

Chapter 10

The Manufacture of Pig Iron in the Blast Furnace

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10.1 Production and Types of Pig Iron

10.1.1 Introduction

As discussed in Chapter 1, the extraction of iron from its ores dates back to prehistoric times. However, it was not until the 14th century that furnaces were developed that could both reduce the iron and melt it so that the product could be cast from the furnace in liquid form. Today's modern large blast furnaces, with their very high production rates and excellent fuel efficiency, are the result of years of technical and engineering development of this same metallurgical process that was first operated over 500 years ago. Other processes for extracting iron from its oxides are described in Chapter 11.

The term pig iron is generally applied to the metallic product of the blast furnace when it contains over 90% iron. It is used to distinguish this product from other blast furnace products such as ferromanganese, spiegeleisen, ferrophosphorus, ferrosilicon and silvery iron. This term arose from the old-fashioned method of casting blast furnace iron into molds arranged in sand beds in such a manner that they could be fed from a common runner. Because the group of molds resembled a litter of suckling pigs, the individual pieces of iron were referred to as pigs and the runner was referred to as a sow.

The importance of pig iron in the 20th century can be seen from Table 10.1, which shows that the world-wide annual production of pig iron and ferroalloys increased from less than 43 million tonnes (47 million net tons) to more than 544 million tonnes (598 million net tons) between 1900 and 1997. It is interesting to note that the annual production rate of pig iron and ferroalloys in the United States reached a maximum in 1973 that was one and a half times its 1950 production rate while the world-wide annual production rate reached a peak in 1997 that was over four times its 1950 rate. The rapid growth of the steel industry in foreign countries since 1950 has been accompanied by a substantial increase in the size of blast furnaces, a significant improvement in the preparation of burden materials, a better distribution of the burden materials in the furnace, a more elevated top-gas pressure, and a higher hot-blast temperature. A bibliography is included at the end of this chapter to provide an historical perspective on the evolution of the blast furnace process.

10.1.2 Types of Grades of Pig Iron

Most of the iron produced in blast furnaces is transported to the steelmaking shop while it is still liquid and is then used directly for the manufacture of steel. In the liquid form the iron is generally referred to as hot metal. Because the basic oxygen processes are most commonly used for converting the iron into steel, most of the iron is of the basic grade.

Table 10.1 Production of Pig Iron and Ferroalloys for Selected Years in the Three Major Steel-Producing Countries of the World^(a) (Thousands of Tons)

Year	United States ^(a)		Japan		U.S.S.R. ^(b)		World	
	Tonnes	Net Tons	Tonnes	Net Tons	Tonnes	Net Tons	Tonnes	Net Tons
1997	49,708	54,679	76,683	86,551	60,919	67,011	543,799	598,179
1996	51,350	56,485	74,769	82,246	57,870	63,657	524,222	576,644
1995	50,997	56,097	75,078	82,586	59,779	65,757	530,820	583,902
1994	49,478	54,426	73,949	81,344	58,655	64,521	511,766	562,943
1993	48,256	53,082	73,908	81,299	71,579	78,737	502,293	555,522
1992	47,476	52,224	73,255	80,580	85,343	93,877	490,929	540,022
1991	44,215	48,637	80,170	88,187	91,163	100,279	505,933	556,526
1990	49,773	54,750	80,415	88,456	110,421	121,463	533,172	586,489
1989	50,794	55,873	80,364	88,400	112,579	123,837	540,127	594,140
1988	50,677	55,745	79,458	87,407	114,238	125,662	533,944	587,338
1987	44,009	48,410	73,572	80,929	114,138	125,552	506,242	556,866
1986	39,956	43,952	74,573	82,228	113,837	125,221	498,124	547,936
1985	45,860	50,446	80,737	88,811	110,207	121,228	499,944	549,938
1984	47,185	51,904	80,570	88,627	112,235	123,458	491,565	540,721
1983	44,278	48,706	73,088	80,397	110,684	121,752	461,530	507,683
1982	39,372	43,309	77,817	85,599	106,946	117,641	457,850	503,635
1981	66,728	73,570	80,030	88,236	107,377	118,387	501,088	552,468
1980	62,343	68,721	87,039	95,945	108,999	120,151	507,719	559,779
1975	72,505	79,923	86,877	95,765	102,967	113,502	470,785	518,952
1973	91,804	101,208	90,006	99,215	95,932	105,747	496,026	546,775
1970	83,294	91,816	68,047	75,009	85,932	94,724	428,783	472,652
1965	80,611	88,858	27,502	30,316	66,198	72,971	327,078	360,542
1960	61,078	67,327	12,341	13,604	46,756	51,540	253,737	279,697
1955	70,570	77,790	4751	5237	33,000	36,376	191,476	211,060
1950	59,366	65,440	2299	2534	19,504	21,499	132,795	146,381
1945	49,138	54,165	3115	3434	17,053	18,798	83,284	91,805
1940	42,999	47,398	4012	4422	14,968	16,499	97,166	107,107
1935	21,715	23,937	2784	3069	12,507	13,787	71,054	78,985
1930	32,261	35,562	1687	1860	4982	5492	78,086	86,075
1925	37,290	41,105	933	1028	1309	1443	76,868	84,732
1920	37,518	41,357	732	807	115	127	63,858	70,391
1915	30,396	33,506	336	392	3685	4062	60,658	66,864
1910	27,742	30,580	N.A. ^(c)	N.A. ^(c)	N.A. ^(c)	N.A. ^(c)	72,265	79,659
1905	23,290	25,673	N.A.	N.A.	N.A.	N.A.	59,289	65,355
1900	14,010	15,443	N.A.	N.A.	N.A.	N.A.	43,059	47,464

^(a) Based on information from American Iron and Steel Institute Annual Statistical Reports.

^(b) U.S.S.R. prior to 1993, C.I.S. (Kazakhstan, Russia and Ukraine) 1993 and later.

^(c) N.A. means not available.

Table 10.2 shows the annual production of the different grades of pig iron in the United States for selected years between 1950 and 1984. During this period the basic grade increased from 76% to 98% of the total production, and the bessemer grade decreased from 12.5% to zero. The demand for foundry and malleable iron also decreased as many foundries began using steel scrap instead of pig iron in cupolas and electric furnaces to produce iron for castings. The production of ferroalloys and silvery iron in blast furnaces has also decreased as it has become more feasible to make these grades in electric smelting furnaces. Table 10.3 shows the total U. S. blast furnace production, consumption and sales

Table 10.2 Annual Blast Furnace Production in the United States for Selected Years, by Grade^(a) (Thousands of Tons)

Net Year	Basic		Bessemer		Foundry		Malleable		All Other Including Ferroalloys and Silvery Iron		Total	
	Tonnes	Net Tons	Tonnes	Net Tons	Tonnes	Net Tons	Tonnes	Net Tons	Tonnes	Net Tons	Tonnes	Net Tons
1984 ^(b)	46,462	51,108	—	—	181	199	518	570	25	27	47,185	51,904
1983	43,756	48,132	—	—	118	130	379	417	25	27	44,278	48,706
1982	38,731	42,604	—	—	217	239	343	377	81	89	39,372	43,309
1981	64,548	71,166	51	56	1107	1221	843	929	180	198	66,718	73,570
1980	60,749	66,964	35	39	647	713	881	799	187	206	62,343	68,721
1970	78,415	86,438	1313	1447	1549	1707	1284	1415	734	809	83,294	91,816
1960	52,853	58,260	3088	3404	1331	1467	2425	2673	1381	1522	61,078	67,327
1950	45,250	49,880	7340	8091	2545	2805	2886	3181	1345	1483	59,366	65,440

^(a) Based on information obtained from American Iron and Steel Institute Annual Statistical Reports.

^(b) Not reported after 1984.

Table 10.3 Pig Iron Production, Consumption and Sales^(a) (Thousands of Tons)

Year	Total Blast Furnace Production	Consumption		
		Steelmaking	Other than Steelmaking	Outside Sales
1997	54,679	53,656	6	666
1996	54,485	53,967	7	401
1995	56,097	55,371	41	403
1994	54,426	53,937	119	120
1993	53,082	52,582	159	47
1992	52,224	51,720	195	35
1991	48,637	48,154	232	106
1990	54,750	54,081	238	289
1989	55,873	55,299	414	298
1988	55,745	54,833	702	564
1987	48,410	47,413	315	668
1986	43,952	43,312	357	283
1985	50,446	49,547	619	435
1984	51,904	45,282	1499	192
1983	48,706	45,783	868	658
1982	43,309	42,013	777	568
1981	73,570	70,858	3055	1228
1980	69,721	66,111	2794	1206

^(a) Based on information obtained from American Iron and Steel Institute Annual Statistical Reports.

from 1981 through 1997. While the tonnage of pig iron produced has remained essentially constant from the early 1980s to the present, the number of operating blast furnaces has decreased. Table 10.4 shows the number of operating and idle blast furnaces in the United States from 1986 through 1998.

The general composition ranges for the different metallic products of the blast furnace are shown in Table 10.5.

Table 10.4 Reducing the Number of U.S. Blast Furnaces^(a)

Date	Active	Idle	Total
1998	39	4	43
1997	39	4	43
1996	40	3	43
1995	41	4	45
1994	41	4	45
1993	40	10	50
1992	40	11	51
1991	38	19	57
1990	46	24	70
1989	45	25	70
1988	47	25	72
1987	45	32	77
1986	48	35	83

^(a) Surveys conducted by Industrial Economics Research Institute, Fordham University

Table 10.5 Chief Metallic Products of the Blast Furnace^(a)

	Composition Range				
	Silicon (%)	Sulfur (%)	Phosphorus (%)	Manganese (%)	Total Carbon ^(b) (%)
Iron for Steelmaking					
Basic Pig	1.50	0.05 max.	0.400 max.	1.01–2.00	3.5–4.40
In steps of	0.25	—	—	0.50	—
Acid Pig, Bessemer	1.00–2.25	0.045 max.	0.04–0.135	0.5–1.00	4.15–4.40
Acid Pig, Open Hearth	0.70–1.50	0.045 max.	Under 0.05	0.5–2.50	4.15–4.40
Oxygen Steelmaking Pig	0.20–2.00	0.05 max.	0.400 max. ^(c)	0.4–2.50	3.5–4.40
Merchant Iron for Foundries					
Low Phosphorus	0.50–3.00	0.035 max.	0.035 max.	1.25 max.	3.0–4.50
Intermediate					
Low Phosphorus	1.00–3.00	0.050 max.	0.036–0.075	1.25 max.	3.0–4.50
Bessemer	1.00–3.00	0.050 max.	0.076–0.100	1.25 max.	3.0–4.50
Malleable	0.75–3.50	0.050 max.	0.101–0.300	0.50–1.25	3.0–4.50
Northern Foundry	3.50 max.	0.050 max.	0.301–0.700	0.50–1.25	3.0–4.50
Southern Foundry	3.50 max.	0.050 max.	0.700–0.900	0.40–.75	3.0–4.50
All grades in steps of	0.25	—	—	0.25	—
Ferroalloys					
Spiegel (3 grades)	1.0–4.5	0.05 max.	0.14–0.25	16–30	6.5 max.
Standard Ferromanganese (3 grades)	1.2 max.	0.05 max.	0.35 max.	74–82	7.5 max.
Ferrosilicon, Silvery Pig	5.00–17.00	0.06 max.	0.300 max.	1.00–2.00	1.5 max.
Ferrophosphorus	1.5–1.75	Under 0.05	15–24	0.07–0.50	1.10–2.0
Foreign Practice					
Basic Bessemer (Gilchrist or Thomas)	0.3–1.00	0.20	1.9–2.5	0.7–2.5	3.50–4.0
Duplex Iron	1.2–1.75	Under 0.060	0.7–1.5	0.4–0.90	4.00–4.20

^(a) Further information in: Steel Products Manual—Section 1—Pig Iron and Blast Furnace Alloys, published by the American Iron and Steel Institute; and ASTM Standards, Part I—Ferrous Metals (Specifications), published by the American Society for Testing and Materials (latest editions).

^(b) Carbon not specified.

^(c) Up to 2.00% phosphorus may be used by double slagging in the basic oxygen furnace.

10.2 Outline of the Blast Furnace Process

10.21 Blast Furnace Proper

The blast furnace is a tall shaft-type furnace with a vertical stack superimposed over a crucible-like hearth. Iron-bearing materials (iron ore, sinter, pellets, mill scale, steelmaking slag, scrap, etc.), coke and flux (limestone and dolomite) are charged into the top of the shaft. A blast of heated air and also, in most instances, a gaseous, liquid or powdered fuel are introduced through openings at the bottom of the shaft just above the hearth crucible. The heated air burns the injected fuel and much of the coke charged in from the top to produce the heat required by the process and to provide reducing gas that removes oxygen from the ore. The reduced iron melts and runs down to the bottom of the hearth. The flux combines with the impurities in the ore to produce a slag which also melts and accumulates on top of the liquid iron in the hearth. The iron and slag are drained out of the furnace through tapholes. Production of a tonne (1000 kg) of pig iron requires approximately 1.7 tonnes of ore or other iron-bearing material, 350 to 550 kilograms of coke and other fuel, 250 kilograms of limestone or dolomite and 1.6 to 2.0 tonnes of air. Stated in fps units, production of one net ton (2000 lbs) of pig iron requires approximately 1.7 net tons of ore or other iron-bearing material, 700 to 1100 pounds of coke and other fuel, 500 pounds of limestone or dolomite and 1.6 to 2.0 net tons of air. Very often, the limestone and dolomite are precalcined by mixing them with the iron-bearing material to be sintered or pelletized to improve the efficiency of the blast furnace process. For every tonne of iron, the furnace also produces 200–400 kg of slag, 25–50 kg of flue dust and 2.0–3.0 tonnes of blast furnace gas: in fps units, for every net ton of iron produced, the furnace also produces 400–800 lbs of slag, 50–100 lbs of flue dust and 2.0–3.0 net tons of blast furnace gas.

Fig. 10.1 is a schematic representation of a typical American blast furnace plant, showing the receiving and storage of raw materials, the weighing of the burden and the charging of the blast furnace. It shows the hot metal from the furnace going to a steelmaking shop or a pig-casting machine. The slag goes to a water-spray granulator, a dry slag pit or a slag dump.

The gas from the top of the furnace goes through the gas cleaning system, and then a portion goes to fire the hot-blast stoves with the balance being used in other parts of the plant. The dust is removed from the gas in the cleaning system and often goes to the sinter plant or briquetting plant to be agglomerated for recycling back into the blast furnace. Also shown are the boiler house that generates the power for the operation of the furnace and the turbo-blowers that compress the blast air which goes first to the stoves to be heated and then to the blast furnace through the tuyeres.

10.22 Description of the Charge Materials

10.221 Iron-Bearing Materials

The function of the iron-bearing materials is to supply the element iron, which is 93–94% of the pig iron produced. The major iron-bearing materials are ore, sinter and pellets. Most of the ore is the ferric oxide known as hematite (Fe_2O_3) or the hydrated ferric oxides known as limonite or goethite ($\text{Fe}_2\text{O}_3 \cdot \text{XH}_2\text{O}$). However, in some instances the ores contain magnetite (Fe_3O_4) or siderite (FeC_2). Chemically pure ferric oxide contains 70% iron, but most ores contain only 50–65% iron as they contain 2 to 10% gangue (which consists mostly of alumina and silica) and chemically combined water. Most of the iron-bearing materials are screened to remove fines, to permit the achievement of higher wind and production rates and to permit smooth burden movement. The portion of the ore that is too fine to be charged directly is usually agglomerated in a sintering plant or as waste oxide briquettes. In the sintering process, which is described in Chapter 8, a fine carbonaceous fuel is added to the fine ore and the mixture is placed on a grate and ignited. Air drawn through the mixture burns the fuel at a temperature high enough to sinter the small particles together into a cake so that they can be charged into the blast furnace satisfactorily. For best results, pulverized flux is added to the sinter mix to combine with the gangue of the ore in the sintering process. Sinter usually contains 52–60% iron and typically provides 75–85% of the flux required by the process.

Table 10.6 Imports of Iron Ore by Countries of Origin (Thousands of Gross Tons)

Country	1995	1994	1993	1992	1991
Brazil	4738	3553	2827	2402	2442
Canada	8904	9914	7213	6726	7183
Mauitania	312	122	202	276	452
Venezuela	2407	2734	3124	2500	2719
Other	851	857	379	399	324
Total	17,212	17,180	13,745	12,303	13,120

Source: U.S. Geological Survey, Minerals Information Office (formerly U.S. Bureau of Mines, Division of Mineral Commodities)

Pellets are agglomerates made from very finely divided (-0.074 mm or -200 mesh) iron ore concentrates to which a binder, and sometimes a small quantity of fuel, have been added. The mixture is then balled to form green pellets slightly larger than 6 mm (0.24 inch) but smaller than 20 mm (0.80 in.) in diameter. The fuel may also be provided by coating the green pellets (made originally in a balling drum) with fine particles of a suitable carbonaceous material. In any case, the pellets are then hardened by firing in a shaft-type furnace or rotary kiln or on a traveling grate. Pellets usually contain from 60–67% of iron. Chapter 8 describes the technology used for pelletizing. Much of the ore consumed in the United States is indigenous, however considerable quantities are imported, see Table 10.6.

The minor iron-bearing materials are roll scale, open hearth furnace or basic oxygen furnace slag, and scrap.

Roll scale consists of oxides that form on the surface of steel during heating for rolling, and is usually a source of relatively pure iron oxide except from mills where it gets contaminated with hot-top brick or other refractories. Roll scale can be charged directly or consumed in sinter or briquette plants.

Basic oxygen furnace slags contain approximately 25–35% iron and an excess of bases compared with acids. Consequently, they can replace a certain quantity of (basic) flux in the blast furnace burden. Using the slag often increases the total quantity of slag produced per ton of hot metal. Steelmaking slag also contains sufficient manganese to make it a useful source of this element. BOF slag use is limited by the specification for the maximum phosphorus content of the iron produced. It was not used in blast furnaces producing ‘blowing iron’ for the acid Bessemer process, because the manganese it contained would adversely affect the properties of the slag in the converter; however, it may be desirable for increasing manganese in otherwise excessively low manganese hot metal, as it is thought to prevent slopping in the basic oxygen furnace.

Scrap removed from steelmaking slag and blast furnace runner scrap may also be charged for recovery of the iron units they contain. Also, small scrap that is not amenable to use in steelmaking is often charged into the blast furnace, however the amount is limited because of the adverse effect on furnace permeability.

10.2.2.2 Coke

The main functions of coke are: to produce the heat required for smelting, to supply the chemical reagents—carbon (and carbon monoxide generated at the tuyeres) for reducing the iron ore, and to support the burden. In addition, it supplies the carbon that dissolves in the hot metal (approximately 40–45 kg/tonne of iron, equivalent to 80–90 lbs/net ton). Because carbon sublimes rather than melts, the coke retains its strength at temperatures above the melting temperature of pig iron

and slag and provides the structural support that keeps the unmelted burden materials from falling into the hearth and provides a lattice through which the reducing gasses generated at the tuyeres can pass.

As a result of chemical equilibrium limitations, all of the carbon monoxide produced in the blast furnace cannot be consumed in the reduction of the burden. Consequently, the gas issuing from the top of the furnace contains sufficient carbon monoxide to have a calorific value of 3–4 million joules/normal cubic metre (76–101 Btu/standard cubic foot). This gas is typically used to preheat the blast air and to generate power for running the turbo-blowers; thus, much of the energy is returned to the blast furnace operation. The excess gas is often used in other portions of the plant. As a consequence of economic and technical necessity the blast furnace process continues to become more and more efficient. Higher specific productivity requires lower coke rates. Table 10.7 shows this trend. The impact on coal consumption is shown in Table 10.8.

Table 10.7 Lowering the Coke Rate^(a) (Million of Net Tons)

Year	U.S. Blast Furnace Production	Coke Consumed	Coke Rate^(b)
1997	54.7	24.3	0.444
1996	54.5	22.7	0.417
1995	56.1	24.5	0.437
1994	54.4	24.2	0.445
1993	53.1	23.7	0.446
1992	52.2	25.0	0.479
1991	48.6	24.8	0.510
1990	54.8	27.5	0.502
1989	55.9	29.2	0.522
1988	55.7	29.4	0.528
1987	48.4	25.5	0.527
1986	44.0	22.3	0.507
1985	50.4	25.6	0.508
1984	51.9	27.4	0.528
1983	48.7	26.3	0.540
1982	43.3	23.3	0.538
1981	73.6	40.5	0.550
1980	68.7	39.1	0.569
1979	87.0	50.0	0.574
1978	87.7	51.3	0.585
1977	81.3	48.5	0.597
1976	86.9	51.6	0.594
1975	79.9	48.8	0.611

^(a) Based on information obtained from American Iron and Steel Institute Annual Statistical Reports.

^(b) Coke rate indicates the tons of coke consumed per ton of blast furnace iron produced.

Table 10.8 Consumption of Coal^(a) (Thousands of net tons)

Year	Coke Production	Other^(b)	Total
1997	21,312	2609	23,921
1996	23,710	3762	27,472
1995	26,239	1509	27,748
1994	25,050	1010	26,060
1993	26,445	1359	27,805
1992	26,520	1411	27,931
1991	27,367	1282	28,649

^(a) Based on information obtained from American Iron and Steel Institute Annual Statistical Reports.

^(b) Includes coal consumed in generating electric power.

10.2.2.3 Fluxes

The major function of the fluxes, limestone and/or dolomite is to combine with the ash in the coke and the gangue in the ores to make a fluid slag that can be drained readily from the furnace hearth. The ratio of basic oxides to acid oxides must be controlled carefully to preserve the sulfur-holding power of the slag, as well as its fluidity and melting point. In instances where the acids in the coke ash and ore gangue are not sufficient to make enough slag volume to provide control of the process, silica gravel or quartzite may be added with the charge.

10.3 Chemistry of the Blast Furnace Process

10.3.1 Production of Heat and Reduction of Iron

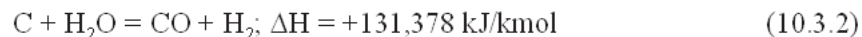
When the burden materials and coke that are charged into the top of the blast furnace descend through the stack, they are preheated by the hot gases ascending from the tuyeres. As a result of this preheat, the coke burns with great intensity when it reaches the lower portion of the furnace adjacent to the tuyeres and comes in contact with the hot-blast air. However, because of the very high temperature (1650°C or approximately 3000°F) and the large quantity of carbon (C) present as coke, the carbon dioxide (CO₂) formed is not stable and immediately reacts with additional carbon to form carbon monoxide (CO). Consequently, the combustion of carbon (coke) in the blast furnace can be expressed by the chemical equation:



(* To convert kJ/kmol to cal/g, multiply by 0.2390; to convert kJ/kmol to Btu/lb mol, multiply by 0.4299.)

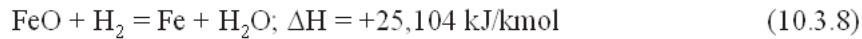
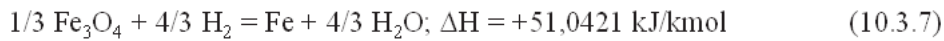
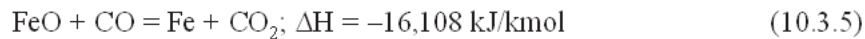
In modern blast furnace operation, between 250 and 400 kilograms of carbon react in this manner for every tonne of hot metal produced; this is equivalent to 500 to 800 pounds of carbon per net ton of hot metal. This reaction is the main source of heat for the smelting operation and also produces a reducing gas (CO) that ascends into the furnace stack where it preheats and reduces most of the iron oxide in the burden as it descends to the hearth.

Any moisture (H₂O) in the blast air also reacts with some of the carbon in the coke in the combustion zone. This reaction does not produce heat as combustion does but, rather, consumes heat. However, for every unit of carbon, this reaction produces more reducing gas than that produced when carbon is burned in air. (When carbon burns in air, it produces only one unit of CO, but when it reacts with H₂O, it produces one unit of CO and one unit of H₂.) Consequently, in certain instances, where the inherent reduction rate of the burden materials is lower than normal and where a relatively high hot-blast temperature is available—between 1000°C and 1100°C (1832°F and 2012°F)—it has been thought to be advantageous to keep the moisture content of the blast at a uniformly high level by moisture (steam) additions to increase the reducing power of the blast furnace gas. Natural gas injection provides a similar benefit. This chemical reaction is expressed by the following equation:



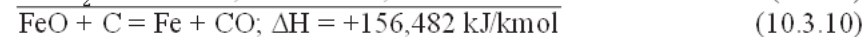
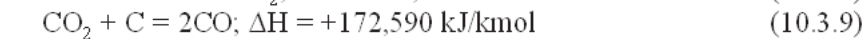
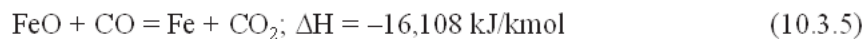
An additional benefit is derived from the introduction (or increase) of hydrogen in the furnace reducing gases, as the percent hydrogen increases the density of the gas decreases. This results in an equivalent volume of reducing gas providing less resistance to burden descent.

The ascending gases start to reduce the iron oxide of the burden in the upper portion of the blast furnace where the temperature is below 925°C (1700°F). At this temperature, chemical equilibrium prevents all of the CO and H₂ from being used for reduction (the equilibrium CO/CO₂ ratio is approximately 2.3 for the reduction of wustite, if the ratio falls below this value iron is reoxidized). Consequently, the molecular ratio of CO or H₂ to iron oxide must be approximately three times the amount shown by the following stoichiometric reactions:

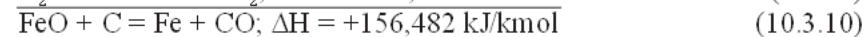
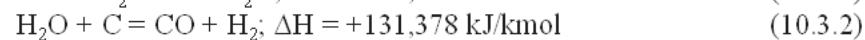
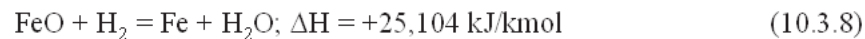


In the past, this type of reduction was called indirect reduction in contrast to the type occurring at higher temperatures that was called direct reduction. However, this nomenclature has become confusing because these same chemical reactions are called direct reduction in describing the Wiberg, the HIB, the FIOR and similar processes (see Chapter 11). For this reason, these terms are not used as generally as they were in the past.

The portion of iron oxide that is not reduced in the upper part of the furnace where the temperature is relatively low must be reduced in the lower part where the temperature is very high. Because CO_2 and H_2O are not stable at these temperatures in the presence of large quantities of coke, they react with carbon almost as rapidly as they form. Consequently, the overall reduction reaction in this part of the furnace can be represented by reaction 10.3.10 no matter whether H_2 or CO is the reactant. As can be seen, reaction 10.3.10 is obtained by algebraically adding either reactions 10.3.5 and 10.3.9 or reactions 10.3.8 and 10.3.2:



or

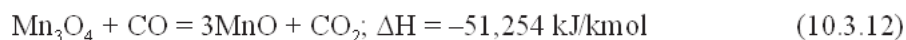
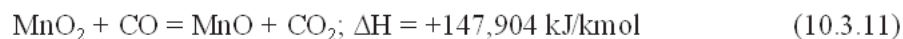


Reaction 10.3.10 absorbs a large amount of heat; consequently, the larger the amount of reduction occurring in this way, the larger the quantity of heat that must be supplied to the furnace. Notice also that reaction 10.3.10 produces CO , which is the gas used in reactions 10.3.3, 10.3.4 and 10.3.5 in the blast furnace stack. In most instances the most efficient operation is obtained when roughly one-third of the reduction is done according to reaction 10.3.10 and the balance according to reactions 10.3.3 through 10.3.8.

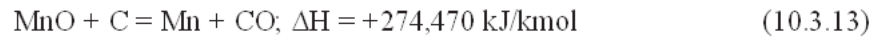
The heat for the process is not produced entirely by the combustion of coke, because at most blast furnaces roughly 40% is supplied from the sensible heat of the hot-blast air. A significant portion of the fuel can be economically injected through the tuyeres as natural gas, tar, fuel oil or coal in either pulverized or granular form. In such instances, the carbon in the fuel burns to CO , but because of the large amount of coke present the hydrogen remains as H_2 and is not oxidized until it reduces iron oxide somewhere above the tuyeres.

10.3.2 Reduction of Manganese, Phosphorus and Silicon

At the temperature in the upper part of the blast furnace stack the higher oxides of manganese are reduced by CO according to the following types of chemical reactions:

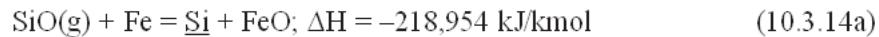


However, the lower oxide of manganese (MnO) cannot be further reduced by CO or hydrogen at any of the temperatures that are encountered in the stack. Consequently, the only chemical reaction that can be used to express the final reduction of this element is as follows:

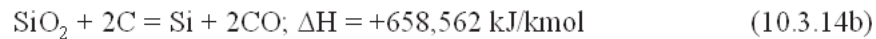


This reaction takes place only at temperatures above 1500°C (2732°F) and absorbs large quantities of heat. At higher temperatures the percentage of manganese that can be reduced in a blast furnace increases, but in most basic practices this amounts to approximately 65–75% of the manganese charged. The manganese that is reduced dissolves in the hot metal while the unreduced portion remains as part of the slag. As a result manganese partitioning is an indicator of the thermal state of the hearth, and as shown below, silicon partitioning is an even more sensitive indicator.

There are two different reactions governing silicon transfer to the hot metal. Among the ways silicon monoxide gas can form is when coke burns in front of the tuyeres and the silica in the ash is reduced and volatilized. The silicon monoxide reacts with molten iron and the silicon content of the iron increases

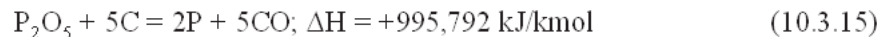


The FeO is subsequently reduced by the ever present CO. The reduction of SiO₂ also takes place at very high temperatures according to the following chemical reaction:



The rate of this reaction is relatively slow but accelerates with an increase in temperature. For any particular burden and slag composition the silicon content of the hot metal is proportional to the hot metal temperature. The percentage of silicon in the hot metal can be increased by increasing the silicon content of the charge and the coke rate.

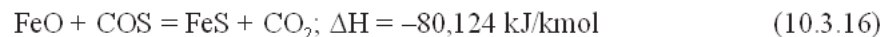
The reduction of phosphorus is expressed by the reaction:



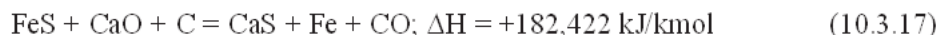
The final reduction of phosphorus also takes place only at very high temperatures; however, unlike manganese and silicon the phosphorus is essentially completely reduced. For this reason, virtually all of the phosphorus in the charge will dissolve in the hot metal. The only means of controlling the phosphorus content of the hot metal is by limiting the amount charged to the furnace.

10.3.3 Elimination of Sulfur

Sulfur enters the blast furnace mainly in the coke and is released into the blast furnace gas stream as H₂S or a gaseous compound of carbon monoxide and sulfur (COS) when the coke is burned. As the gas ascends through the stack some of the sulfur combines with lime in the flux and some combines with the iron. The exact mechanism of the reaction by which sulfur combines with iron is not known; however, it is generally believed to be as follows:



The sulfur that combines with the iron must be removed at the very high temperatures that exist in the hearth. This is done by reduction of iron sulfide in the presence of a basic flux such as lime (CaO). The chemical equation for this reaction is often written as follows:



The amount of sulfur removed depends on the temperature in the hearth, the slag volume, and the ratio of basic oxides lime (CaO) and magnesia (MgO) to acid oxides silica (SiO₂) and alumina (Al₂O₃) in the slag. For a more complete explanation of the effect of slag composition on fluidity and melting temperature, please refer to Chapter 2.

10.3.4 Reaction of Less-Abundant Elements

In addition to the elements that are normally considered in reporting the chemical composition of an iron-bearing material (that is Fe, P, Mn, Si, Al, Ca, Mg and S) there are a number of the less-abundant elements that undergo chemical reactions in the blast furnace.

Some of these can cause considerable operating difficulty and some can contaminate the product and make it unsuitable for certain steelmaking applications. The source of these elements is not only from natural iron ores, but also from waste materials such as scrap, steelmaking dust, grindings, etc. that are recycled through the blast furnace. Some of the more important of these elements are arsenic, barium, chlorine, chromium, cobalt, copper, fluorine, lead, molybdenum, nickel, potassium, sodium, tin, titanium, vanadium and zinc.

10.3.4.1 Arsenic

Arsenic is found in a number of iron ores, particularly ores from Russia and Turkey. The behavior of arsenic is very much like that of phosphorus, in that it is almost completely reduced and dissolves in the hot metal. It increases the fluidity of the hot metal and, for that reason, it appears to increase the wear of refractories. It is not completely removed during the steel refining process and imparts brittleness to the finished steel.

10.3.4.2 Barium

Barium is chemically similar to calcium and occurs as a very basic oxide in some iron and manganese ores. It is not reduced in the blast furnace but becomes part of the slag, increasing the slag basicity. It may cause difficulty in controlling the metal composition if the operator is not aware of its presence.

10.3.4.3 Chlorine

Chlorine occurs as alkali chlorides in several iron ores and as a contaminating compound in ores processed with sea water. Chlorine is also present in some coals used for injection. In the high-temperature zone of the blast furnace these compounds are volatilized and as they rise toward the top of the furnace they condense around cooling plates and cause corrosion. They can also condense in uptakes and downcomers where they form accretions that can eventually restrict the passage of the top gas, or react to form HCl and attack the gas cleaning system steelwork.

10.3.4.4 Chromium

Chromium is found in some ores and is reduced to a certain extent depending on the basicity of the slag and the operating temperature. Normally, approximately 50–60% of the chromium is reduced into the hot metal.

10.3.4.5 Cobalt, Copper and Nickel

Cobalt, copper and nickel occur in several different ores and particularly in Cuban ores. They are also present in iron-bearing tailings from the copper industry that are sometimes sintered and used in blast furnaces to recover the iron. All three of these elements are reduced almost completely into the hot metal and are not oxidized in the steel refining process. Consequently, in operations that produce steel that must meet stringent ductility specifications, such ores cannot be used.

10.3.4.6 Fluorine

Fluorine compounds are found in several Western U.S. ores and behave somewhat like chlorine compounds; the ability of HF to attack the gas cleaning system is well known.

10.34.7 Lead

Lead occurrence in iron ores is quite rare, although there are some ores from Spain and Portugal that contain appreciable amounts. Lead is reduced in the blast furnace; however, it has a very high vapor pressure and a large portion of it vaporizes. As the lead vapor rises through the furnace stack, it oxidizes into small particles that escape to the dustcatcher. Molten lead is not soluble in molten pig iron (hot metal) and in blast furnaces using lead-bearing ore, the liquid lead collects in a pool below the hot metal in the hearth. In several furnaces in Portugal, a special tapping hole is provided so that the lead can be drained from the hearth every few weeks. Because of its low melting temperature lead can penetrate cracks in the hearth and through a freeze-thaw cycle hasten structural damage.

10.34.8 Molybdenum and Tungsten

Molybdenum and tungsten occur very rarely and only in such minute quantities that they can be ignored. If any compounds of these elements were present in the blast furnace, they would be at least 90% reduced into the hot metal.

10.34.9 Potassium and Sodium

Potassium and sodium are alkalis that occur quite frequently in iron ores (they appear in significant concentrations in bentonite—a common binder used in pelletizing) and also to a large extent in coke ash. They cause particular operating difficulty because they are reduced in the blast furnace at a temperature below the temperature of the hot metal but above their own vaporization temperature. As explained by Stephenson¹ the alkali metals are vaporized near the hearth of the blast furnace and condense on the coke and burden materials as well as on the blast furnace inwalls. Thus, these elements recycle and build up in the furnace, causing deterioration of the coke and forming accretions on the walls. Modern blast furnace operations attempt to limit alkali loading to less than 1–1.5 kg/tonne (2–3 lbs/NTHM.) Blast furnace operators typically attempt to remove greater than 85% of the charged alkalis in the slag. Low slag basicities are required for alkali removal in direct contrast to the need for high basicity to effect sulfur removal.

10.34.10 Tin

Tin is an element that enters the blast furnace mostly by way of recycled materials such as scrap or sintered dusts. It is almost entirely reduced and dissolves in the hot metal.

10.34.11 Titanium

Titanium is found with iron in several important iron-bearing deposits in the Adirondack Region and in Alaska and Russia. It also occurs in iron sands in Australia and Japan. It cannot be easily separated from iron by mechanical means because it is usually in chemical combination with the iron as FeTiO_3 . The titanium oxide is reduced to titanium carbide in the blast furnace and also to carbonitrides. These materials have a limited solubility in iron and often can be found in iron salamanders as their presence makes the iron viscous and raises its solidification temperature. If the TiO_2 content of the burden exceeds 13 kg/tonne (26 lbs/net ton) of iron, the slag and the metal are usually very viscous and the iron forms skulls in the trough, the runners and the ladle. Because of this tendency for causing the metal to solidify at a higher temperature, titanium-bearing materials are sometimes added to the burden in the range of approximately 5–9 kg/tonne (10–18 lbs/net ton) of iron, when it is determined that the hearth is eroding too rapidly, to start solidification of the salamander and decrease the rate of hearth erosion. This approach to hearth maintenance has on some occasions been successful.

10.34.12 Vanadium

Vanadium occurs and behaves in a manner somewhat similar to chromium. Approximately 50% of the vanadium in the burden is reduced and enters the hot metal.

10.34.13 Zinc

Zinc is a very troublesome element and causes many serious operating problems. It is found in several iron ores and in copper residues that are sintered for blast furnace use. It is also a component of steelmaking flue dust, particularly where galvanized scrap is used. Its chemical behavior in the blast furnace is similar to that of sodium and potassium, for it is reduced and vaporized at a temperature below that of the hot metal, and it condenses before it can leave the blast furnace. Some of the ZnO goes to the dustcatcher with the flue dust but the balance recycles in the furnace or forms accretions on the walls and reacts with the refractory lining. Because of the trouble caused by this element, the zinc content of the burden must be kept below 0.4 kg/tonne (0.8 lbs/net ton) of hot metal. It is not unusual to find traces of zinc on the cooling elements at tuyere level during shutdowns, even if the burden zinc content is kept at low levels. Some operations have found that enough zinc accumulated on the surface of cooling members to form a surface layer of bronze.

10.34.14 Selenium and Tellurium

Selenium and tellurium, though somewhat rare, may be present in some raw materials; in their reactions they are similar to sulfur but possess an even greater tendency to remain with the metal.

10.3.5 Blast Furnace Material and Energy Balance

A better appreciation of the quantity of material and the amount of energy required for producing hot metal in the blast furnace can be obtained by referring to the material balance in Fig. 10.2 and the energy balance in Table 10.9. These balances are for a modern blast furnace with a working volume of 2889 m³ (102,000 ft³) operating with a wind rate of 6565 Nm³/min (245,000 scfm) and a hot-blast temperature of 1056°C (1933°F). The top pressure is 206.8 kPa (30 psig), and the blast air is enriched with oxygen to approximately 22.9% oxygen. The production rate of this furnace is roughly 8725 tonnes of hot metal per day (9615 net tons of hot metal per day).

The net energy introduced into the process by the combustion of coke and tuyere-injected fuel to CO and H₂ and the sensible energy of the blast is 3.75 gigajoules per tonne of hot metal (approximately 3.23 million Btu per net ton of hot metal). This energy is required for the reduction of iron oxides and metalloids, the sensible heat of hot metal, slag and top gas, vaporization of the burden moisture, and furnace heat loss. In the process, top gas is produced with a chemical heat content of 5.1 gigajoules per tonne of hot metal (4.4 million Btu per net ton of hot metal), which is used for heating the blast air before it enters the tuyeres, and for other uses external to the blast furnace.

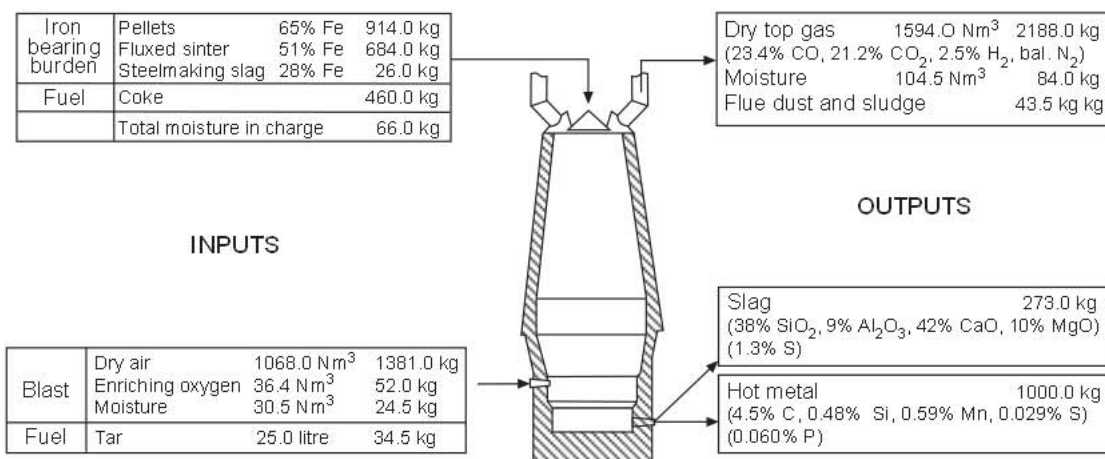


Fig. 10.2 Blast furnace material balance.

Table 10.9 Blast Furnace Energy Balance

	Gigajoules per Tonne of Hot Metal	Million Btu per Net Ton of Hot Metal
Energy Input		
Blast sensible heat	1.64	1.41
Coke combustion	2.10	1.81
Injected fuel combustion	0.27	0.23
Decomposition of water	-0.26	-0.22
Total	3.75	3.23
Energy Output		
Reduction of iron oxides	1.17	1.01
Reduction of metalloids	0.15	0.13
Slag sensible heat	0.48	0.41
Hot metal sensible heat	1.36	1.18
Top gas sensible heat	0.20	0.17
Vaporization of moisture from burden	0.13	0.11
Furnace heat loss	0.26	0.22
Total	3.75	3.23

10.4 Operation of the Furnace

10.4.1 Blowing-in

The process of starting a blast furnace is called blowing-in. It is made up of several steps which include drying out the lining, filling the furnace with a specially arranged high-coke blow-in charge, igniting the coke, and gradually increasing the wind rate with frequent casts to assure raising the temperature of the hearth. During this period, the ratio of burden to coke is adjusted according to a predetermined schedule until good quality hot metal is obtained and normal operations are established.

10.4.1.1 Drying

Newly constructed furnaces must be carefully dried before the coke is ignited because the large amount of water contained in the slurry used for bricklaying and the water absorbed by the brickwork must be driven off as much as possible to avoid extreme thermal shock. There is ample evidence that blowing-in a furnace may cause damage to the lining even when it has been properly dried. Furthermore, if the water from these sources is not removed from the furnace before it is put into operation, it will absorb more heat than that provided for the blow-in charge and will prevent the hearth from reaching the desired temperature. In such instances, metal and slag entering the hearth might freeze there and it would be impossible to remove them from the furnace.

Any one of several methods can be used to dry a furnace and stoves. The usual method for stoves, where natural gas is available, is to put a gas pipe in the lower combustion chamber and start with a small flame and increase the gas input for several days until a small quantity of blast furnace gas can be used, keeping the natural gas as a pilot light. It is desirable to increase the heat slowly for at least ten days to two weeks in a new stove before starting to bring the unit up to operating temperatures. Stoves which have had previous service have been warmed up in 36–72 hours without apparent difficulty. Another method of drying or heating in the past was to use a wood fire built in

the bottom of the combustion chamber. The wood fire required constant attention until wall temperatures were sufficient to insure proper combustion of blast furnace gas.

A method for drying a blast furnace is the use of hot-blast air. It is simple and drying is under control at all times. In applying this method, the conventional hot-blast system is used except that initially the blast temperature is held to roughly 205°C (400°F) and wind volume is held at a low blast level. The temperature is slowly increased over several days to 425°C (800°F) and maintained at that temperature for a few additional days. The entire operation can be accomplished in a week. Some operators install elbows and pipes inside a few of the tuyeres to direct heated air down to the hearth. It is desirable during the latter part of the period to turn low-pressure steam into the hearth cooling staves and bosh plates to assist drying. The large bell is closed while drying, and furnace bleeders are adjusted to retain as much heat as possible. No pressure reading should be observable at the blast pressure gauge while drying.

In single furnace plants where blast furnace gas is not available, the method just described must be modified because an auxiliary fuel of either natural gas or oil must be used to heat the stoves. However, for the low level of heat required, this can be done satisfactorily.

Other methods of drying out are discussed below.

104.1.1.1 Hearth Fire

An alternative is the hearth fire method. It simply consists of a wood, coke or coal fire built in the hearth of the furnace and controlled similarly to the other methods with tuyere shutters and bleeders. Fire temperature regulation is difficult and frequent replenishment of fuel interrupts the process. If used for drying only, this method is as simple as stated, but it could be applied as the start of a controlled or slow blow-in process. Some operators claim that improved warm-up is achieved through this technique. After drying, as noted above, a very heavy coke blank is charged, followed by a regular blow-in burden. A low blast is then maintained, and hearth and inwall temperatures are slowly raised before wind rates are increased to conventional blow-in rates. Several days may elapse before actual blow-in takes place. In theory, the scheme has merit in that there is less chance of damage to brick from thermal shock with a reduced tendency for the brick to spall; however, the process is time-consuming and expensive. Superior campaign life has been obtained through the use of conventional methods, and no evidence to date has been observed to indicate superior results from slow burn-in techniques.

104.1.1.2 Gas

Another method is an open gas flame inside the furnace. One practice is to install a gas pipe through the taphole and ignite the gas by a small wood fire maintained at all times. Tuyere openings are equipped with shutters to regulate air input, and the top temperature of the furnace is regulated as in the two previous methods. The obvious hazards of this method precludes further discussion and it may be regarded as obsolete. This practice has been superseded by the use of burners inserted through the tuyeres that generate hot air from the combustion of natural gas.

104.1.1.3 Dutch Ovens

Two, three or more furnaces or ovens are constructed outside the blast furnace and the products of combustion from the ovens plus excess heated air are directed through pipes into the taphole and some tuyere openings. Other tuyere and cooler openings are blocked off and draft is regulated by adjusting furnace bleeders. As in hot-blast drying, the large bell remains closed. The dutch ovens are fired with coke, coal or wood and require a crew to maintain the fires, haul fuel, and clean out ashes. Temperature control is more difficult in this case, but some regulation is maintained by the intensity of the oven fires and adjustment of furnace bleeders.

104.1.2 Filling

At the conclusion of the drying operation, furnace bells and bleeders are opened, blow pipes are taken down, some tuyeres and coolers are removed, if desirable, and paraphernalia around the casthouse

used in the drying process is cleared away. In a relatively short time the interior of the furnace will have cooled sufficiently to permit entering the hearth to prepare for filling. In the event a hearth fire was used for drying, all ashes and refuse are cleaned out.

An inspection of the furnace cooling system is now made and water is turned on. It is usual practice to maintain a constant watch on all cooling members starting at this time. In cases where the furnace lining is not new and the furnace is empty, the above inspection affords an excellent opportunity to find leaking cooling members. Any plates considered suspicious or showing a sign of moisture must be replaced before filling is started. Many hours of grueling and frustrating work may be avoided by attention to these details. In fact, this checkout detail applies to all mechanical, electrical and physical equipment before filling is started. Usually a checklist is prepared, and each item checked off as reports are received that the item is satisfactory.

Other preparations have preceded and some continue at this point coincident to the start of the filling operation. For example, iron ladles are being heated, stockhouse bins are being filled according to prearranged plan, cinder ladles, if used, are being prepared for service, furnace gas lines are inspected and vents are opened or closed as directed. Steam purging lines are checked to make sure steam will be available when needed and the casthouse iron and slag runners are prepared. Activities in the power house and blowing-engine house are going on with equal intensity. Perhaps turbines were opened for inspection and numerous preventative maintenance chores performed. Boilers are being warmed up, turbo-blowers are warmed and turned over, speed-trip mechanisms are checked out, water is turned on to condensers, pumps are inspected and placed in operation, wind schedules are posted and reconfirmed with blast furnace personnel, boiler-water treating plant are started and the switch house and sub-station are activated.

Some of the final activities before starting up a blast furnace are installing and drying the lining materials for the troughs and runners, setting the skimmers and gates and making certain that the mud guns and drills are mounted correctly so that they will contact the iron notch properly. In some instances where the blast furnace is to be operated at very high pressure, the furnace is pressurized with cold-blast air prior to the start up to determine if there are any leaks that must be eliminated.

There are many different arrangements for placing the start-up charge in the furnace. In most cases, it consists of only coke and a small amount of flux below the mantle. Above the mantle there is a gradual increase in the burden to coke ratio. Very often, wooden cribbing (usually old railroad ties) is placed in the hearth at the tapholes so that there is sufficient open space for gas to exit. In some blow-ins, blast furnace slag and limestone are charged with the coke in the bosh region. The purpose of the slag is to provide a material that will melt readily and carry heat down into the hearth. The purpose of the limestone is to combine with the coke ash and form a fusible slag. To increase the slag volume during the early period of the start up, silica gravel is sometimes added.

Fig. 10.3 shows a start-up filling that was used in a new, large blast furnace with a working volume of 2800 m³ (98,880 ft³). In this instance, the burden was 100% fluxed sinter. Consequently, as the sinter to coke ratio was increased toward to top of the furnace, the limestone to coke ratio was decreased and the gravel to coke ratio was increased slightly.

In calculating the relative amounts of coke, burden and flux, it is anticipated that the first few casts of iron will contain 2.5–4.5% silicon. Consequently, the amount of basic flux must be planned accordingly so that the slag will not be too limy (viscous). As the furnace starts to move normally and the wind rate is increased, the silicon content of the hot metal will drop and then additional flux must be provided for the silica that remains unreduced in the slag.

104.1.3 Lighting

Several different methods can be used to light the blast furnace; however, the one most commonly used at present is igniting the coke with hot-blast air. In this method, a relatively low blast volume is first used at a temperature ranging between 550°C and 650°C (1022°F and 1202°F) and within a matter of minutes the coke at these tuyeres will ignite. To use this method, it is necessary to have

Percent of working volume	Tonnes of coke charged*	Sinter to coke ratio	Blast furnace sinter to coke ratio	Gravel to coke ratio	Limestone to coke ratio
9	80 (88.2)	1.70	0.04	0.110	0.09
10	95 (104.7)	1.20	0.12	0.100	0.12
5	63 (69.5)	0.70	0.18	0.085	0.12
7	80 (88.2)	0.50	0.21	0.085	0.12
6	67 (73.8)	0.30	0.23	0.077	0.13
8	95 (104.7)	0.20	0.20	0.068	0.14
7	80 (88.2)	0.10	0.20	0.068	0.14
5	63 (69.5)	0.05	0.21	0.068	0.14
5	63 (69.5)	0.01	0.17	0.064	0.15
16	190 (209.4)	0	0.13	0.054	0.14
22	285 (314.1)	0	0.03	0.042	0.15

* Net ton equivalents in parentheses

Fig. 10.3 Start-up filling for a large blast furnace with a working volume of 2800 m³ (98,880 ft³).

steam that is vented through the blast furnace downcomer and discharged through the furnace bleeders. When the wind rate at the blast furnace has been increased sufficiently to maintain a good, steady flow of gas, the purging medium is shut off and the bleeders are closed. When a positive pressure of gas is obtained up to the isolating goggle valve, it is opened and the gas is allowed to flow into the main gas system. Significant precautions to avoid an explosion must be taken throughout this period, and the area around the furnace, the gas cleaning system and the valves must be monitored for potential gas leaks.

When the blast furnace is started up, the wind rate is only a small fraction of what it is to be at normal operation. Consequently, it is customary to open only a few of the tuyeres so that the velocity through each tuyere will be sufficient to carry the blast well into the furnace and keep the hot gases from channeling up along the walls. This is usually accomplished by plugging the tuyeres that are not be used with clay balls and poking them open later as the wind rate is increased. In some instances, bushings have been placed inside the tuyeres to decrease the diameter of the opening during the early stages of the blow-in. These are then knocked out when the higher wind rates are used. At first the wind rate is increased every few hours so that by the end of the first 24 hours it is approximately 40–50% of full wind. After this, it is increased roughly 25% per day until the ultimate rate is attained.

When the furnace is started, the iron notch is usually left open, and some of the gas generated by the combustion of the coke exits through the taphole. At first, this gas must be ignited, but as the wind rate increases it heats the coke in the hearth and ultimately discharges at a temperature high enough to remain lit. The taphole generally remains open until slag begins to appear. This is indicated by a

the stoves preheated. In a single furnace plant or in a multiple furnace plant where all of the furnaces are off, this may present a problem. Frequently where blast furnace gas is not available, natural gas is used to preheat the stoves until the gas from the blast furnace can be used.

Another method, used less frequently, is to place easily combustible material in front of the tuyeres that can be ignited with torches or red-hot bars. The natural draft through the furnace will usually provide enough air to raise the temperature of the coke near the tuyeres to the combustion temperature, and then a light flow of blast air can be started.

Before the furnace is lighted, the gas system is isolated from the furnace by a goggle valve, usually located downstream of the gas cleaning system. The gas cleaning system is purged from this goggle valve to the furnace with steam or some type of inert gas. During the early stages of the blow-in, the bleeders at the top of the furnace are kept open and a purging gas is kept in the gas cleaning system up to the valve that separates the gas cleaning system from the main plant gas system. Gas cleaning systems may vary from furnace to furnace, and sometimes separate sections of the gas cleaning system are isolated from one another and purged separately. In most instances, there is no isolating valve between the dustcatcher and the furnace and, consequently, the dustcatcher is purged with

decrease in gas volume and a puffing or pulsation at the taphole. When this occurs, the mud gun is swung into position and the hole is plugged. Every few hours after that, the hole is reopened to remove any slag that has formed. On furnaces with more than one iron notch, usually a different hole is opened with each successive attempt.

Within approximately 24–28 hours after start up, the first iron will be cast. This iron will typically be very high in silicon content because of the slow operating rate and the high ratio of silica to iron oxide in the materials in the first portion of the furnace charge. As the wind rate is increased, and the burden to coke ratio approaches the normal operating level, the silicon content of the metal decreases. Consequently, the ratio of flux to the other materials must be adjusted to provide sufficient basic oxide to flux the unreduced silica that reports to the slag.

Generally, during the blow-in period, it is advisable to keep the ratio of burden to coke in a range that will produce high-temperature hot metal at approximately 1500°C (2732°F) to assure that some unforeseen problem will not cause a freeze-up. The hot-blast temperature is generally not raised to the maximum output of the stoves during this period because most operators prefer to have a reserve that will enable them to introduce additional heat into the hearth in case of an emergency.

10.4.2 Routine Operations

After a blast furnace has been blown-in, it is expected to remain in operation continuously for at least five or six years with only short outages for maintenance or repair of some of the equipment that is subjected to extreme wear, or for replacement of damaged cooling devices. Once the wind rate and the hot-blast temperature have reached their normal operating level, a routine casting schedule is established. This schedule depends to a great extent upon the physical quality and the chemical composition of the burden materials that are available. For example, if the burden materials are low in iron content and high in gangue content, the hot metal production rate will be relatively slow and it may be necessary to flush slag from the furnace between casts. In this case, the furnace may be cast only six times a day. However, in modern furnace practice an attempt is made to establish a casting schedule that keeps the tapholes open in excess of 85% of the operating time, with the goal to match the iron removal rate closely to the production rate.

At one time, after each cast the trough was drained so that slag and scrap could be removed from the trough and runners. Between casts, the trough and runners were cleaned and resurfaced with a protective material. Gates and dams were also reset and dried out in preparation for the next cast. In the modern casthouse iron is held in the trough in excess of three weeks; low silicon hot metal and modern casthouse refractory materials allow this type of practice.

On some large blast furnaces with multiple tapholes, furnace casting can be made almost continuous. In such cases, two tapholes are used alternately while the trough at the third (and fourth) is rebuilt or repaired. The drill used for opening the taphole is of such a size that the hot metal flows out through it at a slightly slower rate than that at which it is accumulated in the hearth. As the cast proceeds, the taphole erodes slightly so that the casting rate then exceeds the rate at which hot metal accumulates in the hearth. After some time, the taphole is plugged by the mud gun, and the next taphole is opened. With the soaking bar practice that has been adopted by many blast furnaces in North America, taphole clays are of a quality such that very little erosion occurs. This allows the operator to more closely match iron production and removal, and consequently operate more closely to steady state. A casting rate of 1.25–1.4 times the instantaneous iron make is typically the optimum.

10.4.3 Sampling the Iron

Sampling the pig iron for chemical analysis is an important function at each cast. The samples were previously taken from the main runner beyond the skimmer. Typically, the first sample is taken when the first ladle is between three-quarters and completely full, and additional samples are taken at just about the time that each subsequent ladle is completely filled. It is now understood that a

more accurate analysis is obtained when samples are taken directly from the ladle. The samples are rushed to the chemical laboratory for analysis for silicon, sulfur, manganese and phosphorus so that the results will be available before the hot metal is used in a steelmaking process. Today most steelmaking shops will take another sample from the transfer ladle to use in calculating the oxygen requirements for the heat to be made. From observation of the sparking of the liquid metal in the runner, the silicon content can be estimated fairly accurately, and from observation of a test piece poured in the casthouse, the sulfur content can also be estimated. In shops where the laboratory facilities are not able to provide rapid analyses, these methods for estimating silicon and sulfur contents may serve as a preliminary analysis of the cast for making decisions regarding disposition of the hot metal. In most plants, a sample of the slag is also analyzed at each cast. In some older plants, the composition of the slag is estimated from observation of a slag sample, solidified in a test mold, and portions of the slag samples from each cast are combined for a daily analysis by the chemical laboratory.

In steel plants today external desulfurization is common and as a result hot metal samples are taken in the steel transfer ladle after desulfurization in order to provide the BOF operator with a more accurate analysis of the hot metal to be charged.

10.4.4 Charging the Furnace

Charging of the blast furnace is an extremely important part of the blast furnace operation and must be done correctly to obtain the best operating performance. Several requirements for satisfactory charging include: keeping the furnace filled to the desired level, drawing the correct weight of each material for each skip load and keeping the charge materials in the proper sequence. At a large number of the plants in the United States, the blast furnaces are charged by a scale car operator who draws the burden materials from the stockhouse into the scale car until the indicator on the scale shows that he has drawn the ordered amount of that particular material. He then deposits the material into the skip according to the sequence that has been established for him to follow. A signal from the stockline recorder lets him know when to activate the skip hoist for each round of charges. In these instances, the opening and closing of the small bell are automatically interconnected with the travel of the skips, and as soon as the prescribed number of skip loads has been deposited through the small bell onto the large bell, the large bell opens (with the small bell closed) and the material is charged into the furnace. At a few of the older furnaces, both the coke and the burden materials are measured out with the scale car, but in most instances, the coke is charged automatically by two weigh hoppers. The coke is fed to the weigh hoppers over screens for removal of fines, and when the load cells on which the hopper is mounted indicate that the hopper has received the correct weight, the coke feeders are shut off automatically. At the proper position in the charging sequence, the coke is automatically discharged into the skips, and the feeders are started so that a full weigh hopper will be ready when the sequence requires another skip load of coke. Many modern blast furnaces are fed through automatic, belt fed stockhouses where the charge material (coke, sinter, pellets, etc.) is automatically weighed out, then placed on a series of conveyor belts until it reaches the top of the furnace where it is placed into a receiving hopper and ultimately charged to the furnace.

In many plants, nuclear gauges are used to determine the moisture content of the coke in the weigh hopper, regardless of stockhouse design, and these gauges generate an electronic signal that automatically resets the shutoff point of the coke feeder so that the weight of dry coke in each skip load is kept as nearly constant as possible.

The size of the charge depends to a large extent on the size of the blast furnace, but in some cases special consideration must also be given to other factors such as the size of the large bell hopper and the capacity of the skip hoist. The total volume of all the materials in a full charge is generally the equivalent of a layer approximately 1–2 metres (3.3–6.6 ft.) deep on the cross-sectional area of the stockline. In the modern blast furnace a parameter that is considered very important is the coke

layer thickness in the belly (or at the mantle). Generally a layer thickness of 300 mm (≈ 12 in.) in the belly is considered appropriate. This layer thickness is thought to ensure adequate gas penetration and distribution throughout the stack.

The sequence of the skip loads of different materials in the charge (or equivalently the placement of material on the main belt) is an important factor in determining the radial burden distribution in the furnace, which in turn affects the contact between the hot gases rising in the furnace and the solid particles of the charge, that is the radial gas distribution. The gas–solid contact must be optimized to obtain the required heat transfer and to permit the optimum rate of the desired chemical reactions.

Because of variations in the quality of burden materials and also in the physical characteristics of different blast furnace bell fed tops, charging sequences will differ from plant to plant. An example of a common sequence for the skip loads of materials is burden–coke–limestone–burden–coke–coke. After these six skip loads are placed on the large bell in this order, the large bell is opened and the charge is dumped into the furnace. This particular filling sequence is usually designated by a set of symbols as follows: OCSOCC/. Each letter denotes a skip load of material, and the slash (/) indicates the point in the sequence when the large bell is dumped. The letter O is used to denote iron-bearing materials. Originally, this letter stood for ore, but currently the letter O is used to denote sinter or pellets, the high iron content material charged to the furnace. The letter S (originally used as the symbol for limestone) denotes flux such as limestone or dolomite or BOF slag. C is the designation for coke, and in some instances M is used to indicate miscellaneous material. Placing ore on the bell first as described above is referred to as forward filling. At some plants this filling is split into two sections and in such cases is called a split filling and its designation in symbols is OCS/OCC/. The practice of placing coke on the bell first, e.g. CCOO/, is referred to as reverse filling or a full-kicker fill. A variation of the full-kicker charge is the mini-kicker charge in which a small amount of coke (1500–3000 kg or 3000–6000 lbs) is placed on the large bell first followed by one or more ore charges. This charging pattern may be represented by the following notation, ^COO/. With the stockline set at the correct height the ore will push the coke to the center of the furnace. This technique is useful in fine tuning the amount of central gas flow in a furnace.

Considerable effort has been expended to understand and control radial burden distribution in the blast furnace. With the appearance of movable armor (with two or three bell tops) or the bell-less top, where a rotating chute can be positioned at virtually any angle, investigators began to study and understand the importance of burden distribution. That understanding has resulted in extending the principles of burden distribution to conventional bell tops with fixed armor. U.S. Steel in the United States has made extensive use of a full scale burden distribution model to study various charging sequences for essentially all their furnaces. This includes those equipped with movable armor and those without.

The principles of burden distribution are a subset of blast furnace process control. Optimum performance on a blast furnace usually results in a characteristic temperature and gas composition (CO and CO₂) distribution across the top of the furnace. The parameters that control the gas distribution are embodied in burden distribution; they are the radial placement of fines and the radial distribution of ore relative to coke. Burden distribution control consists of determining where to place the fines in the furnace, how to accomplish that placement, and determining and achieving the optimum radial coke to ore ratio in the furnace. The furnace charging hardware (bell-less top, bell/movable armor, or bell/fixed armor) dictate the techniques used to optimize burden and consequently gas distribution. Some of the more important variables to be considered are the annular distance between the bell and the throat of the furnace, the stockline height, the number of charges placed on the bell the material in those charges, and the pattern in which the charges are placed in the furnace. In practice the process is generally an iterative one, in which a burden distribution pattern is established, the gas distribution is measured, or estimated depending on the availability of data, and once steady state is achieved (usually in seven to ten days when a burden distribution change is made) the furnace performance is noted. The process is repeated until the desired operating parameters (e.g. coke rate, fuel rate, and productivity) are achieved. A complicating factor on

belt-fed furnaces with bell charging systems is the potential for circumferential maldistribution of fines as a result of the segregation of large and fine material on the belts and at transfer points as the belts carry material from the stockhouse to the furnace.

Of course the overriding factor with respect to charging the furnace is keeping it full. The most exotic burden distribution techniques are of no value if the stockhouse and charging system are unable to keep the furnace full, (maintain the stockline) at a given wind rate. The ability to catch up, that is regain the stockline when it is lost for a short period of time, must be considered when developing charging practices.

10.4.5 Operation of the Stoves

The temperature of the hot metal is a matter of great importance in controlling the uniformity of the hot metal quality and, therefore, it is important for the blast furnace operator to keep the temperature in a specific range. Before blast furnace burden materials were beneficiated as well as they are today, there were large changes in the size and composition of the burden materials from day to day, and this had a significant effect on the extent of exothermic indirect reduction of the burden in the blast furnace stack. When the quality of the material suddenly changed for the worse, the percentage that was reduced by the exothermic indirect reduction reaction decreased and a larger percentage of the burden came to the hearth unreduced and had to be reduced by the endothermic direct reduction reaction that occurs there. When this happened, additional heat was required in the hearth, and the only way it could be supplied quickly was to raise the hot-blast temperature until additional coke could be charged and worked down to the hearth or until the burden could be restored to its normal quality. For this reason, operators were reluctant to reduce the silicon content of the hot metal, or to use the full capacity of the stoves for normal operation because they preferred to have reserve capacity for raising the hot-blast temperature during such critical periods.

Today, however, with the use of well-prepared burdens and good control of burden distribution, the furnace operation is much more uniform. Consequently, furnaces usually are operated very near the maximum hot-blast temperature that the stoves can maintain or that the particular burden materials will accept without causing premature melting and poor burden movement (that is, at high adiabatic flame temperature). With higher hot-blast temperature, the blast furnace operation is more efficient because a larger percentage of the heat consumed is furnished by the sensible heat of the hot blast (heated by the blast furnace offgas) and less solid or liquid fuel is required.

In the operation of the hot-blast system, the ceramic checkerwork of the stoves is heated by the combustion of blast furnace gas sometimes supplemented by natural gas, and then the air from the blowers is passed through the stoves and is heated by the hot checkerwork. In the heating cycle, the stoves are fired until the temperature of the exit gases at the stack valves has reached an established maximum temperature of approximately 400–450°C (approximately 750–840°F) while simultaneously being careful not to overheat the stove domes. During the heating cycle the temperature at the dome of the stove is controlled so that it does not exceed a maximum, which is determined primarily by the type of refractory material used to line the dome. If the dome temperature reaches this maximum before the stack temperature reaches its maximum, excess air is added through the burner to hold down the flame temperature and prevent the dome from being overheated while the firing is continued until the stack gas temperature reaches its limit. However, if the dome temperature does not increase rapidly enough to reach its maximum allowable temperature by the time the stack gas temperature reaches its maximum, the blast furnace gas is usually enriched with a fuel of higher calorific value to obtain a faster heating rate.

After the stove has been heated, it is ready to be put on blast. This is done by first shutting off the gas and the air supply to the burner and then closing the burner shutoff valve and the chimney valves. The cold-blast valve is then opened in such a way that the air entering the stove will bring it to a pressure equal to the blast pressure without reducing the blast pressure excessively. At some very modern installations, the blower controls are switched from constant volume control to con-

stant pressure control during a stove change. In such a system, the blower speeds up so that the stove can be filled and pressurized rapidly without causing a detectable decrease in the blast pressure. After the stove is filled, the mixer valve (which controls the amount of cold air which is bypassed around the stove to be mixed with the very hot air from the stove to produce the desired hot-blast temperature) is set at approximately the correct opening. The hot-blast valve is then opened to put the stove on blast and, once the stove is on blast, the hot-blast temperature controller automatically adjusts the mixer valve opening to maintain the desired hot-blast temperature.

The spent stove is then taken off blast by closing first the cold-blast valve and then the hot-blast valve. The blowoff valve is then opened to de-pressurize the stove and, after de-pressurizing, the chimney valves are opened and the blowoff valve is closed. Next, the burner shutoff valve is opened, and the air supply to the burner is turned on. Finally, the gas shutoff valve is opened to obtain the desired gas flow rate.

At most modern furnaces, the stove valves are motorized and the valve changing is automated so that only about three minutes are required for a stove change. With the shorter changing time, the heating time can be increased so that higher hot-blast temperatures can be used and greater efficiency can be obtained. The automatic stove changing cycle can be initiated either by having the stove tender push a button when the change is required or by a completely automatic electronic signal. This signal can be based on the extent of the mixer valve opening (as, for example, when the mixer valve is 85% closed), on the dome temperature, or strictly on a time cycle.

Typically, blast furnaces are equipped with three hot-blast stoves, and each stove is kept on blast approximately one hour. Thus, the amount of heat that is extracted from the stove while it is on blast must be put back into the stove in the heating period which is simply twice the on-blast time minus twice the stove changing time. At some furnaces, there are four stoves. With the extra stove, the firing rate does not have to be as great because the heating cycle is three times the on-blast cycle minus twice the stove changing time. Another advantage of the extra stove is that if there is a problem with the stove equipment, the stoves can be repaired one at a time without significantly affecting the operation of the furnace. Fig. 10.4 shows the display for the automatic stove changing system for a modern blast furnace equipped with four stoves. A more thorough explanation of the operation of blast furnace stoves is presented by Agarwal.²

10.4.6 Blast Furnace Irregularities

In spite of the many improvements in burden materials and operating procedures that have been made in recent years, the blast furnace does not always run as smoothly as the casual observer may be led to believe. Furnace upsets are not as frequent as they were in former years; however, irregularities still do occur that cause considerable concern and often require quick thinking and the use of good judgment and skill on the part of the operator to prevent serious trouble.

10.4.6.1 Slips

Slips are caused initially by hanging or bridging of the burden material in the stack of the furnace. When this occurs, the material below the hang continues to move downward, forming a space that is void of solid material but filled with hot gas at very high pressure. This space continues to grow until the hang finally collapses. In severe cases, the sudden downward thrust of the hanging material forces the hot gas upward with the force of an explosion. This sudden rush of gas opens the explosion bleeders and sometimes is so great that it causes severe damage to the furnace top gear.

The hanging that precedes slipping is caused by any of a number of different conditions in which the permeability of the charge is decreased because some of the material plugs up the voids between the charged particles and bonds them loosely together. When there is a high percentage of fines in the burden and the velocity of the furnace gas is relatively high, the fines will plug the openings between the other particles and cause hanging. In some instances, slag that has



Fig. 10.4 Real time status of the stoves is reviewed in the control room. (Courtesy of Kvaerner Metals.)

been melted is blown upward in droplets; when it subsequently contacts colder burden material it resolidifies and plugs up the openings between the particles and tends to cement them together. In some cases, the carbon monoxide decomposition reaction



will be catalyzed, and the carbon deposited as soot will plug up the openings between the particles and will hold the particles together. In some instances, where the alkali content of the burden is high, the alkali compounds will be reduced to alkali vapor that ascends with the furnace gas and condenses in the cooler portion of the charge to cause the same type of hanging condition. Another type of hanging sometimes occurs in furnaces that are being run very efficiently and are being pushed to their best production rate. Under these conditions, if there is a slightly unfavorable change in the gas distribution, the strength of the coke or the particle size of the burden, the iron oxide will not reduce to metallic iron rapidly enough, and iron oxide will melt and run down as a liquid onto the coke particles. When this occurs, the liquid iron oxide will be reduced to solid iron and considerable heat will be consumed by the reduction. Thus, the coke particles will be cemented together and the permeability of the mass will be significantly decreased so that hanging will result. A similar type of hanging may also occur if the furnace is being run at too high a flame temperature for the quality (particularly the reducibility) of the burden material. When the high temperature isotherms expand far enough up the furnace they can begin to melt unreduced material; as that material descends into a more reducing environment it reduces and, depending on the temperature, it may solidify (the melting point of FeO is roughly 1370°C and pure iron is roughly 1535°C), and plug the burden.

When the burden is not moving properly through the furnace, the operator must take corrective steps immediately to prevent a disastrous slip and determine the cause of the hanging so that changes can be made in the operating procedure to prevent the hang from recurring.

104.6.2 Scaffolding

Scaffolding is the term used when accretions or scabs build up on the furnace walls and cause a decrease in the cross-sectional area of the furnace stack. Scaffolding can occur relatively high in the furnace stack or relatively low, near the top of the bosh.

The formation of scaffolds near the top of the bosh often results because of excessive fines in the burden material and a higher than normal lime chemical composition of the slag. The solution of lime into the slags formed in the furnace stack increases the slag melting point. Because the slag often carries some of the fine particles from the burden in suspension, the increase in melting point can cause this mixture of fines and slag to adhere to the upper bosh walls; this buildup deflects the hot gases farther into the center of the furnace. With less hot gas along the walls, the accretions tend to cool down and solidify completely, and they can then grow until they block a large percentage of the furnace cross-section and render it ineffective for smelting. This increases the fuel rate, decreases the hot metal production rate and promotes hanging and slipping. Scaffolds can also be caused by alkali or zinc compounds that are reduced to metallic vapor near the bottom of the furnace and rise with the furnace gases to the cooler top portion where they are reoxidized to very fine solid particles. These very fine particles adhere to the furnace inwalls and entrap other fine material there to start the formation of a scaffold. Such scaffolds decrease the production capacity and distort the gas flow so that poor fuel efficiency results. Also, scaffolds can dislodge from the walls and descend into the hearth, causing serious furnace upsets and poor quality metal, or if large enough they can cause the furnace to freeze.

104.6.3 Channeling

For satisfactory blast furnace operation the burden must be properly distributed both radially and circumferentially. If a preponderance of fines is charged in a particular area of the furnace the ascending gasses will be diverted from that area and channel around the fines. This channeling will upset the preheat and reduction processes and result in off chemistry hot metal or unscheduled bleeder openings or worse.

104.6.4 Breakouts

Breakouts are caused by failure of the walls of the hearth, with the result that liquid iron or slag or both may flow uncontrolled out of the furnace and cause considerable damage to the furnace and surrounding auxiliaries. Slag breakouts are usually not as serious as iron breakouts, because there is not as much danger from explosions as in the case where molten iron and water come into contact. With either type of breakout, it is essential, if at all possible, to cast the furnace, thereby draining off as much liquid material as possible, and to take the furnace off blast.

A slag breakout may be chilled by streams of water, and the hole where the breakout occurred may be closed by replacing the brick, pumping fireclay grout into the opening, or ramming a plastic cement or asbestos rope into it.

However, there is practically no control over an iron breakout, and the iron runs out of the hole until the furnace is dry. After the accumulated iron has been cleared away, a suitable refractory may be used to close the hole. It may be necessary to renew one or several of the hearth cooling staves or the breakout may be so severe that the operator will have to take the furnace out of service for a complete hearth repair. The use of carbon brick in the hearth sidewall and modern construction techniques have resulted in a robust hearth design, at least in North America.

104.7 Fanning

Occasionally during the campaign of a blast furnace situations arise when the full productive capacity of the furnace is not required for a period of time. When this occurs, the problem can be solved by shutting the furnace down or curtailing the operation of the furnace by reducing the quantity of wind being blown. The wind rate is usually reduced until the hot-blast pressure at the

tuyeres is very low. A positive pressure must be kept in the hot-blast system to assure that there is no danger of gas coming back from the blast furnace into the blower system. The technique of reducing the wind volume to less than 20–25% of normal is known as fanning. Fanning has the advantages of keeping the gas system pressurized and furnishing a small quantity of blast furnace gas for use as fuel, and enables a resumption of near full operation on relatively short notice. This technique is used for emergency situations or short periods only. Prolonged use, such as eight hours out of every 24, or on weekends, often results in a hearth buildup and frequently promotes inwall scab formation.

104.8 Back Drafting

Occasionally it is necessary to take the furnace off blast for short periods, often less than two hours, to perform various maintenance functions such as the replacement of tuyeres or repairing skip cables. In such instances, the furnace is not banked but is back drafted. In this operation, as soon as the wind is stopped, the bustle pipe is put under negative pressure. This is done usually by opening the chimney valve and the hot-blast valve to a stove that has already been prepared by heating it to temperature and then shutting off the gas valve. As the furnace gas is drawn back into the stove, air is admitted through the peep sights and stove burner, and the operator makes certain that the gas burns in the stove. During the operation, the bleeders at the top of the furnace also are opened to pull some of the furnace gas out through the top.

At several furnaces, a special back draft stack is installed so that it is not necessary to draw the furnace gas back through a stove. This stack is connected to the bustle pipe or to the hot-blast main. In some instances, it is closed by a water-cooled gate valve at the level of the bustle pipe and in others it is closed by an uncooled cap valve at the top of the stack. Opening the valve allows the furnace gas to draft to the atmosphere where it burns without difficulty.

104.9 Banking

Modern blast furnace practice very seldom includes banking as a standard technique unless the outage is of short duration. Furnaces are usually blown down, that is, they are run without being charged until the burden level reaches the tuyeres. Plans for an extended shutdown or interruption to furnace operation either for a breakdown, scheduled repair or because business conditions indicate a pause in production is desirable, may influence management to blow down a blast furnace.

A description of the banking process is included for two reasons: first, an adaptation of this procedure is useful for short outages, and second, a description of the banking process provides an interesting historical perspective on blast furnace practice. The word banking is applied because of a similarity to the operation of banking a fire. The origin is lost in antiquity, however, generally it means covering a fire with ashes or fresh fuel to restrict air, reducing the combustion rate, and thus preserving the fuel for future use.

Also, banking was resorted to as an emergency measure when some unforeseen event requires a furnace shutdown. In this case, the blast was taken off, the blowpipes were dropped and the tuyere openings were plugged with clay to prevent air from drafting through. Thus, hearth heat was preserved and the furnace could be returned to operation with a minimum effort. If the downtime exceeded four or five days in duration, some difficulty could be expected in resuming operation, although instances are on record that no trouble was experienced after a seven day bank.

More common was the furnace bank carried out as a planned event. Preparations made depended upon the length of banking time anticipated. If the furnace was to be banked for only a few days, an extra blank or two of coke may be charged without flux and the furnace taken off when the coke descends to the bosh zone. If it was to be banked for a slightly longer time, the ore and stone burden may have been reduced by 5–10% following the coke blank, possibly for ten or fifteen charges before normal charge weight is resumed. This technique is still used for very short outages.

A banking burden for a shutdown for an undetermined length of time is very similar to a blow-in burden. Prior to the start of a banking burden, miscellaneous iron-bearing materials are removed from the charge and a large reduction in the amount of limestone charged is made. Extra coke also may be charged ahead of the banking burden. The purpose was to develop a hot, siliceous slag which had a tendency to clean off the lime accumulation on the bosh walls and prevent an excessively high lime slag during blow-in. High lime slag has a higher melting point and is apt to cause some operating problems early in the blow-in period. Often during the initial warm-up period, temperatures may be very high in the bosh which will increase reduction of silica to silicon with the result that slag contains a higher proportion of lime. For this reason, effort is made to have a hot, siliceous slag at the time the furnace is banked because a similar condition upon the resumption of operation is expected.

Following initial preparatory charges noted above, a heavy coke blank is charged and subsequent charging parallels a characteristic blow-in burden. Charging continues until the coke blank reaches the upper bosh area of the furnace. At this time, the final cast is made. Effort is made to drain the hearth until a dry blow of the taphole is observed to insure a clean hearth for the future startup and eliminate as much as possible the need for melting cold slag early in the blow-in period. Prior to the last cast, the furnace dustcatcher is emptied. Accumulated dust has a tendency to consolidate into a rock-like mass if undisturbed for a time and could present a difficult problem after operation began again.

About the end of the cast, before the furnace is taken off, a heavy blanket of ore may be dumped in the furnace to cover the upper burden surface, thus reducing the natural drafting tendency of the furnace.

At the conclusion of the cast, the taphole is plugged, wind is taken off the furnace, bleeders are opened, steam is turned into the dustcatcher, the furnace is isolated from the common gas system and stove valves are manipulated to draft gas back through the bustle pipe, hot-blast main and out through the stove chimney. Furnace operators quickly drop the blowpipes and plug the tuyeres with clay. Many operators prefer to remove the tuyeres to avoid any chance of a stray water leak permitting water to accumulate in the furnace and also to provide an opportunity to observe the coolers for possible leaks. Clay is solidly packed into the tuyere openings and backed up with sand to eliminate any chance of air filtering in. Often this is followed by bricking up the openings as further insurance against air infiltration.

As soon as the blowpipes are down after the final cast, blowing engines are stopped, and stove burner valves, chimney and hot-blast valves are closed to preserve heat as long as possible. As a precaution, blowoff valves are opened slightly to prevent a pressure buildup from developing in the stoves resulting from an undetected water leak or from some unsuspected source.

Within a day or two, the furnace bells are opened and steam is shut off in the dustcatcher. **Daily inspection of the stock line is important.** A slow stock movement is an indication that air is infiltrating and coke is being consumed. A movement of a few feet can be expected but a continual drop is undesirable and may force operators to spray the bosh with a sealing material. A thin mixture of water, clay and water glass is sometimes used because the material is inexpensive and does an effective job.

If the furnace is banked for an extended period, after a lapse of a month to six weeks, water flow will be reduced on the cooling members and finally, after two to three months, turned off entirely except for the hearth staves.

Very often after a bank of six or more weeks, when tuyeres are opened, all signs of fire in the tuyere area will have disappeared. Furnace operators are pleased when this condition is discovered because full benefit of the coke blank will be available to supply heat when operation begins.

104.10 Blowing-in from Bank

Blowing-in a banked furnace has developed to the point where operators accept the process as a routine event. At one time, blowing-in a banked furnace was a task approached with misgiving and the performance was usually a disappointing experience.

Nearly the only obstacle which otherwise upsets an otherwise smooth routine operation is when an undetected water leak may cause extended delays and setbacks in returning to operation. Accompanying this difficulty, and often resulting from the water leaks noted above, are other delays from breakouts around cooling plates and coolers. In these older furnaces there may be only a little brickwork remaining in the slagline area and the natural carbon and lime buildup is dissolved from the action of the siliceous slag intentionally developed. This condition is conducive to opening up the spaces between the bricks and is aided by temperature changes as bosh heat is increased during blow-in.

Skill, experience and good judgment on the part of operators is of inestimable value and is never more important to the success of any undertaking than in bringing on a furnace from bank.

A discussion of methods of blowing-in a furnace from an extended emergency bank, where no preliminary preparation was made, is omitted because of the numerous circumstances which affect the actions taken by operators. The job, at best, is a lengthy, laborious undertaking. This is one of the principal reasons the technique of blowing-down a furnace was developed.

Blowing-in from bank, when adequate preparation was made, follows somewhat the pattern of blowing-in a new or relined furnace. The exception which alters the technique is that the hearth level is higher and cold slag in the hearth must be heated and liquefied to prevent chilling of the new slag which begins to form when wind is put on the furnace. Under these circumstances, operators must be sure communication is established between the taphole and the areas in the hearth where liquid is being formed in order to get it out of the furnace as fast as it is made. Working with this goal in mind, heat is brought down into the hearth as the new slag forms, which transfers some heat to the bottom, and is removed before it has a chance to chill.

Several methods are used in starting; all of them have proven successful and operators are apt to choose any one of them which they deem may fit their particular problem. But, in all cases, when wind is first put on, only a few tuyeres will be opened. These are directly above and on each side of the taphole. As the blow-in progresses, often following each cast, a tuyere next to an open tuyere will be opened and wind volume increased. If the following cast is not up to expectation, that is, if the volume or temperature of the slag is lower than it is thought it should be, then opening of the next tuyere will be postponed until hearth heat is built up again.

In general, earlier preparations are similar to blowing-in a relined furnace. Coolers are opened up and coke ash and refuse cleaned away. Operators make sure good clean coke is in front of the coolers before installing tuyeres. Then all but the few mentioned above are securely packed with clay or clay and brickbats to prevent any blast air from entering until the plug is removed.

The taphole is dug and burned back to where coke is visible and then made up similar to the method used on a new furnace. Some operators lightly plug the taphole, others let the furnace gas blow out through the taphole until slag appears to insure that the hot gas warms the hearth in the taphole area. Another method has produced good results and is unique. The taphole is made up and a blow-in pipe is installed to blow air or an air-oxygen mixture into the taphole. Tuyeres are closed during this four to eight hour operation. Then the pipe is pulled, the taphole is plugged and air is blown in a few tuyeres as above.

Regardless of the method chosen, casts are made at two to three hour intervals until operators are certain the hearth is heated sufficiently to keep the contents fluid. The taphole is drilled straight in early in the blow-in and the angle slowly increased as temperatures increase and the entire body of the hearth begins to return to normal operating temperature.

Burden regulation follows blow-in practice with regular increases in iron-bearing materials as the blow-in progresses.

10.4.11 Blowing-out/Raking-out

If business conditions deteriorate to the extent production is no longer required, the decision may be made to blow-out a furnace. Starting the furnace again under conditions approaching those of starting a new furnace is generally accomplished faster and with less effort than starting from a bank. However, the costs in connection with blowing out, raking out and cleaning preparatory to starting is likely to exceed the cost of banking.

When a furnace has reached the end of its campaign (that is, the lining has worn out), it was usually blown-out except under most unusual circumstances. Modern practice is to blow the furnace down.

For an historical perspective the blow-out practice will be described. Roughly twelve to sixteen hours before the last cast is to be made, the operation is discontinued for a short period of time to permit the installation of water sprays in the top of the furnace and thermocouples in the uptakes. The burden composition is then changed to produce a very siliceous slag to help in removing as much lime as possible from the bosh and hearth walls. The purpose of this is to prevent the formation of calcium hydroxide which would occur if lime were to come in contact with the cooling water during the later stages of the blow-out. (The formation of calcium hydroxide from lime imbedded in the lining could generate sufficient force to crack the steel hearth shell or to lift the furnace off its columns).

After installation of the blow-out equipment, the blast is put on and charging is continued. If a gravel blow-out is the method chosen, a heavy coke blank will be charged first. The volume will be equivalent to approximately the volume of the bosh. Following the coke blank, washed and screened silica gravel, roughly -50 mm to +25 mm (-2 to +1 in.) size is charged. The furnace is kept full early in the blow-out and then the stockline is permitted to drift down roughly 6-9 metres (20-30 ft.) toward the end (when all the iron-bearing burden has been reduced). During blow-out, water is judiciously used to control top temperature. However, the additional charges of gravel are very effective in keeping top temperature low. A decrease in the wind rate is required as the height of the column of material in the furnace decreases. From the time that the special spray equipment is installed until the blow-out is completed requires only from six to eight hours.

A coke blow-out is the same as above except that coke is used instead of gravel. Sometimes +20 mm to -25 mm (+3/4 to -1 in.) coke screenings are used. This size is commonly called domestic coke.

Following the last cast, the stock is watered down as described above. When cooling has progressed far enough, sluice ways frequently are built from a few cooler openings to an open-top railroad car and the contents of the furnace washed out with high pressure water jets.

10.4.12 Blowing-down

In the 1970s it became apparent to blast furnace operators that the procedures of banking and blowing-out blast furnaces were expensive. Often banking resulted in difficult startups because of water problems, or any number of unforeseen reasons. Also there was enough technical understanding of the process to allow operators to blow the furnace down. Blowing a furnace down means running the furnace without charging until the burden level in the furnace is reduced to approximately the tuyere level. There are several reasons why this technique is preferable to banking or blowing-out a furnace. Some are when a furnace is blown-down it can be thoroughly inspected for leaking coolers or staves, and no effort is required to stop air infiltration because the furnace is empty. And, if the furnace is to be relined it is faster and less expensive to tear apart an empty furnace than one containing burden.

The blow-down technique varies from operation to operation but basically the procedure is as follows. Atomizing water sprays are installed at the top of the furnace on a shutdown prior to the blow-down, somewhere in the vicinity of the 3-5 metres (10-15 ft.) stockline level. There are usually four to six spray nozzles installed equally spaced around the furnace. The purpose of the water

sprays is to control the top temperature. An approximation of the water flow rate required would be 500 gpm at 120 psi. Emergency backup water supplies are often provided for safety. Depending on the type of top and its condition, emergency water sprays are sometimes installed in the event of a grease fire during the blow down.

Steam sprays are also installed on one to three levels to provide some cooling and to maintain furnace pressure. If one level is used it is generally placed low in the stack at roughly the 45–50 ft. stockline level. If additional levels are used they are placed roughly equidistant between the top water sprays and the bottom steam sprays. The steam injectors are activated once the burden descends below them. Some companies will also run nitrogen to the steam sprays as backup in case the steam pressure would be lost. Nitrogen injection is provided for purging the furnace at the end of the blow down. Usually the nitrogen is introduced through the bustle pipe; if nitrogen is used as backup to the steam injection system, that system can also be used to purge the furnace when the blow-down is complete. Desired nitrogen flow and pressure levels required are roughly 5000 scfm at 50 psi.

Provision is made for process offgas analysis, often this simply requires recalibration of the top gas analyzer. Hydrogen and oxygen analyses are required. Hydrogen levels must be kept low (below 15%) and essentially no oxygen should be detected. Stockline measurement is required, and should be capable of extending well into the furnace.

The wind rate and hot blast temperature are reduced as the burden descends to control the top temperature and hydrogen and oxygen content of the top gas. Typically the maximum allowable top temperature is in the range of 315–425°C (600–800°F).

10.4.13 Draining the Salamander

Subsequent to blowing down, particularly when the furnace is to be completely relined (i.e. the hearth is to be replaced), the salamander is usually drained. This operation saves days and possibly weeks in relining time which otherwise might be lost in blasting out the heavy chunk of solid iron that would be formed if the metal (that accumulated in the hearth as bottom block eroded during the campaign) were permitted to solidify. Initial preparation is made before blowing-down by drilling a predetermined distance into the furnace bottom below the hearth staves and installing a trough or runner for the iron. If the furnace layout is amenable, pig beds will be constructed and made ready for use immediately after the last cast is completed. In case an outside area is not available for a pig bed, then, after the last cast, ladle tracks will be removed and the pig beds arranged under the casthouse. The eight to twelve hour delay in this case is negligible because residual heat in the hearth will keep the salamander molten for several days.

When all is ready, a long oxygen lance is inserted in the drilled hole and the remaining brickwork is burned through into the pool of iron. Usually the flow of iron is slow and several hours are required to empty out an accumulation of up to four hundred to six hundred tons. Tapping the salamander is still, to a large extent, an art. Heat transfer calculations based on thermocouples located in the under hearth allow the depth of penetration of the iron pool to be estimated. However this point is at best an estimate. Consequently, the location of the drilled hole is somewhat arbitrary and some, usually small, portion of the salamander often remains.

10.5 The Blast Furnace Burden

The regulation of the proportions of ore, pellets, sinter, flux, coke and miscellaneous materials charged into the blast furnace is called burdening. Proper burdening is essential to keep the operation of the furnace at maximum efficiency, the energy consumption in balance, and to control the hot metal composition.

A term often used in relation to burdening is the burden ratio, which is the ratio of the weight of iron-bearing materials per charge to the weight of coke. However, because of the widespread use

Table 10.10 Burden Calculation for a Blast Furnace

Furnace Charge Material	kg		lb		kg/m ³ H ₂ M ^(a)		lb/NTHM ^(b)		Silica		Alumina		Lime		Magnesia			
	kg	lb	kg	lb	kg/m ³ H ₂ M ^(a)	lb/NTHM ^(b)	%	kg	lb	%	kg	lb	%	kg	lb	%	kg	lb
Pellets	50,000	110,000	1060	2120	4.90	2450	5390	0.39	165	429	0.29	145	319	0.29	145	0.29	145	319
Sinter	22,727	50,000	482	964	5.00	1136	2500	1.00	227	500	13.70	3114	6850	13.70	3114	2.50	568	1250
BOF Slag	1636	3600	35	69	13.00	213	486	4.50	74	162	58.00	622	1366	58.00	622	10.00	164	360
Dolomite	606	2000	16	39	0.05	0	1	0.05	1	2	50.23	275	605	50.23	275	21.37	164	427
Coke	20,000	44,000	424	848	3.75	750	1650	2.25	450	990	0.15	30	66	0.15	30	0.15	30	66
Total	95,273	209,600				4550	10,009		947	2083		4185	9208		1101		1101	2422

	Phosphorus		Manganese		Iron		Sulfur		
	%	kg	lb	%	kg	lb	%	kg	lb
C	0.015	6	17	0.15	75	165	0.004	2	4
Fe	0.040	9	20	0.80	182	400	0.014	3	7
Si	0.300	5	11	2.50	41	90	0.092	2	5
P	0.001	0	0	0.01	0	0	0.040	0	1
Mn	0.007	1	3	0.10	20	44	0.050	170	374
Total		23	50		318	699		177	390

	Pig Iron Produced (theoretical)		Slag Produced (theoretical)		Operating Ratios
	kg	lb	kg	lb	
C	2122	4668	3643	8075	Coke Rate = 424 kg/tonne 848 lb/net ton
Fe	44,467	97,828	647	2083	
Si	283	622	4185	9208	Slag Rate = 223 kg/tonne 447 lb/net ton
P	23	50	1101	2422	
Mn	236	524	102	225	Slag Basicity Ratio (CaO+MgO)/(SiO ₂ +Al ₂ O ₃) = 1.08
S	25	54	153	336	
Total	47,158	103,747	10431	22949	
			Total	10536	

(a) m³H₂M represents tonne (metric ton) of hot metal.

(b) NTHM represents net ton of hot metal.

of fluxed sinter and fluxed pellets, this term has become somewhat ambiguous as, in some instances, the weight of the iron-bearing materials also includes the weight of the fluxes. In addition the use of HBI or similar materials adds even more ambiguity to the term.

A typical burden calculation is shown in Table 10.10. The amount of each material in the charge is shown in the first column and the percentage of each of the components (on a natural basis) silica, alumina, lime, magnesia, phosphorus, manganese, iron and sulfur are shown in the appropriate columns. With this information, the total amount of each constituent is determined and thus the total amount of pig iron that will be produced and the composition and amount of slag that also will be produced can be calculated. In the example given in Table 10.10, it is planned to make hot metal with a chemical composition of 0.80% of silicon and 0.03% of sulfur. At this silicon content, the carbon content of the iron will be roughly 4.50%; consequently, the remaining constituents that report to the hot metal will be 94.67% ($100\% - 4.50\% - 0.80\% - 0.03\% = 94.67\%$). The remaining constituents reporting to the hot metal (100% of the iron, 100% of the phosphorus and 70% of the manganese) total 35,825 kg (78,815 lbs) representing the sum of 35,650 kg (78,430 lbs) of iron, 31 kg (68 lbs) of phosphorus and 144 kg (317 lbs) of manganese, so that the total hot metal produced will be 37,842 kg or 37.84 tonnes, equivalent to 83,252 lbs or 41.7 net tons.

To calculate the amount of slag and the slag composition, all of the constituents reporting to the slag are totaled, and this is assumed to be 99% of the total slag because there are generally a few constituents that are also present but are not included in the chemical analysis. In determining the amount of silica reporting to the slag, the amount reduced to metallic silicon must be deducted from the total silica. In the example shown, the silicon in the hot metal is 300 kg (667 lbs); consequently, 648 kg (1426 lbs) of silica was reduced ($303 \times 2.14 = 648$ kg) and only 4136 kg (9099 lbs) reported to the slag (4784 kg $-$ 648 kg $=$ 4136 kg (9099 lbs)). The amount of manganese oxide (MnO) is determined by multiplying the 30% of unreduced manganese by 1.28 to convert it to the oxide. In this example, 79 kg (174 lbs) of MnO report to the slag (206 kg \times $0.30 \times 1.28 = 79$ kg (174 lbs)). The balance of the calculations are self-explanatory.

If the calculation indicates that the sulfur content of the slag is higher than that which experience shows it can absorb, then additional slagmaking constituents and fluxes must be added. In the past, burden calculations were made only when there were major changes in the raw materials or in the grade of iron to be produced. On an hour to hour basis, small adjustments to the burden were made by the furnace supervisor, in accordance with experience, to compensate for changes in the chemical composition of the hot metal or the appearance of the slag. However, at present, the burden calculations are made by computer, and at some plants where the composition of the raw material changes from hour to hour, the computation is made every few hours. By entering into the computer the slag composition range desired for good slag fluidity and the limit of sulfur desired in the slag, the computer will actually notify the operator of the burdening changes that must be made. In fact, on some blast furnaces equipped for automatic charging, these changes can be made automatically.

In computer burdening, the calculations show not only the amounts of material required to give slag of the desired composition but also the changes in fuel ratio required as different materials are added to or removed from the burden. These calculations require a knowledge of the wind rate, the hot-blast temperature, the blast moisture and the injected fuel rate. This information can be transmitted to the computer by manual entries or by direct readings from the control instruments.

The fuel consumption can be approximated through the use of the standard coke rate formula, developed through regression analysis by Flint.³ Table 10.11 is a listing of the coefficients used in this formula.

Today most blast furnace operators use the rules of thumb shown in Table 10.12 to estimate changes in coke rate on the blast furnace. These rules are derived from theoretical heat and mass balance calculations and blast furnace trials. They serve exactly the same function as the Flint calculation referred to above, however they are less cumbersome to use.

Table 10.11 Carbon Rate Formula— Summary of Variables and Coefficients From Ref. 3.

Category	No.	Variable Description 1	Unit of Measure		Carbon Coefficient		Minimum Practice Range Studied		Approximate Actual Practice Range Studied	
			SI	fps	SI	fps	SI	fps	SI	fps
Slag	1	Slag from coke est	+1 kg/mt-M ^(a)	+1 lb/NTH-M ^(b)	+C.6C	+0.60	50	6C	175	35C
	2	Slag from urcalcirec CaCC ₃ and MgCO ₃	+1 kg/mt-M	+1 lb/N THM	+C.6C	+0.60	0	0	5C0	1C0C
	3	Slag—all other	+1 kg/mt-M	+1 lb/N THM	+C.15	+0.15	10C	20C	9C0	180C
Metallc bearing materials size consist	4	SI -1 mrr	+1 kg/mt-M	+1 lb/N THM	+C.08	+0.0E	75	15C	6C0	120C
	5	+1 mm, -1C mm	+1 kg/mt-M	+1 lb/N THM	+C.04	+0.04	20C	40C	9C0	180C
	6	+25mrr, -5Cmrr	+1 kg/mt-M	+1 lb/N THM	+C.03	+0.03	50	10C	750	150C
	7	+50mrr, -10C mm	+1 kg/mt-M	+1 lb/N THM	+C.06	+0.0E	0	0	750	150C
	8	+1C0 mrr	+1 kg/mt-M	+1 lb/N THM	+C.10	+0.1C	0	0	3C0	60C
Other	9	Chargec sulfur in total burcer	+1 kg/mt-M	+1 lb/N THM	+E.00	+5.0C	E.5	7	17.5	35
	10	Chargec free metallics	+1 kg/mt-M	+1 lb/N THM	+C.30	+0.3C	00	?	350	70C
	11	Chargec iron contairec in iron silicetes	+1 kg/mt-M	+1 lb/N THM	+C.30	+0.3C	?	?	?	?
	12	Chargec corrtirec water	+1 kg/mt-M	+1 lb/N THM	+C.10	+0.1C	0	0	115	23C
Hot Metal Analysis Variables	13	Silicon	+1%	+1%	+6C	+120	C.4	0.4	3.5	5.5
	14	Margenese	+1%	+1%	+1C	+20	C.1	0.1	3.0	5.0
	15	Phosphorus	+1%	+1%	+1C	+20	C.1	0.1	1.8	1.8
	16	Sulfur	+1%	+1%	Curvi-linear	Curvi-linear	0.020	C.020	C.06C	0.160
Operating Practice	17	Hot-blast temperature	+1°C	+1°F	-0.1E	-0.20	E.1E	60C	10E0	200C
	18	Wind rate	+1 mrr ² /mir	+1 ft ² /min	+5C	+1C0	C.7E	1.5	1.4	2.8
Variables	19	Elast humicity	per m ³ wind vol.	per ft ³ wind vol.	+C.4C	+0.40	10	2C	1C0	20C
	20	Days on stack lining	+1 kg H ₂ O/mtHM	+1 lb H ₂ O/NTH-M	+0.015	+0.03	15	1E	27C0	270C
	21	Metallic loss in runner and ladle scrap	+1%	+1%	+5	+10	0	0	3.0	5.0

(a) mt-M represents tonne (metric ton) of hot metal. (b) NTHM represents net ton of hot metal.

Table 10.12 Rules of Thumb for Estimating Blast Furnace Coke Rate Changes^(a)

Process / Raw Material Variable	Parameter	Increase	Coke Rate Change (lbs/NTHM)
Ferrous Burden	2 in. × 4 in.	100 lbs/NTHM	+15
	1 in. × 2 in.	100 lbs/NTHM	+9
	1/2 in. × 1 in.	100 lbs/NTHM	+3
	1/4 in. × 1/2 in.	100 lbs/NTHM	0
	-1/4 in.	100 lbs/NTHM	+8
Pellets	3/8 in. × 5/8 in.	100 lbs/NTHM	0
	-1/4 in.	10% of pellets	+40, {-5.2% productivity}
	Tumble Index	-1 unit	+21 {per unit <95}
	Lump Ore vs. Pellets	100 lbs/NTHM	+4
	Sinter vs. Acid Pellets	1% exchange	-1.6
	Fluxed vs. Acid Pellets	1% exchange	-0.5
Coke	Ash	1%	+20
	S	1 lb./NTHM	+10
	Stability ^(b)	1%	-2.5 for stability >62.0 -5.0 for stability <62.0
	Reactivity ^(b,c)	1%	+3.0 for reactivity >13.0 +1.5 for reactivity <13.0
Slag Volume	100 lbs/NTHM	+ 20	
	Raw Flux	100 lbs/NTHM	+0 for <200 lbs/NTHM +10 for 200 to 400 lbs/NTHM
Blast	Volume	CFM/100 ft ³ working vol.	+0.7
	Temperature	100°F	-(0.05 × Fuel Rate - 32.0)
	Moisture	1 gr/SCF	+(0.01 × Fuel Rate - 6.5)
	Oxygen enrichment	1% of dry wind	+1.5% productivity at constant BGV and RAFT
		1% of dry wind	+2.6% productivity at maximum BGV
Injectant ^(d)	Oil	1 lbs/NTHM	-1.2
	Tar	1 lbs/NTHM	-1.1
	Natural Gas	1 lbs/NTHM	-1.4
	Coal	1 lbs/NTHM	-1.0
Hot Metal	Si ^(e)	0.1%	+10
	Mn	0.1%	+2.5

^(a) This table was reproduced from the McMaster University Intensive Course in Ironmaking, used with permission.

^(b) Indirect effect, only at high levels of stability and CSR, coke savings due to more aggressive operation; lower Si, higher flame temperature, etc.

^(c) CSR (coke strength after reaction) = 77.4 - 1.33 (Reactivity).

^(d) Theoretical values, based on specific raw material chemistries, they should be considered nominal.

^(e) As the result of thermal changes, not for changes in driving rate or raw material quality, otherwise use 10 lbs coke/NTHM for every 20°F change in hot metal temperature.

A few examples of the application of these rules of thumb follow.

If pellets are a major portion of the iron-bearing charge to a blast furnace (e.g. >40%) and the fines content of the pellets increase by 3%, what effect would this have on the furnace coke rate and productivity? The rule of thumb states that an increase of 10% in the amount of $-1/4$ in. material in the pellets results in a 40 lbs/NTHM increase in the coke rate. Therefore, using the ratio $3/10 = x/40$, it is found $x = 12$. Consequently an increase of 3% in the charged pellet fines would result in an increase to the coke rate of 12 lbs/NTHM. The productivity decrease that can be expected is calculated in a similar fashion using the ratio $3/10 = x/-5.2\%$, yielding a productivity change of $x = -1.56\%$. The rule of thumb indicates that an approximate decrease in productivity of 1.6% can be expected with the above increase in pellet fines. Thus, it can be seen from this application of the rules of thumb that a 3% increase in the fines content of pellets can have a significant effect on blast furnace operation.

Another example shows how the rules of thumb can be applied to the situation of changing from one injected fuel to another. Assume that for economic reasons it is necessary to switch from injecting oil to injecting natural gas. Given the conditions of a current oil injection rate of 150 lbs/NTHM and a desired natural gas injection rate of 140 lbs/NTHM, from Table 10.12 it is found that decreasing the oil injection rate 150 lbs/NTHM increases the coke demand by 150×1.2 , or 180 lbs/NTHM. Increasing the natural gas injection rate 140 lbs/NTHM decreases the coke demand by $140 \times (-1.4)$, or 196 lbs/NTHM. Thus, the net effect on the blast furnace is that the coke demand has been decreased by 16 lbs/NTHM. Based on this calculation the blast furnace will become hot because of the higher fuel (coke) value associated with natural gas. In this case the operator would likely increase the iron ore charge to the furnace at the same time while switching to natural gas. The effect of switching the fuel would be essentially instantaneous. The burden change would likely take six to eight hours to reach the tuyeres, and as a result the furnace would likely get hot for a few casts before the burden change reached the tuyeres.

Other rules of thumb included in Table 10.12 are applied in a similar fashion.

10.6 Modern Techniques for Improving Blast Furnace Operating Performance

During the twenty five years between 1950 and 1975, many new techniques were adopted by the steel industry that greatly improved blast furnace operating performance and increased the efficiency. During that period the average hot metal production rate per unit of volume for all of the blast furnaces in the United States more than doubled. In the same period, the coke rate decreased from 925 to 550 kg of coke per tonne of hot metal (1850 to 1100 lbs/net ton). In the 1980s furnaces as large as 14 metres (46 ft.) in diameter produced more than 10,000 tonnes (roughly 11,000 net tons) of hot metal per day, at a fuel rate of less than 450 kg/tonne (900 lbs/net ton).

This progress continues in the 1990s, and blast furnaces have become more efficient, both with respect to productivity and fuel consumption. It appears that, just as the blast furnace process is about to be supplanted by newer technology, it is pushed to new levels of efficiency to regain its position as the low cost means of producing iron. In 1998, blast furnaces are operating for sustained periods of time in excess of 3.6 tonnes hot metal per day per cubic metre (11.25 tons per day per 100 ft³) of working volume. Coke rates below 300 kg per tonne (600 lbs/NTHM) are not uncommon because of the ubiquitous use of injected fuels.

10.6.1 Beneficiated Charge Material

The physical and chemical composition of the materials used in blast furnaces has improved significantly since 1950. As described in Chapter 6, the practice of washing coal to remove ash and sulfur has greatly improved the chemical composition of the coke. Coke strength has been improved also by suitable pulverizing and blending of the coals. The use of high strength coke,

crushed to a top size of 65 mm (roughly 2.5 in.) and screened to remove the –35 mm (roughly 1.375 in.) fines will significantly improve the production rate and furnace efficiency. Uniformly sized coke improves the permeability of the stock column and the rate of heating of the burden, and the improved coke strength prevents the formation of fines which would distort the gas flow and interfere with the gas–solid contact.

At many of the blast furnaces, the ores that are used are first crushed to –50 mm (roughly –2 in.) and screened to remove the –10 mm (roughly –3/8 in.) fines. In some instances, the ore is crushed to –25 mm (roughly 1 in.) because the ideal size for blast furnace ore is generally conceded to be –25 mm, +10 mm (–1 in., + 3/8 in.). The fines that cannot be used directly in the blast furnace are either sintered or pulverized and pelletized. The iron-bearing material from taconite deposits and many other ore bodies must be pulverized to finer than 0.1 mm (roughly 0.004 in.) so that the iron oxide can be satisfactorily separated from the gangue, and consequently these fines are pelletized.

The incorporation of fluxes in the agglomerates provides a means for further improvement in the blast furnace operation because it pre-calcines the flux. In addition, it often improves the reduction rate of the agglomerate and helps to prevent the formation of low-melting iron silicates. This keeps the agglomerate from melting before it has been sufficiently reduced to metallic iron, and for this reason it is believed that it permits the use of higher flame temperature and improves fuel efficiency in the blast furnace.

10.6.2 High Hot-Blast Temperatures

In the forty six year period between 1950 and 1996, the average hot-blast temperature for all the blast furnaces in the United States increased from approximately 550°C (about 1025°F) to approximately 1110°C (1940°F). This improvement was accomplished through the use of better stove firing techniques, higher quality refractories, better designs and better stove changing equipment. Furthermore, improvements in burden materials, the use of tuyere-level injected fuels and the control of blast moisture made it possible for the blast furnace to accept the higher hot-blast temperature. The 500°C (roughly 875°F) increase in hot-blast temperature, along with fuel injection has resulted in an average coke rate of approximately 398 kg/tonne of hot metal (795 lbs/net ton) in 1996 in the United States.

10.6.3 Fuel Injection

With the development of techniques for increasing hot-blast temperatures to the range of 1000–1220°C (1832–2250°F) and the need for controlling the flame temperature because of the type of burden materials in use, it was discovered that hydrocarbon fuels could be injected into the blast furnace through the tuyeres to control the flame temperature, increase the reducing power of the bosh gas and at the same time replace some of the (expensive) coke. In the presence of large quantities of coke, the hydrocarbon fuels can burn only to carbon monoxide and hydrogen; consequently, they produce less heat than the coke they replace resulting in control of the flame temperature, but the reducing gas they produce is more effective than that produced by combustion of coke. Many different fuels have been tried—natural gas, coke oven gas, oil, tar and pulverized coal, even slurries of coal in oil. The equipment for injection of natural gas is the least expensive. The gas is generally fed at a pressure well above that of the air blast to a pipe encircling the furnace, and from this circle pipe individual lines carry the gas to each tuyere. Gas is introduced into the furnace through a lance in the side of the blowpipe, as shown in Fig. 10.5, and combustion takes place in the zone just inside the furnace in front of the tuyere, the raceway. The rate of injection is controlled by the rate of gas flow into the circle pipe. Check valves prevent air from backing up into the gas lines and automatic shutoff valves between the circle pipe and the tuyeres close when the hot-blast pressure exceeds or drops below a predetermined range. In some operations natural gas is injected through a channel cast into the tuyere. This method is usually used where lances are inconvenient.

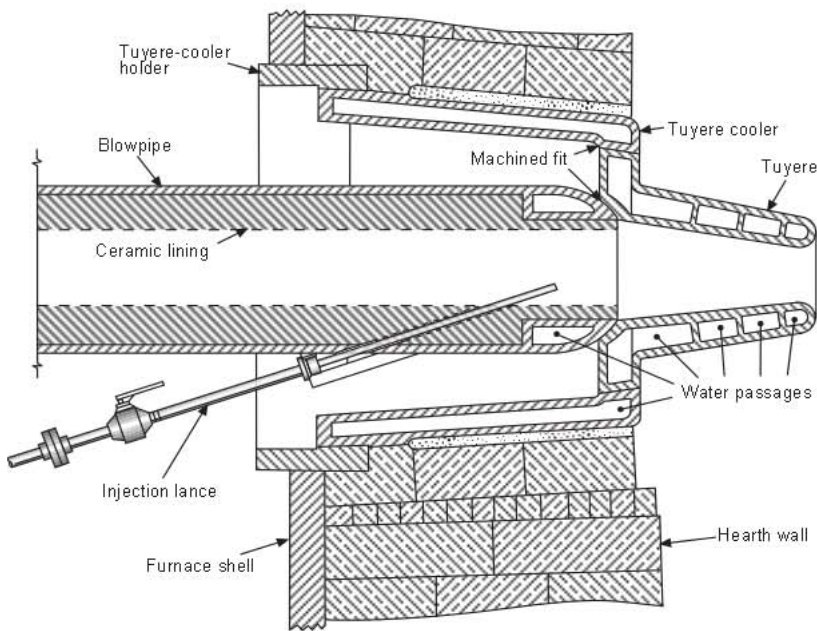


Fig. 10.5 Tuyere and blowpipe assembly, with injection lance.

When coal is used, it is also introduced into the air blast by a lance entering the air stream through the sides of the blowpipes. It is most desirable to have the injected coal completely gasified and combusted before it leaves the raceway just inside the furnace. Because of its relative abundance and low cost, coal has become the injectant of choice in the 1990s. There exist several schemes to deliver coal to the tuyeres, each having its merits and drawbacks. All appear to be workable with proper installation and care. When oil is used it is fed to a circle pipe and then to each tuyere in much the same manner as gas. Steam is used to atomize the oil, which enhances combustion. Coal must be pulverized or granulated and then conveyed to the tuyeres in high pressure air, usually by dense phase transport.

When injecting fuel special precautions are required to avoid the buildup of fuel in the bustle pipe or blowpipe and its subsequent combustion.

10.64 Oxygen Enrichment of the Blast

Although the enrichment of blast air with oxygen to increase hot metal production rates is by no means a new idea, the use of oxygen for this purpose had little commercial interest 35 years ago because of the high cost of oxygen. Furthermore, when the blast air is enriched with oxygen, the flame temperature increases and high flame temperatures were incompatible with the relatively low quality burden materials used then. However, with the discovery of methods for controlling flame temperature with blast moisture and fuel injection, the use of oxygen enrichment has become quite common. There are furnace operations in 1998 using in excess of 12% oxygen enrichment. For every percent of oxygen above that for normal air blast (approximately 21%), the production rate can be increased roughly 2–4%. In instances where the burden materials have good reducibility, that is, they will reduce rapidly, the flame temperature can be increased significantly and the fuel efficiency can be improved. The judicious use of oxygen instead of wind provides a means of controlling the bosh gas mass flow rate so that furnace throughput can be maximized while controlling hot metal quality.

In the manufacture of ferromanganese, where the high temperature heat requirements are much greater than those for basic pig iron, oxygen enrichments as high as 30% in the blast are used commercially.

10.6.5 High Pressure Operation

One of the limiting factors in attempting to increase the wind rate of a blast furnace is the lifting effect that is caused by the large volumes of gases blowing upward through the burden. This lifting effect (the mass flow rate) prevents the burden from descending normally and causes a loss rather than an increase in production. To increase production rates above normal, many furnaces are equipped with septum valves in the top gas system to increase the exit gas pressure. This increase in pressure compresses the gases throughout the entire system and permits a larger amount of air to be blown. With this increase in the quantity of air blown per minute, there is a corresponding increase in production rate; in addition, the formation of SiO is suppressed resulting in lower hot metal silicon content.

When the pressure of the top gas is thus increased, the pressure of the inlet air blast is increased proportionately. At many furnaces, if the top pressure were increased, it would be necessary to use a larger blower, capable of delivering the increased blast volume at the higher pressure.

The furnace shell, stove shells, dustcatcher, primary washer, and gas mains must have the structural integrity to withstand the increased pressure. The throttling valve that is used to increase top pressure is located beyond the primary gas washer where the sandblasting effect of the gas has been reduced by removal of a large portion of the dust carried by the gas from the furnace. The exit water line from the primary washer must be equipped with a regulator so that the gas pressure within the washer will not destroy the water seal. Clean gas or nitrogen is piped into the space between the large and small bells to equalize the pressure in that space with the pressure in the furnace. The equalization of pressure in this location permits the large bell to be opened and reduces erosion that is caused by top gas leaking past the seat of the large bell. The pressure between the bells is reduced to atmospheric by a bypass valve to permit opening of the small bell. With the use of high top pressure, many maintenance problems have been encountered with the bells, hoppers, bleeders, and so on. Experiments are still being conducted with abrasion-resistant materials of construction and such new designs as a 3-bell top and the bell-less top to improve high pressure operation.

At some blast furnaces, top pressures in excess of 200 kPa (2 kg/cm² or 29 psig) have been used successfully. At some of these furnaces, expanding turbines have been installed in the top gas system to recover some of the energy of compression to decrease the cost of operating with such high pressure.

10.6.6 Improved Burden Distribution

As a means of obtaining better control of burden distribution in the blast furnace stack and thereby improving the gas–solid contact and the fuel efficiency, several new developments have been used in recent years.

One such development is a device, movable stockline armor, that can be shifted in and out to change the diameter of the circle of armor and, in this way, change the position where each material will be deposited as it slides off the bell and rebounds from the armor. The use of armor effectively changes the size of the annulus on each bell dump; consequently, by setting the stockline height, the position of the armor and the sequence that materials are placed on the large bell a wide range of burden distribution options can be accomplished. A second development is the elimination of the large bell entirely, and the use of a rotating chute that can be set at different angles and rotated at different speeds so that each charge can be placed exactly where it will give the best distribution. Although it is difficult to install these improvements on older blast furnaces, such devices are being incorporated into the designs wherever new furnaces are built.

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