct Reduction:** The set of process conditions to which the iron ore is subjected using solid or gaseous reductants to eliminate or reduce out the oxygen content and obtain a solid, porous and metallized product.
16. **Direct Reduction Plant:** For comparative purposes, a direct reduction plant is composed on a battery limits basis of all the facilities (reactors, loading and unloading systems, electric systems, water supply, instrumentation, electric power substation, controls, reducing gas generating unit, equipments and structures, without including foundations) for the production of direct reduced iron in a given location. This does not consider infrastructure, personnel services, offices, labs, maintenance facilities, cost of land, improvements, general facilities, etc. For the effects of cost, utilities and their distribution within the battery limits are considered.
17. **Drying:** The operation consisting of the elimination of moisture in the ore.
18. **Energy Consumption:** The total amount of energy consumed in a direct reduction plant from the raw material yard to product storage, expressed in Giga Calories per metric ton of product (G.Cal/T).
19. **Experimental Process:** The processes that have outlined their theoretical fundamentals and are in laboratory research stages.
20. **Fluidized Bed:** The condition obtained in direct reduction when the iron oxides are charged into the reactor in the form of fines which, due to the pressure and temperature of the flowing reduction gas, behave as a fluid.
21. **Gangue:** In ores for iron production, gangue includes all nonferrous minerals and substances present in the ore itself, except for the elements which contaminate the iron when melted, which are named impurities (i.e.: P, S, Sn, etc).
22. **Gas, Cooling:** A gas generally rich in inert elements, used to cool the product of certain direct reduction processes.
23. **Gas, Natural:** A gas from the subsoil which may or may not be associated with oil.
24. **Gas, Recycled:** The volume of gas which after leaving the reactor due to its reducing or energetic content, can be used again for reformation or fuel purposes.
25. **Gas, Reducing:** A gas which because of its affinity with oxygen is used in direct reduction processes to partially or totally reduce the iron oxides.
26. **Gas, Reformed:** The gas originated in a catalytic reaction of natural gas or other fluid or solid fuels in the pres-

ence of oxidizing agents, in which H_2 and CO are the main, active components.

27. **Gas, Sealing:** A gas, not necessarily inert, which is used to prevent leaks in the process.
28. **Hot Briquetted Iron (HBI):** Hot direct reduced material which is agglomerated by mechanical pressure (usually a roller press) with or without the use of binding compounds.
29. **Impurities:** The undesirable elements contained in direct reduced iron which pollute iron when it is melted, expressed in percentage terms. The most common are phosphorus and sulfur.
30. **Industrial Process:** Those processes which have surpassed the experimental stage in which the production levels and characteristics of the operating plant are very near those established for its nominal capacity.
31. **Iron Ore Fines:** Solids, usually below 4 mm., generally suitable for feeding fluidized-bed direct reduction processes.
32. **Load, Kinetic:** Applies to the load of the reactors in continued or intermittent direct reduction processes, where the material is constantly in movement.
33. **Load, Static:** Applies to the load of the reactors in intermittent direct reduction processes where, once the material is loaded, it does not move until the process is finished. The loading and unloading is done in batches.
34. **Metallic Iron:** The quantity of free iron or iron combined with carbon

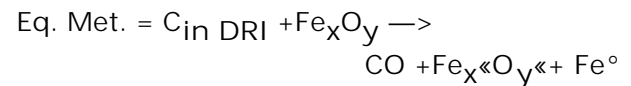
(Fe_3C) present in direct reduced iron.

35. **Metallization:** The transformation of the iron oxides into metallic iron (in a free state or combined with carbon as Fe_3C) when they lose oxygen through the action of the reductants used. Percent metallization is the level of metallization multiplied by 100:

$$[\text{Fe}^\circ + \text{Fe in Fe}_3\text{C}] \times 100$$

$$\% \text{ Met.} = \frac{\text{Fe Total}}{\text{Fe Total}}$$

36. **Metallization, Equivalent:** The metallization theoretically obtained when the metallizing power of the carbon contained in the direct reduced iron is added to the metallization itself.



37. **Passivation:** The decrease in the tendency of direct reduced iron to reoxidize, obtained through physical or chemical means.
38. **Pellets:** Iron ore fines which have been concentrated and agglomerated and which have approximately a spherical shape. Often called green pellets. Pellets which have been hardened by heating to sintering temperature are called indurated pellets.
39. **Pilot Process:** Those processes which have surpassed the laboratory stage and are operating in a small scale and in similar conditions to the commercial and/or industrial process.
40. **Power Consumption:** The total amount of electric power consumed by





a direct reduction plant, from the raw materials yard to

product storage, expressed in Kilowatt-hours per metric ton of product (kWh/T). Also referred to as Electric Energy Consumption.

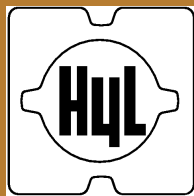
41. **Productivity:** Plant output, discarding delays, expressed as metric tons per day.
42. **Pyrophoricity:** The tendency of materials to produce spontaneous combustion when exposed to air.
43. **Reactor:** The furnace, varying in shape, within which the reduction of the oxidized iron ore by the action of the reducing agents is achieved.
44. **Reducibility:** The ability of oxidized iron ores to give up their oxygen by the action of reducing agents.
45. **Reductants:** The solid or gaseous substances used in direct reduction which have a great affinity for oxygen contained in oxidized iron ores.
46. **Reduction:** The chemical removal of the combined oxygen within the iron ore during the direct reduction process by the action of the reductants.
47. **Reduction Rate:** The time required by the iron oxides to reach a given degree of reduction, under conditions which were previously defined.
48. **Reformer:** The equipment within which, through a thermo-catalytic action, the transformation and/or enrichment of the reducing agents (H_2 and CO) of the gas used in direct reduction is achieved.
49. **Reoxidation:** The reversion of metallic iron or direct reduced iron oxides to iron oxide through the action of environmental atmosphere and/or humidity.
50. **Residence Time:** The necessary time the ore and/or the reducing gas must remain inside the reactor, in order to obtain the desired metallization level.
51. **Residual Metals:** Tramp elements or metallic impurities which may be present in scrap metal or other iron charges, and which have a negative effect on steel processing and steel quality when present in excess of specified limits. DRI and HBI typically have insignificant levels of residuals content.
52. **Retort (Fixed Bed):** Intermittent processes reactor with a static charge and the shape of a crucible, in which the necessary heat for the reaction is obtained by heating the outside crucible wall.
53. **Rotary Kiln:** A tubular reactor, horizontal or slightly inclined, of equal or various diameters throughout its length and in constant rotation.
54. **Screening:** The operation which consists of passing the material through sieves with the purpose of classifying by size.
55. **Shaft Furnace (Moving Bed):** A stationary vertical reactor, for continuous or intermittent processing, with external or internal heating. Solids flow is downward by gravity with a countercurrent uprising flow of reducing and/or cooling gas.



56. **Specific Gas Consumption:** The amount of gas used in a direct reduction plant to produce one metric ton of direct reduced iron at a given metallization, expressed in Giga Calories (G. Cal/T).
57. **Swelling:** The increase in volume experienced by iron ores when submitted to a direct reduction process.
58. **Swelling Ratio:** The magnitude of the swelling expressed as percent experienced by a piece of iron ore when it is transformed into direct reduced iron. It is calculated by dividing the increment in volume by the original volume and multiplying by 100.

$$H = \frac{V_r - V_o}{x \ 100} \times 100$$

59. **Total Iron:** The amount of free iron and combined iron present in direct reduced iron.



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