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Technical Report
On Blast Furnace Issues
In the Matter Of
Carbon Injection Systems LLC, et al.
Docket No. RCRA-05-2011-0009

Prepared For
Brouse McDowell
Cleveland, Ohio, USA
Privileged and Confidential

Attachment B

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1. Executive Summary

Rorick Inc. has been retained by Brouse McDowell to provide technical and expert assistance on the following specific points:

1. **Are the Carbon and Hydrocarbon Carriers, used in the blast furnace process, fuels or chemical raw materials from a scientific and technological point of view?**

From the seminal work "Summary Evaluation and Assessment of Carbon and Hydrocarbon Raw Materials for Iron Ore Reduction", by Rudolf Jeschar and Gerritt Dombrowski, Institute of Energy Process Engineering and Fuel Technology, Clausthal-Zellerfeld, Germany, and presented at the International Congress on the Science and technology of Ironmaking, held in Toronto Canada in May 1998 we find the following conclusions, quoted directly:

- The carbon and hydrocarbon carriers used for the reduction of iron ore cannot be classified as fuels as they cannot be replaced by another perhaps chemically inert energy carrier or other non-physical energy source
- These materials should therefore be classed as chemical raw materials as their components are involved in the chemical reactions of the iron ore reduction

The justification for these conclusions is derived from a complete thermodynamic analysis of the blast furnace process, supported by actual data from an operating blast furnace. The energy balance data showed that 70% of the energy supplied by the coke and hydrocarbon carriers is converted into energy that is chemically bonded to the hot metal, 13% equated to the heating value of the top gas which is inevitably produced in this process, 14% converts into the measureable heat of the hot metal and slag, and only about 3% is lost through the furnace walls and measureable heat of the top gas. Further, it is clearly shown on the basis of process interactions that the energy supplied by the coke and hydrocarbon carriers cannot be replaced by any other known inert energy carrier or other non physical energy source, because the coke and hydrocarbon carriers are direct and active participants in the chemical reactions. No other energy form has the ability to replace both the physical and chemical functions of the coke and hydrocarbon carriers. If this were not so, and the coke and hydrocarbon carriers were not active participants and could be equivalently replaced by another energy form, a totally different conclusion would have resulted.

There are a number of additional conclusions which, while very important for those involved in the process technology, are not so relevant to the simple point of the assignment. The complete original paper is shown in Appendix II of this report.

2. **Provide an analysis of the accuracy and relevance of the technical points raised in the "Cadence" discussion, Federal Register, Vol. 50, No. 230., pgs 49171 - 49174**

The "Cadence" discussion as shown in the Federal Register, Vol. 50, No. 230, pages 49171-49174 is unfortunately too simplistic and quite incomplete by today's understandings. The central focus on the blast furnace process as a combustion" process, not unlike a boiler in a power generating plant, where fuels are "burned" to release their "heat energy", accepted by everyone including blast furnace operators in former times, has been found to be fundamentally wrong. The work of Jeschar and Dombrowski, other blast furnace scientists and technicians, and a world of blast furnace operators have clearly demonstrated that the blast furnace process is a chemical process, not constrained by the limitations inherent in the "combustion" theory. As a specific example of the technical difference between the two methodologies we can cite the use and expansion of hydrocarbon injection. If one accepts the "combustion" methodology, then it follows that the maximum hydrocarbon quantity that could be efficiently injected would be that quantity which could react within the "combustion zone", the blast furnace raceway, and that coke would remain the principal reductant in the blast furnace input. Some operators accepted this limitation during the 1970's, and constructed facilities accordingly. Other operators, particularly in western Europe and China did not feel so constrained, and they pushed the technology until today it is not unusual to see actual blast furnace data with the quantity of hydrocarbon carrier injection greater than the quantity of coke consumed per ton. This is because the chemical reactions inside the blast furnace are not limited to the 2% of blast furnace volume encompassed by the raceways, but rather includes the remaining 98% of volume as well. More than 50%, and up to 60% of the injected hydrocarbon carriers are found to actually react outside the raceway zone. The conclusions drawn from the incorrect process analysis and characterization led to very expensive reconstruction and new construction costs for those who previously adhered to the false doctrine.

Likewise the adherence to the "combustion" doctrine, as in the "Cadence" discussion, methodology and its focus on carbon as the principal reductant, totally missed the extremely powerful role of hydrogen, an important part of the injected hydrocarbon energy carriers. Hydrogen is a better reducing agent than carbon monoxide; so good, in fact, that nearly all injectable hydrocarbon energy carriers have a replacement ratio of greater than 1 unit of coke replaced per unit of hydrocarbon injected. Hydrogen also has significant aerodynamic advantages inside the blast furnace where reducing gas flow and contact with the material to be reduced is the absolute key to modern blast furnace efficiency. In fact, as Jeschar and Dombrowski point out, the expanded use of hydrogen-containing hydrocarbon energy carriers leads inevitably and directly to a reduction in the generation of so-called greenhouse gas CO_2, a point that the "combustion" adherents fail to recognize.

The "combustion" characterization, and its use of terms like, "fuel", "burning", "burning for energy recovery", "concentration on calorific heating value", and so on are as anachronistic as the term "woods" for certain golf clubs which actually have not been made of wood since the 1930's. Yet the terms persist, and in the case in point, lead directly to incomplete and/or inaccurate analysis and assessment because the underlying science was incorrect.

There also is presented in the "Cadence" discussion in the Register an energy balance, again based upon the old characterization, which is submitted to buttress the "combustion" aspects of the regulator's view of the blast furnace and the Cadence product. The much more precise and more scientifically appropriate thermodynamic calculations of Jeschar and Dombrowski contrast sharply with the previous approach, and clearly demonstrate that the blast furnace process is not a "combustion" process, but is rather a chemical process. It would be better for everyone if the old terms could be abolished, but that is very difficult. The best that we can do is to not allow future decisions and analysis to be governed by the old, discredited science.

There also is a contention, by Cadence, in the document that there are beneficial effects for the blast furnace to the presence of chlorine in their product. In fact, there are zero beneficial effects of chlorine.

2. The Assignment

Rorick Inc. has been retained by Brouse McDowell to provide technical and expert assistance on the following specific points:

1. Are the Carbon and Hydrocarbon Carriers, used in the blast furnace process, fuels or chemical raw materials from a scientific and technological point of view?
2. Provide an analysis of the accuracy and relevance of the technical points raised in the "Cadence" discussion, Federal Register, Vol. 50, No. 230., pgs 49171 - 49174

3. General Blast Furnace Operation and Key Principles

Before beginning the analysis of the points in question, it is necessary to have some understanding of how the blast furnace works. Unfortunately, that can be a very substantial task. The following explanation is intended to develop that understanding without too great a technical development. A more substantial explanation is attached to this Report as Appendix III. For those inclined to have an even more complete understanding, the following references are recommended:

1. "The Making, Shaping, and Treating of Steel", published in several editions by the Association of Iron and Steel Engineers, and its current organization the Association for Iron and Steel Technology
2. "Blast Furnace Theory and Practice", by Strassburger et al, published for American Institute of Mining, Metallurgical, and Petroleum Engineers Inc., by Gordon and Breach Publishers
3. Course material from the "McMaster Intensive Course in Ironmaking", given biannually by The McMaster University, Hamilton, Ontario, CANADA
4. "Modern Blast Furnace Ironmaking – an introduction", by Geerdes et al, published by The German Iron and Steel Institute in 2004.

The Blast Furnace Facility

The blast furnace is a very large complex, perhaps one square mile in size, and costing about $1 Billion to construct. The purpose of the entire facility is to receive and convert iron ore and other raw materials into molten iron, an essential ingredient in the manufacture of steel. The following photograph shows only one part of the complex, and the relative size can be appreciated considering the size of the full-size pickup truck indicated by the yellow arrow.

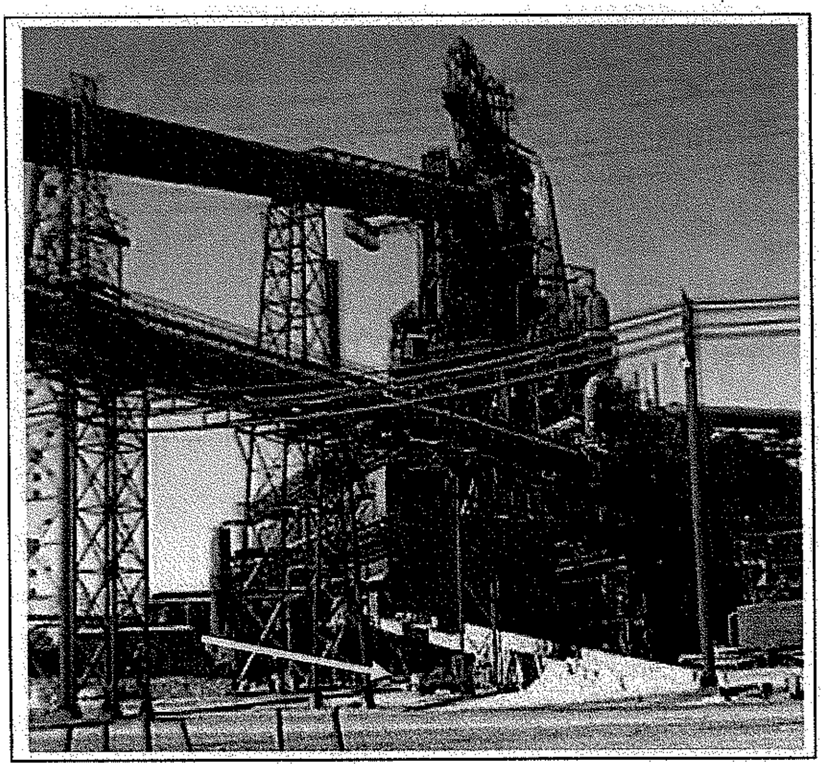


Figure 1: Photograph of modern blast furnace

The Blast Furnace Proper

Located within the complex is the blast furnace itself, which is visualized in Figure 2.

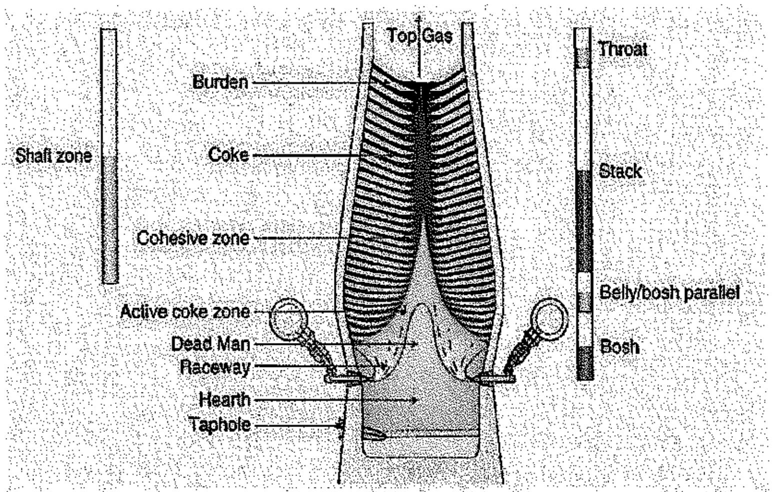


Figure 2: The Zones in a Blast Furnace; Source – "Modern Blast Furnace Ironmaking" by Geerdes et al

The blast furnace is a very large reactor, about 45 feet in diameter and 100 feet high, designed to process iron ore into liquid iron, using metallurgical coke and other hydrogen and carbon bearing materials to provide the chemical reagents and the heat needed for the processing. The furnace is a closed system, thus containing all of the reactions, hot and dangerous gases, and liquids inside.

Iron ore and coke are put into, or charged, at the top of the furnace, in very particular and organized ways, forming a packed bed which moves downwards by gravity, as void space is created in the lower parts of the furnace. The process starts with hot blast, i.e. preheated air and sometimes enriching oxygen, forced through the tuyeres, a very special type of nozzle, which partially gasifies the coke and injected hydrocarbon. The term "partial" is very important because, while it was once believed that all of the carbon and hydrocarbons were consumed in the relatively small raceway directly in front of the tuyere, it is nowadays known that a considerable portion, particularly of the injected hydrocarbons, is actually consumed elsewhere in the furnace. The hot reducing gas is forced upwards by high pressure through the void spaces in the packed bed, and exits at the furnace top. The counter-current flow, that is solids and liquids downward and hot gases upward, is the key factor in how the blast furnace process actually works.

The hottest part of the furnace is near the bottom, where the hot blast enters at nearly 2250° C (4000° F). The gases gradually transfer their heat to the descending solids, leaving the furnace top at about 175° C (300° F). The solids meanwhile enter the furnace top at ambient temperature, gradually increase in temperature as they descend, ultimately soften, and finally melt forming liquid iron and slag, which both drain into the hearth. The iron ore charged at the furnace top is initially a complex mixture of iron and oxygen. As the materials descend inside the furnace, temperature increases, and the oxygen molecules are being stripped off by the ascending gases, creating essentially pure iron and slag. All of these reactions are quite complex, and are explained more fully in the other references. It is a fundamental point to understanding the blast furnace process to recognize that the hot reducing gases perform chemical work all through the vertical height of the blast furnace. In the raceway region, the gases actually provide the heat energy to liquefy the iron and slag. As the gases rise, and cool, the temperature is no longer sufficient to liquefy, and a somewhat plastic zone occurs, wherein the last of the chemically bound oxygen in the iron ore is removed, which incidentally also generates additional quantities of reducing gas. Above the plastic zone, the reducing gases still rise and they serve to strip the oxygen from the iron ore, and other materials, and preheat those materials. These reactions and their effects are depicted in the stylized view of the blast furnace, in Figure 3 on the following page.

The only reason to have and operate a blast furnace and that is to chemically separate the iron and oxygen in the iron ore. If we attempted to produce iron just by heating the ore, without the reducing gases, the result would just be hot pieces of iron ore. If we heated it much further, past the point of melting, the result would be hot liquid iron oxide. Neither hot rocks nor hot liquid iron oxide are suitable to produce steel. To produce steel we must chemically separate the oxygen from the iron.

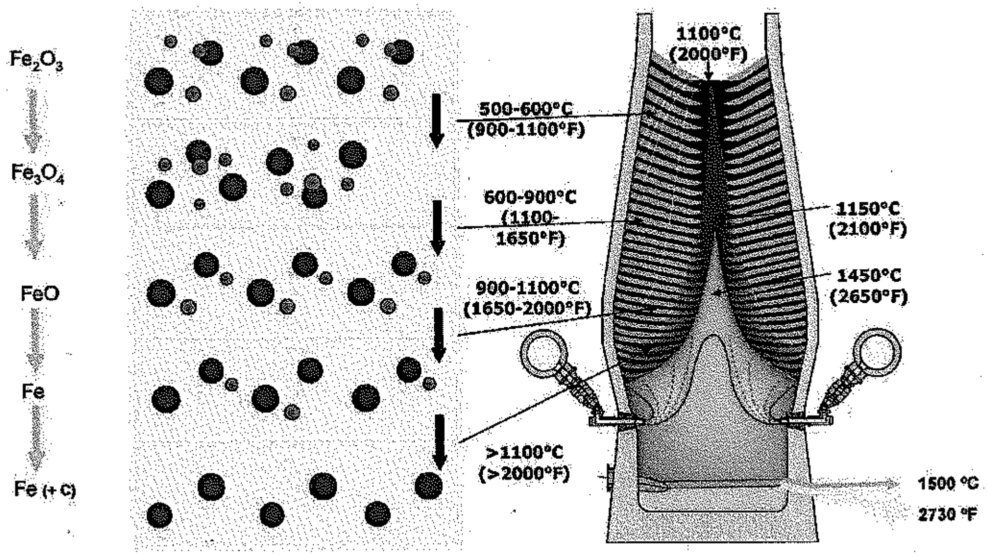
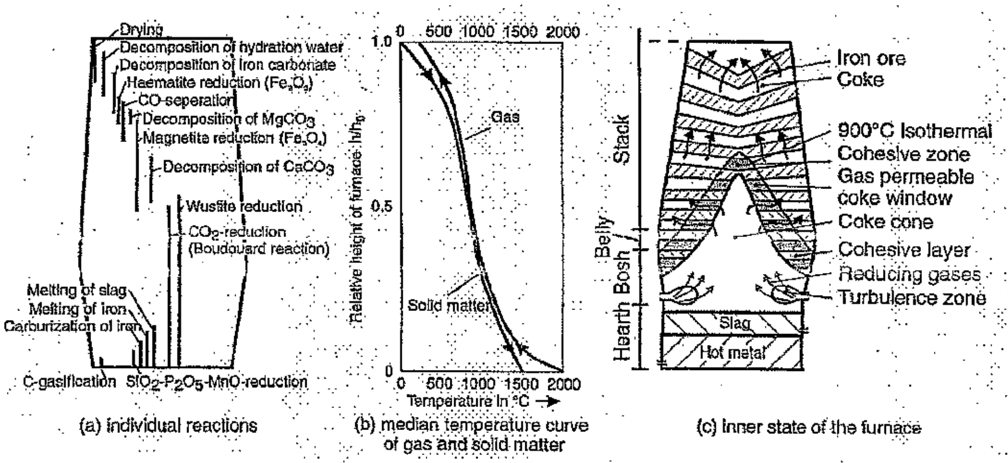


Figure 3: Stylized View of Blast Furnace Process; Source – Modern Blast Furnace Ironmaking" by Geerdes et al

4. Are the Coke and Hyrdrocarbon Carriers Used in the Blast Furnace Fuels or Chemical Reductants, from a Scientific and Technological Point of View

At first glance, this seems to be a very simple problem to resolve. One could go to any of the hundreds of blast furnace texts from the mid-1800's through the late 1960's and find numerous references to the specification of coke as a fuel. Therefore, it would seem to be pre-established that this must be so, since the experts at the time viewed it in that way. History, and the benefits of blast furnace research and development, including specifically the introduction and expansion of injected hydrocarbon carriers, changed everything. The seminal research and development with regard to the final determination whether coke and hydrocarbon carriers are chemical raw material or fuel was undertaken by Rudolf Jeschar and Gerritt Dombrowski, of the Institute of Energy Process Engineering and Fuel Technology located in Clausthal-Zellerfeld, Germany. Their work was prompted by a European Union proposal in the mid-1990's to tax fuels. Blast furnace technology by this time had begun to clearly show that the coke and hydrocarbon carriers should more accurately be characterized as chemical raw materials, but no single work had clearly and fully documented that conclusion. In April 1998 Jeschar and Dombrowski presented their findings at the International Congress on the Science and Technology of Ironmaking held in Toronto, Canada, in conjunction with the Iron and Steel Society annual congress. Subsequently their paper was formally presented to the EU governing body, and it was accepted that the coke and hydrocarbon carriers were in fact chemical raw materials and not fuels, by the EU governing body and Industry. I will not attempt to replicate the complete paper and conclusions of Jeschar and Dombrowski in totality, but will try to summarize in the following paragraphs the key elements of their work. By necessity, I will borrow heavily from their work in the remainder of this paper, and offer this citation for my use of their words and work.

The first step in the analysis was the specification of the technical aspects of the blast furnace process, in some detail, and which would form the basis for their calculations. They began with 3 standard charts explaining the process, as shown in Figure 4.



(a) individual reactions

(b) median temperature curve of gas and solid matter

(c) Inner state of the furnace

Figure 4: Diagram of the Individual Reactions (a), of the Median Temperature curve of Gas and Solid Matter (b), and of the Inner State of the Blast Furnace (c)

These diagrams are not unique to Jeschar and Dombrowski, but are widely used in the ironmaking industry. One key observation is the magnitude of the chemical work done in the upper furnace versus the raceway zone.

Next they moved to a recounting of the various reaction formulae which explain the various chemical reactions inside the blast furnace. These are standard, and fully accepted items, and are not recounted here.

The next step was to evaluate the blast furnace process by determining the amount of reducing agents required, the necessary blast volume, and the chemical gas utilization and temperature of the top gas, which is produced as an inevitable by product of the process. The key to that analysis was the division of the furnace into three zones, and the use of mass and energy balances, such that the amount of carbon which is gasified in front of the tuyeres, C_V, and the amount of carbon converted by the Boudouard reaction within the burden material, C_B, could be determined. The balance is shown in Figure 5. From this one can clearly see that the distribution between those two values depends upon the processes in the lower furnace. Although they did not present the actual calculation, they did reaffirm that the methodology for hydrogen would be identical. This is in agreement with actual practical experience.

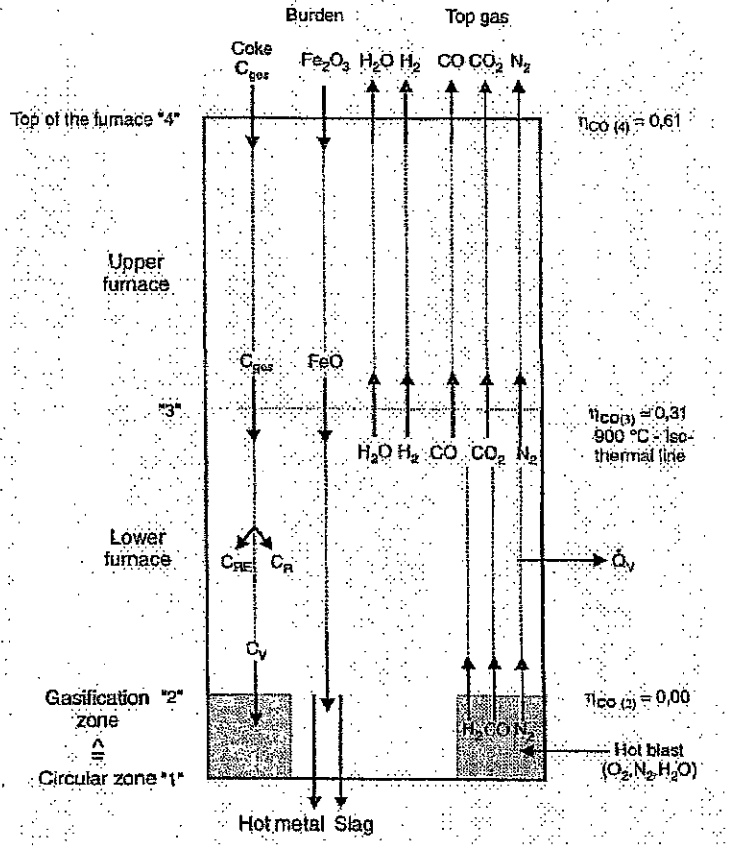
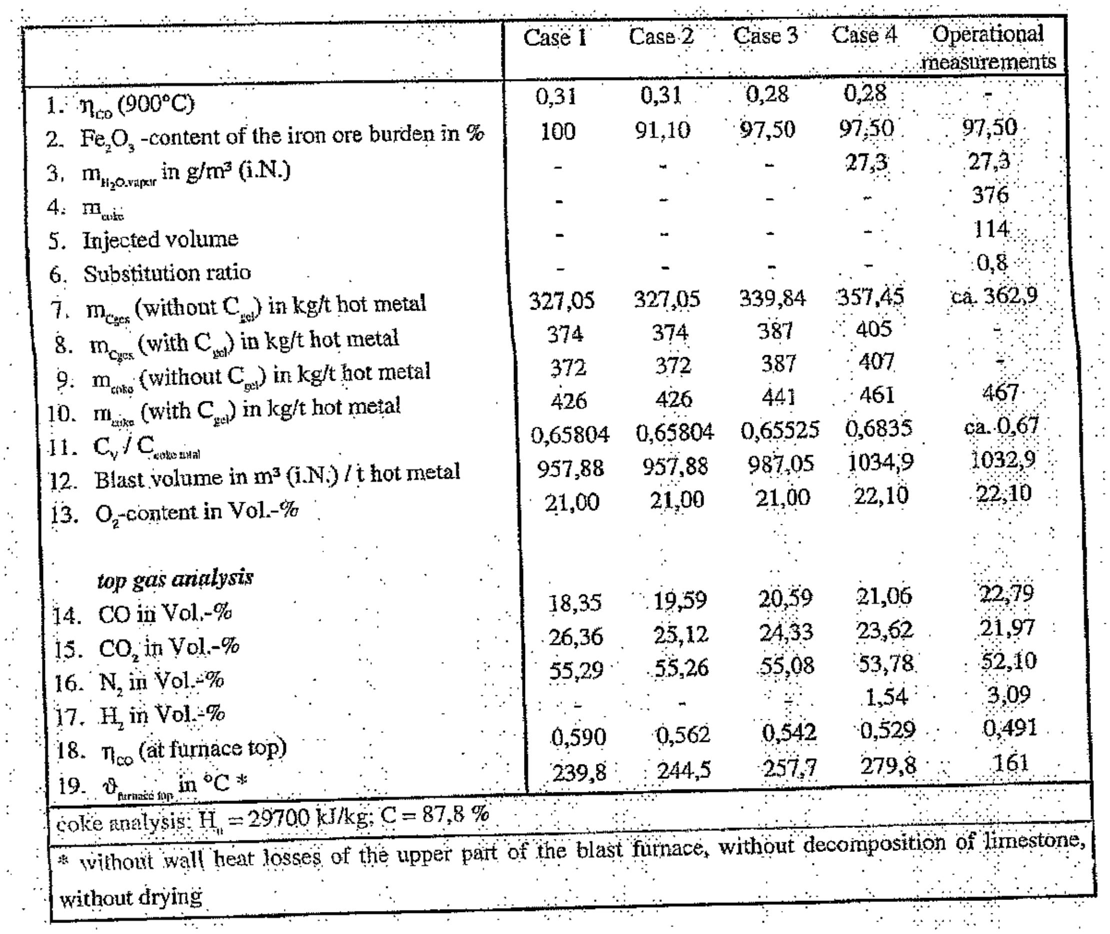


Figure 5: Total Balance of the Blast Furnace; Source, Jeschar and Dombrowski

Next, they created a calculation of four separate cases, varying the percentage of Fe_2O_3, one specific form of iron ore, in the input burden, and compared their results with an actual operating blast furnace. Those results are shown in Figure 6. Case 1 was selected for their benchmark, and the energy balance for that case is shown in Figure 7.



	Case 1	Case 2	Case 3	Case 4	Operational measurements
1. η_{CO} (900°C)	0,31	0,31	0,28	0,28	-
2. Fe_2O_3 -content of the iron ore burden in %	100	91,10	97,50	97,50	97,50
3. $m_{H_2O,vapor}$ in g/m³ (i.N.)	-	-	-	27,3	27,3
4. m_{coke}	-	-	-	-	376
5. Injected volume	-	-	-	-	114
6. Substitution ratio	-	-	-	-	0,8
7. m_{Cges} (without C_{gel}) in kg/t hot metal	327,05	327,05	339,84	357,45	ca. 362,9
8. m_{Cges} (with C_{gel}) in kg/t hot metal	374	374	387	405	-
9. m_{coke} (without C_{gel}) in kg/t hot metal	372	372	387	407	-
10. m_{coke} (with C_{gel}) in kg/t hot metal	426	426	441	461	467
11. $C_V / C_{coke\ total}$	0,65804	0,65804	0,65525	0,6835	ca. 0,67
12. Blast volume in m³ (i.N.) / t hot metal	957,88	957,88	987,05	1034,9	1032,9
13. O_2-content in Vol.-%	21,00	21,00	21,00	22,10	22,10
top gas analysis					
14. CO in Vol.-%	18,35	19,59	20,59	21,06	22,79
15. CO_2 in Vol.-%	26,36	25,12	24,33	23,62	21,97
16. N_2 in Vol.-%	55,29	55,26	55,08	53,78	52,10
17. H_2 in Vol.-%	-	-	-	1,54	3,09
18. η_{CO} (at furnace top)	0,590	0,562	0,542	0,529	0,491
19. $\vartheta_{furnace\ top}$ in °C *	239,8	244,5	257,7	279,8	161

coke analysis: $H_u = 29700$ kJ/kg; C = 87,8 %

* without wall heat losses of the upper part of the blast furnace, without decomposition of limestone, without drying

Figure 6: Comparison of Various Computed Cases with Operational Measurements; Source – Jeschar and Dombrowski

	H_i in GJ/ t hot metal	base H_{uc} in %	End distribution of the enthalpies in %
1. supplied enthalpies			
Coke, H_u, m_C incl. C_{gel}	12,6647	100,00	
Hot blast	1,6220	12,81	
Sum	14,2867	112,81	
2. Reaction enthalpies			
Reduction of Fe-oxides Fe_2O_3 - FeO	6,7698	53,45	
Heating value C_{gel}	1,5922	12,57	
Reduction SiO_2, MnO	0,1597	1,26	
Sum	8,5217	67,29	67,29
3. Enthalpy of the top gas			
(latent enthalpy)			
Heating value CO	3,3596	26,53	26,53
less the preheating of the blast		-	-12,81
Sum		26,53	13,72
4. Enthalpy of the slag			
(sensible enthalpy)			
Hot metal	1,0531	8,31	
Slag	0,6465	5,10	
Sum	1,6996	13,42	13,42
5. enthalpy of the top gas			
(sensible enthalpy)			
CO	0,0537	0,42	
CO_2	0,0878	0,69	
N_2	0,1662	1,31	
Sum	0,3077	2,43	2,43
6. Losses in the furnace	0,1480	1,17	1,17
Sum 2 -6	14,0366	110,83	98,03
7. Variance	0,250	1,97	1,97

Figure 7: Total Balance of the Furnace: Source – Jeschar and Dombrowski

Note: Enthalpy is a thermodynamic term for the total energy of a thermodynamic system. It includes the internal energy, which is the energy required to create the system, and the amount of energy required to make room for the system by displacing its environment and establishing its volume and pressure.

Now to perhaps the most important point of the entire paper. The calculations clearly show that nearly 70% of the energy supplied by the coke is converted into energy that chemically bonded in the hot metal, 13% equates to the heating value of the top gas which is inevitably produced in this process, 14% converts into the measurable heat of the slag and hot metal, and only about 3% is lost, through heat loss of the furnace walls or through the measurable heat of the top gas. Similar results were obtained if coke replacement materials were injected via the tuyeres. One interesting point was developed, and which also has been borne out by practical operating experience since 1998. That is that the modern blast furnace is operating at near the theoretical optimum in terms of process technology, and that future decreases in the total amount of reduction material required are highly unlikely. Moving back to the 70% figure, we find that also is generally supported by our own individual experiences. Many of the chemical elements in our universe exist not in a pure form but rather as oxides. Typical examples would be copper, lead, tin, silicon, as well as iron. The only way to convert the oxide into the base element is the application of sufficient energy chemically bonded to the element. We see this in copper and lead smelters, for example. Left to their own devices with sufficient time and exposure to oxygen these elements inevitably return to their more stable oxide state. Here we can think of the greenish blue patina of aged copper, or the rusted form of steel discarded and exposed to the elements. In our personal lives we have seen this specifically in automobile design when, after high visibility for corrosion degradation of cars in the 1970's, the automakers moved to corrosion resistant alloys to retard corrosion, and even plastics and fiberglass where the corrosion could be avoided entirely. In short, the pure iron that is generated in the blast furnace step of the steelmaking process can exist in its pure form only so long as it contains a very large quantity of chemically bonded energy, sufficient to overcome the forces of oxidation inevitably working to return the iron to its original and more stable oxide form.

Now Jeschar and Dombrowski could move to answer the question of Fuel or Chemical Material. As an aide in that analysis they created a matrix, shown in Figure 8, and four example processes as illustrations, which are shown in Figure 9.

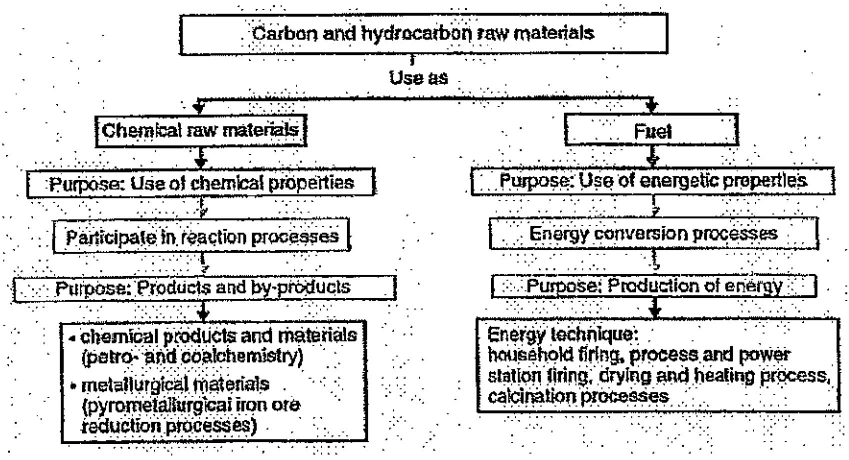


Figure 8: Analysis Matrix for the Use of Carbon and Hydrocarbon Raw Materials: Source – Jeschar and Dombrowski

A critical factor in the determination of whether a particular item should be characterized as a Fuel or Chemical Raw Material is whether or not the energy actually used in the process is interchangeable with other forms of energy. Case 1a of Figure 9 represents a process typical for a reheating furnace. In this specific case it makes no difference whether the energy source is fossil fuel combustion, electricity, or any other option. The process works in exactly the same way. No chemical reactions occur with the material A, and the criteria for evaluating the energy carrier are 100% based upon energetical considerations. In case 1b, an example of which would be a lime kiln, even though there is a dissociation of material AB into its constituent parts, the evaluation of the energy carrier is again based solely upon energetical considerations.

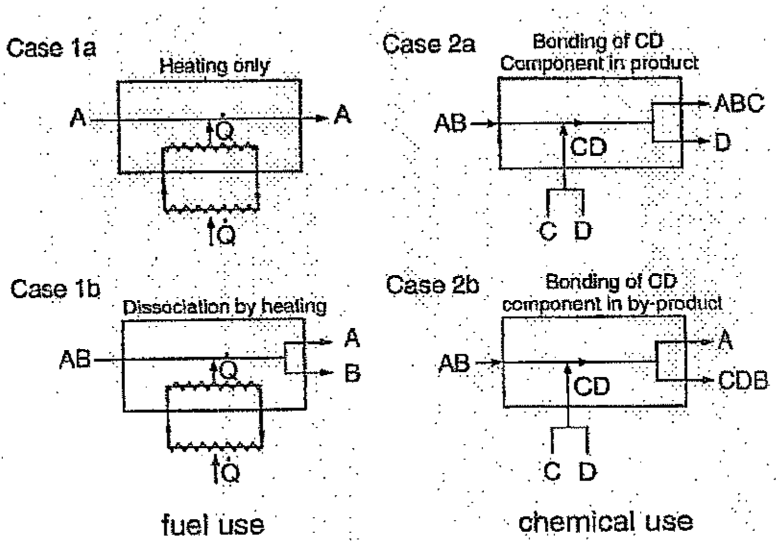


Figure 8: Example Process: Source – Jeschar and Dombrowski

Cases 1a and 1b, on the left, are in sharp contrast with the two cases to the right. Case 2a, representing examples from the petrochemical industry, illustrates a process where a component of the energy carrier is bonded to the process product of the energy carrier, and Case 2b, which actually represents an iron ore reduction process, where a component of the energy carrier is bonded to the exhaust gas of the energy carrier. In both cases the energy carrier not only supplies the energy for the processes which are assumed to be endothermic, but it is also physically involved in the reactions. Substituting another energy carrier for the one actually is use will only work if the new carrier can perform the identical energetical and physical functions. In all of this we can form a strong contrast between such processes and typical combustion processes, such as power plants, etc. which represent a purely energetical utilization of energy.

In summary, Jeschar and Dombrowski concluded, among other things, that

1. The carbon and hydrocarbon carriers used for the reduction of iron ore cannot be classified as fuels as they cannot be replaced by any other, perhaps chemically inert, carrier or any other non-physical energy source.
2. These materials should therefore be classified as chemical raw materials as their components are directly involved in the chemical reactions of iron ore reduction

5. Comments on the "Cadence" Discussion

As I understand it, the "Cadence" discussion, Federal Register, Vol. 50, No. 230, pages 49171-49174 pertains to a certain chemical product which was used in blast furnaces, but came under regulatory scrutiny. Certain parties, including the provider of the material among others, requested to be excluded from certain specific rules and regulations. My comments to follow relate only to technical matters as they relate to the blast furnace process, and I take no position on legal determinations pertaining to whether or not this particular product should or should not be excluded from the rules and regulations as specified.

My first impression, and actually an over-riding observation, is that both the regulators and the Cadence representatives have a specific and unfortunately incorrect view of how the blast furnace process actually operates. In their language and by their arguments they focus on a combustion process, while we know from the previous section of this report that the blast furnace is actually a chemical process. The improper focus held by these individuals is not a total surprise, as I have previously stated that, in earlier times, even the blast furnace operators and technicians held the same views. In just the first 4 paragraphs of the document there are 6 separate references to "burning", plus specific references to heat energy, heating value, incidental energy. However, there are zero references to chemical energy, or even total energy, which would be much more relevant. Even when the discussion seems poised to move to a more thorough process understanding, as in the last paragraph on page 49172 where we see activity "outside the combustion zone" is specifically noted, the writer returns within two sentences to boiler discussion. By focusing on a "combustion technology," any analyst becomes limited to the reactions of the raceway, less than 2% of the furnace volume, when we know from the visualization of Figure 4a that the vast majority of the actual work performed in the furnace is accomplished in the remaining 98%. What actually happens when one adopts the "combustion" orientation as a precondition is that there are limits imposed on the understanding that one can develop of the process, sometimes with very powerful consequences, as I will explain later.

Now is a good time to discuss the use of the term "fuel" which appears throughout the report. In golf the term "woods" refers even today to certain specific clubs none of which have actually been made of wood since the 1930's. Likewise the term "fuel" as it relates to the blast furnace process is an anachronism. It comes from those earlier times when everyone believed that the blast furnace was a combustion process, similar to a boiler at a power generation plant, and spawned the whole litany of terms like "burned for energy recovery" which we now know are insufficient and inaccurate. Unfortunately, there are recurring examples of such thinking, such as the EU proposal on taxing fuels and including blast furnace reductants, which prompted Jeschar and Dombrowski's work cited earlier. It would be better if the terms "fuel" and "burning" would never be used with regards to the blast furnace process, but, as we all know, old habits die hard.

Also, on page 49171, we find a discussion of chlorine, and an argument by Cadence that chlorine has a beneficial effect upon blast furnace operations. In fact, there is no beneficial effect of chlorine. Chlorine and chlorides existing inside the blast furnace attack and destroy the refractory lining which protects the furnace steel shell, which in turn contains the gases, heat, liquid metal and slag, and pressure which would be a danger to the workers and the environment if unconstrained. Once the chlorine and chlorides leave the blast furnace with the exhaust gas they combine with water in the gas cleaning system to form hydrochloric acid, which then attacks the unlined steel structures which form that system. As a result, blast furnace operators world-wide strictly limit the amount of chlorine which is permitted in the raw material input to the furnace. When greater than acceptable amounts of chlorine are unavoidable, for example naturally occurring in the iron ore source, the blast furnace engineers must either redesign their unlined steel structures using acid resistant steels, which are very limited in availability and very high in cost, or they must rely on epoxy resin coatings for the unlined steel surfaces, which then places stringent and permanent restrictions upon the temperatures to which the operator can allow the exhaust gas stream to be subjected.

On page 49172, there is a brief (probably by limitations of space) and incomplete explanation of the blast furnace process, even by 1985 standards. For example, the discussion on reducing coke rates is disappointingly simplistic. It is true that coke was becoming scarcer and more expensive at that time, and that is true to this day. Without regard only to that, however, blast furnace operators are always looking for more economically viable methods to control their costs of chemical raw materials through utilization of less expensive hydrocarbon carriers. These efforts range from powdered coal, to tars, oils both virgin and recycled, coke oven gas, and to even such seemingly extreme examples as animal wastes from a meat processing plant in Germany and waste plastics in Austria. Each particular type of hydrocarbon carrier is evaluated upon its ability to perform the chemical and physical work of the coke it replaces, and its specific and different efficiency.

This brings us to a fundamental gap in the report. There is a clear focus, drawn from the "combustion" thinking, which places carbon at the heart of the blast furnace process, almost to the exclusion of other elements. On page 49172, it is noted that "coke is both the primary fuel and the primary source of reducing gas", and yet there is substantial actual blast furnace operating data from both China and western Europe which shows blast furnaces operating with more injected hydrocarbon carriers than coke. We have to ask, how can that be? The answer is hydrogen, a more powerful reducing agent than carbon, and yet it is mentioned in the discussion only once, by Cadence, and only in a general way. Because of the chemical, and aerodynamic, benefits of hydrogen nearly all of the hydrocarbon carriers injected into blast furnace tuyeres have a replacement ratio of greater than 1 unit of coke replaced per unit of specific hydrocarbon carrier. For natural gas the ratio is 1.3:1, and for oil it is 1.1:1. The limitation of the "combustion" analysis and concentration solely on carbon have missed the point of the chemical process, i.e. the chemical power of hydrogen, and thus one of the most important technological breakthroughs in the history of ironmaking.

One final point on hydrogen deserves mention. Because hydrogen replaces carbon in the reactions, and because the replacement ratio is greater than 1:1, there is definitely an ultimate reduction in so-called greenhouse gas emissions as a direct consequence of the expansion of hydrocarbon carriers because less CO_2 is generated. Only Jeschar and Dombrowski have even mentioned this point.

Following on the topic of reducing coke consumption, and another limitation of the "combustion" thinking which we see in the report, we can consider coal injection. A number of blast furnace facilities, principally in Japan, constructed equipment with the capacity to process only that amount of coal which could be reacted in the raceway zone. A key factor was, and is, that the residence time for any particle in the raceway is only 0.005 seconds, as a result of the velocity of the hot blast through the tuyeres and the limited depth of the raceway itself. Of course, they were wrong, and it is now well known that hydrocarbon carriers which do not have sufficient time to react in the raceway zone simply react elsewhere in the furnace. Pressing the limits of this technology has resulted in consumption of more injected hydrocarbon carriers per ton of hot metal than coke, with as much as 60% of the hydrocarbon carriers reacting outside the raceway. There are issues that currently limit progress beyond that level, but they are being diligently attacked, with further progress likely. For the Japanese ironmakers and their companies, the costs required to reconstruct existing facilities and build new replacement facilities ran into the hundreds of millions of dollars.

The last point I would like to make regards "energy". The "combustion" mindset focuses only on thermal energy, heating values of hydrocarbons in Btu/cf for example, and misses completely the whole concept of the chemical work performed by the blast furnace process. Consider the blast furnace energy balance cited in the "Cadence" discussion on page 49173, and contrast that to the thermodynamic balance prepared by Jeschar and Dombrowski. The balance in the "cadence" discussion looks just like a combustion balance for a boiler, with terms like calorific value of the reductants as the input. Chemical work and energy requirement is not included, and yet we know that 70% of the input energy supplied by the reductants is converted to energy that is chemically bonded to the hot metal. No one would, I believe, propose such an incomplete energy balance these days, and yet it still sits as a basis for decision-making by anyone relying on this section of the Federal Register for future decisions and analysis.

6. Opinions and Bases

The conclusions and opinions I have reached as a result of my investigations are based, upon a reasonable degree of engineering certainty, my education, background and experience in the operation of blast furnaces and their associated equipment. I reserve the right to alter, amend, supplement, or modify my opinions should other new information become available

Frederick C Rorick

Appendix I

Frederick C. Rorick Jr.

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Bel Air, MD 21014
rorickinc@aol.com

Phone (410) 838-9123
Email

Experience

RORICK, INC	BEL AIR, MD
President	**May 2002 to Present**

- Performed consulting services for various steel companies and suppliers with technical and operating issues, including US Steel after the top incident at Gary #6 Blast Furnace, and Stelco Hilton Works with both operating and governmental issues.
- Advised legal counsel on technical matters relating to pending lawsuits
- Partial List of Clients
    - AK Steel Corporation, Ashland Works
    - Armstrong, Teasdale, L.L.P., St. Louis, MO, representing Dango and Dienenthal, Inc
    - Corus U.K.
    - DTE Coal Services, Ann Arbor, MI
    - DTE Energy Services, Inc., Ann Arbor, MI
    - Falcon Foundry Company, Lowellville, OH
    - Foran, Glennon, Palandech & Ponzi P.C., Chicago, IL
    - Health & Safety Executive, national government of U.K., Cardiff, Wales
    - Lander & Rogers, Lawyers, Melbourne, AUSTRALIA
    - Magneco – Metrel Inc, Addison, IL
    - Morris and Stella, Chicago, IL representing Paul Wurth, Inc.
    - Nordia Law Group, Stockholm, SWEDEN, representing SSAB Tunnplåt
    - Nucor Corp, Charlotte, NC
    - Republic Engineered Products, Akron, OH
    - S/D Engineering, Pittsburgh, PA, representing Perry Capital, L.L.P.
    - Siderar, Gral Savio Works, ARGENTINA
    - Stelco, Inc., CANADA
    - UCAR Carbon Co., Inc., Columbia, TN
    - United States Steel, Fairfield Works

BETHLEHEM STEEL CORPORATION	BALTIMORE, MD
Director of Primary Production, Sparrows Point Division	**May 2001 toApril 2003**
BETHLEHEM STEEL CORPORATION	BALTIMORE, MD
Manager of Ironmaking, Sparrows Point Division	**1988 to May 2001**
BETHLEHEM STEEL CORPORATION	CHESTERTON, IN
Assistant Superintendent of Steelmaking, Burns Harbor Division	**Jan 1986 to Dec 1987**
BETHLEHEM STEEL CORPORATION	CHESTERTON, IN
Assistant Superintendent of Ironmaking, Burns Harbor Division	**Oct 1983 to Dec 1985**
BETHLEHEM STEEL CORPORATION	LACKAWANNA, NY

Superintendent of Ironmaking, Lackawanna Plant **Dec 1982 to Oct 1983**

BETHLEHEM STEEL CORPORATION
Various positions of increasing responsibility, Ironmaking Department, Lackawanna Plant **July 1967 to Dec 1982**

Additional Experience

AMERICAN IRON AND STEEL INSTITUTE WASHINGTON, D.C.
1988 TO 2001

- Four terms as Secretary of the AISI Technical Committee on Ironmaking, One term as Vice Chairman, and the only two term Chairman in the organization's history.
- Chaired project to create a data exchange between North American iron producers electronically, vs. previous paper system.
- Led the creation of a formalized system of personal, professional, and technical interchange between European and North American ironmakers.
- First non-European to be formally seated as a guest member of the European Ironmaking Committee.

BETHLEHEM STEEL CORPORATION
1988 TO 2001

- 1990 to 1997 Member of Board of Directors, Iron Ore Company of Canada, prior to Bethlehem's sale of that asset.
- 18-year lecturer on abnormal and challenging operations, and former member of the Organizing Committee, for the McMaster University Intensive Course on Ironmaking.
- Author of numerous technical papers on blast furnace operations.

Education

DICKINSON COLLEGE CARLISLE, PA
B.Sc. in Physics, Chemistry, and Mathematics, specializing in Nuclear Physics **1967**

Additional Education

DUKE UNIVERSITY, FUQUA SCHOOL OF BUSINESS DURHAM, N.C.
Graduate Level Business Courses

UNIVERSITY OF VIRGINIA CHARLOTTESVILLE, VA
Graduate Level Business Courses

Annex

Publications and Presentations

1. Paper, "Sparrows Point's Blast Furnace Tuyere Level Control System" presented at McMaster Symposium, Hamilton, CANADA, June 1991
2. Paper and Lecture, "Challenging Blast Furnace Operations" presented at McMaster University Intensive Course on Ironmaking, Hamilton, CANADA, May 1988, June 1990, June 1992, May 1994, June 1996, June 1998, June 1999, June 2000, June 2002, June 2004, May 2006, May 2008, June 2010.
3. Presentation, " Tuyere Practice and Parameters at North American Blast Furnaces" presented at A.I.S.I. Technical Committee on Ironmaking, Granite City, ILL, May 1993
4. Paper, "L Blast Furnace Hearth Breakout and Recovery", presented at MatTech Colloquium on Blast Furnace Disturbances, Helsinki, FINLAND, November 1994
5. Paper, "Operating Improvements – Sparrows Point L Furnace, Rorick and Youmans, presented at McMaster Symposium, Hamilton, CANADA, June 1995
6. Paper, "Current Status of Coal Injection in North America", Rorick, Ranade, White, et al, presented at the 3rd European Ironmaking Congress, Ghent, BELGIUM, September 1996
7. Presentation, "Coke Quality for Larger Blast Furnace Operation" presented at European Blast Furnace Committee at Koverhar, FINLAND, September 1997
8. Presentation, "Survey of Alkali, Zinc, and Chloride Levels in North American Blast Furnaces", O'Donnell and Rorick, presented at European Blast Furnace Committee Meeting, Port Talbot, Wales, UK, October 1998
9. Presentation, "Burden Quality Improvements and Control for High Productivity and Low Coke Rate" presented at European Blast Furnace Committee, Lulea, SWEDEN, September 1999
10. Paper, "Water Quality Control at Bethlehem Steel's Sinter Plant Using Magnets", Davis, Tate, Saul, and Rorick, presented at ISS of AIME 59th Ironmaking Conference, Pittsburgh, March 2000
11. Presentation, "Year 1999 North American Blast Furnace Results" presented at European Blast Furnace Committee, Piombino, ITALY, April 2000
12. Paper, "Outlook for North American Ironmaking", Cheng, Rorick, and Ranade, presented at 4th European Ironmaking Congress, Paris, FRANCE, June 2000
13. Paper and Lecture, " Recovery of a Chilled Hearth", presented at Continuing Education Course, I.S.S. of A.I.M.E. Conference, Baltimore, March 2001
14. Presentation, "Recent Developments in North American Ironmaking", presented at European Blast Furnace Committee Meeting, Ghent, BELGIUM, April 2001
15. Paper. "Coke Quality Requirements from a North American Perspective, Rorick, Poveromo, and O'Donnell, presented at IISI Seminar on Coke, Brussels, BELGIUM, September 2001
16. Paper, "The Role of the Blast Furnace in Future Steelmaking Trends", Rorick and Luengen, presented at IISI Seminar on Coke, Brussels, BELGIUM, September 2001
17. Presentation, " Year 2001 Summary and Perspective of North American Blast Furnace Operations", presented at European Blast Furnace Committee Meeting, Gijon, SPAIN, April 2002
18. Paper, " Cost Improvement at Bethlehem Steel's Sparrows Point 'L' Blast Furnace", presented at European Blast Furnace Committee Meeting, Raahe, FINLAND, Oct 2002
19. Presentation, "Year 2002 Summary and Perspective of North American Blast Furnace Operations', presented at European Blast Furnace Committee, Ekostahl, GERMANY, May 2003
20. Keynote Paper and Lecture, "Blast Furnace Upsets: Avoidance and Recovery", presented at 31rst McMaster Symposium, Hamilton, Ontario, CANADA, June 2003
21. Paper and Lecture, "Ironmaking in North America", Rorick and Poveromo, presented at 3rd International Congress on Science and Technology of Ironmaking, Dusseldorf, GERMANY, June 2003

22. Presentation, "Ironmaking in North America, presented at European Blast Furnace Committee, Corus Port Talbot Works, Wales, UK, February 2004
23. Paper, "Update on North American Ironmaking", Poveromo and Rorick, presented at ABM (Associacao Brasilieira de Metalurgia e Materials) 2nd International Meeting on Ironmaking, Vitoria – Espirito Santo, BRAZIL, September 2004
24. Presentation, "Special Developments in North American Ironmaking", presented at European Blast Furnace Committee, Arcelor Dunkerque Works, FRANCE, March 2005
25. Paper, "Improvement in Blast Furnace Results by Reprofiling the Furnace Stack by Robotic Shotcreting", Rorick et al, prepared for Magneco Metrel presented at European Ironmaking Congress, June 2005, Stockholm, SWEDEN
26. Paper, "Recent Developments in North American Ironmaking", Rorick and Poveromo, presented at European Ironmaking Congress, June 2005, Stockholm, SWEDEN
27. Presentation, "Developments in North American Ironmaking during 2005", presented at the European Blast Furnace Committee Meeting, SSAB Oxelosund Works, SWEDEN, March 2006
28. Paper and Lecture, "Managing Blast Furnace Systems, Process, and Refractory Cooling for Endless Campaigns", presented at the McMaster Symposium, McMaster University, Hamilton, Ontario, CANADA, May 2006
29. Paper, "Technical Developments in North American Ironmaking", Rorick et al, presented at 4th ICSTI, Osaka, JAPAN, November 2006
30. Presentation, "Developments in North American Ironmaking during 2006", presented at the European Blast Furnace Committee Meeting, Ruukki Raahe Works, FINLAND, April 2007
31. Presentation, "Prolonging the Life of the Blast Furnace', presented at the European Blast Furnace Committee Meeting, Voest Alpine Linz Works, AUSTRIA, October 2007
32. Presentation, "Coal Injection in Blast Furnaces", presented at Eastern States Blast Furnace and Coke Oven Association, January 2008
33. Paper and Lecture, "Technical Progress in North American Ironmaking", Rorick and Poveromo, ABM (Associacao Brasilieira de Metalurgia e Materials) 3rd International Meeting on Ironmaking) Conference, Sao Luis, BRAZIL, September 2008
34. Paper and Lecture, "Technical developments in North American Ironmaking", Rorick Poveromo and Cheng, 4th International Congress on the Science and technology of Ironmaking, Shanghai, P.R. of CHINA, October 2009
35. Presentation, "Consequences to North American Ironmaking as a Result of the recent Economic Crisis", presented at the VDEh, Dusseldorf, GERMANY, October 2009
36. Presentation, "Effects of Raw Material Properties on Blast Furnace Performance"' presented at European Blast Furnace Committee Meeting, Salzgitter, GERMANY, May 2010
37. Paper and Lecture, "Ironmaking in North America", Rorick and Poveromo, presented at European Ironmaking Congress, Dusseldorf, GERMANY, June 2011
38. Presentation, "Long Lifetime of Blast Furnace Stoves", presented at European Blast Furnace Committee Meeting, Scunthorpe, UK, September 2011
39. Blast Furnace Operations Course at IAS Conference, Rosario, ARGENTINA, on "Challenging Blast Furnace Operations", to be presented October 2011
40. Keynote Paper and Lecture, "Operations Disasters – Why Do Some Plants Have Them and Others Do Not?", to be presented at IAS Conference, Rosario, ARGENTINA, November 2011

Awards and Recognition

1. September 1976, Lackawanna Safety Award for individually saving two bricklayers during a blast furnace gas incident
2. September 1984, Bethlehem Steel Team Excellence Award for performance by Burns Harbor Blast Furnace Department
3. October 1984, 1rst recipient of Bethlehem Steel's Gold Award for individual achievement for " Invention and Development of a Permeability Inducing Device" for increased sinter plant production
4. September 1987, Bethlehem Steel Team Excellence Award for performance by Burns Harbor Steelmaking Department
5. July 1989, Bethlehem Steel Team Excellence Award for performance by Sparrows Point Blast Furnace Department
6. 1990 thru 1995, Named Chairman, American Iron and Steel Institute Technical Committee on Ironmaking
7. March 1991, Bethlehem Steel Team Excellence Award for performance by Property Insurance Claims Settlement Team
8. May 1995, Special recognition by AISI after 2+ terms as Ironmaking Chairman
9. 1997, named North American representative to European Blast Furnace Committee
10. July 1999, Bethlehem Steel Team Excellence Award for performance by Coke Purchase Team
11. March 2001, Thomas L. Joseph Award for Lifetime Achievement in Ironmaking presented by Iron and Steel Society, A.I.M.E. at 60th Ironmaking Conference, Baltimore, MD

Appendix II

SUMMARY EVALUATION AND ASSESSMENT OF CARBON AND HYDROCARBON RAW MATERIALS FOR IRON ORE REDUCTION

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ABSTRACT

Introducing the blast furnace and Midrex iron ore reduction for reduction of iron ore is described, compared and the individual occurrences in iron ore reduction at the example of the blast furnace process is examined more precise. As a basis the zone balance model is served in order to depict the occurrences in the upper and lower blast furnace and in front of the tuyere region. In sight of this examination it gets clear that the, in the blast furnace process used carbon- and hydrocarboncarrier coke and its substitutes heavy oil, injected coal and waste plastics, are primarily used for the generation of reducing gases with different proportions of carbon monoxide and hydrogen. Without these reducing gases the iron ore reduction could not course. It follows from this that the use of these carbon and hydrocarbon carriers in the blast furnace process is chemical in nature. It is just the same with the in the Midrex process used natural gas from which the reducing gas is generated catalytically in a gas reformer. It is also following from the investigation that, due to the given charge materials and process engineering, blast furnaces nowadays operate close to the optimum process limits, both from the chemical and thermal viewpoint, such that only a small further decrease in the consumption of the reductants can be expected.

INTRODUCTION

The reduction of iron ore is one of the most important basic metallurgical processes[1]. In Germany, this process for the production of liquid hot metal is carried out in the classic blast furnace and Midrex processes are used for the production of metallized iron ore. The reducing agents are predominantly reducing gases with varying contents of carbon monoxide CO and hydrogen H_2. These reducing gases are produced through the gasification of carbon and hydrocarbon carriers with atmospheric oxygen, additional injections of pure oxygen O_2 as well as with carbon dioxide and water vapour H_2O as a gasification agent[2]. The heat balance of the processes depends on the relationship between these two types of gasification. Further factors to take into account are the preheating of the blast in the furnace and, for the Midrex process, the heat supplied by the heating of the gas regenerator. There are no further types of energy supply in these processes. The main point is that the reducing gases are produced within the blast furnace directly in front of the tuyeres and, in the Midrex process, outside the reduction stack in a separate gas regenerator.

In the blast furnace, the carbon and hydrocarbon carriers used are coke and coal products such as coal dust, heavy oil and since recently also granulated recovered plastics. In the Midrex process, natural gas is used exclusively. The coke is charged together with the burden materials in the stack while the above mentioned other materials are injected via the tuyeres in the lower part of the furnace. The natural gas used in the Midrex process is supplied to the gas regenerator.

This report has the objective to assess whether the carbon and hydrocarbon carriers used for the reduction of iron ore represent in the main chemical raw materials or fuels from a scientific and technological point of view. This is of particular importance for materials such as heavy oil and granulated plastics which are injected via the tuyeres of a furnace as the classification of such materials depends on this assessment with regard to energy tax, the tax on injection oil and the injection of plastics.

DESCRIPTION OF THE REDUCTION PROCESSES

Figure 1 shows a typical furnace with adjoining cowper section for the preheating of the blast which is then led into the furnace for the gasification process. These blast preheaters are heated by purified top gas which forms a natural by-product of the blast furnace process[3]. The preheating of the blast serves to reach the necessary process temperatures immediately in front of the tuyeres and also allows the recycling of the chemical energy contained within the top gas. The figure further indicates the charging of burden and coke, hot metal and slag tap holes as well as top gas vents. The process can be summarised as one where the lumpy burden materials charged in the stack are confronted with the upward flowing reducing gases. The blast furnace process is characterized by the separation of hot metal and slag in their liquid state.

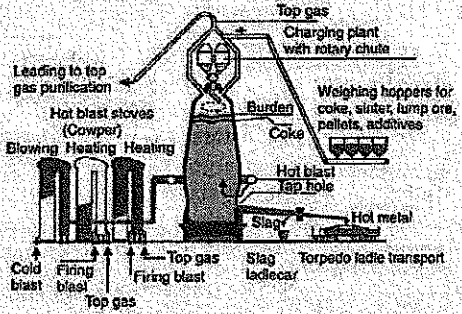


Fig. 1. Schematic diagram of a blast furnace with cowpers

The above mentioned Midrex process is shown in figure 2. This process is characterised by the fact that the iron oxides used are reduced to solid metallized iron ore by reducing gases which are produced outside of the reduction stack. Accordingly, the most important parts of this plant are the stack for the reduction of the ore and the gas regenerator for the generation of the reducing gas. The figure further gives an analysis of this gas. This indicates a process where hydrogen H_2 plays a substantial role besides CO in the reduction of iron ore. The figure shows the reactions occurring between the iron oxides and the gases. Natural gas is the initial raw material in the generation of reducing gases which catalytically reacts in the regenerator with the CO_2 and H_2O containing top gas. The relevant reaction equations are also indicated in the figure. The regenerator needs to be heated as these reactions are endothermic. Top gas from the same process is therefore used for this purpose. The top gas composition depends on the thermodynamic balances of the reduction process as in the case of the blast furnace and the generation of top gas as a by-product of the process is equally inevitable.

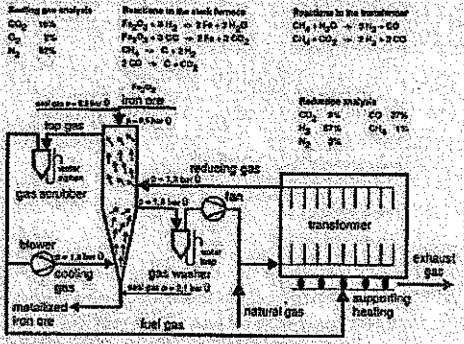


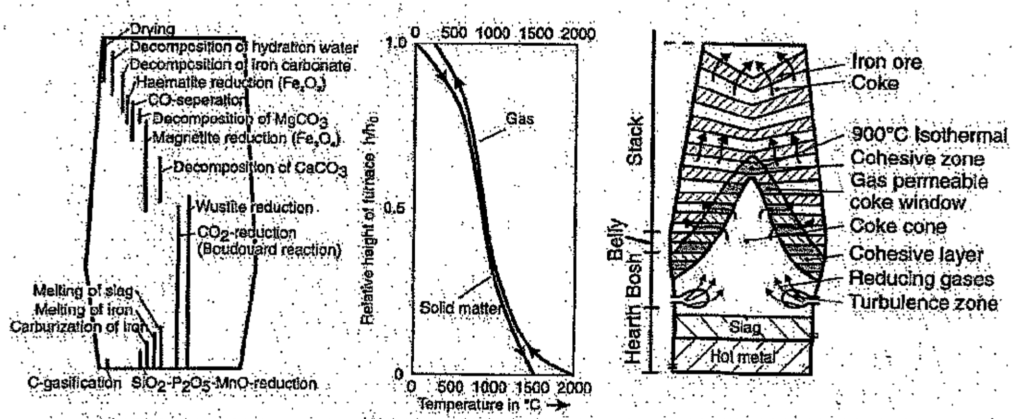
Fig. 2. Gas reduction process for the production of metallized iron ore (Midrex process)

THE OPERATIONS IN THE BLAST FURNACE

The chemical and physical processes which go on inside these reactors during the iron ore reduction are further described only for the blast furnace process. They do, however, also apply to the Midrex process as the chemical reactions occurring in the Midrex stack are in the main the same as those occurring in the upper part of the blast furnace. The chemical reactions occurring in the blast furnace are shown in the three sections of figure 3. Section A indicates the many chemical reactions that take place in the furnace, section B shows the temperature curves of the burden material and the gas. Section C indicates the inner structure of the burden material[3]. Section A shows that the higher oxides are reduced to wustite in the upper part of the furnace which is then further reduced to Fe in the lower part. The reducing gas is mainly generated with atmospheric oxygen O_2 immediately in front of the tuyeres and partially with CO_2 which already formed according to the Boudouard reaction in areas of higher temperatures in the lower furnace.

As already mentioned, section B shows the temperature curves of the reaction partners which are transported in counter flows towards each other. The s-shaped form of the curve is typical and the closest approximation is reached at about 900 °C. Based on the thermodynamic state of the heat balance, these isotherms allow deductions about the state of the gas and the iron ore burden. These conditions form the basis for the determination of the amount of reducing agents required.

Section C indicates the importance of the coke network for the permeability of the burden. This structure of the burden material is maintained in a specific form by a sophisticated charging technique.



(a) individual reactions (b) median temperature curve of gas and solid matter (c) inner state of the furnace

Fig. 3. Diagram of individual reactions (a), of the median temperature curve of gas and solid matter (b) and of the inner state of the furnace (c)

The most important equations for the chemical reactions occurring in the furnace are given here quantitatively[4]. The main equations are the slightly endothermic reduction of Fe_2O_3 to Fe_3O_4 and then FeO in the upper furnace according to the total equation

$$Fe_2O_3 + CO \leftrightarrow 2\,FeO + CO_2 + 8508\ kJ/kmol \quad (1)$$

the slightly exothermic reduction of FeO to Fe in the lower furnace according to the equation

$$FeO + CO \leftrightarrow Fe + CO_2 - 17038\ kJ/kmol \quad (2)$$

apply to the Midrex process as the chemical reactions occurring in the Midrex stack are in the main the same as those occurring in the upper part of the blast furnace. The chemical reactions occurring in the blast furnace are shown in the three sections of figure 3. Section A indicates the many chemical reactions that take place in the furnace, section B shows the temperature curves of the burden material and the gas. Section C indicates the inner structure of the burden material[3]. Section A shows that the higher oxides are reduced to wustite in the upper part of the furnace which is then further reduced to Fe in the lower part. The reducing gas is mainly generated with atmospheric oxygen O_2 immediately in front of the tuyeres and partially with CO_2 which already formed according to the Boudouard reaction in areas of higher temperatures in the lower furnace.

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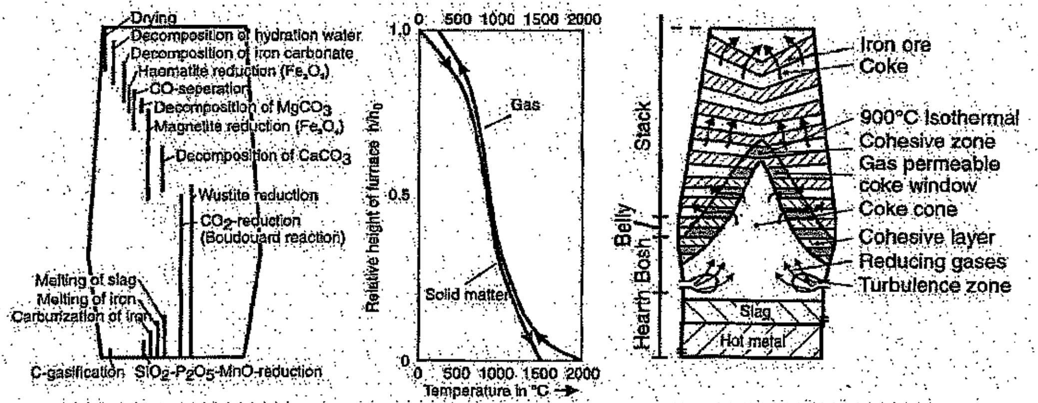

(a) individual reactions

(b) median temperature curve of gas and solid matter

(c) inner state of the furnace

Fig. 3. Diagram of individual reactions (a), of the median temperature curve of gas and solid matter (b) and of the inner state of the furnace (c)

The most important equations for the chemical reactions occurring in the furnace are given here quantitatively[4]. The main equations are the slightly endothermic reduction of Fe_2O_3 to Fe_3O_4 and then FeO in the upper furnace according to the total equation

$$Fe_2O_3 + CO \leftrightarrow 2\,FeO + CO_2 + 8508\ kJ/kmol \qquad (1)$$

the slightly exothermic reduction of FeO to Fe in the lower furnace according to the equation

$$FeO + CO \leftrightarrow Fe + CO_2 - 17038\ kJ/kmol \qquad (2)$$

follow closely the course of the Boudouard-balance, then quickly move towards the curve of the Fe-FeO-balance at temperatures above 1000 °C and finally fall nearly vertically in line with the temperature in the range between $\eta_{CO} = 0{,}3$ and $\eta_{CO} = 0{,}4$.

The comparison between the measuring results and the balance curves indicates that the Boudouard-reaction is no longer effective at temperatures below 900 °C[6]. In the direction of the furnace top, chemical reactions are therefore only possible between the reducing gases and the iron oxides.

Research publications based on more recent test results additionally take the effect of hydrogen H_2 into account. Furthermore, gas utilisation at the furnace top has been much improved nowadays.

DESCRIPTION OF THE ZONE BALANCE MODEL

In order to evaluate the blast furnace process, it is necessary to determine the amount of reducing agents required, the necessary blast volume as well as the chemical gas utilisation and the temperature of the top gas which is produced as an inevitable by product of the process. It is therefore appropriate to divide the furnace into three typical zones as shown in figure 5 whose boundaries are so defined as to allow the indication of typical states in terms of temperatures, partial gas pressures and the composition of the burden material. For each of the three zones, separate balances with regard to components such as Fe, C, O and N as well as the prevailing energy balance can be stated.

It is evident from this division into zones that the amount of carbon required and its distribution between the carbon volume C_V which is gasified in front of the tuyeres and the carbon volume C_R which is converted according to the Boudouard-reaction within the burden material depends entirely on the processes in the lower furnace. The same principle applies if the reducing gas contains a higher fraction of H_2, for instance due to the input of water in the hot blast, or if hydrogen-containing additives such as heavy oil or recycled plastics are used.

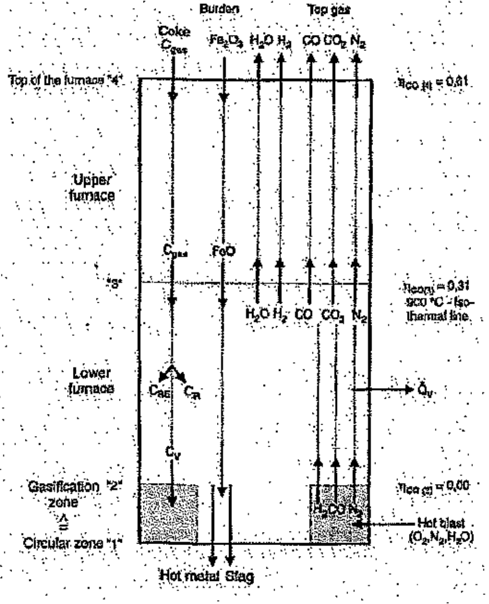

Fig. 5. Total balance of the furnace

PRESENTATION OF THE RESULTS

Table I shows the computed results for four different cases in comparison to the operational values of a modern blast furnace.

The difference in the input data should be noted and, as the result, in line 10 the computed amount of coke required, and in line 11 the fraction of the coke which has to be gasified in front of the tuyeres.

Case 1 serves as the benchmark. The iron in the burden material consists here solely of Fe_2O_3 and the gas utilisation at 900 °C is assumed to be $\eta_{CO} = 0{,}31$. It is further

Table I. Comparision of various computed cases with operational measurements

	Case 1	Case 2	Case 3	Case 4	Operational measurements
1. η_{CO} (900°C)	0,31	0,31	0,28	0,28	-
2. Fe_2O_3 -content of the iron ore burden in %	100	91,10	97,50	97,50	97,50
3. $m_{H_2O,vapor}$ in g/m³ (i.N.)	-	-	-	27,3	27,3
4. m_{coke}	-	-	-	-	376
5. Injected volume	-	-	-	-	114
6. Substitution ratio	-	-	-	-	0,8
7. $m_{C_{ges}}$ (without C_{gel}) in kg/t hot metal	327,05	327,05	339,84	357,45	ca. 362,9
8. $m_{C_{ges}}$ (with C_{gel}) in kg/t hot metal	374	374	387	405	-
9. m_{coke} (without C_{gel}) in kg/t hot metal	372	372	387	407	-
10. m_{coke} (with C_{gel}) in kg/t hot metal	426	426	441	461	467
11. $C_V / C_{coke\ total}$	0,65804	0,65804	0,65525	0,6835	ca. 0,67
12. Blast volume in m³ (i.N.) / t hot metal	957,88	957,88	987,05	1034,9	1032,9
13. O_2-content in Vol.-%	21,00	21,00	21,00	22,10	22,10
top gas analysis					
14. CO in Vol.-%	18,35	19,59	20,59	21,06	22,79
15. CO_2 in Vol.-%	26,36	25,12	24,33	23,62	21,97
16. N_2 in Vol.-%	55,29	55,26	55,08	53,78	52,10
17. H_2 in Vol.-%	-	-	-	1,54	3,09
18. η_{CO} (at furnace top)	0,590	0,562	0,542	0,529	0,491
19. $\vartheta_{furnace\ top}$ in °C *	239,8	244,5	257,7	279,8	161
coke analysis: H_u = 29700 kJ/kg; C = 87,8 %					
* without wall heat losses of the upper part of the blast furnace, without decomposition of limestone, without drying					

assumed that the blast is dry and that it has a temperature of 1185 °C. Coke is the only raw material for the generation of reducing gas. This requires a coke volume of 426 kg/t thm with a proportion of $C_V/C_{Coke\ total}$ = 0,66 to be gasified in front of the tuyeres. The input data are systematically varied in the other cases. Case 4 finally reflects the operational conditions of the comparison furnace chosen. There are hardly any differences anymore with regard to coke requirements and other important variables. This mathematical technique is therefore suitable for the computation of all relevant variables in order to assess the different carbon and hydrocarbon carriers. In view of the great differences between the top gas temperatures of the four cases and the measurements of the comparisonfurnace, it needs to be added that the computational examples disregard factors such as burden humidity, lime decomposition anderosion products from furnace walls. A rough estimate indicated that the divergencies between the computations and the measurements are solely due to such influences. They have no impact on the computed volume of coke required.

Table II shows the energy balance for case 1. The figure indicates that about 70% of the energy supplied by the coke is converted into energy, that is chemically bonded in the hot metal, 13% equates to the heating value of the top gas which is inevitably produced in this process and which is used in other parts of the plant and that only 14% of the energy converts into the measurable heat of the hot metal and the slag. Only about 3% is lost through the heat loss of the furnace walls or through the measurable heat of the top gas. Similar conditions prevail if coke replacement materials are injected via the tuyeres. With regard to heat management and materials technology, the modern blast furnace process comes close to the operational optimum in terms of process control technology. A further decrease in the amount of reduction material required can therefore hardly be expected.

With regard to the computed volume of top gas, it should be added that the respective proportion of energy is slightly higher for the cases 2 - 4 than in the case 1 that is discussed here. Case 4 most closely approximates normal operational measurements.

Table II. Total balance of the furnace

	H_i in GJ/ t hot metal	base $H_{u,C}$ in %	End distribution of the enthalpies in %
1. supplied enthalpies			
Coke, H_u, m_C incl. C_{gel}	12,6647	100,00	
Hot blast	1,6220	12,81	
Sum	14,2867	112,81	
2. Reaction enthalpies			
Reduction of Fe-oxides Fe_2O_3 - FeO	6,7698	53,45	
Heating value C_{gel}	1,5922	12,57	
Reduction SiO_2, MnO	0,1597	1,26	
Sum	8,5217	67,29	67,29
3. Enthalpy of the top gas			
(latent enthalpy)			
Heating value CO	3,3596	26,53	26,53
less the preheating of the blast		-	-12,81
Sum		26,53	13,72
4. Enthalpy of the slag			
(sensible enthalpy)			
Hot metal	1,0531	8,31	
Slag	0,6465	5,10	
Sum	1,6996	13,42	13,42
5. enthalpy of the top gas			
(sensible enthalpy)			
CO	0,0537	0,42	
CO_2	0,0878	0,69	
N_2	0,1662	1,31	
Sum	0,3077	2,43	2,43
6. Losses in the furnace	0,1480	1,17	1,17
Sum 2 -6	14,0366	110,83	98,03
7. Variance	0,250	1,97	1,97

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	H_i in GJ/ t hot metal	base H_{uc} in %	End distribution of the enthalpies in %
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chamber and transfer the energy there in the form of heat onto the process material without coming into contact with this material directly. This process arrangement is, of course, only possible if the energy carrier is not needed to act as a reaction partner in the chemical conversions of the process in question.

The top left section assumes a typical heating process of material A. As no chemical reactions with this material occur, it is of no importance how the energy is supplied. The evaluation of the energy carrier, for instance for the heating of a circulating heating agent, is solely based on energetical criteria. The various types of furnaces for heat treatment with protective gas which are heated indirectly serve as examples. The same also applies to such processes where material transformations occur but where the fuel material does not participate. The heating of such chemical process does therefore also represent a purely energetical utilisation. Examples for such processes are lime burning, the calcination during cement production as well as the calcination of aluminium hydroxide in the aluminium industry. In all these three cases heat is only required for the separation of the initial raw materials.

In contrast, the two examples on the right assumes energy carriers which are physically involved in the conversion of the raw material A. In the upper section, a component of the energy carrier is bonded in the process product and in the lower section, a component of the raw material is bonded in the exhaust gas of the energy carrier. The product as the planned outcome of the process is material ABC in the upper section and material A in the lower section. In both cases, the energy carrier not only supplies the necessary energy for these processes which are assumed to be endothermic but is also physically involved in the reactions. An exchange of this energy carrier is therefore only possible if both the energetical as well as the physical properties of the energy carrier remain compatible. This principle shown in the lower right section applies to the reduction process of iron ore here discussed with the carbon and hydrocarbon carriers coke, coal dust, heavy oil, granulated plastics and natural gas for the generation of reducing gases. The example indicated in the upper right section, however, mainly refers to chemical processes used in coal and petroleum chemistry such as the hydration of coal and crude oil. The criteria by which a substance should be assessed as a chemical raw material do, however, apply to both groups shown on the right. The carbon and hydrocarbon carriers such as coke, coal dust, heavy oil and granulated plastics which are used in the reduction of iron ore are therefore to be regarded as chemical raw materials.

Based on the before mentioned findings, it appears appropriate to compare once more the various possibilities for the use of fossil fuels as primary energy carriers (figure 8). The fossil fuels as primary energy carriers are here termed energy raw materials. Following this representation, they can be used as chemical raw materials as well as fuels, and, in more refined forms, as motor fuel. Combustion processes typically represent a purely energetical utilisation such as in power engineering, and in combustion engines[7].

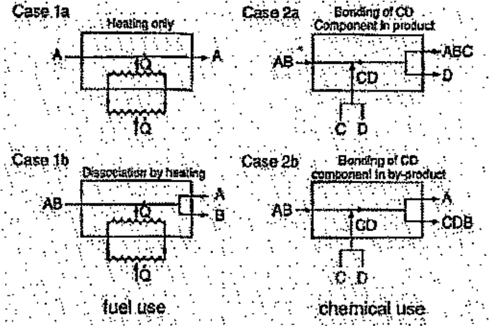

Fig. 8. Comparison of different cases for processes with fuel and chemical use of carbon and hydrocarbon raw materials

Such materials, however, need to be classified as chemical raw materials if a physical utilisation occurs in the conversion of materials. Due to the different nature of such processes, it is advisable to differentiate between the utilisation for the production of chemical products and materials such as in the coal and petroleum industry and the utilisation for the production of metallic materials, for instance with the aid of pyrometallic processes. In both groups, certain physical properties of the carbon and hydrocarbon carriers are indispensable for the processes in question.

VALUATION OF THE REDUCING AGENTS

The main evaluation criteria for the carbon and hydrocarbon carriers used for the reduction of iron ore may be briefly summarised as follows:

- The carbon and hydrocarbon carriers used for the reduction of iron ore primarily serve the generation of reducing gases with varying contents of CO and H_2.
- The generation of the reducing gas occurs inside the furnace stack in the blast furnace process and, in the Midrex process, outside the reduction stack in a separate gas regenerator.
- The reducing gases are generated in varying proportions by exothermic gasification with atmospheric oxygen O_2 and by endothermic gasification with CO_2 and H_2O.
- The mass of the carbon and hydrocarbon carriers needed in the blast furnace process is mainly determined by the energy bonded in the hot metal, the slag and the top gas.
- The maximum gas utilisation in the lower furnace that is theoretically possible is 31% and this level is normally achieved under regular operational conditions.
- Due to comprehensive integrated system, most of the energy which is inevitably generated in the furnace is used by efficiently linked downstream parts of the plant.
- The use of hydrocarbon carriers with a high proportion of hydrogen as a coke substitute is ecologically advantageous as it reduces the emission of the hot house gas CO_2.
- The use of hydrocarbon is also advantageous from a technological view point as it allows control of the form gas temperatures by process control measures and therefore enhances the control of the process.
- There are limits for the reduction of the coke mass required through the use of replacement materials with higher proportions of hydrogen.
- The carbon and hydrocarbon carriers used for the reduction of iron ore cannot be classified as fuels as they cannot be replaced by another, perhaps chemically inert energy carrier or other non-physical energy source.
- These materials should therefore be classed as chemical raw materials as their components are involved in the chemical reactions of the iron are reduction.
- The volume of the top gas produced and the chemical composition of the top gas are process related and depend on the prevailing chemical thermodynamic balance and the kinetic nature of the reactions. The top gas is therefore an inevitable by-product of the process. As modern blast furnaces operate close to the theoretical minimum of reducing agents in terms of volume and as only a certain proportion of the carbon monoxide can be replaced by hydrogen, it is no longer possible to substantially change the volume of top gas or its composition.

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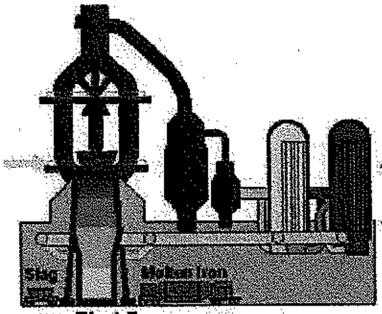
Appendix III

More Detailed Explanation of the Blast Furnace Process

(Source: The American Iron and Steel Institute)

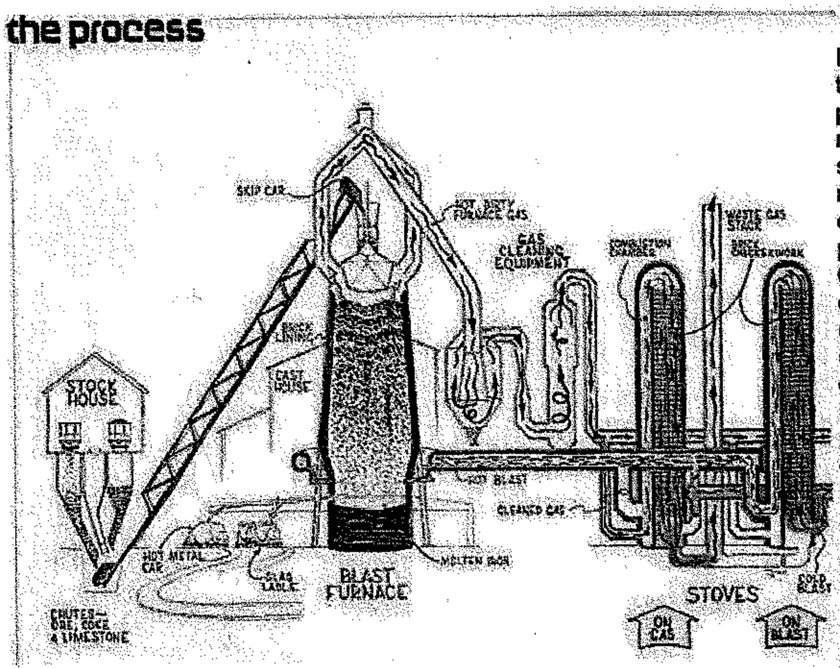
HOW A BLAST FURNACE WORKS



Blast Furnace
Produces molten pig iron from iron ore.

The purpose of a blast furnace is to chemically reduce and physically convert iron oxides into liquid iron called "hot metal". The blast furnace is a huge, steel stack lined with refractory brick, where iron ore, coke and limestone are dumped into the top, and preheated air is blown into the bottom. The raw materials require 6 to 8 hours to descend to the bottom of the furnace where they become the final product of liquid slag and liquid iron. These liquid products are drained from the furnace at regular intervals. The hot air that was blown into the bottom of the furnace ascends to the top in 6 to 8 seconds after going through numerous chemical reactions. Once a blast furnace is started it will continuously run for four to ten years with only short stops to perform planned maintenance.

The Process



Iron oxides can come to the blast furnace plant in the form of raw ore, pellets or sinter. The raw ore is removed from the earth and sized into pieces that range from 0.5 to 1.5 inches. This ore is either Hematite (Fe_2O_3) or Magnetite (Fe_3O_4) and the iron content ranges from 50% to 70%. This iron rich ore can be charged directly into a blast furnace without any further processing. Iron ore that contains a lower iron content must be processed or beneficiated to increase its iron content. Pellets are produced from this lower iron content ore. This ore is crushed and ground into a powder so the waste material called gangue can be removed. The remaining iron-rich powder is rolled into balls and fired in a furnace to produce strong, marble-sized pellets that contain 60% to 65% iron. Sinter is produced from fine raw ore, small coke, sand-sized limestone and numerous other steel plant waste materials that contain some iron. These fine materials are proportioned to obtain a desired product chemistry then mixed together. This raw material mix is then placed on a sintering strand, which is similar to a steel conveyor belt, where it is ignited by gas fired furnace and fused by the heat from the coke fines into larger size pieces that are from 0.5 to 2.0 inches. The iron ore, pellets and sinter then become the liquid iron produced in the blast furnace with any of their remaining impurities going to the liquid slag.

The coke is produced from a mixture of coals. The coal is crushed and ground into a powder and then charged into an oven. As the oven is heated the coal is cooked so most of the volatile matter such as oil and tar are removed. The cooked coal, called coke, is removed from the oven after 18 to 24 hours of reaction time. The coke is cooled and screened into pieces ranging from one inch to four inches. The coke contains 90 to 93% carbon, some ash and sulfur but compared to raw coal is very strong. The strong pieces of coke with a high energy value provide permeability, heat and gases which are required to reduce and melt the iron ore, pellets and sinter.

The final raw material in the ironmaking process in limestone. The limestone is removed from the earth by blasting with explosives. It is then crushed and screened to a size that ranges from 0.5 inch to 1.5 inch to become blast furnace flux . This flux can be pure high calcium limestone, dolomitic limestone containing magnesia or a blend of the two types of limestone.

Since the limestone is melted to become the slag which removes sulfur and other impurities, the blast furnace operator may blend the different stones to produce the desired slag chemistry and create optimum slag properties such as a low melting point and a high fluidity.

All of the raw materials are stored in an ore field and transferred to the stockhouse before charging. Once these materials are charged into the furnace top, they go through numerous chemical and physical reactions while descending to the bottom of the furnace.

The iron ore, pellets and sinter are reduced which simply means the oxygen in the iron oxides is removed by a series of chemical reactions. These reactions occur as follows:

1) $3 Fe_2O_3 + CO = CO_2 + 2 Fe_3O_4$	Begins at 850° F
2) $Fe_3O_4 + CO = CO_2 + 3 FeO$	Begins at 1100° F
3) $FeO + CO = CO_2 + Fe$ or $FeO + C = CO + Fe$	Begins at 1300° F

At the same time the iron oxides are going through these purifying reactions, they are also beginning to soften then melt and finally trickle as liquid iron through the coke to the bottom of the furnace.

The coke descends to the bottom of the furnace to the level where the preheated air or hot blast enters the blast furnace. The coke is ignited by this hot blast and immediately reacts to generate heat as follows:

$C + O_2 = CO_2 + \text{Heat}$

Since the reaction takes place in the presence of excess carbon at a high temperature the carbon dioxide is reduced to carbon monoxide as follows:

$CO_2 + C = 2CO$

The product of this reaction, carbon monoxide, is necessary to reduce the iron ore as seen in the previous iron oxide reactions.

The limestone descends in the blast furnace and remains a solid while going through its first reaction as follows:

$CaCO_3 = CaO + CO_2$

This reaction requires energy and starts at about 1600°F. The CaO formed from this reaction is used to remove sulfur from the iron which is necessary before the hot metal becomes steel. This sulfur removing reaction is:

$FeS + CaO + C = CaS + FeO + CO$

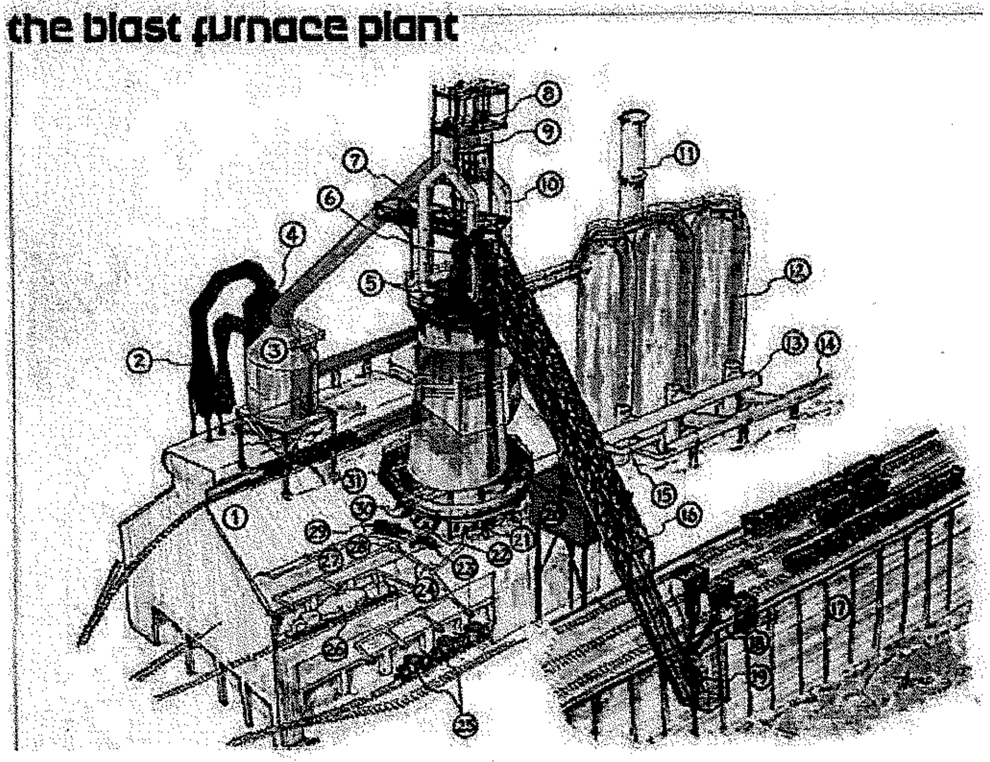
The CaS becomes part of the slag. The slag is also formed from any remaining Silica (SiO_2), Alumina (Al_2O_3), Magnesia (MgO) or Calcia (CaO) that entered with the iron ore, pellets, sinter or coke. The liquid slag then trickles through the coke bed to the bottom of the furnace where it floats on top of the liquid iron since it is less dense.

Another product of the ironmaking process, in addition to molten iron and slag, is hot dirty gases. These gases exit the top of the blast furnace and proceed through gas cleaning equipment where particulate matter is removed from the gas and the gas is cooled. This gas has a considerable energy value so it is burned as a fuel in the "hot blast stoves" which are used to preheat the air entering the blast furnace to become "hot blast". Any of the gas not burned in the stoves is sent to the boiler house and is used to generate steam which turns a turbo blower that generates the compressed air known as "cold blast" that comes to the stoves.

In summary, the blast furnace is a counter-current realtor where solids descend and gases ascend. In this reactor there are numerous chemical and physical reactions that produce the desired final product which is hot metal. A typical hot metal chemistry follows:

Iron (Fe)	= 93.5 - 95.0%
Silicon (Si)	= 0.30 - 0.90%
Sulfur (S)	= 0.025 - 0.050%
Manganese (Mn)	= 0.55 - 0.75%
Phosphorus (P)	= 0.03 - 0.09%
Titanium (Ti)	= 0.02 - 0.06%
Carbon (C)	= 4.1 - 4.4%

The Blast Furnace Plant



Now that we have completed a description of the ironmaking process, let s review the physical equipment comprising the blast furnace plant.

There is an ore storage yard that can also be an ore dock where boats and barges are unloaded. The raw materials stored in the ore yard are raw ore, several types of pellets, sinter, limestone or flux blend and possibly coke. These materials are transferred to the "stockhouse/hiline" (17) complex by ore bridges equipped with grab buckets or by conveyor belts. Materials can also be brought to the stockhouse/hiline in rail hoppers or transferred from ore bridges to self-propelled rail cars called "ore transfer cars". Each type of ore, pellet, sinter, coke and limestone is dumped into separate "storage bins" (18). The various raw materials are weighed according to a certain recipe designed to yield the desired hot metal and slag chemistry. This material weighing is done under the storage bins by a rail mounted scale car or computer controlled weigh hoppers that feed a conveyor belt. The weighed materials are then dumped into a "skip" car (19) which rides on rails up the "inclined skip bridge" to the "receiving hopper" (6) at the top of the furnace. The cables lifting the skip cars are powered from large winches located in the "hoist" house (20). Some modern blast furnace accomplish the same job with an automated conveyor stretching from the stockhouse to the furnace top.

At the top of the furnace the materials are held until a "charge" usually consisting of some type of metallic (ore, pellets or sinter), coke and flux (limestone) have accumulated. The precise filling order is developed by the blast furnace operators to carefully control gas flow and chemical reactions inside the furnace. The materials are charged into the blast furnace through two stages of conical "bells" (5) which seal in the gases and distribute the raw materials evenly around the circumference of the furnace "throat". Some modern furnaces do not have bells but instead have 2 or 3 airlock type hoppers that discharge raw materials onto a rotating chute which can change angles allowing more flexibility in precise material placement inside the furnace.

Also at the top of the blast furnace are four "uptakes" (10) where the hot, dirty gas exits the furnace dome. The gas flows up to where two uptakes merge into an "offtake" (9). The two offtakes then merge into the "downcomer" (7). At the extreme top of the uptakes there are "bleeder valves" (8) which may release gas and protect the top of the furnace from sudden gas pressure surges. The gas descends in the downcomer to the "dustcatcher", where coarse particles settle out, accumulate and are dumped into a railroad car or truck for disposal. The gas then flows through a "Venturi Scrubber" (4) which removes the finer particles and finally into a "gas cooler" (2) where water sprays reduce the temperature of the hot but clean gas. Some modern furnaces are equipped with a combined scrubber and cooling unit. The cleaned and cooled gas is now ready for burning.

The clean gas pipeline is directed to the hot blast "stove" (12). There are usually 3 or 4 cylindrical shaped stoves in a line adjacent to the blast furnace. The gas is burned in the bottom of a stove and the heat rises and transfers to refractory brick inside the stove. The products of combustion flow through passages in these bricks, out of the stove into a high "stack" (11) which is shared by all of the stoves.

Large volumes of air, from 80,000 ft^3/min to 230,000 ft^3/min, are generated from a turbo blower and flow through the "cold blast main" (14) up to the stoves. This cold blast then enters the stove that has been previously heated and the heat stored in the refractory brick inside the stove is transferred to the "cold blast" to form "hot blast". The hot blast temperature can be from 1600°F to 2300°F depending on the stove design and condition. This heated air then exits the stove into the "hot blast main" (13) which runs up to the furnace. There is a "mixer line" (15) connecting the cold blast main to the hot blast main that is equipped with a valve used to control the blast temperature and keep it constant. The hot blast main enters into a doughnut shaped pipe that encircles the furnace, called the "bustle pipe" (13). From the bustle pipe, the hot blast is directed into the furnace through nozzles called "tuyeres" (30) (pronounced "tweers"). These tuyeres are equally spaced around the circumference of the furnace. There may be fourteen tuyeres on a small blast furnace and forty tuyeres on a large blast furnace. These tuyeres are made of copper and are water cooled since the temperature directly in front of the them may be 3600°F to 4200°F. Oil, tar, natural gas, powdered coal and oxygen can also be injected into the furnace at tuyere level to combine with the coke to release additional energy which is necessary to increase productivity. The molten iron and slag drip past the tuyeres on the way to the furnace hearth which starts immediately below tuyere level.

Around the bottom half of the blast furnace the "casthouse" (1) encloses the bustle pipe, tuyeres and the equipment for "casting" the liquid iron and slag. The opening in the furnace hearth for casting or draining the furnace is called the "iron notch" (22). A large drill mounted on a pivoting base called the "taphole drill" (23) swings up to the iron notch and drills a hole through the refractory clay plug into the liquid iron. Another opening on the furnace called the "cinder notch" (21) is used to draw off slag or iron in emergency situations. Once the taphole is drilled open, liquid iron and slag flow down a deep trench called a "trough" (28). Set across and into the trough is a block of refractory, called a "skimmer", which has a small opening underneath it. The hot metal flows through this skimmer opening, over the "iron dam" and down the "iron runners" (27). Since the slag is less dense than iron, it floats on top of the iron, down the trough, hits the skimmer and is diverted into the "slag runners" (24). The liquid slag flows into "slag pots" (25) or into slag pits (not shown) and the liquid iron flows into refractory lined "ladles" (26) known as torpedo cars or sub cars due to their shape. When the liquids in the furnace are drained down to taphole level, some of the blast from the tuyeres causes the taphole to spit. This signals the end of the cast, so the "mudgun" (29) is swung into the iron notch. The mudgun cylinder, which was previously filled with a refractory clay, is actuated and the cylinder ram pushes clay into the iron notch stopping the flow of liquids. When the cast is complete, the iron ladles are taken to the steel shops for processing into steel and the slag is taken to the slag dump where it is processed into roadfill or railroad ballast. The casthouse is then cleaned and readied for the next cast which may occur in 45 minutes to 2 hours. Modern, larger blast furnaces may have as many as four tapholes and two casthouses. It is important to cast the furnace at the same rate that raw materials are charged and iron/slag produced so liquid levels can be maintained in the hearth and below the tuyeres. Liquid levels above the tuyeres can burn the copper casting and damage the furnace lining.

CONCLUSION

The blast furnace is the first step in producing steel from iron oxides. The first blast furnaces appeared in the 14th Century and produced one ton per day. Blast furnace equipment is in continuous evolution and modern, giant furnaces produce 13,000 tons per day. Even though equipment is improved and higher production rates can be achieved, the processes inside the blast furnace remain the same. Blast furnaces will survive into the next millenium because the larger, efficient furnaces can produce hot metal at costs competitive with other iron making technologies.