METALLURGICAL CALCULATIONS

Published by the
McGraw-Hill Book Company
New York

Successors to the Book Departments of the
McGraw Publishing Company Hill Publishing Company

Publishers of Books for
Electrical World The Engineering and Mining Journal
The Engineering Record Power and The Engineer
Electric Railway Journal American Machinist

METALLURGICAL CALCULATIONS

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PART II.
IRON AND STEEL.

SECOND EDITION
Corrected

McGRAW-HILL BOOK COMPANY
239 West 39th Street, New York
6 Bouverie Street, London, E.C.

1910

PREFACE.

In presenting in book form the series of articles which appeared in Electrochemical and Metallurgical Industry from April 1906 to May 1907, the writer wishes to call attention to the idea or plan of the work. The intention is to show how the general chemical, physical and mechanical principles which were elucidated at length in Part 1, can be applied to solving the special problems arising in the metal urgy of iron and steel. To this end, descriptions of processes have been made as brief as was consistent with the clear statement of the particular principles involved, and familiarity with the general principles explained in Part I has been assumed. To gain advantage from the use of this work, the student or reader should master the principles taught in Part I, and posess a certain body of information as to the *modus operandi* of the various processes of making iron and steel.

Part III, which is now running serially in the above-mentioned journal, is concerned with the application of these same principles to the metallurgy of metals other than iron, it is intended on its completion (middle of 1908) to print it uniform with this volume, and so to complete the whole work.

Joseph W. Richards.

Lehigh University,
May 15, 1907.

CONTENTS.

CHAPTER I.

BALANCE SHEET OF THE BLAST FURNACE.

As the most important factor in the production of the most important metal, the blast furnace is the most important furnace or piece of metallurgical apparatus in the world. It is, therefore, proper that we should commence a series of articles on the application of metallurgical principles and calculations to the metallurgy of iron, by a discussion of the blast furnace; and since this discussion, to be complete, must include a wide range of topics, we will commence with the simplest, viz.: the balance sheet of materials, entering and leaving the furnace. Later we can discuss the balance sheet of heat entering in, developed within and leaving the furnace, the reactions taking place in the furnace, the action of hot and of dried blast, the calculation of the proper constituents of the charge, the temperatures attained before the tuyeres, unused combustible energy of the gases, efficiency of the hot-blast stoves, and other interesting and practically valuable factors in the running of the furnace.

The blast furnace may be regarded from several points of view; we will mention two. First, it may be regarded as a huge gas producer, run by hot, forced blast, in which the incombustible portions of the contents are melted down (with a little unburnt carbon) to liquid metal and slag, and are run out beneath, while the gaseous products pass upwards through 50 to 100 feet of burden, and escape above. The escaping gases are primarily of the composition of producer gas, with some of its carbonous oxide changed to CO^2 by the oxygen abstracted from the burden, with some CO^2 added from the decomposition of the carbonates of the charge, and with the usual increment of moisture from the charge and volatile matter (if any) from the distillation of the fuel. From this point of view, the blast furnace is a huge gas producer, giving a rather inferior quality of combustible gas in very large quantities, and incidentally reducing to metal and slag the burden of iron ore and flux (limestone) which is put in with the fuel. The treatment of the furnace as a metallurgical problem may then proceed as the discussion of a gas producer, with the composition of the gas produced somewhat modified by the amount of oxygen given up to the gas by the reducible portions of the charge of the furnace.

The other viewpoint is to regard the furnace as primarily an apparatus for deoxidizing or reducing iron ore, for which purpose the ore is charged with sufficient carbonaceous fuel to do two things, viz.: to abstract all the oxygen from the reducible metallic oxides, and to furnish enough heat, or high enough temperature, to melt down to superheated liquids the pig iron and slag (combinations of irreducible metallic oxides) formed. In this view, the fuel must supply the reducing energy and the melting-down or smelting requirements; the first by acting upon the metallic oxides at a red to a white heat and abstracting their oxygen; the second, by being burned at the foot of the furnace by hot air blast, and there generating the heat and higher temperatures necessary for the smelting down of the already reduced materials.

Materials Charged and Discharged.

The materials put into a blast furnace may all be classed under four heads:

Fuel	Charged at the throat.
Iron ore	
Fluxes	
Blast	Blown in at the tuyeres.

The materials discharged from the furnace may be classed under four heads also:

Pig iron	Tapped from the crucible.
Slag	
Gases	Passing out at the top.
Dust	

We will discuss the resolution of each of the four materials charged into the four avenues of escape.

Fuel.

The fuel used is sometimes charcoal, but in the great majority of cases coke, with perhaps some raw bituminous coal or anthracite coal, or in a few cases all raw bituminous coal. The composition of these fuels consists of moisture, volatile matter, fixed carbon, sulphur and ash consisting of silica, lime, iron, alumina, alkalies, etc.

The moisture is driven off near the top, and goes into the gases as moisture. The volatile matter is expelled near to the top; almost all of it goes unchanged into the gases, but part of the hydrocarbons thus expelled may be decomposed and deposit fixed carbon on the iron oxides, etc., surrounding them. This carbon, however, will take up oxygen from the charge lower down in the furnace, and thus eventually pass into the gases as CO or CO^2. We can, therefore, assume without error that all the volatile constituents of the fuel pass into the gases, but cannot be certain in exactly what state of combination, except as regards the moisture. It will be quite exact if we know the ultimate composition of the volatile matters of the coal, as so much carbon, hydrogen, oxygen, nitrogen, sulphur, etc., to charge them thus entirely to the gases.

The fixed carbon all finds its way ultimately into the dust or the gases, either as CO, CO^2, CH^4 or HCN, or alkali cyanides, excepting the amount represented by the carbon in the pig iron. Subtracting the carbon in the pig iron from the total fixed carbon in the fuel, the difference can safely be put down as entering the gases or being in the dust carried away by the gases.

The sulphur in the fuel has a more varied history. When it is partly present in the form of iron pyrites, some may go into the gases as sulphur vapor, and eventually be burned to SO^2 when the gases are burned; another part may be oxidized in the furnace itself to SO^2, and as such appear in the gases; the rest, along with organic sulphur, passes either into the slag or the pig iron. Sulphur passing into the slag seems to do so as calcium sulphide, CaS, formed by some such reaction as

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

or, if the sulphur was present in the fuel as gypsum,

$$CaSO^4 + 4C = CaS + 4CO$$

The amount of sulphur going into the iron depends really upon the opportunity for it to go into the slag. If the temperature of the furnace at the tuyeres is very high, and especially if the slag is low in silica, sulphur will keep out of the iron and go into the slag, to the extent of ten or twenty times as much being in the slag as in the iron; but if the temperature is low and the slag rich in silica the reverse may be the case. A high temperature and a high percentage of lime in the slag are the blast furnace manager's means of keeping down the sulphur in the iron, although high magnesia or high alumina are also efficacious. In casting up the balance sheet it can be assumed that when using coke or charcoal all the sulphur of the fuel goes either into the slag or the iron, and knowing from the analysis of the pig iron made how much goes into it, the rest can be calculated as going into the slag as CaS. If raw coal is used, it is uncertain how much sulphur goes into the gases, and an exact analysis of either the slag or gases, for sulphur, in addition to that of the pig iron, would be necessary to fix its distribution.

The ash of the fuel counts in with the other incombustible ingredients of the charge. Some of the silica in it may be reduced to silicon, and some of the CaO to Ca, to form CaS; while most of the iron will pass into the pig iron. It is in most cases uncertain whether the silicon in the pig iron comes at all from the fuel ash, so it is usual to assume it as coming from the silica of the ore only; as to the iron, it is best to assume it all reduced to the metallic state, as is probably always the case.

Besides all these avenues of escape for the constituents of the fuel, it is sometimes necessary to take into account the possibility of some of it, in fine particles, being carried out of the furnace bodily with the outgoing gases. If the amount of this in the dust is determined, it must be subtracted *in toto* from the fuel charged, and then the remainder distributed as just discussed.

Illustration.—A blast furnace is charged, per 1,000 kilos. of pig iron produced, with 925 kilos. of coke, containing by analysis: Fixed carbon, 86 per cent.; volatile carbon, 2; hydrogen, 1; oxygen, 0.5; nitrogen, 0.5; sulphur, 1.0; iron, 2; silica, 5; lime, 1; moisture, 1. The pig iron contains 3.5 per cent. of carbon and 0.1 per cent. of sulphur. The dust carries 15 kilos. of dry coke per metric ton of pig iron. Required the distribution of the coke in the furnace per ton of pig iron made:

Charges.		Pig Iron.	Slag.	Gases.	Dust.
Coke........	925.0 kg.				
Dust........	15.0 "	....	....	....	Coke 15.0
Fixed C.....	782.6 "	C 35.0	....	C 747.6	....
Volatile C....	18.2 "	....	....	C 18.2	....
H...........	9.1 "	....	....	H 9.1	....
O...........	4.5 "	....	....	O 4.5	....
N...........	4.5 "	....	....	N 4.5	....
S...........	9.1 "	S 1.0	S 8.1	....	....
Fe..........	18.2 "	Fe 18.2	....	....	....
SiO^2.........	45.5 "	....	SiO^2 45.5	....	....
CaO.........	9.1 "	....	CaO 9.1	....	....
H^2O.........	9.3 "	....	....	H^2O 9.3	....

ORE.

Whatever the varieties of ore used they can be averaged together, so as to get the average composition of the ore charged. Then, knowing its weight per unit of pig iron made, the distribution into pig iron, slag, gases and dust can be made.

There may, first of all, be blown out as ore dust up to 25 per cent. of the ore charged. This must be first deducted as dry ore and then the rest distributed to pig iron, slag and gases.

The moisture of the ore, also any carbonic acid, may be considered as going over bodily into the gases. The sulphur may partly go into the gases if present as iron pyrites (this amount would have to be checked by an analysis of the gases for sulphur or hydrogen sulphide), but mostly into the slag as CaS. Some of it may be put down as going into the pig iron, if the sulphur in the fuel does not account for all that appears in the analysis of the iron. The iron oxides present must be assumed reduced to metallic iron sufficient to furnish the iron in the pig iron from its analysis; the excess, if any, if put down as going into the slag as FeO; all the oxygen given off (the difference between the weight of iron oxide in the ore and the sum of iron going in the pig iron and ferrous oxide passing in the slag) goes to the gases. If there is not enough iron in the ore to account for all in the pig iron, then none is assumed to go into the slag.

The manganese oxides in the ore furnish the manganese in the pig iron, the excess going into the slag as manganous oxide MnO, the oxygen (by difference) goes to the gases. The proportion of manganese reduced to metal increases with the temperature at which the furnace is run and as the slag is less siliceous. The amount reduced is known, however, only by the analysis of the pig iron.

Zinc in the ore is partly found as ZnO in the slag, and partly as flakes of white zinc oxide in the gases, which latter partly deposit in the dust catcher and are partly carried by the current of gases into the stoves and under the boilers. The relative amounts going into slag and gases can be best controlled by analysis of the slag.

Copper, silver, gold, nickel, cobalt, phosphorous, antimony and arsenic are almost completely reduced into the pig iron; careful analysis of the latter will show exactly to what extent, but without this careful analysis they may be assumed to pass completely into the iron. Lead is mostly carried out as fume, a small amount passes into the pig iron, and, if present in quantity, a large amount may collect as metallic lead beneath the pig iron and, if it can, soak into the foundation of the furnace.

Alumina usually passes completely, as such, into the slag. When present in large amount, producing a slag rich in alumina, and with very hot blast, the pig iron may contain as much as 1 per cent. of aluminium, the oxygen thereof passing into the gases. Magnesia may be assumed as passing completely into the slag; none is reduced. Lime goes into the slag, except a not-unimportant quantity which is reduced by carbon in the presence of sulphur compounds, and forms CaS, its oxygen passing into the gases; a very small amount may go as calcium into the pig iron. Alkaline metals partly go into the slag, while some may pass into the gases as alkaline cyanides. Titanium oxide, tungsten oxide, chromium oxide and the oxides of molybdenum, uranium, vanadium are sometimes reduced in small amounts, the more the hotter the furnace is run and the more basic the slag, while the bulk of them passes into the slag as the lowest oxide which each is capable of forming.

Silica mostly goes into the slag as SiO^2, but a portion is always reduced to silicon in the pig iron. The amount reduced is greater the hotter the furnace is run, the more slowly it is run, and the more siliceous the slag. In some cases as much as one-quarter of all the silica going into a furnace is reduced to silicon. It is probably reduced only by carbon dissolved in iron at the lower part of the furnace. The oxygen of the silica reduced goes into the gases.

Illustration.—1956.8 kilograms of ore is charged into a furnace per metric ton of pig iron made. The ore analyses: Fe^2O^3, 71.43 per cent.; SiO^2, 14.24; CaO, 2.05; MgO, 1.51; MnO^2, 4.15; SO^3, 1.40; H^2O, 5.00; Cu^2O, 0.22 per cent. The pig iron contains 93.03 per cent. iron, 3.27 carbon, 1.20 manganese, 0.08 sulphur, 0.40 copper, 2.02 silicon. Assume the dry ore dust to weigh 4 per cent. of the weight of ore charged, and that there is no sulphur found in the gases, but all the sulphur in the pig iron comes from the fuel. Cast up the distribution of the ore:

Charge.		*Pig Iron.*	*Slag.*	*Gases.*	*Dust.*
Ore..........	1956.8 kg.				
Dust.........	78.1 "	....	....	....	Ore 78.1
Fe^2O^3........	1339.2 "	Fe 930.3	FeO 9.1	O 499.8	....
SiO^2.........	267.0 "	Si 20.2	SiO^2 223.6	O 22.2	....
MnO^2........	77.8 "	Mn 12.0	MnO 48.0	O 17.8	....
Cu^2O........	4.1 "	Cu 3.6	....	O 0.5	....
CaO.........	38.4 "	....	CaO 20.1 Ca 13.1	O 5.2	....
MgO.........	28.3 "	....	MgO 28.3	....	....
SO^3..........	26.3 "	....	S 10.5	O 15.8	....
H^2O.........	97.6 "	....	....	H^2O 97.6	....

In calculating the above we note that the dust is dry, and weighs 4 per cent. of the ore, making 78.1 kilos. of dry dust, representing 82 kilos. of moist ore, leaving 1874.8 kilos. of moist ore to be distributed, plus the 3.9 kilos. of water from the dust, which also goes into the gases. This 1874.8 kilos. contains the weights given, calculating from its analysis. The 1339.2 kilos. of Fe^2O^3 contains 937.3 kilos. of iron; but there are only 930.3 kilos. in the ton of pig iron, therefore the other 7.0 kilos. must go into the slag as $7.0\times\frac{72}{56}= 9.1$ kilos. of ferrous oxide, while $1339.2-(930.3+9.1) = 499.8$, the weight of oxygen going into the gases. The 267.0 kilos. of silica contains 124.6 kilos. of silicon, but there are only 20.2 kilos. in the pig iron, therefore, 104.4 kilos. must remain unreduced, passing into the slag as $104.4\times\frac{60}{28} = 223.6$ kilos. of silica, while $267-(20.2+223.6) = 22.2$ kilos. of oxygen goes into the gases. Another, and equally logical procedure, is to start with the 20.2 kilos. of silicon in the pig iron, which must have required $20.2\times\frac{60}{28} = 42.4$ kilos. of silica to furnish it, yielding $42.4-20.2 = 22.2$ kilos. of oxygen to the gases, and leaving $267.0-42.4 = 223.6$ kilos. of silica unreduced to go into the slag.

The 12.0 kilos. of manganese in the pig iron would be reduced from $12.0\times\frac{87}{55} = 19.0$ kilos. of MnO^2, furnishing, therefore, 7.0 kilos. of oxygen to the gases, and leaving $77.8-19.0 = 58.8$ kilos. of MnO^2 to go into the slag as MnO. The molecular weights of MnO and MnO^2 being respectively 71 and 87, there is $58.8\times\frac{71}{87} = 48.0$ kilos. of MnO going into the slag, while 10.8 kilos. more of oxygen will be supplied to the gases, making altogether $10.8+7 = 17.8$ kilos. of oxygen given up by the MnO^2. The 4.1 kilos. of Cu^2O contain 3.6 kilos. of copper, all of which enters the pig iron and contributing 0.5 kilos, of oxygen to the slag.

The 38.4 kilos, of CaO must supply enough Ca to form CaS with the S of the SO^3. The latter quantity is $26.3\times\frac{32}{80} = 10.5$ kilos., to supply which there is needed $10.5\times\frac{40}{32} = 13.1$ kilos. of calcium. The latter will be supplied by $13.1\times\frac{56}{40} = 18.3$ kilos. of CaO, furnishing 5.2 kilos. of oxygen to the gases, and leaving $38.4-18.3 = 20.1$ kilos. of CaO unreduced to go into the slag. The MgO in the ore goes directly into the slag. The oxygen of the SO^3 goes into the gases. The 5 per cent. of water of the whole quantity of ore charged goes into the gases. as vapor.

FLUX.

The flux is used for the purpose of making a fusible slag with the slag-forming ingredients, contributed by the ore and fuel. If we consider the distribution of ore and fuel given in the preceding illustrations we see that the chief material to be fluxed is silica, with smaller quantities of FeO, MnO, CaO, MgO and CaS. The cheapest and most available material to flux silica is limestone, the slag formed being a silicate of lime, magnesia and alumina, with CaS and smaller quantities of other basic oxides. We will not discuss at present the considerations governing the amount of flux used, since this is a calculation requiring separate treatment, as the proper working of the furnace depends fundamentally upon it. We may remark here that enough flux must be used to make an easily fusible fluid slag, rich enough in lime, magnesia or alumina to carry away satisfactorily the bulk of the sulphur, and so produce good pig iron.

The flux usually contains CaO, MgO, Al^2O^3, SiO^2, FeO, CO_2 and H^2O. Its H^2O and CO^2 are driven off in the upper third of the furnace, and may be put down as going as such into the gases. The FeO may be reduced if the slag is very clean, but under ordinary conditions may be put down as all going into the slag, unless in quite large amount, because the iron in ore and fuel usually supplies the total weight of iron in the pig iron. The silica and alumina may be carried over bodily into the slag. The magnesia can be put at once into the slag, but the lime cannot in many cases be treated that way, because quite frequently some is needed to supply calcium for the sulphur of the fuel. In the fuel previously illustrated, for instance, there is not enough CaO present to furnish Ca for the S, whence it follows that some CaO from the flux will be needed to make up the deficit. We may, in such a case, either consider all the CaO of the fuel to form CaS with part of the sulphur, and then take enough CaO from the flux to unite with the remainder, or, it is equally permissible to take all the CaO necessary to furnish Ca to all the sulphur of the fuel, and to let the CaO of the fuel figure as passing entirely into the slag. The latter requires a little less calculation.

Illustration.—A blast furnace receives 503 kilos. of limestone flux per metric ton of pig iron made, which analyses CaO, 29.68 per cent.; MgO, 20.95; SiO^2, 3.07; Al^2O^3, 2.66; FeO, 0.48; CO^2, 42.66; H^2O, 0.50 per cent. Assume 8.1 kilos. of sulphur in the fuel, for which the flux must provide calcium. Required the distribution of the flux, assuming it to make no dust:

Charge.		*Pig Iron.*	*Slag.*		*Gases.*	
Flux	503.0 kg.	....				
CaO	149.3 "	....	Ca CaO	10.1 135.1	O	4.1
MgO	105.4 "	....	MgO	105.4	....	
SiO^2	15.4 "	....	SiO^2	15.4	....	
Al^2O^3	13.4 "	....	Al^2O^3	13.4	....	
FeO	2.4 "	....	FeO	2.4	....	
CO^2	214.6 "	....	......		CO^2	214.6
H^2O	2.5 "	....	......		H^2O	2.5

The only calculation needed above is that 8.1 kilos. of sulphur require $8.1\times\frac{40}{56} = 10.1$ kilos. of calcium, which would be furnished by $10.1\times\frac{32}{40} = 14.2$ kilos. of lime, leaving 4.1 kilos. of oxygen to go into the gases and 135.1 of lime to go into the slag.

BLAST.

The remaining item needed to complete the balance sheet is the amount of blast. This may be roughly estimated by obtaining the piston displacement of the blowing engines, and assuming a coefficient of delivery into the furnace. This is very rough, because the efficiency is not known, and may vary anywhere between 0.5 and 0.95. Another rough approximation may be obtained by observing the pressure of the blast, its temperature, the back pressure in the furnace, and knowing the area of the tuyeres, and assuming a coefficient of contraction of the hot air jet as it emerges from the tuyeres. Here, again, are several uncertain factors, and the coefficient may vary between 0.9 and 0.98. Calculations on this basis are very rough.

The only satisfactory way to determine the blast is to carefully analyze the gases, determining carefully all the carbon, oxygen and nitrogen which they contain. Since the carbon comes only from the charges, the amount of gases produced per unit of pig iron made becomes known, and thence the oxygen and nitrogen contained in them. These, minus the oxygen and nitrogen coming from the solid charges, leave the oxygen and nitrogen which must have come from the blast. The oxygen in the blast, minus $\frac{3}{10}$ the nitrogen, gives the oxygen entering as water vapor; but this last calculation is not so satisfactory as to observe the atmospheric conditions, and calculate the air and moisture on the basis of the contained nitrogen.

The blast contains oxygen, nitrogen and moisture. All its constituents pass into the gases, being put down as so much oxygen, nitrogen and hydrogen. Just how much of that hydrogen gets into the gases as free hydrogen and how much as water vapor is not known. Argon and other rare gases in the blast are counted and treated as nitrogen. The carbonic acid of the air is present relatively in such a small amount that it can be neglected, as far as all ordinary calculations are concerned.

Problem 51.

A blast furnace at Herrang, Sweden, is run on ore briquettes made by pressing and calcining fine concentrates. The analyses of briquettes, charcoal and limestone flux are as follows (see Journal Iron and Steel Institute, I., 1904):

	Briquettes.	*Limestone.*	*Charcoal.*
$Fe^{2}O^{3}$	85.93	0.18	0.32
FeO	3.96	....	C 80.31
SiO^{2}	5.50	3.14	0.19
MnO	0.63	....	N 0.08
$Al^{2}O^{3}$	0.76	0.32	O 3.54
CaO	2.23	53.74	0.89
MgO	0.97	0.17	0.10
$P^{2}O^{5}$	0.006	0.006	0.0068
S	0.010	0.001	0.017
Cu	0.007	CO^{2} 42.42	$H^{2}O$ 14.04
			$K^{2}O$ 0.50

The pig iron contains phosphorus, 0.012 per cent.; sulphur, 0.007; manganese, 0.025; silicon, 0.60; carbon, 2.70; iron, 96.656. There is used in charging the furnace:

Briquettes	1,190 pounds
Limestone	.90 "
Charcoal	530 "

And the fuel consumption is 682 pounds of charcoal per 1,000 pounds of pig iron made.

The gases at the throat (dried) analyze: N^2, 57.3 per cent.; CO, 23.1; CO^2, 14.8; H^2, 4.3; CH^4, 0.5 (Rinman). Assume blast dry. Dust in gases neglected.

Required: (1) A balance sheet of materials entering and leaving the furnace, per 1,000 pounds of pig iron made. (2) The percentages of iron, manganese, silicon, sulphur and phosphorus going into the furnace, which go into the pig iron.

Solution:—(1) See table opposite page.

(2) The total iron in the charge is 969.2 kilos., while that in the pig iron is 966.6; the efficiency of the reduction of iron is therefore 99.7 per cent.

The total manganese in the charge is $9.6\times\frac{55}{71} = 7.4$ kilos., of which only 0.25 gets into the pig iron, or 3.4 per cent.

The total silica charged is 89.1 kilos., representing 41.6 kilos. of silicon, of which 6.0 kilos. enters the pig iron, or 14.4 per cent.

The sulphur charged is 0.270 kilos., of which the pig iron contains 0.07, or 25.9 per cent.

The phosphorus charged is 0.063 kilos., while the analysis of the pig iron shows in it 0.12 kilos. It is thus evident that all the phosphorus goes into the pig iron; for while the analysis shows more phosphorus in the pig iron than was put into the furnace, yet the divergence is evidently due to segregation or concentration of phosphorus in the sample taken, and the practical conclusion is that all the phosphorus in the charge finds its way into the pig iron.

NOTES ON THE BALANCE SHEET.

The Fe^2O^3 of the ore is assumed all reduced, because the 920.4 kilos. of iron in it is less than the 966.6 kilos. of iron known to be in the 1,000 kilos. of pig iron from its analysis.

Solution.- (1)

BALANCE SHEET (PER 1000 OF PIG IRON).

Charges		*Pig Iron*		*Slag*		*Gases*	
Ore	1530.2						
Fe^2O^3	1314.9	Fe	920.4	......		O	394.5
FeO	60.6	Fe	46.2	FeO	1.2	O	13.2
SiO^2	84.2	Si	6.0	SiO^2	69.6	O	8.6
MnO	9.6	Mn	0.25	MnO	9.3	O	0.1
Al^2O^3	11.6	......		Al^2O^3	11.6	.....	
CaO	34.1	......		CaO	34.1	O	0.03
MgO	14.8	......		MgO	14.8	....	
P^2O^5	0.092	P	0.04	......		O	0.05
S	0.153	S	0.07	CaS	0.19	....	
Cu	0.11	Cu	0.11	......		O	0.01
Limestone	115.8						
Fe^2O^3	0.2	......		FeO	0.2	O	0.02
SiO^2	3.6	......		SiO^2	3.6	....	
Al^2O^3	0.4	......		Al^2O^3	0.4	....	
CaO	62.2	......		CaO	62.2	....	
MgO	0.2			MgO	0.2	....	
P^2O^5	0.007	P	0.003	......		O	0.00
S	0.001	......		CaS	0.0	....	
CO^2	49.1	......		......		CO^2	49.1
Charcoal	682.0						
C	547.7	C	27.0	......		C	520.7
N	0.5	......		......		N	0.5
O	24.1	......		....		O	24.1
Fe^2O^3	2.2	......		FeO	2.0	O	0.2
SiO^2	1.3	......		SiO^2	1.3	....	
CaO	6.1	......		CaO	5.9	O	0.06
MgO	0.7	......		MgO	0.7	....	
P^2O^5	0.046	P	0.02	......		O	0.03
S	0.116	......		CaS	0.25	....	
K^2O	3.4	......		K^2O	3.4	....	
H^2O	95.8	......		......		H^2O	95.8
Blast	2416.8						
O^2	557.7	......		......		O	557.7
N^2	1859.1	......		......		N^2	1859.1
Totals	4744.0		1000.0		220.8		3543.7

The FeO, however, cannot be assumed all reduced, because it would furnish 47.1 kilos. of iron, and there is only 966.6 − 920.4 = 46.2 kilos. of iron yet to be supplied. We, therefore, put down 46.2 kilos. of iron as going to the pig iron, thus furnishing all the iron in the pig iron, and leaving 0.9 kilos. of iron to go over into the slag as 1.2 kilos. of FeO. Having thus allowed for all the iron in the pig iron, the Fe^2O^3 in the limestone and fuel must be assumed as passing entirely into the slag as FeO.

The 6 kilos. of silicon in the pig iron is put down as coming entirely from the SiO^2 of the ore, of which 14.6 kilos. is thus used up, leaving 15.6 kilos. to go into the slag. The SiO^2 of flux and fuel must then be regarded as passing entirely into the slag.

The 0.25 of manganese in the pig iron comes from the MnO of the ore, requiring 0.35 of MnO, and leaving 9.3 of MnO to go into the slag.

The Al^2O^3 and MgO of ore, flux and fuel go bodily into the slag.

The sulphur in the ore, 0.153 kilos., is more than enough to supply the 0.07 kilos in the pig iron. We, therefore, put down 0.07 kilos. as going into the pig iron, supplying all the latter contains, and calculate the remaining 0.083 kilos. to CaS going into the slag. The CaO necessary to furnish this calcium is 56 for every 32 of sulphur (CaO = 56, S = 32), or 0.14 kilos., which, therefore, must be deducted from the 34.1 kilos. of CaO present in the ore. The oxygen of this 0.14 kilos. of CaO finds its way into the gases.

The 0.092 kilos. of P^2O^5 present in the ore contain only 0.04 kilos. of phosphorus, and since the pig iron contains, from its analysis, 0.12 kilos., we may assume all of this going into the pig iron. The same remarks are true of the P^2O^5 in flux and fuel; altogether, they come somewhat short of supplying all the phosphorus in the pig iron, and are, therefore, considered as completely reduced. The copper goes entirely into the pig iron, although not given in the analysis.

The Fe^2O^3 of the limestone must be transferred entirely as FeO to the slag, since all the iron needed for the pig iron has been already provided. The same is true of the Fe^2O^3 of the fuel; and an analogous statement applies to the SiO^2 and sulphur of both flux and fuel. The sulphur of the fuel does not produce an amount of CaS which counts in significant figures, and the CaO required is likewise insignificant, as is also the oxygen thus furnished the gases. In such cases, instead of ignoring the item altogether, or putting down wholly insignificant quantities, the amounts are expressed as 0 00, denoting no significant amount.

The fixed carbon of the fuel, only, furnishes the carbon in the pig iron, the rest going into the gases. The blast is calculated as follows:

Carbon in CO^2 of flux $= 49.1\times\frac{12}{44}$ = 13.39 kilos.
Carbon in gases from fuel = $\underline{520.70}$ “
Carbon in gases altogether = 534.09 “
Carbon in 1 cu. meter of gas $(0.231+0.148+0.005)\times 0.54$ = 0.20736 “
Volume of gas per 1,000 of pig iron $534.09\div 0.20736$ = 2575.6 m^3
Nitrogen in this gas 2575.6×0.573 = 1475.9 “
Weight of nitrogen 1475.9×1.26. = 1859.6 kg.
Nitrogen from fuel = 0.5 “
Nitrogen from blast........................= 1859.1 “
Oxygen from blast 1859.1×0.3..............= 557.7 “

CHAPTER II.

CALCULATION OF THE CHARGE OF THE BLAST FURNACE.

In the last chapter we discussed the balance sheet of materials entering and leaving the furnace, showing the distribution of the ingredients of the charge and the blast into the various products and by-products of the furnace. We did not there go into the question as to how the proportions of the charge are determined by the metallurgist in charge of the furnace. There are, however, very few factors of the charge which can be controlled at will. The blast furnace reduces practically all of the iron present in the ore into the pig iron, and, therefore, if the ore contains 50 per cent. of metallic iron and the pig iron 90 per cent., it will take $0.90 \div 0.50 = 180$ parts of ore to furnish the iron in 100 parts of pig iron. The amount of ore to be used per unit of pig iron made is therefore fixed by the richness or poverty of the ore, and is not capable of variation. The amount of fuel used per unit of pig iron made is not fixed *a priori*, as is the amount of ore, but is governed by the calorific requirements of the furnace while in operation. If the pig iron and slag run colder than they should, it is evident that more heat must be put in or developed within the furnace, which the manager promptly proceeds to accomplish by increasing the temperature of the air blast (if he can), or by relatively increasing the amount of fuel in the charge (which he always can). The ratio of the weight of the ore and flux in the charge to the weight of fuel used is called the burden of the furnace, and in practice it is usual to charge at one time a fixed weight of fuel, and to vary the burden according to the heat requirements of the furnace. Changing the burden is therefore only another expression for changing the relative amount of fuel used, and this is varied simply from observation of the temperatures of iron and slag and the conclusions therefrom as to whether the burden is too heavy or unnecessarily light. The amount of blast used is another factor relatively fixed per unit of pig iron produced. Blow more blast, and more pig iron is produced; blow no blast (bank the furnace), and no pig iron is made; the ratio is not quite exact, but it is quite nearly true that, other conditions being equal, the output of pig iron is nearly proportional to the amount of blast blown. Variations in the temperatures of the blast produce important changes, which will be separately discussed.

The amount of flux used is really the one factor in which the manager has the greatest freedom of action. The amount of this indispensable substance used is determined by many factors, and can be varied between quite wide limits without fundamentally deranging the furnace. It is here a question of using sufficient flux in the charge to make with the unreduced constituents of ore and ash of the fuel a slag which shall be well-fused at the temperature of the furnace, shall carry off considerable sulphur, if much is present, and shall not corrode the lining of the furnace. These considerations are so important, and often so little understood, that we will discuss them more at length.

CALCULATION OF THE FLUX AND SLAG.

From the balance sheet of problem 51 it will be seen that the metallurgist running the Swedish blast furnace at Herrang, used, per 1,000 of pig iron made, 1530.2 of ore, 115.8 of limestone flux, 682 of charcoal, and blew in 2416.8 parts by weight of blast. It may with safety be believed that the amount of charcoal used was the minimum which he found by experience necessary to keep his furnace at proper temperature; and most American blast furnace managers will wonder how he could get along with so little. The amount of ore used was the necessary proportion to furnish the iron. The amount of blast was probably all that could be gotten out of the blowing apparatus with which the furnace was provided. Finally, the amount of flux was that amount necessary to make a proper slag. Let us investigate the question as to how its amount was determined and the characteristics of the proper slag.

The ingredients of the slag produced in the case in question are, from the balance sheet:

	From Ore.	*From Flux.*	*From Fuel.*	*Total*
SiO^2.........	69.6	3.6	1.3	74.5
Al^2O^3........	11.6	0.4	....	12.0
CaO.........	34.0	62.2	5.9	102.1
MgO.........	14.8	0.2	0.7	15.7
FeO.........	1.2	0.2	2.0	3.4
MnO........	9.3	....	....	9.3
K^2O.........	....	....	3.4	3.4
CaS.........	0.2	....	0.25	0.45
	140.7	66.6	13.55	220.85

And the percentage composition of the slag:

SiO^2 = 33.73 per cent. FeO = 1.54 per cent.
Al^2O^3 = 5.43 " MnO = 4.21 "
CaO = 26.23 " K^2O = 1.54 "
MgO = 7.11 " CaS = 0.20 "

The crucial question now presents itself, " What guided the metallurgist in choosing the quantity of lime stone used, and in making a slag of the above composition? " The answer to this will develop the whole practice of fluxing.

Primarily, the fundamental guide in this matter is previous experience, as revealed in recorded analyses of slags which have worked properly. Such analyses have been made for a hundred years, and freely published; they show what compositions of slag have been found practicable and suitable in blast furnace practice. As reported by the chemists, the analyses show the varying percentages of SiO^2, Al^2O^3, CaO, MgO, FeO, MnO, etc., found in actual slags made in successful practice, and this information would be the metallurgist's guide in calculating the amount of flux to use to produce a good slag. On studying these analyses, we find that silica and lime are the predominating constituents of all blast furnace slags, the reason being that silica is the principal material to be fluxed, and that lime (from limestone) is the cheapest material which will flux it, and form a fusible slag.

Analyses of numerous blast furnace slags show the following variations of composition:

SiO^2	25 to 65 per cent.	FeO	0 to 6 per cent.
Al^2O^3	3 " 30 "	MnO	0 " 14 "
TiO^2	0 " 10 "	K^2O Na^2O	0 " 3 "
CaO	12 " 50 "		
MgO	0 " 18 "	CaS	0 " 9 "

The above limits are not reached simultaneously by one and the same slag. The ordinary variations may be summarized as follows (according to Ledebur):

	SiO^2	Al^2O^3	CaO + MgO
Producing gray iron, using charcoal	45—65	10— 5	45—25
Producing gray iron, using coke	30—35	15—10	50—55
Producing white iron, using charcoal	45—50	10— 5	45—50
Producing white iron, using coke	30—40	10— 5	60—55
Producing spiegeleisen, using coke	30	10	55—45

In the latter case there is present 5—15 per cent, of MnO.

Among these varied compositions, however, there are various degrees of fusibility, and of suitability to the blast furnace's needs. The most easily fusible slags are those (considering only the main ingredients) which contain 35 per cent. of lime, and in which, if alumina is present, each 1 per cent. of alumina is balanced by the presence of 0.5 per cent. additional lime. This rule gives good slags up to about 65 per cent. of lime and alumina counted together. Another observation is, that with 33 to 40 per cent. of lime in the slag, the amount of silica and alumina together being some 60 to 70 per cent., it is possible to change the relations of silica to alumina within large limits (*i.e.*, from 40 to 50 silica and 20 alumina to 25 or 35 silica and 35 alumina) with very little effect upon the fusibility of the slag. On the other hand, with a low proportion of silica in the slag, say 30 to 40 per cent., it is equally possible to change the relations of lime to alumina within large limits (*i.e.*, from 50 lime and 15 alumina to 35 lime and 35 alumina) with very little effect upon the fusibility of the slag.

The blast furnace manager usually decides upon the kind of slag he will make, on one of three or four assumptions:

(1) If there is little alumina present, and practically no magnesia, he usually assumes some ratio between the weights of silica and lime which he desires his slag to possess, and calculates the weight of flux necessary to make slag conforming to that condition. In charcoal furnaces, where there is prac-

tically no sulphur in the charge, the silica may be 1.5 to 2.0 times the lime present; in coke furnaces, where it is necessary to eliminate much sulphur, this ratio is usually 0.5 to 1.0.

Illustration.—If a ton of iron ore carries 300 pounds of silica, how much limestone, which is practically pure calcium carbonate, will be required to slag it, neglecting flux necessary to slag the ash of the fuel?

Solution.—Pure limestone is $CaCO^3$, or $CaO . CO^2$, and carries 56 per cent. of lime, which will go into the slag, and 44 per cent. of carbonic oxide (CO^2), which goes into the gases. Using x pounds of limestone, the weight of lime going into the slag is $0.56\,x$. If we assume the ratio of silica to lime = 1 for a coke furnace, and 1.75 for a charcoal furnace, we get the two equations and corresponding values of x:

$$\frac{300}{0.56\,x} = 1 \text{ whence } x = \underline{536} \text{ pounds.}$$

$$\frac{300}{0.56\,x} = 1.75 \text{ whence } x = \underline{307} \text{ “}$$

(2) If considerable magnesia is present it is usual to either count it simply as so much lime, or else to calculate the weight of lime to which it is chemically equivalent, and add this to the lime, calling the sum the “summated lime.” The ratio of silica to lime is then used as the ratio of silica to lime plus magnesia, or of silica to summated lime. When there is considerable magnesia present the chemical summation should always be made. Small amounts of MnO, FeO and K^2O or Na^2O are also chemically summated as lime. The chemical summation is based on the fact that one molecule of a base containing one atom of oxygen is considered the equivalent in fluxing power of any other similar molecule; *e.g.*, CaO, MgO, FeO, MnO, K^2O, Na^2O are considered as equivalent; but as these molecules weigh differently, we have equivalent fluxing powers in the following weights:

CaO	56
MgO	40

FeO	72
MnO	71
K^2O	94
Na^2O	62

from which we conclude that since 40 parts by weight of magnesia is equivalent to 56 parts of lime, that, therefore, the lime equivalent of any weight of magnesia is $\frac{56}{40}$ of the weight of the magnesia. Similarly, we get the lime equivalent of these bases as follows:

CaO equivalent of any weight of MgO $= \frac{56}{40} \times$ weight MgO
" " " " FeO $= \frac{56}{72} \times$ " FeO
" " " " MnO $= \frac{56}{71} \times$ " MnO
" " " " $K^2O = \frac{56}{94} \times$ " K^2O
" " " " $Na^2O = \frac{56}{62} \times$ " Na^2O

Illustration.—An iron ore contributes to the slag 350 pounds of silica, 12 of FeO and 60 of MnO. It is desired to flux it by using limestone containing 38.1 per cent. lime, 13.6 magnesia, 3.4 silica, and 44.9 carbonic oxide (CO^2). How much flux must be used to produce a ratio of silica to summated lime = 0.8?

Solution.—Letting x be the pounds of limestone used, the ingredients of the slag will be

$$
\begin{aligned}
SiO^2 &= 350 + 0.034\,x \\
CaO &= 0.381\,x \\
MgO &= 0.136\,x \\
FeO &= 12 \\
MnO &= 60
\end{aligned}
$$

The lime equivalents of the MgO, FeO and MnO are:

$$\begin{array}{lll}
\text{CaO equivalent of MgO} & = 0.136\,x \times \frac{56}{40} = & 0.1904\,x \\
\text{" \quad " \qquad FeO} & = 12 \quad \times \frac{56}{72} = & 9.33 \\
\text{" \quad " \qquad MnO} & = 60 \quad \times \frac{56}{71} = & 47.32 \\
\text{" \quad " \qquad CaO} & = 0.381\,x \times 1 = & 0.381\,x \\
\hline
 & \text{Summated CaO} = & 0.5714\,x + 56.65
\end{array}$$

The ratio of silica to summated lime is therefore:

$$\frac{350 + 0.034\,x}{56.65 + 0.5714\,x} = 0.8$$

Whence $x = \underline{720}$ pounds.

It is easily seen that this method of solution, calling x the weight of flux used, and then getting expressions for the weight of each ingredient in the slag and the weight of the whole slag, is a very general solution which is applicable to any kind of assumed composition to which it is desired that the slag shall conform.

(3) If alumina is present in the slag-forming constituents of the ore it also may be reckoned with in several ways. It may be reckoned as so much by weight, and added in as such to the silica or the lime, or it may be calculated to its silica or its lime equivalent, and added into the summated silica or the summated lime. Here we touch on a question which has agitated blast furnace managers and theorists for a generation: Should the alumina be reckoned with the bases or with the acids; summated as silica or as lime? It would be presumptuous to set forth a dictum on a subject which has been so long and so ably discussed by some of the best iron metallurgists, but we will assume, as somewhere near the truth, that as far as the elimination of sulphur in the slag is concerned,

alumina acts in slags low in silica as though it were lime, not in the proportions of its lime equivalent

$$=\left(\frac{168}{102}\times\text{weight of alumina}\right)$$

but rather in about the proportions of its simple weight. As far as fusibility is concerned, in high silica slags alumina increases the fusibility up to a certain point, above which it decreases it. It acts in these, therefore, like lime, and may be classed with the bases. In low silica slags, below 45 per cent., alumina acts like silica when considerable is present, and like lime when less is present; for instance, in a low lime, high alumina slag, alumina and silica may be substituted one for the other within wide limits, without materially affecting the fusibility of the slag; in a high lime, high alumina slag, alumina and lime may be substituted for each other within wide limits without sensibly changing the fusibility. To state the matter as succinctly as possibe, in slags low in silica (30 to 35 per cent.), alumina reinforces the bases in the elimination of sulphur; in regard to fusibility, it acts like silica in a slag low in both silica and lime, and like lime in all other blast furnace slags.

Illustration.—An iron ore carries 10 per cent. of its weight of silica and 6 per cent. of alumina. The lime stone on hand contains 37.3 per cent. lime, 13.3 magnesia, 3.3 silica, 44 carbonic oxide (CO^2), and 2.1 per cent. alumina. How much flux is required per 1,000 parts of ore to make (*a*) a slag with 49 per cent. of silica plus alumina; (*b*) a slag with 33 per cent. silica; (*c*) a slag with summated silica = the summated lime?

Solution.

$$\begin{array}{llcr}
(a) & \text{Weight of } SiO^2 \text{ in slag} & = & 100+0.033\,x \\
 & \text{Weight of } Al^2O^3 \text{ in slag} & = & 60+0.021\,x \\
 & \text{Weight of CaO in slag} & = & 0.373\,x \\
 & \text{Weight of MgO in slag} & = & 0.133\,x \\
\hline
 & \text{Total weight of slag} & = & 160+0.560\,x
\end{array}$$

therefore,

$$160+0.054\,x = 0.49\,(160+0.560\,x)$$

whence

$$x = \underline{370}$$

(*b*) $100+0.033\,x = 0.33\,(160+0.560\,x)$

whence

$$x = \underline{313}$$

(*c*) Silica $= 100 \quad +0.033\,x$

Silica equivalent of alumina $= \frac{180}{204}\,(60+0.021\,x)$

Summated silica $= 153 \quad +0.0515\,x$

Lime $= \quad 0.373\,x$

Lime equivalent of magnesia $= \frac{56}{40} \quad (0.133\,x)$

Summated lime $= \quad 0.5592\,x$

therefore $153+0.0515\,x = 0.5592\,x$

whence $x = \underline{300}$

Returning to the slag resulting from the proportions of flux chosen in Problem 51, and containing:

SiO^2	33.74 per cent.	FeO	1.54 per cent.
Al^2O^3	5.43 "	MnO	4.21 "
CaO	46.23 "	K^2O	1.54 "
MgO	7.11 "	CaS	0.20 "

We see that its percentage of silica is low, therefore it is adapted to produce pig iron low in sulphur; its percentage of alumina is low, and therefore its presence increases the fusibility of the slag, which would otherwise be rather deficient, because of the high lime and somewhat considerable amount of other bases. In such a slag, alumina would be summated with the bases.

The ratio of silica to bases is.................. $\frac{33.74}{66.06} = 0.516$

The ratio of silica to lime plus magnesia is...... $\frac{33.74}{53.33} = 0.632$

The summated lime $= 46.23$

$+CaO$ equivalent of $Al^2O^3 = \frac{168}{102}\,(5.43) = \ 8.94$

$$+\text{CaO equivalent of MgO} = \frac{56}{40}(7.11) = 9.95$$

$$+\text{CaO equivalent of FeO} = \frac{56}{72}(1.54) = 1.20$$

$$+\text{CaO equivalent of MnO} = \frac{56}{71}(4.21) = 3.32$$

$$+\text{CaO equivalent of K}^2\text{O} = \frac{56}{94}(1.54) = \underline{0.92}$$

$$70.56$$

$$\text{Ratio silica to summated lime} = \frac{33.74}{70.56} = 0.478$$

Problem 52.

In a blast furnace charge, consisting of 1530.2 pounds of ore and 682 pounds of charcoal, per 1,000 pounds of pig iron made, it is known from the balance sheet of above materials that they will contribute to the slag the following slag-forming ingredients. (See balance sheet, Problem 51):

SiO^2	70.9 pounds.	FeO	3.2 pounds.
Al^2O^3	11.6 "	MnO	9.3 "
CaO	39.9 "	K^2O	3.4 "
MgO	15.5 "	CaS	0.4 "

The limestone at hand contains:

CaO	53.74 per cent.	Al^2O^3	0.32 per cent.
MgO	0.17 "	Fe^2O^3	0.18 "
SiO^2	3.14 "	CO^2	42.42 "

Required.—The weight of limestone to be used to make: (1) A slag containing 33.74 per cent, of silica. (2) A slag in which the ratio of silica to bases is 0.516. (3) A slag in which the ratio silica to summated lime is 0.478.

Solution.—This problem embodies the conditions which confront the metallurgist when desiring to calculate the flux needed by any given furnace, and we have assumed certain working ratios to be aimed at in the slag, in order to elucidate the method of solution.

Constituents of Slag.

	From Ore and Fuel.	*From Flux.*	*Total.*
SiO^2	70.9	$0.0314\,x$	$70.9+0.0314\,x$
Al^2O^3	11.6	$0.0032\,x$	$11.6+0.0032\,x$
CaO	39.9	$0.5374\,x$	$39.9+0.5374\,x$
MgO	15.5	$0.0017\,x$	$15.5+0.0017\,x$
FeO	3.2	$\frac{144}{160}\,(0.0018\,x)$	$3.2+0.0016\,x$
MnO	9.3	......	9.3 ....
K^2O	3.4	......	3.4 ....
CaS	0.4	......	0.4 ....
	154.2	$0.5753\,x$	$154.2+0.5753\,x$

(1) To make a slag with 33.74 per cent. of silica we must have

$$70.9+0.0314\,x = 0.3374\,(154.2+0.5753\,x)$$

whence $x = \underline{116}$ pounds.

(2) To make a slag with ratio of silica to bases 0.516 we must have

$$70.9+0.0314\,x = 0.516\,(82.9+0.5439\,x)$$

whence $x = \underline{116}$ pounds.

(3) To make a slag with ratio of silica to summated lime 0.478, we must first summate the lime as follows:

Lime $= 39.9+0.5374\,x$

Lime equiv. of $Al^2O^3 = \frac{168}{102}\,(11.6+0.0032\,x) = 19.1+0.0053\,x$

" " $MgO = \frac{56}{40}\,(15.5+0.0017\,x) = 21.7+0.0024\,x$

" " $FeO = \frac{56}{72}\,(3.2+0.0016\,x) = 2.5+0.0012\,x$

" " $\mathrm{MnO} = \frac{56}{71}(\ 9.3) \qquad = \ 7.3$

" " $\mathrm{K^2O} = \frac{56}{94}(\ 3.4) \qquad = \ 2.0$

Summated lime $= 92.5 + 0.5463\,x$

therefore

$$70.9 + 0.0314\,x = 0.478\,(92.5 + 0.5463\,x)$$

whence $x = \underline{116}$ pounds.

COMPARISON OF FUELS, FLUXES AND ORES.

By properly utilizing the preceding principles, it is possible to compare different varieties of fuels, fluxes or ores with each other, and thus to determine their relative values to the furnace, as far as can be inferred from their chemical composition. (Some of the following methods are from a paper by Mr. F. W. Gordon, Trans. Am. Institute Mining Eng., 1892, p. 61.)

COMPARISON OF FUELS.

If different qualities of fuel are available it is possible to calculate which is the most advantageous to use in the furnace. The fixed carbon only is efficient for the furnace, and not all of that, because the ash of the fuel needs to be fluxed to slag. and a certain amount of the fixed carbon will need to be burned simply to melt this slag. Then the cost of the limestone to be used to flux this ash must be counted in, and finally part of the labor costs of running the furnace must be charged against the slag. We can thus calculate the total charges against the fuel to supply one part of available carbon, which is the best basis upon which to compare different fuels.

Illustration.—Two varieties of coke are available for a blast furnace, analyzing respectively:

	No. 1.	No. 2.
Fixed carbon	84 per cent.	90 per cent.
Volatile matter	2 "	1 "
Moisture	5 "	3 "
Ash	9 "	6 "

And costing respectively $4.50 and $5.50 per ton. The ash of the fuels analyzes respectively:

	No. 1.	No. 2.
Silica	55 per cent.	25 per cent.
Alumina	25 “	5 “
Lime	15 “	50 “
Magnesia	5 “	10 “
Ferric oxide	— “	10 “

They are to be fluxed with the limestone of preceding problem, assumed to cost $1.00 per ton, and to make a slag carrying 40 per cent. of silica and alumina together. Assume an average of 0.228 parts of fixed carbon necessary to melt down 1 part of slag, and that the manufacturing costs borne by the slag amount to $1.00 per ton. What are the relative values of the two fuels in this furnace?

Solution.—The amounts of flux needed to 100 parts of each fuel burned will be found as follows, letting x be the amount of flux used:

	Slag No. 1.	Slag No. 2.
Silica	$4.95+0.0314\,x$	$1.50+0.0314\,x$
Alumina	$2.25+0.0032\,x$	$0.30+0.0032\,x$
Lime	$1.35+0.5374\,x$	$3.00+0.5374\,x$
Magnesia	$0.45+0.0017\,x$	$0.60+0.0017\,x$
Ferrous oxide	$0.0016\,x$	$0.54+0.0016\,x$
Total weights	$9.00+0.5753\,x$	$5.94+0.5753\,x$

Therefore, in case No. 1:

$$7.20+0.0346\,x = 0.40\,(9.00+0.5753\,x)$$

whence $x = 18.4$

And in case No. 2:

$$1.80+0.0346\,x = 0.40\,(5.94+0.5753\,x)$$

whence $x = -2.9$

The negative value in case No. 2 simply means that the ash of fuel No. 2 is more basic than the slag, and, therefore, requires no limestone, but itself acts as a basic flux. Per ton of fuel burned, there would be required respectively 0.184 and −0.029 tons of limestone, and the weights of slag would be 0.196 tons and 0.0427 tons. (Substituting values of x in the total weights of slags.)

The weights of fixed carbon necessary to smelt these weights of slag would be:

No. 1. 0.196 × 0.228 = 0.0447 tons.
No. 2. 0.0427 × 0.228 = 0.0097 "

Leaving as available fixed carbon for the furnace in each case:

No. 1. 0.84 − 0.0447 = 0.7953 tons.
No. 2. 0.90 − 0.0097 = 0.8903 "

From these figures the cost of 1 ton of available carbon furnished by each fuel, adding in manufacturing cost chargeable against the slag, is

No. 1.
Cost of coke, $4.50 ÷ 0.7953 = $5.658
Cost of limestone, $1.00 × 0.184 ÷ 0.7953 = 0.231
Costs against slag, $1.00 × 0.196 ÷ 0.7953 = 0.246
$6.135

No. 2.
Cost of coke, $5.50 ÷ 0.8985 = $6.233
Cost of limestone, $1.00 × (− 0.092) ÷ 0.8903 = −0.101
Cost against slag, $1.00 × 0.0065 × 0.8903 = 0.007
$6.139

The two fuels, at the prices given, are therefore of almost exactly the same value to the furnace.

The solution along the lines shown is general, for any desired composition of slag, or for use with any given limestone, and is a valuable means of comparing the values of different fuels. The cost of a ton of pure, available carbon, when furnished by any given fuel, is an item which is useful when comparing the relative values of different fluxes or ores with each other.

Comparison of Fluxes.

If different qualities of flux are available it is very desirable to be able to calculate which is the most economical to use in the furnace. Any acid ingredients in the flux diminish very sharply its efficient fluxing power, because they must first be satisfied from the bases present in the same proportions as acid to bases in the final slag. The slag thus formed from the impurities requires further to be melted, and other costs are properly chargeable against it. The best comparison is finally obtained by calculating for each flux available the cost from it of pure net lime, or net summated lime, analogous to the calculation for pure net carbon in the case of fuels. Any ordinary condition may be imposed upon the slag which the furnace is to produce.

Illustration.—There are available for a furnace two qualities of limestone, containing respectively:

CaO	53.74	per cent.	47.80	per cent.
MgO	0.17	"	4.61	"
SiO^2	3.14	"	5.12	"
Al^2O^3	0.32	"	3.36	"
Fe^2O^3	0.18	"	1.10	"
CO^2	42.42	"	37.55	"

The first costs $1.00 per ton, the second $0.80. Assume them smelted with fuel furnishing pure available fixed carbon at $6.135 per ton; that 0.228 tons of pure fixed carbon is needed to smelt 1 ton of slag; that manufacturing costs against slag are $1.00 per ton, and that the slag to be made in the furnace must have summated silica equal to summated lime. Compare the relative values of the two fluxes.

Solution.—We will direct our calculations towards finding the net cost of 1 ton of pure available summated lime from each of the two limestones. The summated lime and silica in each flux are:

	No. 1.	No. 2.
Summated lime	0.5411	0.5502
Summated silica	0.0342	0.0808
Excess of summated lime	0.5069	0.4694

The weights of slag formed from the impurities present in each limestone will be:

	No. 1.	No. 2.
CaO (difference between amount present and excess of summated lime found)	0.0305	0.0086
MgO	0.0017	0.0461
FeO	0.0016	0.0099
SiO^2	0.0314	0.0512
Al^2O^3	0.0032	0.0336
Totals	0.0684	0.1494

The cost of 1 ton of pure available lime from each of these fluxes will therefore be, adding in costs chargeable against the slags formed by the impurities present:

No. 1.	
Cost of limestone, \$1.00 ÷ 0.5069	= \$1.973
Cost of carbon for melting slag, \$6.135 × 0.228 × 0.0684 ÷ 0.5069	= 0.188
Costs of running, chargeable against slag, \$1.00 × 0.0684 ÷ 0.5069	= 0.135
	\$2.296
No. 2.	
Cost of limestone, \$0.80 ÷ 0.4694	= 1.904
Cost of carbon for melting slag, \$6.135 × 0.228 × 0.1494 ÷ 0.4694	= 0.465
Cost of running, chargeable against slag, \$1.00 × 0.1494 ÷ 0.4694	= 0.318
	\$2.487

The conclusion is that the poorer limestone, at \$0.20 per ton less cost, is in reality costing \$0.191 per ton more for pure available lime, or is in reality 8.3 per cent. dearer than the first, instead of being 20 per cent. cheaper.

The method of calculation here described is quite general for any compositions of limestone or other flux, and for any assumed conditions which the slag must conform to.

Comparison of Ores.

As the more complicated, we come to the comparison of various ores which may be at the iron master's disposal. Here a similar method of procedure is advisable. It can be calculated first, for a unit weight of ore, how much pure lime would be required to flux its impurities, how much pure carbon would be required to melt the slag thus formed, and to the costs of each of these would be added the handling of the slag. Each of these can be also expressed per unit of pure oxide of iron in the ore; and if to their sum we add the cost of ore necessary to furnish unit weight of pure oxide of iron we obtain the total costs per unit weight of pure iron oxide (Fe^2O^3). This is the basis on which different ores may then be compared. It must not be forgotten that one ore may, because of higher sulphur content, require the production of a more basic slag, so that the amounts of flux required and slag formed will be influenced by the condition necessary to impose on the slag in each case.

Illustration.—The iron ore briquettes (of Problem 51) contained Fe^2O^3, 85.93 per cent.; FeO, 3.96; SiO^2, 5.50; MnO, 0.63; Al^2O^3, 0.76; CaO, 2.23; MgO, 0.97 per cent. If these cost $4.40 per ton, and are smelted in a furnace making slag with ratio of silica to bases 0.516, and assuming 0.3 per cent. of the iron, 82.7 per cent. of the silica, and 96.6 per cent. of the manganese to go into the slag, what is the cost per ton of pure Fe^2O^3 from this source, charging pure lime for fluxing at $2.296 per ton, pure carbon for smelting slag at $6.135 per ton, and requiring 0.228 tons of carbon for one of slag, adding also manufacturing costs at $1.00 per ton of slag?

Solution.—The slag-forming ingredients from 1 ton of ore briquettes are:

$$\text{FeO } 0.003\times\frac{72}{56}\times\left[\left(0.8593\times\frac{112}{160}\right)+\left(0.0396\times\frac{56}{72}\right)\right] = 0.0024 \text{ tons}$$

MnO 0.966×0.0063 = 0.0061 "
CaO = 0.0223 "
MgO = 0.0097 "
Al^2O^3 = 0.0076 "
SiO^2 = 0.0455 "

and the bases to satisfy the silica present must
be $0.0455\div0.516$ = 0.0882 "
But, sum of bases already present = 0.0482 "
therefore, pure lime to be added = 0.04~~17~~00 "
and total weight of slag = 0.1337 "

Efficient Fe^2O^3 in 1 ton of ore = 0.8593 "
plus Fe^2O^3 equivalent of reduced FeO

$$= \frac{160}{144}(0.0396-0.0024) = 0.0413 \text{ "}$$

Total available Fe^2O^3 = 0.9006 "

Cost of 1 ton pure available Fe^2O^3 from these briquettes:

Cost of ore, \$4.40 ÷ 0.9006 = \$4.885
Cost of pure lime, \$2.296 × 0.0417 ÷ 0.9025 = 0.106
Cost of carbon for melting slag, \$6.135 × 0.228 × 0.1337 ÷ 0.9025 = 0.207
Costs chargeable against slag, \$1.00 × 0.1337 ÷ 0.9025 = 0.148
Total = \$5.346

A similar calculation is possible with any ore of any given composition, and making any assumed quality of slag. The costs of 1 ton of pure ferric oxide thus calculated will give the relative costs of the iron obtained from these different sources, and therefore indicate the relative values of the different ores to the blast furnace manager.

Problem 53.

Assume a blast furnace manager to use the ore of preceding illustration, furnishing pure Fe^2O^3 at a net cost of \$5.336 per ton, and to use with it fuel furnishing pure carbon at \$6.135 per ton, there being required for reduction and melting the iron produced and furnishing it with carbon, 0.66 tons of pure available carbon per ton of pig iron produced, and the pig iron containing 96.656 per cent. of iron. The running costs of the furnace are \$3.00 per ton of pig iron produced (costs against slag not included).

Required:—The cost of the pig iron per ton.

Solution:

Fe^2O^3 required 160 ÷ 112 × 0.96656 = 1.3808 tons.

Cost of the ore, \$5.336 × 1.3808 = \$7.368
Cost of fuel, \$6.135 × 0.66 = 4.049
Cost of manufacturing (share against pig iron) = 2.000
Total cost = \$13.417

CHAPTER III.

UTILIZATION OF FUEL IN THE BLAST FURNACE.

The blast furnace, in its simplest terms, may be regarded as a huge gas producer, producing in the region of the tuyeres pure producer gas from fixed carbon and heated air; the gas thus produced is partly oxidized in its ascent through the furnace by the oxygen abstracted from the charge (which latter item is almost a constant quantity per unit of pig iron made), and has added to it carbon dioxide from the carbonates of the charge. But, after all, the unoxidized and combustible ingredients of the gas escaping represent a large part, in fact, often the largest part, of the total calorific power of the fuel.

Problem 54.

A blast furnace uses 2,240 pounds of coke, containing 90 per cent. fixed carbon and 350 pounds of limestone, containing 10 per cent. of carbon (as carbonic acid, CO^2) to produce a ton of pig iron containing 4 per cent. of carbon. The gases contain 24 per cent. of carbonous oxide, CO, 12 per cent. of carbonic oxide, CO^2, 2 per cent. of hydrogen, 2 per cent. of methane, and 60 per cent. of nitrogen.

Required.—(1) The volume of gas, as analyzed, produced per ton of pig iron made.

(2) The calorific power of the gas.

(3) The proportion of the calorific power of the coke which has been generated in the furnace.

Solution.—(1) The carbon going into the gases will be that in the coke, less that in the pig iron, plus that in the carbonates of the charge.

Carbon in coke = 2,240 × 0.90 = 2,016 pounds
Carbon in carbonates = 350 × 0.10 = 35 "
Carbon charged = 2,051 "
Carbon in pig iron = 2,240 × 0.04 = 89.6 "

Carbon going into the gases = 1,961.4 "

Carbon in 1 cubic foot of gas:

In CO 0.24×0.54
In CO^2 0.12×0.54
In CH^4 0.02×0.54

Total $0.38 \times 0.54 = 0.2052$ ounces av.
$= 0.012825$ pounds

Gas produced per ton of pig iron $= \dfrac{1{,}961.4}{0.012825} = 152{,}935$ cu. ft. (1)

(2) Calorific power of 1 cubic foot of gas:

CO $0.24 \times 3{,}062 = 734.9$ oz. cal.
H^2 $0.02 \times 2{,}613 = 52.3$ "
CH^4 $0.02 \times 8{,}598 = 172.0$ "

Sum $= 959.2$ "
$= 59.95$ pound cal.
per 152,935 cubic feet = 9,168,450 pound cal. (2)

(3) The calorific power of the coke considering it to contain simply 90 per cent. of fixed carbon, would be

$8{,}100 \times 0.90 = 7{,}290$ pound cal. per pound.

The presence of CH^4 in the gases points, however, to there being probably some available hydrogen in it, which would increase its calorific power somewhat. A closer approximation to the calorific power of the coke could, therefore, be obtained by assuming at least as much available hydrogen in it as would correspond to the hydrogen in the CH^4 in the gas.

CH^4 in 152,935 cu. ft. of gas = 3,059 cu. ft.
Weight of this $= 3{,}059 \times (0.09 \times 8)$ = 2,202 oz. av.
= 137.7 lbs.
Hydrogen $= 137.7 \times (4 \div 16)$ = 34.4 lbs.
Available hydrogen in coke $= 34.4 \div 2{,}240$ = 1.54 per cent.
Calorific power $0.0154 \times 29{,}030$ = 447 lb. cal. per lb.
Total calorific power of the coke = 7,737 " "
Calorific power of coke used per ton $7{,}737 \times 2{,}240$ = 17,330,880 lb. cal.
Calorific power of the gases = 9,168,450 "

Calorific power generated = 8,162,430 "
= 47.1 per cent.

This figure, however, practically over-charges the furnace little bit, because the pig iron with its 4 per cent. of carbon really takes out of the furnace some unburnt fuel, whose heat of combustion may be utilized outside the furnace as in the Bessemer converter. The furnace does not generate heat from this, representing:

$$2{,}240 \times 0.04 \times 8{,}100 = 725{,}760 \text{ lb. cal.}$$

leaving as actually generated in the furnace

$$\begin{aligned} 8{,}162{,}430 - 725{,}760 &= 7{,}436{,}670 \text{ lb. cal.} \\ &= 42.9 \text{ per cent.} \qquad (3) \end{aligned}$$

Such an average blast furnace cannot, therefore, be accused of generating within it over some 43 per cent. of the calorific power of the fuel put into it, while the heat rejected as potential energy of combustion of the waste gases amounts to more than half the calorific power of the fuel. Fifty years or more ago, when these waste gases were allowed to burn truly to waste the blast furnace was indeed a devourer of fuel, but matters have been improved by the utilization of the waste gases to heat the blast, and thus one of the largest " leaks " of heat from the furnace has been patched up to some extent, although yet far from satisfactorily.

Problem 55.

Assume that in problem 54, one-third of the gases produced are burnt in hot-blast stoves, preheating the air blown in at the tuyeres, and that the blast is thus preheated to 450° C.

Required.—(1) The amount of blast blown in per ton of pig iron made.

(2) The heat in the blast.

(3) The efficiency of the hot-blast stoves.

(4) The increased efficiency of the blast furnace plant as a whole in generating the calorific power of the fuel, when thus provided with this hot-blast apparatus.

Solution.

(1) Volume of (dry) gases per ton = 152,935 cu. ft.

Nitrogen present in these (60%) = 91,761 "

$$\text{Air containing this} = \frac{91{,}761}{0.792} = 115{,}860 \text{ "} \qquad (1)$$

This is the volume of the blast per ton of pig iron produced, assuming no nitrogen to come from the coke used, and the blast to be dry. If the blast were moist, and its hydrometric condition known, the volume of moist blast could be calculated.

(2) Assuming the blast dry, it is heated to 450° C., requiring

$$115{,}860 \times [0.303 + 0.000027\ (450)] \times 450 = 16{,}430{,}975 \text{ oz. cal.}$$
$$= 1{,}026{,}936 \text{ lb. cal.}$$

(3) The hot-blast stoves receive one-third of all the gas produced, having, therefore, a calorific power of

$$9{,}168{,}450 \div 3 = 3{,}056{,}150 \text{ lb. cal.}$$

$$\text{Efficiency of the stoves} = \frac{1{,}026{,}936}{3{,}056{,}150} = 0.336 = 33.6 \text{ per cent.} \qquad (3)$$

(4) The blast furnace was primarily rejecting unused 57.1 per cent. of the calorific power of the fuel, 4.2 per cent., however, as a necessary loss, to supply the carbon in the pig iron, but 52.9 per cent. as combustible power of unburnt waste gases. If one-third of these gases are completely burnt in hot-blast stoves, then the combined plant—furnace plus stoves—is utilizing 17.6 per cent. more of the calorific power of the fuel than before, or 42.9+17.6 = 60.5 per cent., and, therefore, rejecting undeveloped 39.5 per cent. of the calorific power. (4)

[The net effect of the use of the hot-blast stove, upon the heat generation in the furnace, is practically to put back into the furnace, as sensible heat, 1-3×33.6 = 11.2 per cent. of the calorific power of the waste gases, equal, therefore, to 0.112× 52.9 = 5.9 per cent. of the total calorific power of the fuel. This renders available, for the working of the furnace, 42.9+ 5.9 = 48.8 per cent. of the calorific power of the fuel, an increase of available heat for reducing and smelting of $\frac{5.9}{42.9}$ = 13.7 per cent. of the former available quantity.]

The practical conclusion is that a blast furnace generates in itself not much over 40 per cent. of the calorific power of the fuel used, and rejects nearly 60 per cent.; by using part of the waste gases to heat the blast, however, some of this rejected heat, to an amount representing net 5 to 10 per cent. of the calorific power of the fuel used, is returned to and injected bodily into the furnace, thus rendering available for the purposes of running the furnace some 50 per cent. of the calorific power of the fuel as a maximum. The efficiency with which the furnace applies this 50 per cent. usefully to the objects of reducing and smelting, is another question for investigation.

Problem 56.

Assume that at the furnace of Problems 54 and 55 the two-thirds of the waste gases are burnt under boilers, raising steam which runs the blowing engines, hoists and pumps, and providing 10 effective horse-power for each ton of pig iron made per day in the furnace.

Required.—(1) The efficiency of development of the calorific power of the fuel in the plant (furnace, stoves, boilers, engines) regarded as a whole.

(2) The thermo-mechanical efficiency of the boiler and engine plant.

(3) The power which could be generated if gas engines, at 25 per cent. thermo-mechanical efficiency, were used in their stead.

Solution.—(1) Since the stoves completely burn one-third of the waste gases, and the boilers the other two-thirds, all the combustible power of the waste gases is developed in the combined plant, and the only part of the calorific power of the fuel which is unused is the 4.9 per cent, represented by the carbon necessarily entering into the composition of the pig iron. The plant as a whole, therefore, develops or generates 95.1 per cent. of the calorific power of the fuel used.

(2) For each ton of pig iron, the heat developed under the boilers will be two-thirds of the calorific power of the gases, or

$$9{,}168{,}450 \times 2\text{-}3 = 6{,}112{,}300 \text{ lb. cal.}$$

There is generated thereby 10 effective horse-power days, equal to

$$10 \times 33{,}000 \times 60 \times 24 = 475{,}200{,}000 \text{ ft. lbs}$$

$$\text{But } 1 \text{ lb. cal.} = 425 \times 3.2808 = 1394.3 \text{ “}$$

Therefore, thermal equivalent of

$$\text{work done} = \frac{475{,}200{,}000}{1394.3} = 340{,}800 \text{ lb. cal.}$$

Thermo-mechanical efficiency of boiler and engine plant:

$$\frac{340,800}{6,112,300} = 0.0557 = 5.57 \text{ per cent.} \qquad (2)$$

(3) Gas engines, at 25 per cent. thermo-mechanical efficiency, would give power representing per ton of pig iron produced:

$$6,112,300 \times 0.25 = 1,528,075 \text{ lb. cal.}$$

Equal to $$1,528,075 \times 1394.3 = 2,130,645,900 \text{ ft. lbs.}$$

or $$\frac{2,130,645,900}{33,000 \times 60 \times 24} = 44.9 \text{ horse-power days.} \qquad (3)$$

A quicker solution is:

$$10 \times \frac{25}{5.57} = 44.9 \quad \text{“} \quad \text{“} \qquad (3)$$

Leaving net *surplus* power per ton of pig iron produced per day = 34.9 horse-power.

The preceding problems have elucidated the question of the small proportion of the calorific power of the fuel which is generated in a blast furnace, showing it to be, in usual practice only 40 to, at most, 50 per cent. of the calorific power. The discussion has not explained “ why,” but a further consideration will throw light on this question also.

The proportion of the calorific power of a fuel which is generated in a blast furnace is solely a question of how much of it is burned to carbonic oxide, CO^2, and how much to carbonous oxide, CO? If all the carbon were burned to CO^2, practically all the calorific power of the fuel would be generated; if all were burned to CO, only $\frac{2,430}{8,100} = 0.30 = 30$ per cent. of the heating power of the carbon would be generated. If a blast furnace was filled with nothing but coke, and air blown in as usual at the tuyeres, carbon would be burned in the furnace only to CO, and but 30 per cent, of its calorific power be generated and available for the needs of the furnace. The entire gain over this percentage is due to the oxidation of CO to CO^2 by the oxygen abstracted from the solid charges, that is, by the act of reduction. In Problem 54 we calculated that under ordinary conditions, between 40 and 50 per cent. of the calorific power of the fuel is generated in the furnace; the excess of this above 30 per cent. is due to the oxidation of CO to CO^2 during the reduction of the metallic oxides in the charge. From this standpoint it is advisable to strive to perform the greatest possible proportion of the reduction in the furnace by CO gas, because in this case the total generation of heat in the furnace per unit of fuel charged will tend towards a maximum. Since no carbon can be burned to CO^2 at the tuyeres, it follows that, *from the standpoint of the generation of the maximum quantity of heat in the furnace, from a given weight of fuel,* Grüner was right in formulating his dictum of the ideal working of a blast furnace. viz.:

GRÜNER'S "IDEAL WORKING."

All the carbon burnt in the furnace should be first oxidized at the tuyeres to CO, and all reduction of oxides above the tuyeres should be caused by CO, which thus becomes CO^2. This dictum is not in Grüner's own words, but expresses their sense, and from the point of view of the present discussion, it is the correct principle upon which to obtain the maximum generation of heat in the furnace from a given weight of fuel. It practically directs us to generate at the tuyeres 30 per cent. of the calorific power of the carbon oxidized in the furnace, and the rest that can be obtained from the carbon is to be generated during the reduction of the charge.

If we apply this principle to the furnace and data of Problem 54, we should first observe that the carbon oxidized in the furnace is:

Carbon in coke charged...............	2016.	pounds
Carbon in pig iron produced...........	89.6	"
Carbon oxidized in furnace............	1926.6	"

Requiring, if all oxidized to CO at the tuyeres

$$1926.6 \times \frac{4}{3} \text{ lbs. oxygen} = 2569. \text{ pounds.}$$

But, Problem 52 shows us that there was actually blown into this furnace 115,860 cubic feet of blast, containing, therefore,

$$115{,}860 \times 0.208 \times (1.44 \div 16) = 2{,}169 \text{ lbs. oxygen,}$$

capable of oxidizing to CO at the tuyeres

$$2{,}169 \times 0.75 = 1{,}627 \text{ lbs. carbon.}$$

Proportion of carbon gasified burnt at the tuyeres,

$$\frac{1{,}627}{1926.6} = 0.844 = 84.4 \text{ per cent.}$$

It is, therefore, true of the furnace under discussion, that if Grüner's ideal working be called standard, this furnace attains to 84.4 per cent. of that ideal; and it is also true that this furnace generates from the carbon burnt at the tuyeres 84.4 per cent. of the amount of heat which could have been generated if Grüner's ideal working had been attained.

It is always possible to find out for any given blast furnace, by similar calculations, how much carbon is burned at the tuyeres, and how much is burned above the tuyeres, and thus to determine how closely the furnace running approximates to Grüner's ideal working. This proportion or percentage will not necessarily express how efficiently the furnace is running, as regards fuel used per unit of iron made, but it will tell what proportion of the calorific power of the fuel used is being generated at the tuyeres, and in possibly nine cases out of ten this proportion indicates the general efficiency of the furnace as regards fuel consumption.

It will be next profitable to inquire when and under what conditions Grüner's ideal working does not correspond to maximum fuel economy, and why it usually does. The answer is not difficult to understand: if all the carbon gasified in the furnace is burned to CO at the tuyeres, 30 per cent, of the total calorific power of the carbon burned is there developed, which is more than half of all the heat generated from carbon in the furnace. To this must also be added the sensible heat in hot blast, which may amount (as in Problem 52) to some 5.9 per cent. of the calorific power of the carbon, making, therefore, a total of 35 per cent. of the calorific energy of the fuel generated at the tuyeres out of a total of about 50 per cent. developed in the furnace. If, however, the blast be heated to a very high temperature, or particularly if it be dried, or if the ore and fuel are extra pure, so that a smaller quantity of heat is needed to melt down slag at the tuyeres, then there may not be needed at the tuyeres the generation by combustion of so much heat as Grüner's ideal working would require and cause to be produced, and to burn at the tuyeres all the carbon oxidized in the furnace would be wasteful of fuel. In this,case although less heat would be generated per unit of fuel, by burning some of it above the tuyeres, yet economy in fuel consumption as a whole would be attained, because of the *better distribution* of the heat which was generated from a smaller total quantity of fuel.

Illustration.—In Problem 55 we assumed that the furnace ran with blast heated to 450° C., and that this hot blast, burning at the tuyeres 84.4 per cent. of all the carbon gasified in the furnace, smelted down pig iron and slag satisfactorily and kept the tuyere region at proper temperature. If the temperature of this blast were raised to 900° C., how much greater proportion of heat would be available in the tuyere region?

We have already calculated that the 115,860 cubic feet of blast used per ton of iron made, brought in at 450° C., 1,026,936 pound calories of heat, equal to 5.9 per cent. of the calorific power of the fuel put into the furnace. If the temperature were 900° C., the heat brought in would be

$$115{,}860 \times [0.303 + 0.000027\ (900)] \times 900 = 37{,}920{,}978 \text{ oz. cal.}$$
$$= 2{,}370{,}061 \text{ lb. cal.}$$

which equals

$$\frac{2{,}370{,}061}{17{,}330{,}880} = 0.137 = 13.7 \text{ per cent.}$$

of the calorific power of the fuel, a gain of 7.8 per cent. added to the heat available in the tuyere region. This causes a very great increase in the smelting-down power of the furnace, enabling the same work per ton of ore smelted to be done with much less consumption of fuel in the tuyere region. An idea of this increased smelting-power may be obtained from the following comparison of heat available for smelting purposes in the tuyere region in the two cases just discussed:

Case 1.

Heat developed by oxidation of carbon per ton of iron made, 1,627 lbs.×2,430	= 3,953,610 lb. cal.
Sensible heat in blast at 450° C.	= 1,026,936 “
Total heat available	= 4,980,546 “

CASE 2.

Heat developed by same quantity of air burning same carbon = 3,953,610 "
Sensible heat in blast at 900° C. = 2,370,061 "

Total heat available = 6,323,671 "

It is, therefore, seen that the heat generated and available at the tuyeres is increased 1,343,125 calories, amounting to 27 per cent. of the amount disposable in Case 1. It follows, therefore, that the smelting down power has been increased 27 per cent., and that, if the 4,980,546 calories were sufficient for satisfactorily smelting down the iron and slag in the first instance, that the extra heat of Case 2 can all be utilized for smelting down 27 per cent. extra burden. We can, therefore, charge 27 per cent. more burden per unit weight of coke in Case 2, because we have the requisite smelting down power at the region of the tuyeres, which amounts to saying that we can charge 22 per cent. less coke for a given weight of pig iron made.

In actual practice, as the amount of burden is increased and the temperature of the blast increased, the change causes more and more of the carbon to be oxidized above the tuyeres, and a smaller proportion to be oxidized at the tuyeres, thus obtaining less service in the furnace from oxidation of carbon as a whole, but compensating for this by the extra heat in the hot blast. Or, looking at it in another way, we may say that the same heat could be made available in the region of the tuyeres, when using hot blast, by the combustion there of a smaller quantity of carbon; therefore, we can burn more of it above the tuyeres and yet work more economically on the whole, than we were working in the first instance, with the colder blast.

MINIMUM CARBON NECESSARY IN THE FURNACE.

Many writers have assumed that in the reduction of iron, oxide, such as Fe^2O^3, the reaction of its reduction by carbonous oxide, CO, is expressed as follows:

$$Fe^2O^3 + 3CO = 2Fe + 3CO^2$$

If this were true, there would need to be burnt to CO at the tuyeres only 3C, or 36 parts of carbon, to ensure the reduction of Fe^2O^3, representing 112 parts of iron. The reaction does not, however, progress as shown, because CO^2 acts oxidizingly on Fe to such a degree that when $1CO^2$ is present in the gas for 1CO left unused, the reduction practically stops, even though the gases are moving slowly through the warm ore. The real reaction of reduction by CO gas is therefore more nearly represented by

$$Fe^2O^3 + 6CO = 2Fe + 3CO + 3CO^2,$$

which shows that 112 parts of iron would require at least 72 parts of carbon to be oxidized at the tuyeres to CO, in order to produce the gas necessary for its reduction. The presence of some CO^2 in the furnace coming directly from carbonates in the charge would neutralize still more of the reducing power of the CO gas, and cause still more of it to be theoretically required for reduction. The minimum amount of carbon necessary to be charged in the furnace will be that necessary to furnish fixed carbon enough for this reducing gas and for the carbon in the pig iron. This would be, per 100 parts of pig iron, containing say 93 iron and 3 carbon, and using coke containing 90 per cent. of fixed carbon:

Carbon burnt at tuyeres = $72 \times 93 \div 112$	= 59.8
Carbon in pig iron	= 3.0
Total fixed carbon necessary	= 62.8
Total coke to supply this = $62.8 \div 0.9$	= 69.8

It results from these calculations that if " Grüner's ideal working " of a blast furnace were carried out to the practical extent of reducing all the charge by carbonous oxide, CO, and oxidizing no carbon at all directly above the tuyeres, that about 63 parts of fixed carbon would be required per 100 of pig iron made, requiring from 70 to 80 parts of fuel, according to its richness in fixed carbon (90 to 80 per cent.). In practice, as is well known, *more* than this is commonly used, because of the larger proportion of unused CO in the gases than above assumed: and *less* than this has been regularly used, showing that economy of fuel can be attained without adhering to " Grüner's ideal working," in fact, by transgressing it as far as one dares.

The principle involved can be best grasped by a calculation of the amount of carbon which would be required by the furnace, supposing all the heat necessary for melting down the charge were supplied by electrical means, thus dispensing, for the purposes of this supposition, with the necessity of blast and the consequent necessity of oxidizing any carbon by any other agent than the oxygen given up by the ore. In this case the gases resulting would be, let us assume, of the same composition as before, that is, containing equal volumes of CO and CO^2, and since this oxygen is abstracted altogether from the ore, the reaction is

$$Fe^2O^3 + 2C = 2Fe + CO + CO^2$$

This would represent the utilization of carbon in an electrically-heated furnace, and would require per 100 of pig iron made, assuming it 3 per cent. carbon and 93 iron:

Carbon for reduction $24 \times 93 \div 112$	= 19.9
Carbon in pig iron	= 3.0
Total fixed carbon necessary	= 22.9

Or only a little over one-third as much as the minimum required when the smelting down is done by blast.

Aside from electrical furnace practice, however, this discussion proves that whatever fixed carbon burns or oxidizes above the region of the tuyeres, in a blast furnace, absorbs oxygen from the charges with three times the efficiency of carbon first burnt at the tuyeres. Every pound of oxygen abstracted from the charges by solid carbon requires the use or intervention of only one-third as much carbon as that which is abstracted by CO gas; or, each pound of carbon abstracting oxygen directly from the charge takes from it three times as much oxygen as a pound of carbon first burnt to CO at the tuyeres possibly can.

The ordinary furnace produces at the tuyeres, in order to get heat enough to melt down the charges, *more* CO gas than is needed to abstract all the oxygen from the charges; under these conditions it is uneconomical to oxidize any carbon at all above the tuyeres. The exceptional furnace, because of pure ores, small amount of slag, pure fuel, high temperature of blast, or dry blast, gets heat enough at the tuyeres to melt down the charges *without* producing enough CO gas to reduce all the charges; under these conditions more or less reduction is effected by solid carbon, and with the greatest economy in quantity of carbon required in the furnace. These are the conditions under which, having passed the turning point, the greater economy of fuel is attained the farther away one can get from " Grüner's ideal working."

CHAPTER IV.

THE HEAT BALANCE SHEET OF THE BLAST FURNACE.

Twenty-eight years ago, Sir Lothian Bell first constructed a satisfactory heat-balance sheet for a blast furnace. His observations were largely, and his experience altogether, confined to the reduction of the argillaceous siderite ores of the Cleveland district, England, and although he made numerous attempts to draw general conclusions from the data at hand applicable to iron smelting in general, yet many of his deductions remain true only for the particular ores and manner of working characteristic of the Cleveland district.

No treatment of this subject, however, can be based otherwise than upon Bell's researches, following the lines laid down, in his "Principles of the Manufacture of Iron and Steel."

HEAT RECEIVED AND DEVELOPED.

The items on this side of the balance sheet are:

(1) Combustion of carbon to carbonous oxide (CO).
(2) Combustion of carbon to carbonic oxide (CO^2).
(3) Sensible heat of the hot blast.
(4) Heat of formation of the pig iron from its constituents.
(5) Heat of formation of slag from its oxide constituents.

(1) and (2) *Combustion of carbon in the furnace.* There is but one satisfactory way to determine with exactness the amounts under this heading. From the balance sheet, the total amount of carbon passing into the gases is obtained; from the analysis of the gases, the weight of carbon per unit volume of gases is calculated; the first divided by the second gives the volume of gases per unit weight of pig iron produced. The amount of CO and CO^2 in these gases is then obtained by use of the gas analysis, and if from the total CO and CO^2 in the gases there be subtracted the CO and CO^2 contributed *as such* by the solid charges, the difference is the CO and CO^2 which have been formed in the furnace. The heat evolved in the formation of these quantities can then be calculated.

Illustration.—In Problem 51 it was calculated that per 1,000 kilos. of pig iron produced, 534.09 kg. of carbon went into the gases; also that the analysis of the gases showed 0.20736 kg. of carbon in each cubic meter of gas. The quotient indicated, therefore, 2575.6 cubic meters of gas produced per ton of pig iron. From the analysis of the gases there was in this volume,

$$2575.6\times 0.231 = 595.0 \text{ m}^3 \text{ of CO}$$
$$2575.6\times 0.148 = 381.2 \text{ m}^3 \text{ of CO}^2$$

whose weights were

$$595.0\times 1.26 = 749.7 \text{ kg. CO}$$
$$381.2\times 1.98 = 754.8 \text{ kg. CO}^2$$

The balance sheet shows, however, 49.1 kg. of CO^2 contained in the limestone flux used, which can be assumed as entering the gases bodily. Subtracting this we have 705.7 kg. of CO^2 formed in the furnace, and 749.7 kg. of CO, containing respectively

$$705.7\times\frac{12}{44} = 192.5 \text{ kg. of C in CO}^2$$

$$749.7\times\frac{12}{28} = 321.3 \text{ kg. of C in CO}$$

The heat generated in the furnace by the oxidation of carbon is, therefore,

$$\begin{aligned} 192.5\times 8100 &= 1{,}559{,}250 \text{ Calories} \\ 321.3\times 2430 &= \phantom{1{,}}780{,}760 \quad \text{``} \\ &\overline{\phantom{=}2{,}340{,}010} \quad \text{``} \end{aligned}$$

If this carbon could have been entirely burnt to CO^2, there would have been generated

$$513.8\times 8100 = 4{,}161{,}780 \text{ Calories}$$

Showing that only 56 per cent. of the calorific power of the carbon was developed in the furnace; the other 46 per cent. exists as potential calorific power in the waste gases, and part of it is really put back into the furnace as sensible heat in the hot blast.

There is a little doubt as to how to consider the CH^4 in the gases; that is, whether the heat of its formation should be reckoned in as developed in the furnace. This would be $(C,H^4) = 22{,}250$, or 1,854 Calories per kg. of carbon contained therein. Its presence in the gas probably results largely from the distillation of the fuel at a high temperature, and the heat required to disunite the CH^4 from the solid fuel is probably as great as is represented by its heat of formation from carbon and hydrogen. The item is, therefore, a doubtful one, and as far as we know, we may be coming about as near to the truth by omitting it altogether as by counting it in. If we wished to add it in the illustration just given the calculation would be:

Volume of CH^4 $= 2575.6 \times 0.005 = 12.88$ m³
Weight of C $= 12.88 \times 0.54 = 6.9$ kg.
Heat of formation $= 6.9 \times 1{,}854 = 12{,}793$ cal.

It should be emphasized that in this calculated heat of oxidation of carbon in the furnace, no account has been taken whatever of *where* in the furnace this heat is generated. Above all, the mistake should not be made of supposing that the 780,760 Calories produced by formation of CO represents the heat generation at the region of the tuyeres; nothing could be further from the truth. A great deal of carbon is burnt to CO at the tuyeres, and some above the tuyeres, but a goodly proportion of this CO oxidizes by abstracting oxygen from the charge and becomes CO^2. It would not be incorrect, however, to divide the heat of oxidation of carbon in the furnace into two parts, viz: to assume all the carbon as first forming CO, and part of this CO afterwards forming CO^2, corresponding to the amount of the latter formed in the furnace. If this were done, we would have

513.8 kg. C to CO $= 513.8 \times 2430 = 1{,}248{,}535$ Cal.
449.2 kg. CO to CO^2 $= 449.2 \times 2430 = 1{,}091{,}475$ "

2,340,010 "

This analysis gives us the information that of the total heat generated by the oxidation of carbon in the furnace, somewhere about one-half is generated by its burning to CO, and the other half by the further oxidation of CO to CO^2; and we also know that the larger part of the former takes place at the tuyeres, and all of the latter takes place during the reduction of the charges in the upper part of the furnace.

If we know, however, or have calculated the amount of the blast received by the furnace, or, more properly speaking, the amount of oxygen in the blast, then the heat generated by oxidation of carbon at the tuyeres becomes known. In the previous illustration, taken from Problem 51, we can also take from the same problem the weight of oxygen in the blast, 557.7 kilos. This would burn $557.7 \times 0.75 = 418.3$ kg. of carbon to CO at the tuyers, generating there

$$418.3 \times 2430 = 1{,}016{,}410 \text{ Calories},$$

or 44 per cent. of all the heat generated by oxidation of carbon in the furnace, leaving 1,323,610 Calories as generated above the tuyeres by the agency of the oxygen of the charges. These figures tell us just where and how the principal items of heat were generated in this particular furnace, and the similar calculation may be made for any blast furnace for which we have the necessary data.

(3) *Sensible heat in the hot blast.* To calculate this item, we need to know the weight or volume of the different constituents of the blast and their temperature. The question at once arises, as to what base line of temperature shall be chosen. It is most convenient to choose 0° C., since that is not over 15° from the average temperature in the largest iron producing countries. However, any other prevailing temperature may be taken as the base line, involving merely a little more calculation, since our specific heats are reckoned from 0° C. The temperature ought, moreover, to be taken as near to the tuyeres as possible, to properly take into account the effect of cooling of the blast in the bustle and feeder pipes, from radiation and expansion. The blast consists of air proper and moisture, the former with a mean specific heat between 0° and t° C of $0.303 + 0.000027t$, in kilogram Calories per cubic meter, or in ounce calories per cubic foot, the latter with a similar mean specific heat of $0.34 + 0.00015t$. Since the moisture at times amounts to as much as 5 per cent. of the blast, it should be calculated separately.

Illustration: With the outside air at 30° C., and saturated with moisture (raining), calculate the heat carried into a blast furnace by blast carrying in 1859.1 kilos. of nitrogen, the temperature of the heated blast being 600° C. Barometer 720 millimeters of mercury. Temperature base line 0° C.

Solution: One cubic meter of the moist blast, as taken into the blowing cylinders, carries all the moisture it can hold, the tension of which is therefore 31.5 millimeters. The tension of the air proper present is therefore 720−31.5 = 688.5 millimeters, and each cubic meter of moist air carries

$$\frac{31.5}{720} = 0.0438 \text{ cubic meter of moisture, and}$$

$$\frac{688.5}{720} = 0.9562 \text{ cubic meter of air proper.}$$

Whatever the temperature of the blast, the moisture and air proper will be in this same proportion whenever its temperature is over 30° C. If the temperature were 0° C. the moisture would be mostly condensed, but for the purposes of calculating the heat brought in we may assume the moist air to be at 0° C., with its moisture uncondensed. That volume of blast which would be 1 cubic meter at 0° and 760 mm. pressure, would, therefore, bring in, at 600° C., the following quantity of heat:

H^2O	$0.0438\times[0.34 + 0.00015\ (600)]\ \times 600 =$	11.3	Calories
Air	$0.9562\times[0.303+0.000027\ (600)]\ \times 600 =$	179.7	"
	Total	191.0	"

Since the nitrogen present in this is

$$0.9562\times 1.293\times\frac{10}{13} = 0.9511 \text{ kg.}$$

the heat brought in per 1859.1 kg. of nitrogen is

$$191.0\times\frac{1859.1}{0.9511} = 373{,}344 \text{ Calories.}$$

An amount equal to over one-third of all the heat generated by combustion of carbon at the tuyeres.

(4) *Heat of formation of pig iron from its constituents.* The

pig iron contains several per cent., some 5 to 10 altogether, of carbon, silicon, manganese, phosphorus, sulphur and other elements. The energy of their combination with the iron is a somewhat indefinite quantity, and in no case can be considable. Berthelot states the energy of combination of carbon with iron as $(Fe^3,C) = 8,460$, which would be 705 Calories per kilogram of carbon, and another investigator (Ponthière) states the heat of combination of phosphorus with iron to be zero. In the present state of uncertainty it is hardly allowable to add in any other than the heat of combination of the carbon in the iron, and leave out that of the other elements.

(5) *Heat of formation of the slag from its constituent oxides.* Here we touch upon a quantity of more than insignificant proportions, yet which is not yet quantitatively known with satisfactory accuracy. The main constituents of the slag are SiO^2, Al^2O^3, CaO, MgO and CaS, which are provided by clay, limestone and iron sulphide. If we allow, on the other side of the balance sheet, for the heat necessary to de-hydrate clay, drive carbonic acid off carbonates, and break up iron sulphide and enough CaO to furnish Ca for CaS, we are then entitled, on the other hand, to place in the heat evolution column the heat of combination of aluminum silicate with lime and magnesia, the heat of formation of CaS and its heat of solution in the silicate slag. The heat of formation of CaS is 94,300 Calories, or 2,947 Calories per kilogram of sulphur; its heat of combination with a silicate slag is unknown. The heat of combination of lime with aluminum silicate has been determined only for the proportions 3CaO to $Al^2Si^2O^7$, that is, for 168 parts of CaO uniting with 222 parts of aluminum silicate. This has been determined in Le Chatelier's laboratory as $(3CaO, Al^2Si^2O^7) = 33,500$ Calories which is 200 Calories per unit of CaO combining, or 150 Calories per unit weight of $Al^2O^3 + SiO^2$. The calculation would be made on the basis of the amount of lime (plus lime equivalent of magnesia present), if it were present in a smaller ratio than 168 to 222 of silica and alumina, and on the basis of the silica and alumina, if their ratio to the summated lime were less than 222 to 168. It is probable that in the near future these quantities will be known more accurately.

One item of heat received by the furnace has not been mentioned, because of its usual absence, viz.: heat in hot charges. Very rarely roasted ore comes hot to the furnace, in which case its sensible heat must be counted in, else the thermal sheet of the furnace will be that much out of balance.

HEAT ABSORPTION AND DISBURSEMENT.

The items on this side of the balance sheet are:

(1) Sensible heat in waste gases, including water vapor only as vapor.
(2) Sensible heat in outflowing slag.
(3) Sensible heat in outflowing pig iron.
(4) Heat conducted to the ground.
(5) Heat conducted and radiated to the air.
(6) Heat abstracted by cooling water, tuyeres, etc.
(7) Heat for de-hydrating the charges.
(8) Heat for vaporizing water from charges.
(9) Heat absorbed by decomposition of carbonates.
(10) Heat absorbed in reduction of iron oxides.
(11) Heat absorbed in reduction of other metallic oxides.
(12) Heat absorbed by decomposition of moisture of the blast.

(1) *Sensible heat in waste gases.* The amount of these gases is known only from the carbon contained in unit volume, by analysis, and the known weight of carbon entering and leaving the furnace. If there is much fine coke carried over by the blast, allowance must be made for the carbon in it, because this would not be represented in the gas analysis. The analysis of completely dried gas is that usually obtained, because if the gas is measured without drying, an uncertain amount of moisture is condensed, and, therefore, it is usual to dry before measuring and analyzing. The amount of moisture in the gases is either assumed as that driven off from the charges, as shown by the balance sheet, or else is determined directly by drawing the gases through a calcium chloride tube or other dessicating apparatus. Several tests should be made to get a fair average, because much more will be in the gases immediately after charging than immediately before. Dust must be excluded from the drying tube by filtering the gases through dry asbestos. The average temperature of the gases should be known over a considerable period; a thermo-couple

in the down-comer gives this most accurately and more uniformly than if inserted above the stock line in the furnace.

The weight of moisture per unit volume of dry gas is then converted into volume at standard conditions by dividing by 0.81 (1cubic meter = 0.81 kg; 1 cubic foot = 0.81 ounce avoirdup.). The sensible heat of the gases is then calculated, using 0° C. as the base line, and the proper mean specific heats of the gases per unit of volume. The water vapor will here be considered simply as a gas, and its sensible heat above water vapor at 0° only calculated. This leaves the latent heat of vaporization of this water to be considered as a separate item (606.5 Calories), that is, as heat absorbed by reactions in the furnace, thus putting it on exactly the same footing as the CO^2 in the gases which has been expelled from carbonates in the furnace. By so proceeding much uncertainty as to the heat in the water vapor is avoided.

If the amount of flue dust is considerable its quantity should be ascertained, and the heat in it also calculated and added in to the heat in the moist gases. Its specific heat may be approximated as so much carbon, iron oxide and silica, the proportions of each of these present being known.

(2) *Sensible heat in outflowing slag.* The weight of slag produced is seldom taken directly, but can be reckoned up with all needful accuracy from the balance sheet of materials entering and leaving. Its temperature and specific heat, solid and liquid, melting point and latent heat of fusion, are unfortunately almost always unknown factors. The one datum which is needful, however, is the total heat in a unit weight of liquid slag as it flows from the furnace, and this is not a difficult quantity to obtain. A rough calorimeter with a reliable thermometer and containing a carefully weighed quantity of water, may be easily constructed. Some liquid slag is run directly into it, and by observing the rise of temperature and afterwards filtering out, drying and weighing the granulated slag, a satisfactory determination can be arrived at. This is corrected to 0° C. by using an approximate specific heat, say 0.20, for the range of final calorimeter temperature to zero. In this connection it is important to note that the calorimetric determinations of Akerman on blast-furnace slags, give the heat in the *just-melted* slag, whereas slags flowing out of a

furnace are considerably, some 200° to 500° C., above their melting point, and therefore contain some 50 to 150 Calories more heat than that given by Akerman for a slag of similar composition. Since Akerman's values run from 350 to 400 Calories, the actual heat in the outflowing slag may be between 400 and 550 Calories. Akerman himself states that an average of twenty-seven Swedish furnaces gave 530 Calories as the actual heat in unit weight of outflowing slag, and Bell uses 550 in most of his calculations on Cleveland (England) furnaces.

(3) *Heat in outflowing pig iron.* The heat in *just-melted* pig iron is evidently too small a quantity to use in this connection. The heat in the outflowing pig iron at 200° to 500° above its melting point will be 50 to 100 Calories greater. The former quantity is about 245 Calories; the latter will be 300 to 350. Bell takes 330 for Cleveland furnaces; Akerman states 250 to 325 for Swedish furnaces. We may conclude then, to use 300 Calories for a coke furnace running cool, and up to 350 Calories for a very hot furnace.

(4) *Heat conducted to the ground.* This is a very uncertain quantity. It varies with the kind of ground, and is more nearly a constant per day than per unit of pig iron produced. It is, therefore, expressed per unit of iron produced, larger for small furnaces run slowly than for large furnaces run fast. It is less when running rich ores and greater with poor ores, other things being equal. As nearly as can be assumed we would put this item as lying between 60 and 200 Calories per unit of pig iron made. Bell uses 169 on one Cleveland furnace, but it is certainly less than 100 in some charcoal furnaces using pure ores and fuel, and consequently with a small heat requirement.

(5) *Heat conducted and radiated to the air.* This item is likewise more nearly a constant quantity per day for a given furnace, and is therefore less per unit of iron produced the faster the furnace is run. It may vary between 60 and 250 Calories per unit of pig iron, the former in furnaces of low heat requirement per unit of iron produced, the latter in those of high heat requirement. If the amount were calculated it would figure out as a time function, and would require the temperature of the outside shell, that of the air, the velocity of the wind, and the total outside surface, in order to calculate

by the principles of heat radiation and conduction, the amount radiated per day. No one has done this yet for any one furnace, and, in brief, items (4) and (5) of this schedule are usually grouped together and determined simply by difference, their sum aggregating from 100 to 500 Calories per unit of pig iron, averaging 100 to 150 for charcoal furnaces of low heat requirement, 200 to 450 for Cleveland furnaces (Bell), and 300 to 500 for large, modern furnaces with thin walls and great height.

(6) *Heat abstracted by cooling water.* In the old-fashioned heavy masonry, cold blast furnace, this item was zero. With the advent of hot blast, the water needed for cooling the tuyeres entered as a heat abstracting factor. It is greater the harder a furnace is blown, but does no increase proportionately with the output. The heat lost by tuyere-cooling water may be 50 to 100 Calories per unit of pig iron made. That for cooling of bosh plates and the outside of the crucible in modern furnaces, may vary all the way up to 200 Calories. These two items are very large in a modern furnace, but are necessary expenditures of heat energy in order to preserve the lines of the furnace during fast running. For any particular furnace they may be determined with all needful accuracy by measuring the amount of water pumped or used for these purposes and its temperature before and after using.

(7) and (8) *Drying and de-hydrating charges.* Water goes into the furnace as moisture and as combined water of the charges. To convert the moisture, such as is evaporated by a current of moderately warm air, into vapor requires 606.5 Calories per unit of water. This allows merely for its vaporization in the furnace, and not for any sensible heat which it may carry out of the furnace at the temperature of the waste gases. This latter item is properly considered in with the sensible heat of the waste gases. The common practice of saying that it takes 637 Calories to evaporate the moisture of the charges is wrong, because this amount would convert water at 0° to vapor at 100°, and, therefore, would include part of what is properly the sensible heat of the waste gases. On the other hand, it is equally wrong to say that this heat of vaporization should be counted in as sensible heat in the hot gases; it would be just as logical or, rather, equally illogical, to count the latent heat of vaporization of CO^2 as sensible heat in the gases.

To drive off water of hydration from hydrated minerals in the charge requires an additional amount of chemically-absorbed heat. As far as is known, this is small for the water driven off hydrated iron oxides, so small as to be a doubtful quantity and safely left out; but if it comes from clay the large amount of 611 Calories is absorbed in merely separating it from its chemical combination $(2H^2O, Al^2Si^2O^7) = 22{,}000$ Calories, which would require $611 + 607 = 1{,}218$ Calories to put into the state of vapor each unit weight of water entering the furnace chemically combined in clay. (This does not concern the ordinary moisture in moist clay, expelled at 100° C., but only the combined water in the dry clay). Where much clay occurs in the ores this quantity becomes important, and its amount explains some of the difficulties met in working clayey charges, particularly since a large part of this chemically combined water is expelled only at a red heat, and, therefore, cools greatly the hotter zones of the furnace.

(9) *Decomposition of carbonates.* Raw limestone, or dolomite, is the usual flux of the blast furnace, and its carbonic acid is evolved at temperatures between 600° and 800°. Whether some of this is subsequently decomposed by contact with carbon and reduced to CO, is immaterial to the balance sheet, because more than enough CO^2 escapes from the furnace to represent the CO^2 of the flux, and we charge the furnace only with the formation of the CO and CO^2 actually found in the gases, less the CO^2 from fluxes. Bell charges up the heat absorbed also in the assumed reaction $CO^2 + C = 2CO$, but this is an error, because it is doubtful how much of the CO^2 is thus decomposed, and the question, in its last analysis, is one of heat *distribution* in the furnace, and does not concern the totals of heat absorbed or evolved. We can, therefore, omit the item of decomposition of this CO^2 (as likewise, and for analogous reasons, the heat evolved in carbon deposition in the upper part of the furnace $-2CO = C + CO^2$), and need consider only the heat required to expel the CO^2 from carbonates. This is:

$(CaO, CO^2) = 45{,}150$ Calories = 1,026 Calories per kg. CO^2

$(MgO, CO^2) = 29{,}300$ " = 666 " "

$(MnO, CO^2) = 22{,}200$ " = 500 " "

$(FeO, CO^2) = 24{,}900$ " = 566 " "

$(ZnO, CO^2) = 15{,}500$ " = 352 " "

By using the above figures, in connection with the known composition of ore and fluxes, the heat required to decompose carbonates can be correctly calculated.

(10) *Reduction of iron oxides.* The heats of formation of the various oxides of iron are:

(Fe,O) = 65,700 Calories = 1,173 Calories per kg. iron
(Fe^3,O^4) = 270,800 " = 1,671 " "
(Fe^2,O^3) = 195,600 " = 1,746 " "

And, therefore, just these quantities of heat are required per unit weight of iron reduced from these compounds. If the ore is a carbonate the heat absorbed in driving of CO^2 from $FeCO^3$ can be first allowed for, and then the heat required for reduction of the FeO calculated on the weight of the reduced iron. If some FeO goes into the slag it will be as FeO, and if the ore was Fe^2O^3, or Fe^3O^4, the reduction of unit weight of iron from the state of Fe^2O^3, or Fe^3O^4, to the state of FeO, absorbs respectively 573 or 498 Calories, as may be readily deduced from the heats of formation of the three oxides concerned. If FeS is present its heat of formation is

(Fe, S) = 24,000 Calories = 429 Calories per kg. Fe.

If the iron is charged partly as silicate, such as mill or tap cinder, an additional amount of heat will be required for reduction, equal to that needed to separate the iron oxides from their combination with silica. The heat of formation of the bi-silicate slag only has been determined.

(FeO, SiO^2) = 8,900 Calories = 148 Calories per kg. SiO^2.

And since the cinders concerned contain relatively more iron than this, we can best make allowance for the heat required to set free the silica. It is necessary, therefore, to take the amount of silica in the iron cinder charged, and allow, as necessary for its decomposition into FeO and SiO^2, 148 Calories for each unit weight of SiO^2 contained.

(11) *Reduction of non-ferrous oxides.* Silicon is usually present in pig iron, its reduction from silica requiring:

(Si, O^2) = 180,000 Calories = 6,413 Calories per kg. Si.

There is a little doubt about this (Berthelot's) figure; more recent determinations, not yet published, point rather to 196,000 and 7,000 Calories respectively.

Manganese is often present in the ores as Mn^2O^3, Mn^3O^4, or MnO^2, and going partly into the slag as MnO. The heat absorbed in reduction to manganese is:

(Mn, O) = 90,900 Calories = 1,653 Calories per kg. Mn
(Mn^3, O^4) = 328,000 " = 1,988 " "
(Mn, O^2) = 125,300 " = 2,278 " "

For the MnO produced and going into the slag, the reduction from Mn^3O^4, or MnO^2, per unit weight of contained manganese, absorbs 335 or 625 Calories respectively.

Sulphur generally comes from the reduction of FeS, requiring 667 Calories per kg. of sulphur; but care must be taken not to allow for this heat twice, since if reckoned once under the head of iron reduction it must not be reckoned on the balance sheet a second time under sulphur. One reduction of FeS liberates both constituents.

Phosphorus may be reduced in large quantity in making basic iron. It probably comes mostly from calcium phosphate, in which case we must reckon on not only the heat of oxidation of phosphoric oxide but also its heat of combination with lime:

(P^2, O^5) = 365,300 Cal. = 5,892 Cal. per kg. of P.
(3CaO, P^2O^5) = 159,400 " = 2,410 " " contained.

Making a total heat requirement of 8,302 Calories to separate unit weight of phosphorus from phosphate of lime, and leave free lime. In a furnace making a pig iron with several per cent. of phosphorus, this item becomes quite large.

Calcium occurs in the slag as CaS, its reduction from lime requiring

(Ca, O) = 130,500 Calories = 3,263 Calories per kg. Ca.

Other elements than the above rarely occur in pig iron in notable quantity. If rare ones occur, their heat of reduction can be sought in thermochemical tables. Those of tungsten, titanium, molybdendum and chromium are, however, not at present known.

(12) *Decomposition of moisture in the blast.* This is to be

counted as vapor of water, the heat required to decompose, which is:

(H^2, O) vapor = 58,060 Cal. = 3,226 Cal. per kg. H^2O.
= 29,030 " " H^2.

It is not correct to allow here for the sensible heat in this water vapor coming in with the hot blast, because that heat should go on the other side of the balance sheet as heat delivered to the furnace. Neither is it correct to subtract the heat of combination of the oxygen of this moisture with carbon to form CO at the tuyeres; because, although that combination actually does take place, yet the heat thereby evolved properly belongs also on the other side of the balance sheet, and is there properly taken care of as part of the heat of oxidation of carbon in the furnace.

Problem 57.

(Data partly from paper by the author, Transactions American Institute of Mining Engineers, 1905).

A blast furnace running on Lake Superior ore has the following charges, per 100 of pig iron produced:

Hematite ore: 177.6; composition	H^2O	—10.0	per cent.
	SiO^2	—10.0	"
	Al^2O^3	— 3.5	"
	Fe^2O^3	—76.5	"
Limestone: 44.4; composition	SiO^2	— 5.0	"
	MgO	— 4.8	"
	CaO	—47.6	"
	CO^2	—42.6	"
Coke: 95.8;composition	SiO^2	— 5.3	"
	CaO	— 5.3	"
	H^2O	— 1.0	"
	C	—88.0	"
Pig iron produced: 100; composition	Si	— 1.0	"
	C	— 4.0	"
	Fe	—95.0	"
Gases produced: composition dry:	CO^2	—13.0	"
	CO	—22.3	"
	N^2	—64.7	"

Blast used: Contained 5.66 grains of moisture per cubic foot of dry air, at 24° C. = 75° F.
Charges in pounds: Coke, 10,200; ore, 20,000; stone 5,000.
Product per day: Pig iron, 358 tons = 801,920 pounds.
Coke used per day: 768,626 pounds.
Temperature of blast 720° F. = 382° C.
Temperature of waste gases = 538° F. = 281° C.
Displacement of blowing engines = 40,000 ft.^{3} per min.
Heat in one unit of pig iron = 325 Calories.
Heat in one unit of slag = 525 Calories.
Cooling water, per day, heated 50° C. = 300,000 gallons.

Required: (1) The volume of gases per 100 kg. of pig iron

(2) A balance sheet of materials entering and leaving the furnace, per 100 unit of pig iron.

(3) The volume and weight of blast per 100 kg. of pig iron.

(4) The efficiency of the blowing plant.

(5) The heat balance sheet of the furnace.

(6) The proportion of the fixed carbon of the fuel burnt at the tuyeres.

(7) The proportion of the whole heat generated at the tuyeres.

(8) The proportion of the iron reduced in the furnace which is reduced by solid carbon from FeO.

(9) The theoretical maximum of temperature at the tuyeres.

(10) The theoretical maximum if all the moisture were removed from the blast.

Solution: (1) To find the volume of the gases:

Carbon in the coke used 95.8×0.88 = 84.3 kg.
Carbon in the limestone $44.4 \times 0.426 \times \frac{3}{11}$ = 5.2 "

Total carbon entering furnace = 89.5 "
Carbon in 100 of pig iron = 4.0 "

Carbon entering gases = 85.5 "

Carbonous and carbonic oxides in gases = 35.3 per cent
Carbon in 1 m^3 of dried gas = 0.54×0.353 = 0.19062 kg.
Dry gas per 100 kg. of pig iron = $\frac{85.5}{0.19062}$ = 448.5 m^3. (1)

Dry gas per 100 oz. of pig iron $= 448.5$ ft.^{3}

Dry gas per 100 pounds of pig iron $= 448.5 \times 16 = 7176.0$ "

Dry gas per 2240 pounds of pig iron $= 7176.0 \times 22.4 = 160{,}742$ "

$$\text{Dry gas per minute} = \frac{160{,}742 \times 358 \text{ (tons)}}{60 \times 24} = 39{,}962 \text{ "}$$

(2) BALANCE SHEET OF MATERIALS, PER 100 OF PIG-IRON.

	Charges		Pig Iron	Slag	Gases	
Ore 177.6	Fe^2O^3	135.6	Fe 95.0	......	O	40.7
	H^2O	17.8	.....	......	H^2O	7.8
	SiO^2	17.8	Si 1.0	SiO^2 15.7	O	1.1
Flux 44.4	SiO^2	2.2	.....	SiO^2 2.2	......	
	CaO	21.1	.....	CaO 21.1	......	
	MgO	2.1	.....	MgO 2.1	......	
	CO^2	19.0	.....	......	CO^2	19.0
Fuel 95.8	C	84.3	C 4.0	......	C	80.3
	SiO^2	5.3	.....	SiO^2 5.3	......	
	CaO	5.3	.....	CaO 5.3	......	
	H^2O	0.9	.....	......	H^2O	0.9
Blast 422.2	O^2	96.4	.....	......	O	96.4
	N^2	321.3	.....	......	N^2	321.3
	H^2O	4.5	.....	......	H	0.5
					O	4.0
	Total	740.0	100.0	58.0		582.0

The charges are calculated simply from the weights of ore, flux and fuel used, and their percentage composition. The blast is calculated as given in solution of requirement (3).

The 1.0 of silicon in the pig iron requires $1.0 \times (60 \div 28) = 2.1$ parts of SiO^2 to furnish it, leaving 15.7 of unreduced SiO^2 to go into the slag, and 1.1 of oxygen to the gases.

(3) The balance sheet shows that the solid charges furnish to the gases 41.8 of O, 190 of CO^2 and 18.7 of H^2O. The H^2O goes as such into the gases, and therefore its oxygen is not present in the sample of dry gas analyzed. The oxygen in CO^2 is $19.0 \times (32 \div 44) = 13.8$ kg., which added to the 41.8 gives 55.6 of oxygen getting into the gases as CO or CO^2, from the solid charges.

The oxygen in the CO and CO^2 of the gases is to be calculated from the oxygen in unit volume of gas and the total volume of gas produced. The oxygen in 1 cubic meter of gas will be:

$$\text{O in CO} = 0.223 \times \left(0.09 \times \frac{28}{2}\right) \times \frac{16}{28} \qquad = 0.16056 \text{ kg.}$$

$$\text{O in CO}^2 = 0.130 \times \left(0.09 \times \frac{44}{2}\right) \times \frac{32}{44} \qquad = 0.18720 \text{ ``}$$

$$\overline{0.34776} \text{ ``}$$

A quicker solution is to note that CO^2 represents O^2, its own volume of oxygen, and CO represents O, or half its volume of oxygen, and since 1 cubic meter of oxygen weighs $0.09 \times (32 \div 2) = 1.44$ kilograms, the weight of oxygen required is

$$\left(\frac{0.223}{2} + 0.13\right) \times 1.44 = 0.34776 \text{ kg.}$$

The total oxygen in 448.5 m^3 of gases is therefore
448.5 × 0.34776 = 156 kg.
subtracting that furnished by the solid charges = 55.6 "
there remains oxygen furnished by blast = 100.4 "
If the blast were perfectly dry air, its nitrogen would be $100.4 \times (10 \div 3)$ = 334.7 "
and the weight of dry blast = 435.1 "
and its volume at 0° C. $435.1 \div 1.293$ = 336.5 m^3

The blast, however, is not dry, and the 100.4 kilos. of oxygen includes that brought in by the moisture. The moisture weighs 5.66 grains per cubic foot of measured dried air; it is, therefore, simplest to calculate the oxygen entering the furnace per unit volume of air proper entering. Since 5.66 grains = $5.66 \div 437.5 = 0.01294$ ounces av., the calculation can be made in ounces per cubic foot or kilograms per cubic meter in identical figures as follows:

$$\text{Oxygen in 0.01294 parts of water} = 0.01294 \times \frac{8}{9} \qquad = 0.0115$$

Oxygen in 1 volume of air proper, at 24° C.

$$= 1.293 \times \frac{3}{13} \times \frac{273}{273 + 24} \qquad = 0.2743$$

$$\text{Sum} = \overline{0.2858}$$

The blast received, per 100.4 kg. of oxygen thus received, is therefore, measured dry at 24° C:

$$\frac{100.4}{0.2858} = 351.8 \text{ cubic meters,}$$

and in cubic feet, per 100.4 pounds of oxygen:

$$\frac{100.4 \times 16}{0.2858} = 5628.8 \text{ cubic feet.}$$

The volume of the moist air containing this will be the volume of assumed dried air plus the volume of the water vapor. The latter is, per unit volume of dried air:

$$0.01294 \div \left(0.09 \times \frac{18}{2} \times \frac{273 + 24}{273}\right) = 0.01738$$

and the volume of moist air received, at 24°, is, therefore,

$$351.8 \times 1.01738 = 357.9 \text{ cubic meters.}$$

Or $$5628.8 \times 1.01738 = 5726.6 \text{ cubic feet.}$$

The weights of water, oxygen and nitrogen received per 100 of pig iron are (as already given on the balance sheet):

H^2O $0.01294 \times 351.8 = 4.52$ kg.
O^2 $0.2743 \times 351.8 = 96.4$ "
N^2 $0.9143 \times 351.8 = 321.3$ "

And the volumes of these, considered theoretically at 0° C. and standard pressure, per 100 kg. of pig iron made:

H^2O vapor $4.52 \div 0.81 = 5.6$ cubic meters.
Air $417.7 \div 1.293 = 322.8$ " "
Sum $= 328.4$ " "

There are several other modifications of this solution which will suggest themselves to anyone who studies out the question, but while half a dozen ways may be equally correct, that one is logically to be preferred which is most easily understood and is the shortest. One solution, however, based on volume relations, is well to know. Water vapor, H^2O, represents half its volume of contained oxygen, while air has 0.208 oxygen. The cubic foot of dried air at 24° C. was accompanied by

$$0.01294 \div 0.81 \times \frac{273+24}{273} = 0.0174 \text{ cubic foot}$$

of moisture, which was removed in making the test. The oxygen per cubic foot of dry blast was, therefore, at 24° C.:

$$\begin{array}{lll} \text{O as } H^2O = 0.0174 \div 2 & = 0.0087 & \text{cubic foot.} \\ O^2 \text{ as air} = 1.0000 \times 0.208 & = \underline{0.2080} & \text{"} \quad \text{"} \\ & 0.2167 & \text{"} \quad \text{"} \end{array}$$

Weight of this oxygen:

$$1.44 \times \frac{273}{273+24} \times 0.2167 = 0.2868$$

And volume of dry blast, at 24°, per 100 of pig iron:

$$\frac{100.4}{0.2868} = 350.1 \text{ cubic meters.}$$

The difference of about 0.4 per cent between this and the previously-calculated result is due to the figures not being carried out to a sufficient number of decimal places.

(4) *The efficiency of the blowing plant* is found by calculating the volume of air and moisture received by the furnace per minute, calculated to 24° C. = 75° F., and comparing this with the piston displacement of 40,000 cubic feet per minute.

Volume of moist air received, at 24° C., per 100 lbs. of pig iron made = 5726.6 ft.^{3}
Volume per day = 5726.6 × 8019.2 = 45,922,750 ft.^{3}
Volume per minute = 45,922,750 ÷ 1440 = 31,891 "

$$\text{Efficiency of blowing plant } \frac{31,890}{40,000} = 79.7 \text{ per cent.} \quad (4)$$

(5) *The heat balance sheet* is based for most of its data upon the balance sheet of materials, the calculations already made and the additional data given in the statement.

The balance sheet shows 80.3 kilos. of carbon oxidized in the furnace. Of this, the amount oxidized to CO and remaining as such in the gases is obtained from the amount of CO in the gases, as follows:

$$\text{C in CO} = 448.5 \times 0.223 \times 0.54 = 54.0 \text{ kg.}$$

$$\text{C oxidized to } CO^2 \text{ is therefore } 80.3 - 54 = 26.3 \text{ kg.}$$

The heat in hot blast is calculated from its volume assumed to be at 0° C., and already calculated, viz.; 322.8 cubic meters of air proper and 5.6 cubic meters of water vapor, with mean specific heats per cubic meter between 0° and 382° C. of 0.313 and 0.40 respectively.

The heat of formation of the pig iron may be taken from the amount of carbon in the iron, as 705 Calories per kilogram of carbon, and that of silicon omitted from consideration.

The heat of formation of the slag, since it contains 29.5 of silica and alumina to 28.5 of lime and magnesia, may be taken as 150 Calories per unit of silica and alumina.

The total heat received and generated, and to be accounted for, in the furnace, is therefore, per 100 kg. of pig iron:

Carbon to CO	54.0×2430	= 131,220	Calories.
Carbon to CO^2	26.3×8100	= 213,030	"
In H^2O vapor	$5.6 \times 0.40 \times 382$	= 39,385	"
In air proper	$322.8 \times 0.313 \times 382$		
Solution of C in iron	4×705	= 2,820	"
Formation of slag	29.5×150	= 4,425	"
	Total	= 390,880	"

The items of heat distribution are 325 Calories in each kilogram of pig iron, 525 Calories in each kilogram of slag, heat in the waste gases at 281°, heat in cooling water, lost by radiation and conduction (by difference), evaporation of the moisture in charges, expulsion of CO^2 from carbonates, decomposition of moisture of blast, reduction of silicon and iron.

Reduction of Fe	95 kg. × 1,746	= 165,870	Calories.
Reduction of Si	1 " × 7,000	= 7,000	"
Expulsion of CO^2 from $CaCO^3$	16.7 " × 1.026	= 18,666	"
Expulsion of CO^2 from $MgCO^3$	2.3 " × 666		
Evaporation of H^2O	18.7 " × 606.5	= 11,342	"

Heat in waste gases:

$$\left.\begin{array}{l} \text{N and CO } 400 \text{ m}^3\times 0.3106 \\ CO^2 \; 58.3 \text{ m}^3\times 0.446 \\ H^2O \; 23.1 \text{ m}^3\times 0.382 \end{array}\right\} \times 281^\circ \quad = 43{,}836 \quad \text{``}$$

Decomposition of moisture of blast:

H^2O 4.5 kg. × (29,040 ÷ 9) = 14,511 "

Heat in slag 58 kg. × 525 = 30,450 "

Heat in pig iron 100 × 325 = 32,500 "

Heat in cooling water (300,000 gallons per diem) 300,000 × 8.3 (lbs.) × 50° ÷ 8019.2 = 15,525 "

Loss by radiation and conduction (difference) = 51,180 "

Total = 390,880 " (5)

(6) *The proportion of the fixed carbon burned at the tuyeres* is obtained by calculating the weight of carbon which the oxygen entering at the tuyeres could oxidize to CO, as follows:

Oxygen entering at the tuyeres = 100.4 kg.

Carbon burned to CO = $100.4\times\frac{12}{16}$ = 75.3 "

Fixed carbon charged = 84.3 "

Proportion burned at tuyeres = 89.3 per cent.

A more just proportion is that between the carbon burned at the tuyeres and the total fixed carbon oxidized, because the fixed carbon which carbonizes the iron cannot be oxidized under any circumstances. This proportion in this furnace is:

$$\frac{75.3}{84.3-4.0} = \underline{93.8} \text{ per cent.} \qquad (6)$$

indicating a very fair approximation to Grüner's ideal working. If we make the further allowance, that the silicon in the pig iron is necessarily reduced by solid carbon, and that therefore the solid carbon needed to reduce the 1 kilogram of silicon [1 × (24 ÷ 28)] is in no case available for combustion at the tuyeres, we have the approach to Grüner's ideal working measured by the ratio

$$\frac{75.3}{80.3-0.9} = \quad 94.8 \text{ per cent.}$$

in spite of which, however, the furnace is not doing very good work.

(7) The proportion of the heat requirement generated or available at or about the tuyeres is determined as follows:

Combustion of C to CO = 75.3×2430 = 182,979 Calories.
Heat in hot blast = 39,385 “
Formaton of pig iron = 2,820 “
Formation of slag = 4,425 “
Total = 229,609 “
Against which must be charged heat required to decompose moisture of blast = 14,511 “
Leaving net heat available = 215,098 “
which is 215,098÷390,880 = 55 per cent.
of the total heat generated and available in the furnace.

Another way in which it is sometimes put, is that the oxidation of carbon to CO or CO^2 furnishes a certain amount of heat to the furnace (346,250 Calories in this case), of which a certain amount is generated by combustion at the tuyeres (182,979 Calories), making the ratio thus considered, in this case, 53 per cent.,—which is almost the same figures as above, but not so significant, since it is illogical to consider the heat brought in by the hot blast as not being available heat for doing work in the tuyere region.

(8) The proportion of iron reduced by solid carbon is found by finding how much carbon is used up in that reduction.

Fixed carbon charged = 84.3 kg.
Fixed carbon carbonizing the pig iron = 4.0 “
Fixed carbon oxidized in the furnace = 80.3 “
Fixed carbon oxidized by the blast = 75.3 “
Fixed carbon oxidized above the tuyeres = 5.0 “
Carbon needed to reduce 1 kg. silicon = 0.9 “
Carbon used for reducing FeO = 4.1 “
Amount of Fe, thus reduced = $4.1\times\frac{56}{12}$ = 19.1 “

Proportion of the total Fe, thus reduced

$$= \frac{19.1}{95} = 20 \text{ per cent.} \qquad (8)$$

(9) The maximum temperature of the gases in the region of the tuyeres is that temperature to which the heat there available will raise the products of combustion. This question is best resolved by simply considering the combustion of 1 kilogram of carbon, evolving 2430 calories, while the heat in the hot carbon itself just before it is burnt, and that in the hot blast required, will also exist as sensible heat in the products,—the whole diminished by the heat necessary to decompose the water vapor blown in.

Since, per 75.3 kg. of carbon burned at the tuyeres there enter 5.6 m³ of water vapor and 322.8 m³ of air proper, measured at 0°, the volume of blast per kilogram of carbon oxidized at the tuyeres is

$H^{2}O$ $5.6 \div 75.3 = 0.0738$ m³ $= 0.0598$ kg.
Air $322.8 \div 75.3 = 4.2869$ m³

The products of the combustion are, per kg. of carbon burned:

CO $22.22 \div 12$ = 1.8519 cubic meters.
N^{2} $321.3 \div 1.26 \div 75.3$ = 3.3865 " "
H^{2} equal to $H^{2}O$ decomposed = 0.0738 " "
Total = 5.3122 " "

The heat available to raise their temperature is:

Heat of combustion of 1 kg. carbon = 2430 Calories.
Heat in hot blast = 39,385 ÷ 75.3 = 523 "
Heat in hot carbon at t° (or very nearly) = $0.5t-120$ "
Less heat absorbed in decomposing steam 14,511 ÷ 75.3 = 193 "
Net heat available in gaseous products = $2640+0.5t$ Cal
Calorific capacity of gaseous products $= 5.3122\,(0.303t+0.000027t^{2})$
Therefore $5.3122\,(0.303t+0.000027t^{2}) = 2640+0.5t$
Whence $t = 1910°$ (9)

This represents the absolute maximum of temperature which the gaseous products formed at the tuyeres can possess.

(10) If all the moisture were removed from the blast, the heat available would be:

By combustion of 1 kg. carbon = 2430 Calories.
Heat in 4.4685 m^3 of dry air at 382° C.
$= 4.4685 \times 0.313 \times 382$ = 574 "
Heat in 1 kg. of carbon at $t°$ $= 0.5t - 120$"
Net heat available in gaseous products $= 0.5t + 2884$ Cal.
Calorific capacity of gaseous products
$= 5.3976\ (0.303t + 0.000027t^2)$
Therefore $5.3976\ (0.303t + 0.000027t^2) = 2884 + 0.5t$
Whence $t = 2018°$ (10)

It is to be noted that this is 108° C. = 194° F. higher than with moist blast; and while the slag and iron in passing through this zone of high temperature will not reach this maximum temperature, yet they would be heated approximately 100° C. higher when using dry blast, if all other conditions were kept constant.

N. B.—In working this problem, the metric measurements and English measures have been purposely used interchangeably, in order that readers may understand better that if weights are taken in pounds and the heat unit is the pound Calorie (1° C.), the same numbers represent a solution in either system. When volumes are concerned, cubic feet and ounces, or ounce calories, have practically the same numerical expression as cubic meters and kilograms or kilogram calories.

CHAPTER V.

THE RATIONALE OF HOT-BLAST AND DRY-BLAST.

Problem 58 (for practice).

The blast furnace of Problem 57 had its blast dried before using, to the extent of leaving on an average 1.75 grains of moisture per cubic foot of air proper, at – 5° C., in the air pumped. The composition of the ore, limestone and coke used was unchanged, also that of the pig iron made. The weights charged per 100 of pig iron were: Ore **177.6**, flux **44.4**, fuel **77.0**, and the blast used calculates out oxygen 76.5, nitrogen 255.0, moisture 1.0. Analysis of gases: CO 19.9, CO^2 16, N^2 64.1 per cent. Product per day 447 tons. Temperature of gases 191° C., of blast 465° C. Piston displacement (air at – 5° C.) 34,000 cubic feet per minute. Assume heat in pig iron and slag same as before, in cooling water 20 per cent. greater per day.

Required.—(1) The volume of gases per 100 kg. of pig iron made.

Answer.—Measured dry, 355.9 m^3.

(2) A balance sheet of materials entering and leaving the furnace, per 100 units of pig iron. (See table on page 281.)

(3) The volume of blast per 100 kg. of pig iron.

Answer.—252.9 m^3 at – 5° C.

(4) The efficiency of the blowing plant.

Answer.—82.3 per cent.

(5) The heat balance sheet of the furnace, per 100 of pig iron.

Developed.

Carbon to CO	92,950	Calories.
Carbon to CO^2	206,955	"
Heat in hot blast	37,850	"
Solution of carbon in iron	2,820	"
Formation of slag	4,260	"
Total	344,835	"

Distributed.		
Reduction of iron	165,870	Calorics.
Reduction of silicon	7,000	"
Expulsion of carbonic oxide (CO^2)	18,666	"
Evaporation of moisture of charges	11,342	"
Heat in waste gases	23,799	"
Decomposition of moisture of blast	3,225	"
Heat in slag	29,820	"
Heat in pig iron	32,500	"
Heat in cooling water	14,922	"
Lost by radiation and conduction (diff.)	37,791	"
	344,835	"

(6) Compare the heat items which are substantially different for the furnace run by moist and dried blast.

	Moist Blast.	*Dried Blast.*
Combustion of C to CO	131,220	92,950
Heat in waste gases	43,836	23,799
Decomposing moisture in blast	14,511	3,225
Loss by radiation and conduction	51,180	37,791

It may be noticed, that using moist blast too much carbon was burnt to CO at the tuyeres; the chief item of economy with dried blast is the ability to get along with less. The smaller total amount of gases, particularly nitrogen, accounts for the lower temperature of the waste gases, with dried blast. The direct saving by reason of decomposition of the moisture is the smallest item of economy. The reduced losses by radiation and conduction are mainly because of the faster rate of running, these losses being nearly constant per day. The ratio of these losses is found to be 0.74, whereas, the inverse ratio of the pig iron productions per day was 0.79.

(7) Calculate the carbon burnt at the tuyeres, the proportion of the carbon available thus consumed. Compare these items with those of the furnace on moist blast.

	Moist Blast.	*Dried Blast.*
Carbon burnt at tuyeres	75.3	58.05
Total fixed carbon charged	84.3	67.8
Proportion burnt at tuyeres	89.3	85.6
Fixed carbon really available	79.4	62.9
Proportion burnt at tuyeres	94.8	92.3

(In some charcoal furnaces of low heat requirement, *i.e.*, with pure ores and fuel, as little as 37 parts of carbon is burned at the tuyeres per 100 of pig iron produced, which represents, moreover, only 70 to 75 per cent. of the available fixed carbon in these furnaces.)

	Charges.		Pig Iron.		Slag.		Gases.	
Ore 177.6	Fe^2O^3	135.7	Fe	95.0	....		O	40.7
	H^2O	17.8	....		....		H^2O	17.8
	SiO^2	17.8	Si	1.0	SiO^2	15.7	O	1.1
	Al^2O^3	6.3	....		Al^2O^3	6.3	....	
Flux 44.4	SiO^2	2.2	....		SiO^2	2.2	....	
	CaO	21.1	....		CaO	21.1	....	
	MgO	2.1	....		MgO	2.1	....	
	CO^2	19.0	....		....		CO^2	19.0
Fuel 77.0	C	67.8	C	4.0	....		C	63.8
	SiO^2	4.2	....		SiO^2	4.2	....	
	CaO	4.2	....		CaO	4.2	....	
	H^2O	0.8	....		....		H^2O	0.8
Blast 332.5	O^2	76.5	....		....		O	76.5
	N^2	255.0	....		....		N	255.0
	H^2O	1.0	....		....		H	0.1
							O	0.9
	Totals	631.5		100.0		55.8		475.7

(8) The proportion of the whole heat requirement available in the region of the tuyeres.

Answer.—**53** per cent.

(9) The proportion of the iron in the furnace which is reduced by solid carbon from FeO.

Answer.—**23.8** per cent.

(10) The theoretical maximum of temperature at the tuyeres.

Answer.—**1965°** C.

HOT BLAST.

For several centuries blast furnaces were run by charcoal as fuel and with cold blast. How great the variations in temperature of the cold blast may be, can be inferred from the experience of a furnace manager in the Urals, Russia, who noted temperatures of the air nearly 40° C. in the summer and – 60° C. in the winter. Assuming an average temperature of 0° C. for unheated blast, burning charcoal to CO, the theoretical maximum of temperature before the tuyeres can be calculated as follows:

Heat generated by combustion		2430 Calories
Heat in hot carbon being burnt	0.5t –	120 "
Volume of CO and N^2 formed		5.3795 cubic meters

$$\text{Temperature} = \frac{2310 + 0.5t}{5.3944\ (0.303 + 0.000027t)}$$

Whence $t = 1678°$

This does not mean that the pig iron and slag will be carried to this temperature, any more than if a locomotive could run alone 90 miles an hour it could therefore pull a train of cars that fast. The hot gases, CO and N^2, are at the start at this temperature, and as they ascend and come in contact with the descending iron and slag, these are raised to temperatures approximating towards, but always lower than, the above. In fact, the temperature to which the iron and slag is raised depends on the relative quantities of iron and slag to fuel burnt, and the speed with which the furnace is worked.

If the blast is heated, its sensible heat is simply added to the numerator of the above expression. We can easily find out how much sensible heat the 4.4685 cubic meters of air brings in, at any temperature desired [$Q = 4.4685\ (0.303t + 0.000027t^2)$], and then solve the quadratic anew. We thus find

Temp. of Blast.	*Heat in Blast.*	*Theoretical Temp.*
0° C.	— Calories	1678° C.
100° "	137 "	1762° "
200° "	276 "	1845° "
300° "	417 "	1929° "
400° "	561 "	2012° "
500° "	707 "	2096° "
600° "	856 "	2180° "

Temp. of Blast.	*Heat in Blast.*	*Theoretical Temp.*
700° C.	1007 Calories.	2265° C.
800° "	1160 "	2350° "
900° "	1316 "	2435° "
1000° "	1475 "	2520° "

The heating of the blast thus raises the maximum temperature available some 85° C. for each 100° C. to which the blast is heated. It not only increases the temperature available, but also the number of heat units, thus increasing both the quantity and the intensity of the heating in the tuyere region. Of these two items of increase, that of the intensity factor is the most important, since it regulates the rapidity of transfer of heat to the charge and the efficiency and speed of the smelting action of the furnace.

Dried Blast.

Each kilogram of water vapor decomposed absorbs 29040 ÷ 9 = 3227 Calories, which would not be needed if the 0.67 kilo. of carbon thus employed was oxidized by air instead of by moisture. Per kilogram of carbon oxidized by water vapor, there is absorbed 58,080 ÷ 12 = 4,840 Calories, while this kilogram of carbon can only furnish 2430 Calories in becoming CO, leaving a net absorption of 2410 Calories per kilogram of carbon thus burned, against which, however, can be credited the heat in the kilo. of carbon burned and the sensible heat in the water vapor itself; the former is 0.5t − 120, and the latter can be calculated from the volume of the water vapor, 1.8519 cubic meters. We thus have, per kilogram of carbon thus oxidized:

Temperature of Water Vapor.	*Heat in Moisture.*	*Heat in Products.*
100°	66 Calories	0.5t − 2460 Calories
200°	137 "	0.5t − 2393 "
300°	214 "	0.5t − 2316 "
400°	296 "	0.5t − 2234 "
500°	384 "	0.5t − 2146 "
600°	478 "	0.5t − 2042 "
700°	577 "	0.5t − 1953 "
800°	682 "	0.5t − 1848 "
900°	792 "	0.5t − 1738 "
1000°	907 "	0.5t − 1623 "

Since the heat in the carbon burnt (0.5t − 120) can never equal numerically 1623, it is seen that under no circumstances can the water vapor do anything but diminish the quantity of heat available at the tuyeres, while the products of its decomposition CO and H^2 increase the volume of the products and so diminish still further the intensity of temperature attainable.

The best way to determine the amount of moisture in the air is to draw it through a tube containing concentrated sulphuric acid, measure the quantity of dry air drawn through, and weigh the amount of moisture caught by the tube. This gives the weight of moisture *accompanying* unit volume of dry air (not weight of moisture in unit volume of moist air). Determinations by the wet and dry bulb thermometers, the whirled psychrometer, humidity gauges, etc., are none of them so reliable as the above described method, which is direct, simple and accurate. The results may be obtained in grains per cubic foot of dry air or milligrams per liter. The best way to express them, for further use, is in ounces avoirdupois per cubic foot, or kilograms per cubic meter. The first is obtained by dividing the number of grains by 437.5, the second by dividing the milligrams per liter by 1000. The numbers thus obtained are practically identical in the two systems.

The theoretical temperatures attainable with moist blast of varying degrees of moisture and heated to various temperatures are obtained by applying the previously explained principles. We have already calculated the temperature obtained by burning carbon with dry air of various temperatures. We have also calculated a table of the deficit of heat available produced by the entrance of 1.5 kilos. of water vapor (which would oxidize 1 kilo. of carbon and produce 1.8519 cubic meters of CO and H^2). We are, therefore, prepared to calculate a table of the maximum temperature attainable using blast of any degree of humidity heated to any practical temperature. Before giving the table we will run through the details of one calculation, to make clear the method employed.

Illustration.—What is the theoretical maximum temperature using air which carries normally 10 grams of moisture per cubic meter of dry air, reduced to standard conditions (*i.e.*,10 grams per 1.293 kilograms of dry air), and heated to 500° C.?

It takes 3.5275 cubic meters of dry air at standard conditions to burn 1 kilogram of carbon. If dry, and at 500°, there is 2430 Calories generated by combustion, 707 Calories in the dry air used, 0.5t − 120 Calories in the hot carbon, and the total heat thus at hand raises the 5.3944 cubic meters of products to the temperature of 2096° C., as is determined by solving the equation

$$t = \frac{2430 + 707 + (0.5t - 120)}{5.3944\ (0.303 + 0.000027t)} = 2096°$$

As modified by the moisture, the 4.4685 cubic meters of dry air would be accompanied by 44.685 grams of moisture, or 0.044685 kg., which would oxidize two-thirds of its weight of carbon, or 0.02979 kg. of carbon, which would contribute to the heat available 0.02979 (0.5t − 2146) Calories, making a contribution of 0.015t − 64 Calories to the numerator of above equation. The products of combustion will be increased by H^2 and CO equal in volume to twice the volume of the moisture, or $2 \times 0.044685 \div 0.81 = 0.1102$ cubic meters, the mean specific heat of which goes into the denominator. We then have

$$t = \frac{3017 + 0.5t + 0.015t - 64}{(5.3944 + 0.1102)\ (0.303 + 0.000027t)} = 2030°$$

Another method of solution, not using the previously calculated tables but based entirely on first principles, is to base the whole calculation on the use of 1 cubic meter of dry air, with its accompanying moisture, as follows:

Oxygen present in 1 m³ dry air = 1,293 × 3/13 = 0.2984 kg.
Oxygen present in the moisture = 0.010 × 8/9 = 0.0089 "
Total = 0.3073 "

Carbon consumed = 0.3073 × 0.75 = 0.2305 "
Volume of moisture = 0.010 ÷ 0.81 = 0.0123 m³
Volume of oxygen in dry air = 0.2078 "
Volume of products from dry air = 1.0000 + 0.2078 = 1.2078 "
Volume of products from moisture = 2 × 0.0123 = 0.0246 "
Total volume of products = 1.2324 "

Heat of combustion of carbon = 0.2305 × 2430 = 560 Cal.
Heat in carbon at t° = 0.2305 × (0.5t − 120) = 0.1152t − 28 "

Heat in dry air at 500° = $1 \times [0.303 + 0.000027\,(500)]\,500$ = 158 Cal.
Heat in moisture at 500° = $0.0123\,[0.34 + 0.00015\,(500)]$ = 3 "
Heat absorbed in decomposing moisture = 0.0123×2614 = − 32 "

Whence results the equation

$$t = \frac{0.1152t + 661}{0.2324\,(0.303 + 0.000027t)} = 2030°$$

By applying either of the two methods of calculation explained, the temperatures in the following table are obtained:

THEORETICAL TEMPERATURES BEFORE THE TUYERES

MOISTURE. { Grams per cubic meter of dry air reduced to 0° C.
Grains per cubic foot of dry air reduced to 0° C.

Grams	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00
Grains.	2.19	4.38	6.57	8.75	10.94	13.13	15.32	17.50
Blast.								
40°	1678°	1647°	1615°	1573°	1536°	1507°	1471°	1443°
100°	1723	1692	1666	1627	1587	1548	1526	1496
200°	1807	1776	1751	1712	1673	1636	1612	1584
300°	1892	1861	1837	1800	1760	1725	1700	1673
400°	1976	1945	1921	1885	1846	1813	1786	1760
500°	2061	2030	2007	1970	1933	1902	1874	1848
600°	2146	2115	2093	2055	2020	1991	1962	1936
700°	2232	2201	2178	2144	2108	2080	2050	2025
800°	2318	2287	2264	2227	2195	2169	2138	2114
900°	2404	2373	2351	2313	2282	2257	2226	2203
1000°	2490	2459	2437	2399	2369	2345	2314	2292

The calculations show that the temperature before the tuyeres may vary as much as 235° C. = 423° F., from change in the moisture of the air, from dryness to warm air saturated with moisture.

CHAPTER VI.

PRODUCTION, HEATING AND DRYING OF AIR BLAST.

This is a subject intimately related to the running of iron blast furnaces, and incidentally related more or less to all classes of metallurgical operations. The principles involved are those of physics—mechanical and thermal—and when once thoroughly understood can be used for the most various classes of metallurgical problems.

PRODUCTION OF BLAST.

There are two different principles upon which air is compressed, represented by the fan and the piston machines. The first is constant in its operation, the second intermittent, the first draws in and expels a continuous current of air, the second draws in a given quantity of air, compresses it and expels it. Measuring the work done by the difference in static conditions of the compressed and of the uncompressed air, the work actually done is a fixed and calculable quantity, independent of what type of machine performs it. During the compression, heat is generated, and the mechanical work done includes the mechanical equivalent of the heat thus generated. This is allowed for in the well-known formula for adiabatic compression:

$$\text{Work} = \frac{\gamma}{\gamma-1} V_0 p_0 \left[\left(\frac{p_1}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

in which

γ = the ratio of the specific heat of air at constant pressure to that at constant volume = 1.408.

V_0 = the volume of the uncompressed air.

p_0 = the tension of the uncompressed air.

p_1 = the tension of the compressed air.

If we use the value of $\gamma = 1.408$, the coefficient $\frac{\gamma}{\gamma-1}$ becomes 3.45, and $\frac{\gamma-1}{\gamma} = 0.29$. If we then use the other dimensions in feet and pounds, the resulting work done will be in foot-pounds; if we use meters and kilograms, in kilogram-meters. The element of time does not enter into this equation, the work actually done is the same for compressing a given amount of air, and is independent of the time. If I lift a kilogram 1 meter high, the same amount of work is done whether I lift it in 1 minute or in 1 second, the *rate of doing work* would be, however, sixty times as great in the last instance as in the first, but the actual amount of work accomplished is the same in each case. If, therefore, we use in the formula the volume of air entering the compressor per minute, the result will give the work done per minute; if we use the volume per second we get the work done per second. If we wish to transpose the work done into horse-power, we bear in mind that a horse-power is understood in English units as 33,000 foot-pounds of work done per minute, and in the metric system as 75 kilogram-meters of work done per second.

In applying the formula we may further notice that $\frac{p_1}{p_0}$ expresses the ratio of compression; that is, by how many times the tension of the original air is increased. If air at one atmosphere tension (such as the air we usually have to breathe) is compressed to two atmospheres tension, the ratio of compression is 2; if air entered a machine at two atmospheres tension and was therein compressed to four atmospheres, the ratio of compression would be likewise 2, and the work done (for a given quantity of air) the same as before. The effective pressure, as shown on a gauge, is the *difference* between these two tensions: it is not p_1. It is highly important that this point be held clearly in mind. The tension of the uncompressed air is its barometric pressure, as measured against a vacuum; the tension of the compressed air is likewise its pressure as measured against a vacuum; the effective pressure of the compressed air is the difference between these two tensions; the tension of the compressed air is, therefore, (by transposition) equal to the barometric pressure of the uncompressed air plus the effective pressure of the compressed air, *i.e.*, plus the gauge pressure. Never use the effective pressure of the compressed air as p_1, but always add to it the barometric pressure of the uncompressed air p_0 for the correct value of p_1.

Regarding the volume of uncompressed air, V_0 is its volume measured at the pressure P_0, *i.e.*, the actual volume of uncompressed air at its actual tension. If more convenient, however, we may use the volume of this air measured at standard barometric pressure, if we multiply it by p_0, the standard pressure. Thus, if we know the volume of uncompressed air measured at one atmosphere standard tension, we may use for the p_0 immediately following it the standard pressure 10.334 (kilos. per square meter), or 2,120 (pounds per square foot). By the law of the reciprocal nature of volume and pressure, the product thus obtained is the same as would be found by multiplying the volume of the same air at any other pressure by that pressure ($V_0\,p_0 = V_1\,p_1 = V^2\,p^2$, etc.). Whatever pressure we use in getting the product $V_0\,p_0$, however, we must use only the actual tension of the uncompressed air as the denominator in getting the ratio of compression ($p_1 \div p_0$).

Problem 59.

A blast furnace requires 2,615 cubic meters of air, measured at $-\ 5°$ C., for every metric ton of pig iron made. Assuming outside barometric pressure 735 millimeters of mercury column, the efficient pressure of the compressed blast to be 1.0 kilogram per square centimeter (as measured in a blast regulating reservoir), a mechanical efficiency of the blowing engine of 90 per cent., of delivery of blast 82.3 per cent., and output 447 tons per day:

Required:

(1) The ratio of compression of the blast.

(2) The piston displacement per ton of pig iron made.

(3) The work of the blowing cylinders, per ton of iron made.

(4) The gross or indicated horse-power of the steam cylinders.

Solution:

(1) The effective pressure being 1.0 kilogram per square centimeter, represents $\frac{1.0000}{1.0334} \times 760 = 735$ millimeters of mercury. But the uncompressed air is at 735 mm. barometric tension, therefore, the total tension of the compressed air, p_1, is 1470 mm. of mercury, and the

$$\text{Ratio of compression} = \frac{1470}{735} = 2.0 \qquad (1)$$

(2) Piston displacement per metric ton of pig iron:

$$\frac{2615}{0.823} = \quad \mathbf{3165} \text{ cubic meters.} \qquad (2)$$

$$= \mathbf{111{,}560} \text{ cubic feet.}$$

(3) The volume displaced must be the basis of calculating the power required, since subsequent losses of air (100 − 82.3 = 17.7 per cent.) do not affect the work done in the blowing cylinder. This volume is 3,165 cubic meters, representing that volume of uncompressed air at − 5° C. and 735 mm. pressure. The initial temperature of the air does not affect the work to be done, and we can either use its volume at 735 mm. tension or correct this to 760 mm. tension, just as we chose. If we consider the volume at 735 mm. tension, then the product of volume and pressure is

$$Vp = 3{,}165 \times \left(10{,}334 \times \frac{735}{760}\right) = 31{,}755{,}000$$

If we first change the volume to standard pressure, we have

$$V_0 p_0 = \left(3{,}165 \times \frac{735}{760}\right) \times 10{,}344 = 31{,}755{,}000$$

The work done in compression, in the blowing cylinder is, therefore,

$$\begin{aligned} W &= 3.45 \times 3{,}073 \times 10{,}334 \times [2^{0.29} - 1] \\ &= 109{,}554{,}750 \times [1.2225 - 1] \\ &= \mathbf{24{,}326{,}800} \text{ kilogrammeters.} \qquad (3) \end{aligned}$$

(4) The steam in the steam cylinders does more mechanical work than would be represented by the compression of air in the blowing cylinders. In this case, we assume 90 per cent. mechanical efficiency, or 10 per cent. mechanical loss. The gross work of the steam is, therefore,

$$24{,}326{,}800 \div 0.90 = 27{,}029{,}800 \text{ kilogrammeters,}$$

or, in horse-power,

$$\frac{27{,}029{,}900 \times 447}{1440 \times 4500} = \mathbf{1{,}865} \text{ horse-power.}$$

This amounts to 4.17 h.p. per metric ton of pig iron made per day.

MEASUREMENT OF PRESSURE.

In making calculations of the work done in furnishing blast, as in the preceding problem, it is important to note how the pressure of the compressed air is measured. The real pressure is measured correctly by a pressure gauge only where the air is comparatively at rest, as on a pressure-equalizing reservoir. If the pipe communicating with a gauge is connected with a blast main, in which the velocity of the air is considerable, the pressure recorded will vary greatly with the direction of the end of this tube relative to the direction of the air current. The total pressure of the air in motion is the pressure which it exerts against the sides of the main, plus the pressure which has been used in giving it velocity. If the pressure gauge tube is cut off at right angles to the flow of air in the main, the pressure recorded is even less than the actual static pressure of the air against the sides of the main (because of suction effect), and does not include at all the pressure represented by the velocity. The only way to measure correctly in a main the total pressure which has been impressed upon the blast is to bend the end of the pressure tube until it is parallel with the axis of the main and faces the current of air. The gauge then records the static pressure, plus the velocity head, and gives the proper pressure to use in calculating the work done by the blowing engine. However, it is still preferable to put the gauge on a blast reservoir, if there is one, where the air is nearly at rest and velocity head approximates zero—for the reason that the velocity of air passing through a tube is greatest in the center and least against the walls, and it is difficult to place the pressure tube so as to measure the mean velocity. An approximation to the mean value is found by placing the end of the pressure tube not in the center but at one-third of the radius of the main from the center.

INDICATOR CARDS.

If the blowing engine cylinder can be tested by pressure indicator cards, then a different method of obtaining the work of producing the blast is furnished. The integration of the diagram gives the mean pressure on the piston during the stroke. Expressing this in kilograms per square meter or pounds per square foot, and multiplying by the area of the piston and the length of the cylinder, we get the work done per stroke; again multiplying by the number of strokes per minute we have the work done per minute, from which is readily obtained the horse-power. These operations are usually combined in the formula:

$$\text{Work} = P \times L \times A \times N$$

If we observe that $L \times A \times N$ is the piston displacement per minute, the formula becomes:

$$\text{Work} = P \times \text{Piston displacement per minute},$$

in which, it must not be forgotten, P represents mean pressure on the piston during the stroke, and is not to be confounded with gauge pressure of the compressed air. Such a formula is, therefore, totally inapplicable to finding the work done by a fan or rotary blower, in which only the final pressure of the compressed air is known. The mistake of so applying it is often made. When only the final pressure of the compressed air is known, the formula for adiabatic compression is the only correct one to use.

It may not be useless to call attention to the fact that when using the formula for adiabatic compression, the raising of the ratio of compression to the 0.29 power has to be done by logarithms:

$$\log.\left[\left(\frac{p_1}{p_2}\right)^{0.29}\right] = \log.\left(\frac{p_1}{p_0}\right) \times 0.29$$

If a table of logarithms is not at hand, a satisfactory approximation may be made by taking the cube root of the ratio, since

$$\sqrt[3]{\left(\frac{p_1}{p_2}\right)} = \left(\frac{p_1}{p_0}\right)^{0.33}$$

Heating of the Blast.

Air blast is commonly heated either continuously, by direct transmission of heat through metal or earthenware pipes, or discontinuously by the heating up of fire-brick surfaces, which are subsequently cooled by the blast. It is not within the province of these calculations to enter into a description of the various types of such hot-blast stoves, but to indicate the principles upon which the metallurgist can base calculations as to the efficiency of such stoves, and thus be prepared to find out which do the best work, and wherein lie the principal advantages or disadvantages of each type.

The efficiency of a hot-blast stove is measured by the ratio of the heat imparted to the blast to that contained in the air and fuel used and generated by combustion. It is a furnace whose useful effect is the heat imparted to the air, and all other items of heat distribution are more or less necessary losses. The problem is simplest when the stove is a recuperator (continuous type), using solid fuel. Then the item of heat generation is perfectly definite, since the amount of fuel used in a given time can be definitely determined. When the hot-blast stove receives gaseous fuel, however, from a blast furnace, the amount of gas received by the stoves is usually a very uncertain quantity, since only part of all the gas produced by the furnace is used by the stoves, and the question of what fraction is thus used is difficult to determine. In such cases, the usual method of comparing the sizes of the pipes leading gas to the stoves and those carrying gas to boilers, etc., affords but a very uncertain determination, since the draft and consequent velocity of the gas may be very different in the two sets of pipes. In such cases, knowing the total volume of gas produced by the furnace, not only the relative sizes of the hot-blast stove pipes should be noted, but also the relative velocities of the gas currents in the two sets of pipes. Another method is to determine the quantity of chimney gas passing away from the stoves into the chimney flues, by measuring the size of the chimney flue, temperature of the gases and average velocity; given in addition the chemical analyses of the chimney gas and of the furnace gas, the quantity of the latter being used can be calculated, using the carbon in the two gases as the basis of calculation.

Problem 60.

Statement: Air for drying peat in a kiln is heated from 0° C. to 150° C. by an iron pipe stove, the latter consuming dried peat, whose ultimate analysis is:

Carbon	49.70	per cent.
Hydrogen	5.33	"
Oxgyen	30.76	"
Nitrogen	1.01	"
Ash	13.23	"

The calorific power of this peat is 4249, and by the combustion of 92.5 kilograms, 5122 cubic meters of air is heated to the required temperature. The products of combustion pass away from the stove at 200° C., and contain (analyzed dry) 14.8 per cent. of CO^2, and no CO or CH^4 or other gas containing carbon.

Required:

(1) The heat generated in the stove.

(2) The heat in the hot air, and the net efficiency of the stove.

(3) The volume and composition of the products of combustion in the stove.

(4) The heat carried out in the chimney of the stove.

(5) The heat lost by radiation and combustion.

(6) The excess of air used in burning the peat.

(1) Heat generated in the stove:

4249×92.5 = 393,033 Calories (1)

(2) Heat imparted to the air:

[0.303+0.000027 (150)]×150×5122 = 235,907 "

Net efficiency = **60.0** per cent. (2)

(3) Volume of products of combustion:

Weight of carbon in fuel burnt – 92.5 ×0.4970 = 45.97 kilos.

Volume of CO^2 thus produced – 45.97 ÷0.54 = 85.13 cub. meters

Volume of (dry) gas produced – 85.13 ÷0.148 = 575.20 " "

Volume of N^2 and O^2 in products – 575.2 – 85.13 = 490.07 " "

Volume of water vapor in products – 92.5×0.0533×9÷0.81 = 54.78 " "

Percentage composition of products of combustion:

	Moist.	*Dried.*
CO^2	13.5	14.8
N^2 and O^2	77.8	85.2
H^2O	8.7	....

To separate the nitrogen and oxygen would necessitate considerable calculation, and is not required just here, because the two gases have the same heat capacity per cubic meter, and therefore can thermally be reckoned together:

(4) Heat in the chimney gases at 200°:

CO^2 85.13 m³×0.4140 = 35.24
N^2 and O^2 490.07 m³×0.3084 = 151.14
H^2O 54.78 m³×0.3700 = 20.27

206.65×200 = 41,330 Cal.
Proportion thus lost = 10.5 P. C. (4)

(5) Loss by radiation and conduction
100 − (60.0 + 10.5) = 29.5 P. C. (5)

(6) The separation of N^2 and O^2 in the products is not easy. It is best based on the consideration that part of these consists of the nitrogen of the air which was necessary for combustion (plus the nitrogen of the fuel) and of the excess air. The first can be calculated, and thus the latter obtained by difference, and then the percentage of air in excess determined. Oxygen necessary for combustion:

C to CO^2 = $45.97\times\frac{32}{12}$ = 122.59 kilos.
H to H^2O = 4.93×8 = 39.44 "
162.03 "
Oxygen present in peat 92.5×0.3076 = 28.45 "
Oxygen to be supplied = 133.58 "
Nitrogen accompanying = 445.27 "
Air necessary = 578.85 "
= 447.7 m³
Nitrogen from coal, 92.5×0.0101 = 0.93 kilos.
Total nitrogen from coal and necessary air = 446.2 "
Volume = 446.2÷1.26 = 354.1 m³
Total N^2 and O^2 in products = 490.1 "
Therefore, excess air = 136.0 "
Percentage of excess air $\frac{136.0}{447.7}$ = 0.303 = 30.3 P. C. (6)

Problem 61.

A blast furnace has three hot-blast stoves, two of which are always on gas and one on blast. Per long ton of pig iron produced there issues from the furnace (reduced to standard temperature and pressure):

Nitrogen	81,763 cubic feet
Carbon monoxide	25,383 " "
Carbon di-oxide	20,409 " "
Water vapor	8,230 " "

For the same quantity of pig iron made, 92,330 cubic feet (standard conditions) of air is heated in the stoves from $-5°$ C. to 465° C. The hot gases reach the stoves at 175° C., are there burned by 10 per cent. excess of air at 0°, and the chimney gases resulting (assume perfect combustion) pass out of the stoves at 120° C.

Required:

(1) The net efficiency of the stoves, assuming they receive 25, 30, 35, 40, 45 or 50 per cent. of the gas produced by the furnace.

(2) Assuming that each stove radiates and loses to the ground one-third as much heat as the blast furnace itself (the heat balance sheet of the furnace showed 846,518 pound Calories thus lost per long ton of pig iron produced), what proportion of the whole gas goes to the hot-blast stoves, and what is the net efficiency of the stoves?

Solution:

(1) We will first calculate the efficiency of the stoves, assuming that they received *all* the gas produced, from which datum can then be obtained the efficiency, supposing any assumed fraction of the gas goes to the stoves.

Heat in the blast ($-5°$ to 465°):

$$92{,}330\times[0.303+0.000027\ (465-5)]\times[465-(-5)]$$
$$=92{,}330\ \times 0.31542\times 470 = 13{,}687{,}683 \text{ ounce cal.}$$
$$= 855{,}480 \text{ pound Cal.}$$

Sensible heat in the hot gases (0° to 175°):

N^2 and CO	107,146×0.3077	=	32,969
CO^2	20,409×0.4085	=	8,337
H^2O	8,230×0.3763	=	3,097
Heat capacity per 1°		=	44,403 ounce cal.
		=	2,775 pound Cal.
Heat capacity per 175.	2,775×175°	=	485,625 " "

Heat generated by combustion:

CO to CO^2 25,383 × 3062 = 77,722,746 ounce cal.
4,857,672 pound Cal.
Total heat available = 5,343,297 " "

If the gas were all used in the stoves the efficiency of the latter would be only

$$\frac{855,480}{5,343,297} = 0.160 = 16.0 \text{ per cent.}$$

With smaller proportions of the whole gas used the efficiency of the stoves calculates out as follows:

Using	50	per cent.	of the gas	....	Efficiency	32.0	per cent.
"	45	"	"	....	"	36.0	"
"	40	"	"	....	"	40.0	"
"	35	"	"	......		45.7	"
"	30	"	"	....	"	53.3	
"	25	"	"	....	"	64.0	
"	16	"	"	....	"	100.0	"

(1)

All that the above analysis tells us is, that certainly over 16 per cent. of the gas produced by the furnace must be used by the stoves; but if we can deduce any probable value for the percentage of the gas actually used, such as by measuring the several gas mains and the velocities of the gas in each, we can then reckon out the value of the efficiency of the stoves, with about the same degree of probability. Blast furnaces use from 33 to 60 per cent. of the gas they produce in the stoves. If we assume 50 per cent., in this case, the efficiency of the stoves would be 32 per cent.

(2) There is another way of solving the problem, which is to either measure, calculate or assume the heat lost by radiation and conduction from the stoves; adding to this the heat going out in the products of combustion, and the net heat in hot blast, the sum is the total heat which has been brought into and generated within the stoves. But, all the gas would bring in and generate in the stoves 5,343,297 Calories; we can, therefore, find easily what proportion of all the gas is being used in the stoves. In requirement (2) we are told to assume that the three stoves lost by radiation and conduction

846,518 pound Calories per long ton of pig iron made, an amount equal to that similarly lost by the furnace itself. The heat in the chimney gases, at 120°, can be thus calculated:

Oxygen required $\left(\frac{1}{2}\mathrm{CO}\right)$ = 12,692 cubic feet
Air required = 61,017 " "
Excess of air used = 6,102 " "
Nitrogen of required air = 48,325 " "
Nitrogen already in gas = 81,763 " "
Nitrogen in these two items = 130,088 " "

Chimney products:

CO^2 = 45,792 " "
$\mathrm{H}^2\mathrm{O}$ = 8,230 " "
N^2 = 130,088 " "
Excess air = 6,102 " "

Heat in chimney gases:

CO^2 $45{,}792 \times 0.3964$ = 18,152 ounce cal.
$\mathrm{H}^2\mathrm{O}$ $8{,}230 \times 0.3580$ = 2,946 " "
N^2 and air $136{,}190 \times 0.3064$ = 41,729 " "

Heat capacity per 1° = 62,827 " "
= 3,927 pound Cal.
Heat capacity per 120° = 471,122 " "

If all the furnace gas were burnt in the stoves, 471,122 pound Calories would go up the stove chimneys. But, since only a part of the gas is so used, only a fraction of this amount of heat is lost to the chimneys. If we call X the proportion of the gases used, then 471,122 X will represent the chimney loss, and the total heat requirements of the stoves will be:

Heat in air blast = 855,480 lb. Cal.
Heat in chimney gases = 471,122 X "
Radiation and conduction = 846,518 "

Total = 1,701,998 + 471,122 X lb. Cal.

The proportion of the total gases needed to supply this, X. is

$$\frac{1{,}701{,}998 + 471{,}122\,X}{5{,}343{,}297} = X$$

whence

$$X = 0.349 = 34.9 \text{ per cent.} \qquad (2)$$

and the net efficiency of the stoves is

$$\frac{855,480}{5,343,297\times 0.349}=\frac{855,480}{1,864,812}=\mathbf{45.9}\text{ per cent.}\qquad(2)$$

Arithmetically, the finding of X can be simplified, perhaps, by considering that the chimney loss represents in any case $471,122 \div 5,343,297 = 0.088 = 8.8$ per cent. of the total heat received by the stoves, leaving 91.2 per cent. to be applied to heating the blast and for radiation and conduction loss. The last two items, however, must amount to 1,701,998 Calories, and, therefore, the total heat requirement of the stoves is

$$\frac{1,701,998}{0.912}= 1,866,200\text{ pound Calories,}$$

requiring

$$\frac{1,866,200}{5,343,297}= 0.349 = 34.9\text{ per cent.}\qquad(2)$$

of all the gas produced by the furnace.

In the above solution the only uncertain factor in the calculation is the radiation and conduction loss from the stoves, and this uncertainty does not largely affect the reliability of the result obtained, allowing that we have assumed an approximately correct value for this loss. All uncertainty could be dispelled, however, were the radiation and conduction losses measured directly. This could be accomplished by finding experimentally the temperature of the outside shells of the stoves, and calculating the external losses of heat by the laws of radiation and conduction; but in order to do this satisfactorily, it would be necessary to divide the shells of the stoves into zones, and determine the temperature and calculate the losses from each zone separately—a rather long operation, but one worth doing.

Drying Air Blast.

The advantage of dried blast has been already discussed at length in these calculations. The advantage is due primarily to the higher temperature obtained when the moisture has been removed.

The means adopted commercially for drying the air have been those of refrigerating the uncompressed air, before its entrance into the blowing cylinders. This has the great advantage of furnishing the cylinders with cold air, and, therefore, of greatly increasing their blowing capacity, since the weight or quantity of air blown is proportional to the absolute temperature of the air entering the cylinders.

Illustration. Outside air being at 30° C., what increase in the amount of air furnished by blowing engines will result if the temperature of the air is artificially reduced to $-5°$ C.? How much slower can the engines be driven, in the second case, in order to furnish the same weight of air as before?

The two temperatures are respectively $273+30$ and $273-5$ absolute, that is, 303 and 268. The engines, if run at uniform speed, would furnish $303 \div 268 = 1.13$ times as much air in the second case, or 13 per cent. more. If the engines were slowed down to $268 \div 303 = 0.884$ of their former speed they would furnish the same amount of air; that is, they could be run 11.6 per cent. slower. In fact, they could be run more than 11.6 per cent. slower in the second case, and yet supply the same quantity of air, because at the slower running the delivery efficiency is somewhat higher.

The disadvantage of cooling the uncompressed blast is that it must be cooled much more, to eliminate from it a given percentage of its moisture, than if it were first compressed, and to obtain nearly dry air the moisture must be practically frozen out.

Illustration: Air at 30° C. and 85 per cent. humidity is to be cooled until 95 per cent. of its moisture is eliminated, without compression; to what temperature must it be cooled?

From the tables of aqueous tension, we find that the maximum tension which aqueous vapor can exert at 30° C. is 31.5 millimeters, which means practically that $\frac{31.5}{760}$ of a cubic meter of moisture accompanies $\frac{728.5}{760}$ of a cubic meter of air proper. If the humidity is 85 per cent., then this same quantity of air is accompanied by

$$\frac{31.5}{760} \times 0.85 = 0.0352 \text{ cubic meters}$$

of moisture, or, per cubic meter of air measured dry—

$$0.0352 \div \frac{728.5}{760} = 0.0368 \text{ cubic meters.}$$

If 95 per cent. of this is removed by cooling, then the moisture left, per cubic meter of air measured dry, is

$$0.0368 \times 0.05 = 0.00184 \text{ cubic meters.}$$

And the relative tensions of air and moisture, to attain this dryness, must have been reduced to

$$1.0000 : 0.00184.$$

Since the sum of these tensions is always 760 mm. in the uncompressed air, the actual tensions of air and moisture will be

$$758.6 : 1.4,$$

that is, the temperature must be reduced until the moisture present can exert only 1.4 mm. pressure. This, on examining the tables of tension of aqueous vapor is found to be less than 0° C., in fact −15° C.

Problem 62.

Air at 30° C., carrying 85 per cent. of its possible amount of moisture, is cooled to 0° C., and the moisture condensed to liquid water at that temperature. Barometer 760 mm.

Required:

(1) The percentage of the moisture condensed.

(2) The amount of heat to be abstracted from each cubic meter of original moist air (refrigerating effect).

(3) The percentage of moisture which would be condensed if the temperature were reduced to −5° C.

(4) The total heat to be abstracted, per cubic meter of original air, in the latter case.

Solution:

(1) From the preceding illustration we can take the figures that in the moist air taken, each cubic meter of air proper is accompanied by 0.0368 cubic meter of moisture. In the cooled

air at 0°, the relative volumes of air proper and residual moisture will be as their relative tensions, viz.:

$$755.4:4.6$$

or

$$1:0.0061.$$

The moisture accompanying the given quantity of air is, therefore, reduced from 0.0368 to 0.0061, showing a condensation of 0.0307, equal to

$$\frac{0.0307}{0.0368} = 0.834 = 83.4 \text{ per cent.} \tag{1}$$

(2) The air at 30° contains, as before figured out, air proper and moisture in the proportions

$$1:0.0368.$$

or, in 1 cubic meter of moist air, in the proportions

$$0.9645:0.0355.$$

We have, therefore, to calculate the heat to be extracted from 0.9645 cubic meter of air proper, falling 30° to 0°, and from 0.0355 cubic meter of water vapor, falling 30° to 0° and 83.4 per cent. of the latter condensing to liquid at 0°. The figures are, remembering that the volumes heretofore handled are at 30°:

Air proper:

$$0.9645 \times \frac{273}{303} \times 0.3038 \times 30 \qquad = \ 7.920 \text{ Calories}$$

Moisture, if all uncondensed:

$$0.0355 \times \frac{273}{303} \times 0.3445 \times 30 \qquad = \ 0.332 \quad \text{"}$$

Heat of condensation:

$$0.0355 \times 0.834 \times \frac{273}{303} \times 0.81 \times 606.5 \qquad = \underline{13.105} \quad \text{"}$$

$$\text{Total} = 21.357 \quad \text{"} \tag{2}$$

(3) If the temperature were reduced to $-5°$ C., the tension of the residual moisture would be 3.4 mm. of mercury, and

that of the air proper 756.6 mm., their relative volumes would be in the same ratio, viz.:

$$756.6:3.4$$

or

$$1:0.0045.$$

showing that out of 0.0368 cubic meter of moisture originally accompanying 1 cubic meter of air proper, 0.0323 had been condensed, or

$$\frac{0.0323}{0.0368} = 0.878 = 87.8 \text{ per cent.} \qquad (3)$$

(4) The condensation is seen to be 87.8−83.4, or 4.4 per cent. more, if the air is cooled to −5° C. A considerably larger amount of refrigeration, however, is required in this case, because the moisture would all be frozen. The 1 cubic meter of moist air at 30°, containing, as before calculated, 0.9645 cubic meter of air proper and 0.0355 cubic meter of moisture, would have 87.8 per cent. of the latter condensed to ice, or 0.03117 cubic meter, and, therefore, 0.00433 cubic meter remaining uncondensed.

Air proper, 30° to −5° C.:

$$0.9645\times\frac{273}{303}\times 0.3037\times 35 \qquad = \ 9.237 \text{ Calories}$$

Moisture, if all uncondensed, 30° to −5° C.:

$$0.0355\times\frac{273}{303}\times 0.3438\times 35 \qquad = \ 0.385 \quad \text{“}$$

Condensation of 0.03177 m^3 to liq. at − 5° C.:

$$0.03177\times\frac{273}{303}\times 0.81\times 605 \qquad = 14.025 \quad \text{“}$$

Freezing of same, at − 5° C.:

$$0.03177\times\frac{273}{303}\times 0.81\times 80 \qquad = \ \underline{1.855} \quad \text{“}$$

$$= 25.502 \quad \text{“} \qquad (4)$$

The conclusion is, that an increased condensation of 4.4 per cent. has been obtained by an increase in the refrigerating requirement of 25.502−21.357 = 4.145 Calories, or nearly

20 per cent. Another way of stating the comparison, is that when not freezing the moisture condensed, about 4 per cent. of the moisture was condensed from each cubic meter of air for one Calorie of refrigeration, whereas, the removal of additional moisture by cooling below zero requires nearly one Calorie refrigeration for each additional per cent. of moisture eliminated.

A practical conclusion is, that the expense of refrigeration might easily be justified down to 0° C., and yet be unjustified by the results when cooling below 0°.

Mr. James Gayley has, I believe, patented the scheme of refrigerating the air in two stages; first, nearly to zero, removing the moisture thus condensed as liquid, and then cooling the nearly dry air further, eliminating more moisture as ice. In this manner, the amount of refrigeration required is reduced by the latent heat of solidification of the larger part of the moisture, and cooling below zero becomes profitable. The saving in the above example would be 80 Calories per kilogram on all the moisture condensed at 0°, viz.:

$$0.0216 \times 80 = 1.728 \text{ Calories,}$$

cutting down the refrigeration required from 25.502 to 23.774 Calories, that is, enabling 4.4 per cent. additional drying to be produced for 2.4 Calories additional refrigeration. This scheme of Mr. Gayley is founded on sound scientific as well as practical considerations.

The idea of cooling the compressed blast by moderately cool water, recently proposed, is also a very practical idea and founded on sound scientific principles. At a given temperature moisture cannot exert more than a maximum vapor tension. It follows that if we start with air saturated with moisture, at a given temperature, and compress it to double its initial tension, keeping its temperature constant, about half of its moisture must condense out. If, at the same time, it is artificially cooled, then more than half of its moisture will condense as liquid.

If we start with air not saturated with moisture, the compression, temperature being constant, will increase the tension of the moisture present until the air becomes saturated, after which increased pressure will cause condensation.

Illustration: Air at 30° C., 85 per cent. saturated with moisture, is compressed. At what effective pressure does it become saturated with moisture, temperature remaining constant?

The moisture present is exerting 85 per cent. of its maximum vapor tension at this temperature. Therefore, the tension must be increased in the ratio of 85 to 100, to make the air saturated, viz.: in the ratio 1 to 1.177. The effective pressure necessary to be applied is, therefore, $1.177-1.000=0.177$ atmospheres (2.6 pounds per square inch).

Illustration: If air at 30° C., 85 per cent. saturated with moisture, is compressed to one atmosphere effective pressure and its temperature kept constant, what proportion of its moisture will condense?

Before compression, the tension of the moisture being $31.5\times 0.85=26.8$ mm., the relative volumes of air proper and moisture are as

$$733.2:26.8$$

or, as

$$1:\ 0.0367$$

After compression, the tension on the mixture being two atmospheres (1520 mm.), and the tension of the uncondensed moisture being it maximum, or 31.5 mm., the relative volumes of air and uncondensed moisture will be as

$$1488.5:31.5,$$

or, as

$$1:\ 0.0212.$$

The proportion of the original moisture remaining uncondensed is therefore,

$$\frac{0.0212}{0.0367}=0.578=57.8 \text{ per cent.}$$

and the amount condensed out = 42.2 per cent.

Problem 63.

Air at 30° C., and 85 per cent. saturated with moisture is compressed to one atmosphere effective pressure (760 mm. of mercury), and simultaneously cooled by river water to 10° C. Barometer 730 mm.

Required:

(1) The percentage of the original moisture, condensed.

(2) The weight of moisture remaining in the air, expressed in grams per cubic meter of dry air at standard conditions (*i.e.*, per 1.293 kilograms of air proper).

Solution: (1)

Tension of uncompressed moist air = 730.0 mm.
Tension of moisture present 31.5×0.85 = 26.8 “
Tension of air proper, uncompressed = 703.2 “
Relative volumes of air proper and moisture = 1 : 0.0381
Tension of compressed moist air 730+760 = 1490.0 “
Tension of uncondensed moisture (maximum tension at 10°) = 9.1 “
Tension of air proper, when compressed = 1480.9 “
Relative volumes of air proper and uncondensed moisture = 1 : 0.0061

Proportion of moisture condensed:

$$\frac{0.0381-0.0061}{0.0381} = 0.84 = \mathbf{8.40} \text{ per cent.} \qquad (1)$$

(2) The relative volumes of air proper and uncondensed moisture are, as found above,

1 : 0.0061,

And the relative specific gravities of air proper and moisture are as the standard weights of 1 cubic meter of each, viz.: as

1.293 : 0.81.

It follows, therefore, that 1.293 kilos. of air proper (1 cubic meter at standard conditions) must be accompanied by

$$0.0061 \times 0.81 = 0.0049 \text{ kg. of moisture,}$$

or

$$= \mathbf{4.9} \text{ grams.} \qquad (2)$$

The original moist air contained, similarly considered,

$$0.0381 \times 0.81 = 0.0309 \text{ kg.}$$
$$= 30.9 \text{ grams.}$$

CHAPTER VII.

THE BESSEMER PROCESS.

The outlines of this famous process are known to every educated person; the mechanical and most of the chemical details are familiar to most technologists; the exact way to run the converter is the source of income to hundreds of superintendents of works, and yet the quantitative side of the chemical and physical operations involved is mastered by very few.

To state the case briefly, melted pig iron is put into the converter, numerous air jets are blown through, the impurities of the iron—carbon, silicon, manganese and, in a special case, phosphorus—oxidize relatively faster than the iron, and the final product is usually nearly pure iron. This is recarburized to steel by spiegel-eisen. During the blow very little free oxygen escapes from the converter, and the gases produced are principally nitrogen, carbon monoxide and some carbon dioxide, while some hydrogen may come from the decomposition of the moisture of the air. The silicon, manganese, phosphorus and iron form silica, manganous oxide (MnO) principally, ferrous oxide (FeO) principally, phosphorus pentoxide, P^2C^5, which go into the slag, while a little Fe^2O^3, Mn^3O^4 and SiO^2 escape as fume.

The applications of calculations to this process are numerous and important. They include such subjects as the amount of air theoretically required per ton of iron, the dimensions and power of the blowing engines, the weight of slag produced, the balance sheet of materials, the balance sheet of heat evolved and distributed, the radiation losses, the discussion of the efficiency of the various impurities as heating agents in the process.

AIR REQUIRED.

Basing our calculations on the analysis of the pig iron used, and assuming it to be blown to pure iron, we must next assume the probable loss of iron itself in the blow. This varies considerably, from 1 to 10 per cent, on the pig iron used in ordinary practice, but as much as 20 to 25 per cent. in some carelessly run "Baby" Bessemers in steel-casting foundries. The silicon all oxidizes to SiO^2; iron mostly to FeO, and a small part, say not over one-tenth, to Fe^2O^3; manganese mostly to MnO, a small part, up to one-fourth, may form Mn^2O^3; phosphorus forms only P^2O^5; carbon burns mostly to CO, but from one-fifth, at times nearly one-half, burns to CO^2. When all the calculated oxygen has been found, the blast to contain it can be calculated, if it is assumed that no free oxygen escapes from the converter; at times, however, up to one-third of all the oxygen blown in may thus escape, but this is very exceptional, ordinarily less than one-fifth thus escapes, and often none at all.

Problem 64.

Pig iron containing 3.10 per cent. carbon, 0.98 silicon, 0.40 manganese, 0.101 phosphorus and 0.06 sulphur is blown in an acid-lined converter, to metal practically free from carbon, silicon and manganese, but no sulphur or phosphorus is eliminated. To get the minimum and the maximum amounts of air which could be needed, make the following assumptions:

	Case 1.	*Case* 2.
Per cent. of iron lost by oxidation.........	1	15
Proportion of iron oxidized to Fe^2O^3.......	none	one-tenth
Proportion of Mn oxidized to Mn^2O^3.......	none	one-fifth
Proportion of C oxidized to CO^2...........	one-fifth	one-half
Proportion of O^2 escaping in the gases......	none	one-third

Requirement: (1) Find the weight of dry air needed per metric ton of pig iron blown, in each case, and its volume at 0° C. Express the results also in pounds and cubic feet per ton of 2,000 pounds.

Solution:

Case 1.

Oxygen needed per 1,000 kg. of pig iron:

$$\text{C to CO}^2 \ldots\ldots\ldots\ldots \quad 6.2 \text{ kg.} \times \frac{32}{12} = 16.53 \text{ kg.}$$

$$\text{C to CO} \ldots\ldots\ldots\ldots \quad 24.8 \text{ ``} \times \frac{16}{12} = 33.07 \text{ ``}$$

Si to SiO^2........................ 9.8 “ $\times\frac{32}{28}$ = 11.20 kg.

Mn to MnO...................... 4.0 “ $\times\frac{16}{55}$ = 1.16 “

Fe to FeO........................10.0 “ $\times\frac{16}{56}$ = 2.86 “

64.82 “

N^2 accompanying = 216.07 “

Air needed................................. = 280.89 “
Volume at 0° C......................... = 217.2 m^3
Volume needed per 1000 oz. Av............... = 217.2 ft^3
Volume needed per 2000 lbs. Av............. = 6,950 ft^3

Case 2.

Oxygen needed per 1000 kg. of pig iron:

C to CO^2........................15.5 kg. $\times\frac{32}{12}$ = 41.33 kg.

C to CO............................15.5 “ $\times\frac{16}{12}$ = 20.67 “

Si to SiO^2........................ 9.8 “ $\times\frac{32}{28}$ = 11.20 “

Mn to MnO...................... 3.2 “ $\times\frac{16}{55}$ = 0.93 “

Mn to Mn^2O^3................ .. 0.8 “ $\times\frac{48}{110}$ = 0.34 “

Fe to FeO.......................135.0 “ $\times\frac{16}{56}$ = 38.57 “

Fe to Fe^2O^3....................15.0 “ $\times\frac{48}{112}$ = 6.43 “

O^2 unused (one-half sum of above)........... = 59.73 “

179.20 “

N^2 accompanying = 597.33 “

Air used................................. = 776.53 “
Volume at 0° C......................... = 600 m^3
Volume used per 1000 oz. Av................ = 600 ft^3
Volume used per 2000 lbs. Av.............. = 19,200 ft^3

For temperatures of the air above 0° C., a corresponding increase in the volume used would be found. Since this is net air received by the converter an allowance for loss of 10 to 25 per cent. (in exceptional cases 50 per cent.) would be needed to get the piston displacement of the blowing engines. The above figures are the maximum and minimum for this quality of pig iron only, blown in an acid-lined converter; other qualities of pig iron might require a little more or less, and if blown in a basic-lined converter considerably more, to oxidize the phosphorus. The detailed calculations can be made in each specific case.

AIR RECEIVED.

The converse of the preceding proposition is to take an actual case, in a Bessemer converter, and to calculate how much air is being received. This will serve as a check on the blowing engines, since the volume received, divided by the piston displacement, gives the volume efficiency of the blowing plant. To make the calculation we need to know the weight and analysis of the pig iron and the analysis of the blown metal, in order to find the weights of impurities oxidized, also the average composition of the escaping gases, to find the proportion of carbon burning to CO^2 and of unused oxygen; also the composition of the slag, to get therefrom the weight of iron oxidized and the weight of slag, if practicable, but this can sometimes be calculated; also the weight and composition of the fume, if it is considerable. The temperature of the air entering the blowing cylinders its hygrometric condition and the barometric pressure should also be noted.

Problem 65.

At the South Chicago works of the Illinois Steel Co. (see paper by Howe, in Trans. American Institute of Mining Engineers, XIX. [1890–91], p. 1127), the charge weighed 22,500 pounds, and contained 2.98 per cent. carbon, 0.94 silicon, 0.43 manganese, 0.10 phosphorus, and 0.06 sulphur. After blowing 9 minutes 10 seconds the bath contained 0.04 per cent. carbon, 0.02 silicon, 0.01 manganese, 0.11 phosphorus and 0.06 sulphur. The slag formed contained 63.56 per cent. silica, 3.01 alumina, 21.39 FeO, 2.63 Fe^2O^3, 8.88 MnO, 0.90 CaO and 0.36 MgO, of which the $Al^{2}O^{3}$, Cal and MgO and part of the SiO^{2} come from the lining. The gases, analyzed dry, show an average composition during the blow of

CO^{2}	5.20	per cent.
CO	19.91	"
H^{2}	1.39	"
N^{2}	73.50	"

and were free from fume.

The piston displacement during the blow was 190,406 cubic feet, air in engine room 36° C., humidity 50 per cent., barometer 756 millimeters.

Requirements: (1) The weight of oxygen acting on the bath during the blow, and the theoretical volume of air at standard conditions to which this would correspond, per 2,000 pounds of metal blown.

(2) The volume of moist air at the conditions of the engine room, received by the converter during the blow, and the volume efficiency of the blowing machine and connections.

(3) The weight of slag produced and the loss in weight of the lining by corrosion during the blow.

Solution: (1) The percentages of impurities left in the bath are so small that we can take them as equivalent to the same percentages reckoned on the original weight of the bath If they had been larger it would be necessary to assume an approximate loss of iron during the blow, find the final weight of the bath and reckon the percentages on this revised weight.

Making this assumption, we know at once the weights of carbon, silicon and manganese oxidized, but we do not know the weight of iron lost. That follows, however, from a consideration of the slag, for the manganese and iron in the slag are derived only from the metallic bath, and the analysis of the slag practically gives us the relation between the weights of manganese and iron in it; since we know the weight of the former oxidized, the weight of iron lost can be calculated. Thus the slag contains:

MnO	8.88	per cent	=	6.88	per cent.	Mn
FeO	21.39	"	=	16.64	"	Fe as FeO
$Fe^{2}O^{3}$	2.63	"	=	1.84	"	Fe as $Fe^{2}O^{3}$

The loss of manganese being 0.42 per cent. = 94.5 pounds, the loss of iron is:

$$94.5 \times \frac{16.64}{6.88} = 228.6 \text{ pounds Fe as FeO}$$

$$94.5 \times \frac{1.84}{6.88} = 25.3 \text{ pounds Fe as } Fe^2O^3$$

The remaining item still undetermined is the weight of carbon oxidizing to CO^2 and to CO. The gas analysis shows 5.20 per cent. CO^2 to 19.91 per cent. CO, and since equal volumes of each of these gases contain equal weights of carbon, it follows that $\frac{5.20}{25.11}$ of the total carbon is present in the gas as CO^2, and the rest as CO. Since the total carbon oxidized is 22,500× 0.0294 = 661.5 pounds, we have

$$661.5 \times \frac{520}{2511} = 137.0 \text{ pounds C burning to } CO^2$$

$$= 524.5 \quad \text{"} \quad \text{"} \quad \text{CO}$$

Weight of oxygen absorbed by the bath:

C to CO^2	137.0	pounds	× 8/3	= 365.3	pounds
C to CO	524.5	"	× 4/3	= 699.3	"
Si to SiO^2	207.0	"	×32/28	= 236.6	"
Mn to MnO	94.5	"	×16/55	= 27.5	"
Fe to FeO	228.6	"	×16/56	= 65.3	"
Fe to Fe^2O^3	25.3	"	×48/112	= 10.8	"
					"
				1404.8	"
N^2 corresponding				= 4682.7	"
Dry air corresponding				= 6087.5	"
Volume at 0° C				= 75,483	ft^3
Weight of O^2 per 2000 pounds				= 124.9	lbs. (1)
Volume of air per 2000 pounds				= 6,710	ft^3(1)

(This result is for comparison with data of Problem 64).

(2) The nitrogen in the gases can be obtained from its volume relation to the carbon, and from this we can calculate the real volume of blast used.

Weight of carbon in 1 cubic foot of gases:

$$(0.0520+0.1991)\times 0.54 = 0.1356 \text{ oz. Av.}$$

Volume of gases produced at standard conditions:

$$\frac{661.5\times 16}{0.1356} = 78{,}057 \text{ ft}^3$$

Volume of nitrogen at standard conditions:

$$\begin{aligned} 78{,}057\times 0.7350 &= 57{,}372 \text{ ft}^3 \\ \text{Weight} = 57{,}372\times 1.26 &= 72{,}289 \text{ oz. Av.} \\ &= 4{,}518 \text{ lbs.} \end{aligned}$$

The question now is, how much nitrogen is contained in each cubic foot of air in the engine room. Knowing that, we are prepared to calculate the volume of this actually received by the converter:

Barometric pressure	=	756 m.m.
Tension of moisture (44×0.5)	=	22 "
Tension of air present	=	734 "
Tension of nitrogen present (734×0.792)	=	580 "

Weight of nitrogen in 1 cubic foot:

$$1.26\times\frac{273}{273+36}\times\frac{580}{760} = 0.8495 \text{ oz. Av}$$

Volume of air actually received:

$$\frac{4{,}518\times 16}{0.8495} = 85{,}095 \text{ ft.}^3 \qquad (2)$$

Volume efficiency of machinery:

$$\frac{85{,}095}{190{,}406} = 0.447 \qquad = 44.7 \text{ p. c.} \; (2)$$

(3) The slag contains 8.88 per cent. of MnO, equal to 6.88 per cent. of Mn, as already calculated. But 94.5 pounds of

manganese is oxidized, therefore, the weight of slag produced is:

$$94.5 \div 0.0688 = 1374 \text{ pounds.} \qquad (3)$$

Weight of SiO^2 in slag (1374×0.6356) = 873 pounds
SiO^2 from the Si of bath ($207.0 + 236.6$) = 444 "

SiO^2 corroded from the lining = 429 "
CaO, Al^2O^3 and MgO (1374×0.0427) = 59 "

Loss in weight of lining = 488 " (3)

BLAST PRESSURE.

It is necessary to use sufficient blast pressure to overcome the static pressure of the metallic bath, plus that of the slag formed, also the back pressure in the converter, to give the necessary velocity to the air in the tuyeres and to overcome friction in the same. When the tuyeres are near to the surface of the bath, pressures of 1 or 2 pounds will run the small converter, but the ordinary converter with bottom tuyeres requires from 15 to 30 pounds pressure per square inch (1.054 to 2.108 kg. per square c.m.). We will consider the latter, the more frequent and the more complex case to discuss.

The metal lies 12 to 24 inches (30 to 60 c.m.) deep in the converter. Since its specific gravity melted is about 6.88 (Roberts and Wrightson), the ferro-static pressure which it exerts is practically 0.25 pounds per square inch for each inch depth of metal, or 0.00688 kilos. per square centimeter for each centimeter depth.

The slag lying on the metal has a specific gravity melted of approximately half that of the metal. Its amount may vary from 5 to 10 per cent. of the weight of the metal treated, in an acid-lined converter, up to from 15 to 35 per cent. in a basic-lined vessel. Taking into account its lower specific gravity, its depth in the converter may be, therefore 10 to 20 per cent. the depth of metal in an acid-lined vessel, and 30 to 70 per cent. in a basic-lined converter; but the static pressure exerted would be only in direct proportion to the relative weights; *i. e.*, 5 to 10 or 15 to 35 per cent. of that exerted by the metal. The static pressure of the slag may, therefore, be reckoned as 0.125 pounds per square inch for each inch in depth, or 0.00344 kilos. per square centimeter for each centimeter depth, and the depth of slag as lying between the following extremes:

		Acid Lined.	*Basic Lined.*
Depth of metal	Inches	12 to 24	12 to 24
	Centimeters	30 to 60	30 to 60
Depth of slag	Inches	1.2 to 4.8	3.6 to 16.8
	Centimeters	3.0 to 12.0	9.0 to 42.0

The probable depth of slag can be calculated in any particular case, when the composition of the metal to be blown is known, its approximate depth in the vessel, and the approximate composition of the slag to be formed.

The back pressure of gases in the converter itself, that is, their static pressure, will vary with the shape of the converter and the size of the free opening for their escape into the air. A measurement at the Pennsylvania Steel Co's. works gave 0.275 pounds per square inch, but it is not stated just how the measurement was made. If we know approximately the volume of gas which must escape from the converter and from its temperature and the time and the size of the outlet calculate its velocity, the static pressure giving it this velocity can be calculated as

$$h = \frac{V^2}{2g}$$

in which, if V is in feet per second, $2g = 64.3$ and the resultant pressure is in feet of the hot gas; if V is in meters per second, $2g = 19.6$, and h is in meters of the hot gas. Knowing the approximate specific gravity of the hot gas (weight of 1 cubic foot in pounds or of 1 cubic meter in kilograms) the static pressure is obtainable in pounds per square foot or kilograms per square meter.

Illustration: The gases escaping from a converter are 78,057 cubic feet (standard conditions), and weigh 0.0801 pounds per cubic foot (standard conditions). They escape from the converter at an average temperature of 1,500° C., and the opening is 24 inches in diameter. What is the gaseous back pressure in the converter? Time of blow 9 minutes 10 seconds.

Volume of gas at 1,500°:

$$78{,}057 \times \frac{1500+273}{273} \qquad = 506{,}940 \text{ ft}^3$$

Volume per second:

$506{,}940 \div 550 \qquad = \quad 921.7$ "

Area of outlet:

$2 \times 2 \times 0.7854 \qquad = \quad 3.1416 \text{ ft}^2$

Velocity (assuming 0.9 coefficient):

$921.7 \div 0.9 \div 3.1416 \qquad = \quad 326$ ft. per second

Head of hot gas giving velocity:

$$h = \frac{326 \times 326}{64.3} \qquad = \quad 1{,}653 \text{ ft.}$$

Pressure of this column per square foot:

$$1.653 \times \frac{273}{1773} \times 0.0801 \qquad = \quad 20.4 \text{ pounds}$$

Per square inch $\qquad = \quad 0.14$ "

This solution omits one consideration; the velocity of the gases in the body of the converter is neglected. This is somewhat counterbalanced by the great friction of the gases against the sides of the converter, so that the one item tends to neutralize the other. If the interior were 8 feet in diameter, the velocity of the gases therein would average only some 20 feet per second, showing the above corrections to be practically negligible, since the pressure thus represented would be only 0.4 per cent. of the total obtained above.

The pressure necessary to force the blast through the tuyeres is calculable on principles similar to the above; the differences are that the blast, at temperatures varying from 100° C. in the blast box to possibly 200° at its entrance into the metal, is divided up into fifty or 150 streams of approximately 1 centimeter (0.4 inch) in diameter, the length of tuyeres being some 50 centimeters (20 inches). The formula similar to that used for chimney draft, or rather, frictional resistance in a chimney, applies to this case.

$$h = \frac{V^2}{2g}\,\frac{KL}{D}$$

in which h is the head in terms of the air passing, V is its velocity, 2g the gravitation constant, L the length of the tuyere, D its diameter, and K the coefficient of friction, which latter is for relatively smooth flues 0.05 (Grashof), and may be so assumed here.

Problem 66.

In the converter mentioned in Problem 65, where 22,500 pounds of metal was blown in 9 minutes 10 seconds, using as therein calculated 85,095 cubic feet of air, at 36° C., and producing 1,374 pounds of slag, assume the inside diameter of the converter as 7 feet, and that the bottom contains fourteen tuyere blocks, each containing eleven openings of 0.5 inch diameter each; blocks 24 inches long. Assume back pressure in converter 0.14 pounds per square inch, total blast pressure in equalizing reservoir 27 pounds per square inch. Temperature of air in the tuyeres 150° C.

Required: (1) The pressure needed to overcome the head of metal and slag.

(2) The pressure absorbed in friction in the tuyeres.

(3) The pressure represented by the velocity of the blast in the tuyeres.

(4) The loss of pressure from the reservoir to the blast-box.

(5) The distribution of the total pressure.

(6) The length of the blow if the blast pressure were reduced to 20 pounds.

(7) The length of the blow if the pressure were maintained at 27 pounds, but twenty-one tuyere blocks (each with eleven $\frac{1}{2}$-inch holes) were used.

Solution: (1) At the start there is 22,500 pounds of melted metal, the volume of which will be

$$\frac{22{,}500}{6.88 \times 62.5} = \frac{22{,}500}{430} = 52.3 \text{ cubic feet}$$

The depth of metal, the inside diameter being 7 feet, is

$$\frac{52.3}{7\times7\times0.7854}=\frac{52.3}{38.5}=\ 1.356 \text{ feet}$$

$$= 16.4 \text{ inches}$$

Static pressure = 16.4× 0.25 = 4.1 lbs. per sq. in.

The slag, formed during the first half of the blow, weighs 1,374 pounds, and has a volume of

$$\frac{1374}{3.44\times62.5}=\frac{1374}{215}=\ 6.4 \text{ cubic feet}$$

The depth of slag, at its maximum, will be

$$6.4\div38.5 = 0.167 \text{ feet}$$

$$= 2.0 \quad \text{inches}$$

Static pressure 2.0×0.125 = 0.25 lbs. per sq. in.

The static pressure during the blow will, therefore, be 4.1 pounds to start with, increasing during the first half of the blow to 4.35 pounds, and staying practically constant at that, and, therefore, will average

$$\frac{4.1+4.35}{2\times2}+\frac{4.35}{2}=\mathbf{4.29} \text{ pounds} \qquad (1)$$

(2) Each of the 14×11 = 154 tuyeres receives 85,095÷154÷550 = 1.005 cubic feet of air per second, measured at 36° C. At 150° C. this volume is

$$1.005\times\frac{273+150}{273+36}=1.375 \text{ cubic feet}$$

And the velocity in the tuyere:

$$1.375\div\frac{0.5\times0.5\times0.7854}{144}=1009 \text{ feet per second}$$

The head absorbed in friction in the 24-inch tuyeres will be

$$h=\frac{1009\times1009}{64.3}\times\frac{0.05\times2}{0.0417}=37{,}893 \text{ feet}$$

Changing this pressure of air at 150° C. to pounds per square inch we have:

Weight of 1 cubic foot of air at 0° = 0.0808 pounds
Weight of 1 cubic foot of air at 150° = 0.0522 "
Weight of air column = 37,893 × 0.0522 = 1978 "
Pressure in pounds per square inch = **13.7** " (2)

(3) The pressure absorbed as velocity has already been expressed in getting the friction in the tuyeres. The velocity head is simply:

$$h = \frac{V^2}{2g} = \frac{1009 \times 1009}{64.3} = 15{,}835 \text{ feet}$$

which becomes in pressure

$$15{,}835 \times 0.0522 = 826.6 \text{ pounds per square foot}$$
$$= \mathbf{5.73} \text{ pounds per square inch} \qquad (3)$$

(4) The remaining part of the 27 pounds pressure used is lost between the blast reservoir and the entrance to the tuyeres. It is

$27.00 - (13.70 + 5.73 + 4.29 + 0.14). = \mathbf{3.14}$ pounds. (4)

(5) Distribution of blast pressure:

Fall between reservoir and tuyeres	= 3.14	pounds	= 11.6%
Absorbed in friction in the tuyeres	= 13.70	"	= 50.7%
Absorbed in velocity in the tuyeres	= 5.73	"	= 21.2%
Static head of liquid bath	= 4.29	"	15.9%
Velocity head of issuing gases	= 0.14	"	= 0.6%
	27.00	"	= 100.0%

(6) All the items of absorption of pressure are proportional to the square of the velocity of the gases, excepting the static pressure of the bath. It remains constant at 4.29 pounds. If the total pressure were reduced to 20 pounds, there would be only $20 - 4.29 = 15.71$ pounds pressure to give velocity and overcome friction, instead of $27 - 4.29 = 22.71$ pounds. The relative quantities of air blown through in a given time in the two instances would be practically proportional to the square roots of the two effective pressures, *i.e.*:

$$\sqrt{22.71} : \sqrt{15.71} = 1 : 0.832$$

and the times of the blows inversely as the latter:

$$550 \text{ sec.} \div 0.832 = 673 \text{ seconds}$$
$$= \mathbf{11 \text{ min. } 13 \text{ sec.}} \qquad (6)$$

(7) If the tuyere area were increased 50 per cent., then the velocity of the air in the tuyeres would be decreased one-third, assuming the amount of air passing to be unchanged. This would decrease the pressure absorbed in friction, and in giving velocity in the tuyeres to $(0.67)^2 = 0.444$ of its former amount. The 19.43 pounds previously absorbed in these two items would then become $19.43 \times 0.444 = 8.61$ pounds, and the total pressure needed to run the converter just as fast as before would be $27 - (19.43 - 8.61) = 16.18$ pounds per square inch. If, however, the pressure were maintained at 27 pounds, giving still $27 - 4.29 = 22.71$ pounds to overcome frictional resistances and to give velocity, then the velocity and consequent amount of air blown through by this 22.71 pounds pressure would increase in proportion to the square root of these two available pressures; *i.e.*, be as

$$\sqrt{16.18 - 4.29} : \sqrt{27 - 4.29} = 1 : 1.38$$

The duration of the blow would be just that much shorter; *i.e.*;

$$550 \text{ sec.} \div 1.38 = 398 \text{ seconds}$$
$$= \textbf{6 min. 38 sec.} \qquad (7)$$

FLUX AND SLAG.

No flux is used in the acid-lined converter, and the silica, iron oxides and manganese oxide formed in the converter unite to a silicate slag which corrodes the lining and thus takes up more silica. The slag being analyzed, its weight is obtained by considering the percentage of manganese which it contains, because the weight of manganese oxidized is known definitely from the analysis of the bath; it is usually all oxidized. Calculation of the weight of slag cannot be based upon the silica, because an unknown amount comes from the lining; nor upon the iron, because the weight of iron left in the converter is not definitely known. Having the weight of the slag, analysis tells us the total weight of silica in it, as also the amount of iron. The silica in the slag minus that formed from silicon in the pig iron, gives silica corroded from the lining.

In the basic Bessemer converter, phosphorus is nearly entirely eliminated from the metal, so that, assuming none to be volatilized, the amount going into the slag is known, and using the slag analysis the weight of slag can be calculated. In this process the lining is mainly dolomite, containing CaO and MgO, in proportion easily determined by analysis. The weight of slag being known, the amount of corrosion of the lining can be determined from the percentage of magnesia therein, which may be assumed as practically coming entirely from the lining; it cannot be told from the CaO in the slag, because nearly pure CaO is added during the blow, and some of it, a variable amount, gets blown out of the converter. For the same reason it is not possible to base a good calculation of the weight of slag on the lime alone which is added, because of the indefinite proportion of it which is blown out. The weight of slag may also be gotten from the silica or manganese oxide in it, assuming these to come almost entirely from the oxidation of silicon or manganese.

Lime must be added as flux, in the basic converter, to protect the lining and to make the slag so basic that the percentage of silica in it is below 15 per cent., phosphoric acid below 20 per cent., and lime over 50 per cent. These considerations must be balanced in each particular case.

Illustration: Pig iron blown in a basic-lined converter contained 1.22 per cent. silicon, 2.18 phosphorus, 1.03 manganese and 3.21 carbon. It is blown until all of these and 2.00 per cent. of iron are oxidized, and burnt lime is added to form slag during the blow. Composition of the burnt lime: MgO, 1.00 per cent.; SiO^2, 2.00 per cent.; CaO, 97 per cent. How much lime should be added per 10 metric tons of pig iron charged?

The slag-forming ingredients from the oxidation of the bath, and the addition of X kilos. of lime, are

SiO^2	$10{,}000 \times 0.0122 \times 60/28$	$= 261.4$ kg.
P^2O^5	$10{,}000 \times 0.0218 \times 142/62$	$= 499.3$ "
MnO	$10{,}000 \times 0.0103 \times 71/55$	$= 133.0$ "
FeO	$10{,}000 \times 0.0200 \times 72/56$	$= 257.1$ "
CaO	$X \times 0.9700$	$= 0.97\ X$
MgO	$X \times 0.0100$	$= 0.01\ X$
SiO^2	$X \times 0.0200$	$= 0.02\ X$

Weight for slag $= X + 1150.8$ kg.

Corrosion of the lining will undoubtedly increase this weight, so some allowance should be made, say to increase it 5 per cent., probably an outside figure. Of this 5 per cent., half can be considered lime and half magnesia. The total weight of slag will then be 1.05 X + 1208.3, and of the ingredients principally in question:

SiO^2 = 261. kg. + 0.02 X
MgO = 28.7 " + 0.035 X
CaO = 28.7 " + 0.995 X

To make our slag 50 per cent. CaO will require the addition of enough to make

$$28.7 + 0.995\ X = 0.50\ (1.05\ X + 1208.3)$$
$$X = \mathbf{1224}\ \text{kg.}$$

To make a slag with at most 15 per cent. of SiO^2 requires

$$261.4 + 0.02\ X = 0.15\ (1.05\ X + 1208.3)$$
$$X = \mathbf{583}\ \text{kg.}$$

To make a slag with at most 20 per cent. of P^2O^5 requires

$$499.3 = 0.20\ (1.05\ X + 1208.3)$$
$$X = \mathbf{1227}\ \text{kg.}$$

The larger of these three amounts would be used, with 10 per cent. added to cover lime dust blown out, making 1350 kg. added, and the calculated composition of the slag:

CaO 1250 kg. = 50.1 per cent.
MgO 723 " = 2.9 "
SiO^2 286 " = 11.4 "
P^2O^5 499 " = 20.0 "
FeO 257 " = 10.3 "
MnO 133 " = 5.3 "

Total **2497** "

Recarburization.

When the bath has been blown to nearly pure iron, melted spiegeleisen is run in, to add the necessary carbon and manganese. Knowing the approximate composition and weight of the bath, and the composition of the melted spiegel, a simple arithmetical calculation would give the amount of the latter to be added, assuming no loss of carbon or manganese in the operation. But experience shows that there is some loss, and that the carbon and manganese in the finished metal are always lower than the calculated amount. An interesting field is open here for calculating the loss of manganese and carbon and the amount of oxygen which must have been in the metal to cause these losses. A tabulation of many such calculations gives the metallurgist the necessary data for assuming the average amounts of carbon and manganese lost during recarburization, under different conditions of working, such as letting the metal stand before pouring or pouring at once, turning on the blast 5 or 10 seconds to mix up the bath, etc.

Problem 67.

At the end of the blowing the converter of Problem 65 contained 21,283 pounds of metal of the composition 0.04 per cent. carbon, 0.02 silicon, 0.01 manganese, 0.11 phosphorus, 0.06 sulphur, an unknown amount of oxygen (probably < 0.3 per cent.) and the rest iron. There is added to it 2,500 pounds of spiegeleisen, containing 4.64 per cent. carbon, 0.035 silicon, 14.90 manganese, and 0.139 phosphorus. The finished metal contained 0.45 per cent. of carbon, 0.038 silicon, 1.15 manganese, 0.109 phosphorus and 0.059 sulphur. Assume no iron oxidized.

Required: (1) A balance sheet of materials before and after recarburizing.

(2) The proportions of carbon and manganese going into the finished metal.

Solution: (1)

	Blown Metal	*Spiegel.*	*Steel.*	*Gases or Slag.*
C	8.5	116.0	106.5	18.0
Si	4.3	0.9	9.0	− 3.8
Mn	2.1	372.5	271.2	103.4
P	23.4	3.5	25.8	1.1
S.	12.8	....	14.0	− 1.2
Fe	21,232	2007	23,239	....

The differences in the sulphur, phosphorus and silicon are within the limits of error of the data, but there is no doubt as to the loss of carbon and manganese.

(2) The proportions of the two elements in question going into the finished steel are:

Carbon..............106.5÷124.5 = 0.85 = 85 per cent.
Manganese...........271.2÷374.6 = 0.72 = 72 "

The calculated percentages in the finished steel should have been, and actually were:

Carbon..............0.53 − 0.45, loss = 0.08 per cent.
Manganese...........1.58 − 1.15, loss = 0.43 "

Concerning oxygen removed, if we assume the loss of carbon and manganese to be due to their combining with oxygen dissolved in the bath, to form CO and MnO, the percentage of oxygen thus absorbed is:

By carbon............$0.08 \times 16/12 = 0.11$ per cent.
By manganese........$0.43 \times 16/55 = 0.12$ "
0.23 "

[The next chapter will consider the thermo-chemistry of the Bessemer process.]

CHAPTER VIII.

THERMO-CHEMISTRY OF THE BESSEMER PROCESS.

The feature of the Bessemer operation which strikes the observer as most wonderful, is that cold air is blown in great quantity through melted pig iron, and yet the iron is hotter at the end than at the beginning. If the observer will reflect a moment, however, he can see that if nothing but fuel, on fire, was in the converter, it would certainly be made much hotter by the air blast; in similar manner, the oxidation or combustion of part of the ingredients of the pig iron furnishes all the heat required for the process. Ten tons of pig iron contains, for example, some 350 kilograms, of carbon which is all burnt out in the bessemerizing, furnishing heat equal to the combustion of some 400 kilograms of coke—a not insignificant quantity, since it is burned and its heating power utilized in a very few minutes.

Elements Consumed.

The usual ingredients of pig iron are:

Iron	90.0	to	95.0	per cent
Carbon	2.5	"	4.5	"
Manganese	0.5	"	4.0	"
Silicon	0.5	"	4.0	"
Phosphorus	0.01	"	4.0	"
Sulphur	0.01	"	0.5	"

Some of the unusual constituents are nickel, chromium, titanium, aluminium, vanadium, tungsten, copper and zinc; all of these are rare, and there is seldom present as much as 0.5 per cent. of any one except in unusual cases.

In the Bessemer operation, carried out with the usual silica lining, iron, carbon, manganese and silicon are freely oxidized, but phosphorus and sulphur remain practically unchanged. In the basic Bessemer, lined with burnt dolomite and tar, phosphorus is also freely oxidized at the end of the operation, but sulphur is only slightly diminished—the more, the more manganese is in the slag. After all the oxidizable impurities are eliminated, iron itself oxidizes in much larger quantity, occasioning great loss if the blast is permitted to continue.

Iron oxidizes during the blow mostly to FeO, which enters the slag as ferrous silicate, and partly to Fe^2O^3. The brown fume which escapes in large amount if the blow is continued too long contains iron as Fe^2O^3.

Fe to FeO	1173	Calories per kg. of Fe
Fe to Fe^2O^3	1746	" " "
Fe to Fe^3O^4	1612	" " "

The amount of iron oxidized can be gotten from the weight and percentage composition of the slag; also from the comparison of the weights of materials used and weight of ingots produced, knowing the weight of other impurities oxidized.

Carbon oxidizes mostly to CO gas, and partly, especially in the early part of the blow, to CO^2 gas. The proportion of each of these formed can only be known by analyzing the gases produced at various stages of the blow. The proportionate volumes of CO and CO^2 express the proportionate amounts of carbon forming each respective gas. A shallow bath allows more CO^2 to pass, on essentially the same principle that a deep layer of fuel on a grate favors the production of CO. The heat evolved by oxidation of carbon is:

C to CO	2430	Calories per kg. of C
C to CO^2	8100	" " "

Manganese oxidizes quickly and mostly to MnO. If the metal is a little overblown, Mn^2O^3 in small amount is found in the slag, while Mn^2O^3 is also present in the fumes. The heat evolved in these oxidations is:

Mn to MnO	1653	Calories per kg. of Mn
Mn to Mn^2O^3	2300 (?)	" " "

The last figure is estimated; it has not yet been determined experimentally.

Silicon oxidizes rapidly and early in the blow to SiO^2, forming silicate slag with the metallic oxides formed. Its heat of oxidation has been usually taken as 7830 Calories per kilogram, but recent investigations have thrown doubt on this figure, Berthelot having found as low as 6414 Calories, and an American experimenter (research not completed; results not yet published) about 7000.* Under these circumstances the best course is probably to use the middle value *ad interim*, and consider

Si to SiO^2.............7000 Calories per kg. of Si

We hope that the exact figure will soon be determined.

Phosphorus oxidizes to P^2O^5, and only towards the end of the blow. It is practically completely eliminated, going into the slag as calcium phosphate:

P to P^2O^5............5892 Calories per kg. of P

Sulphur is not eliminated at all in the acid-lined converter. In the basic converter it is reduced in amount in the last few minutes, while phosphorus is disappearing, and partly escapes, mostly as SO^2 in the gases. The presence of a very basic slag is necessary, but the sulphur, while possibly going into the slag, does not remain there, but passes into the gases. The heat of oxidation of the unusual elements sometimes present are, as far as known,

Ni to NiO............	1051	Calories	per kg.	of Ni
Ti to TiO^2............	5000 (?)	"	"	Ti
Al to Al^2O^3...........	7272	"	"	Al
Zn to ZnO...........	1305	"	"	Zn

The figure for titanium is estimated, and those for chromium, vanadium and tungsten are also unknown, although, as a guess and first approximation, might be used:

V to V^2O^5............	2000(?)	Calories	per kg.	of V
W to WO^3............	1000(?)	"	"	W
Cr to Cr^2O^3...........	3000(?)	"	"	Cr

Heat Balance Sheet.

Taking 0° C. (32° F.) as a base line, we may express the total heat contents of the pig iron, steel, gases, slag, blast, etc.,

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*H. N. Potter, before the Am. Electrochemical Society, May 4, 1907, announced his final result, for crystalline silicon, as 7595.

from this temperature. This method is simpler than to take the bath at any one high temperature and to reckon from there.

The items of heat available during the blow are:

Heat in the body of converter at starting.
Heat in the melted pig iron used.
Heat in the spiegleisen or ferro-manganese added.
Heat in hot lime added (sometimes in basic process).
Heat in the blast, if warm on entering.
Heat developed by oxidation of the bath.
Heat developed by formation of the slag.

The items of heat distribution are:

Heat in the body of the converter at finishing.
Heat in the steel poured.
Heat in the slag at finishing.
Heat in the gases escaping.
Heat in the fume.
Heat in the slag or metal blown out.
Heat absorbed in decomposing moisture of the blast.
Heat to separate the constituents of the bath.
Heat conducted away by supports, blast pipe, etc.
Heat conducted to the air in contact with converter.
Heat radiated during the blow.

These two columns should balance each other if all the items of each are correctly determined.

Heat in Converter Body at Starting.

If the converter were quite cold when the pig iron was run in and the blow started, this item would be zero. But such a case would result disastrously, since the heat absorbed by the converter during the blow would be more than any ordinary heat could afford to lose. It is, therefore, customary, when starting for the first time, to build a fire in the converter and turn on a little air blast, so as to bring the inside up to bright redness, say 900° to 1000° C. The outside shell would, under these conditions, be at about 200°, and the mean temperature of the converter lining, say 400°. If the converter were in regular operation, one charge being introduced as soon as the other was finished, then the heat in the body of the converter at starting could be practically regarded as equal to the heat in the same at finishing, assuming the heats are running regularly. An estimate of the heat in the converter body at starting is therefore only necessary when the converter is first started up, or when it is allowed to stand some time between blows.

Illustration: Assume a converter weighing, without charge, 25 tons, of which 5 tons is iron work and 20 tons silica lining. The mean specific heat of iron (for low temperatures) being $0.11012+0.000025t+0.0000000547t^2$, and for silica $0.1833+0.000077t$, calculate the heat contained in the body of the converter.—

(1) When the temperature of the outside shell is 200° and that of the lining averages 400° (converter warmed up for starting).

(2) When the temperature of the outside shell is 300° and that of the lining averages 725° (converter empty at end of a blow).

Solution: (1)

Heat in 5000 kg. of iron work:

$0.11012+0.000025\ (200)+0.0000000547\ (200)^2 = 0.11731$

$0.11731\times 200\times 5000 = 117{,}310$ Calories.

Heat in 20,000 kg. of silica lining:

$0.1833+0.000077\ (400) = 0.2141$

$0.2141\times 400\times 20{,}000 = 1{,}712{,}800$ Calories.

Total heat in converter body $= 1{,}830{,}110$,,

It may be remarked that this would require the consumption of at least 250 kilograms of coke, with a calorific power of 8,000 Calories, to warm the converter to this extent.

(2) Heat in 5,000 kg. of iron work:

$0.12354\times 300\times 5{,}000 = 185{,}310$ Calories.

Heat in 20,000 kg. of silica lining:

$0.2391\ \times 725\times 20{,}000 = 3{,}466{,}950$,,

Total $= 3{,}652{,}260$,,

This condition is assumed as representing the converter when just emptied and immediately refilled. In this case, in regular working, the heat in the converter body is practically the same at the beginning and at the end of a blow, and the heat losses through it are only those due to conduction to the air and ground and radiation.

Heat in Melted Pig Iron Used.

This quantity depends on the temperature at which the pig iron is run into the converter. If the iron is high in silicon, which would tend to produce a hot blow, it may be run in somewhat cool; but if low in silicon it should be run in much hotter. The minimum quantity of heat contained in a kilogram of melted pig iron may be put at 250 Calories; the maximum, for very hot pig iron, 350 Calories; about 300 Calories would be a usual average figure. This may be easily determined experimentally in any given case by granulating a sample in water in a rough calorimeter.

Heat in Metallic Additions.

Melted spiegeleisen is usually not very hot when run into the converter. It may contain 250 to 300 Calories per kilogram; say an average of 275. Ferro-manganese is sometimes added red-hot, at 800° to 900° C. At this temperature it would contain 120 to 135 Calories per kilogram, assuming a mean specific heat of 0.15.

Heat in Preheated Lime.

Taking the mean specific heat of CaO as $0.1715+0.00007t$, it would contain 154 Calories per kilogram at 700°, and 211 Calories at 900°. The heat content can be calculated for any known temperature at which the lime is used.

Heat in Warm Blast.

No Bessemer converters are run by hot blast, but the air pressure used is so great (20 to 35 pounds per square inch) that the blast is warmed by compression in the cylinders. If air at 1 atmosphere tension (ordinary air) be compressed to 2 or to 3 atmospheres tension, giving effective blast pressures of 1 to 2 atmospheres, the air is heated 60° or 103°, respectively, above its initial temperature. While some of this heat may be lost in the cylinder and conduits, yet the air, unless artificially cooled, passes to the tuyeres at 25° to 50° C. above the outside temperature, and thus imparts some heat to the converter.

Heat Developed by Oxidation.

We have already discussed the thermochemical data required for this calculation. To use the data we must find the weights of each ingredient oxidized (not forgetting the iron itself) and the nature of the oxide it forms. This is deduced from the analysis of slag, gases and steel produced, as compared with those of the pig iron and additions used.

Heat of Formation of Slag.

The slag is a mechanical mixture or mutual solution of silicates of iron and manganese, with a little alumina (up to 5 per cent.) and lime and magnesia from nothing up to 5 per cent. In the basic process a large amount of calcium phosphate is present, representing over half of the entire slag, while magnesia is present in considerable amount, and alumina is almost absent.

Having, in the preceding column, calculated the heat of oxidation of all the metals oxidized in the converter, it remains to calculate the heat of combination of these to form slag. The silicate of alumina contributes nothing, since it occurred combined in the lining or lime added. The same can be said of the lime and magnesia in the acid process slags. The FeO and MnO are then to be considered, and the only thermochemical data we have are:

$(MnO, SiO^2) = 5{,}400$ Calories.
$(FeO, SiO^2) = 8{,}900$ "

These data are for 71 or 72 parts of MnO or FeO respectively, uniting with 60 parts of SiO^2. Since in acid slags there is always proportionately less of the bases, we should utilize the above heats of formation by expressing them per unit weight of MnO or FeO going into combination. These figures are:

Per kg. of MnO $= 5{,}400 \div 71 = 76$ Calories.
Per kg. of FeO $= 8{,}900 \div 72 = 124$ "

From these figures the heat of formation of the slag can be calculated: Any Fe^2O^3 present in the slag would be calculated as its equivalent weight of FeO (by multiplying by $144 \div 160$).

Illustration: A Bessemer slag contained by analysis:

SiO^2	47.25	per cent.
Al^2O^3	3.45	"
FeO	15.43	"
MnO	31.89	"
CaO, MgO	1.84	"

What is its heat of formation per kilogram?

Solution: The Al^2O^3, CaO and MgO are to be neglected, for reasons already given. The heat of combination, per kilogram of slag, is therefore,

FeO uniting with $SiO^2 = 0.1543 \times 124 = 19.1$ Cal.
MnO uniting with $SiO^2 = 0.3189 \times 76 = 23.2$ "

Total = 42.3 "

In basic Bessemer slags the conditions are much more complicated. The content of P^2O^5 is not under 14 per cent., runs as high as 25 per cent., and averages 19 per cent.; the CaO averages 45 per cent., limits 35 to 55; the silica is usually below 12 per cent., and averages 6 to 8 per cent.; magnesia is present from 1 to 7 per cent., average about 4 per cent. In such slags we should first of all assume the P^2O^5 to be combined with CaO as $3CaO.\,P^2O^5$, containing 168 of CaO to 142 of P^2O^5, (1,183 to 1) and having a heat of formation from CaO and P^2O^5 of 159,400 Calories per molecule, or 1123 Calories per unit weight of P^2O^5. Next the iron and manganese present may be calculated to FeO and MnO respectively, and treated as to their combination with SiO^2, the same as in an acid slag. Alumina may be considered in such basic slags as an acid, and equivalent to 120/102 of its weight of silica. These allowances will leave considerable lime and either an excess or deficiency of silica; if an excess, we can assume it combined with lime and magnesia, with a heat evolution equal to 476 Calories per kilogram of silica; if a deficiency, we let the calculations stand without further modification.

Illustration: Slag made at a Rhenish works contained:

SiO^2	7.73	per cent.
P^2O^5	21.90	"
Al^2O^3	3.72	"
Fe^2O^3	1.00	"
FeO	4.73	"
MnO	2.05	"
CaO	50.76	"
MgO	4.00	"
CaS	1.71	"

What is its heat of formation per unit of slag?

Solution: The 21.90 parts of P^2O^5 would be combined with $21.90 \times 168/142 = 25.91$ parts of CaO. This leaves $50.76 - 25.91 = 24.85$ of CaO as either free, dissolved CaO or partly combined, in the slag. The 2.05 MnO would correspond to $2.05 \times 60/71 = 1.73$ SiO^2; the 4.73 FeO to $4.73 \times 60/72 = 3.94$ SiO^2; the 1.00 Fe^2O^3 to $1.00 \times 60/80 = 0.75$ SiO^2; a total SiO^2 requirement for these three bases of 6.42 per cent. The SiO^2 present is 7.73 per cent., adding to which the SiO^2 equivalent to the Al^2O^3 present ($3.72 \times 120/102 = 4.38$), we have 12.11 per cent. of summated silica. The ratio of summated FeO to summated SiO^2 is considerably below the ratio 72 to 60, we can, therefore, consider the summated FeO as all combined with silica. The summated FeO is:

FeO = 4.73 per cent.
FeO equivalent of MnO = 2.08 "
FeO equivalent of Fe^2O^3 = 0.90 "
Total = 7.71 "

And the SiO^2 combining with this as $FeO.SiO^2$ is

$$7.71 \times 60/72 = 6.42 \text{ per cent.}$$

The excess of summated silica free to combine with lime is $12.11 - 6.42 = 5.69$ per cent. As there is 24.85 of CaO and 4.00 of MgO for it to combine with, the heat of this combination must be calculated on the SiO^2 going into this combination.

We then have the formation heat of the slag as:

P^2O^5 to $3CaO\,.\,P^2O^5$.....$21.90 \times 1123 = 24{,}594$ Cal.
MnO to $MnO\,.\,SiO^2$...... $2.05 \times 76 = 156$ "
FeO to $FeO\,.\,SiO^2$...... $5.63 \times 124 = 698$ "
SiO^2 to $3CaO\,.\,SiO^2$...... $5.69 \times 476 = 2{,}708$ "
28,156 "

This equals **281.6** Calories per unit weight of slag, forming a very important item in the heat balance sheet, particularly when the slag is large in amount.

Heat in Converter Body at Finishing.

This item reaches its maximum at the end of the blow, and would be equal to that calculated for the beginning of the blow, with the exception that some of the lining, silica or dolomite has been corroded and passed into the slag, carrying with it its sensible heat.

Heat in Finished Steel.

This should be determined experimentally in each particular case. If not so determined an average value may be assumed, based on the following considerations: The finishing temperature averages 1650° C.; at this heat average Bessemer steel will contain a total of 350 Calories of heat per kilogram. If the temperature is determined by a pyrometer, a correction of 1/5 Calorie can be made for every degree hotter or colder than 1650°.

Heat in Slag.

Some experimental data are badly needed, concerning the heat in slags of different composition at different temperatures. At present it is necessary to make guesses, wherever the heat in the slag produced is not directly determined. At a finishing temperature of 1650° it is likely that the slag contains 550 Calories per kilogram; with a variation of 1/4 Calorie for each degree hotter or colder than 1650°.

Heat in Escaping Gases.

The amount of these gases can only be determined satisfactorily from their analysis and the known weights of carbon oxidized. Direct estimation from the piston displacement is of much less exactness, because the slip and leakage at these high pressures may reach 25 to 50 per cent. or even more. The temperature of the gases is only slightly less than that of the bath, that is, some 1350° at starting and 1650° at finishing. Outside in the air the Bessemer flame may be much hotter than this, but that is due to further combustion of CO to CO^2 outside the converter, and should be disregarded. Where extra air is blown upon the surface of the bath, as in " baby " converters, it is quite possible that the gases in the converter and the escaping gases may be considerably hotter than the bath itself These variations must be taken into consideration. The most satisfactory condition is to insert a pyrometer tube into the opening of the converter and measure the temperature directly. The heat carried out by the gases can then be calculated accurately, using the proper mean specific heats to these high temperatures already used in these calculations.

Heat in Escaping Fume.

This is mostly oxides of iron and manganese, with sometimes silica. It is relatively small in amount. Its quantity being known, consider it at the same temperature as the gases, with a mean specific heat of 0.40 if free from silica, and 0.35 if siliceous.

Heat in Slag or Metal Blown Out.

These can be counted as equal to the heat in an equal quantity of slag or metal at the finishing temperature.

Heat Absorbed in Decomposing Moisture.

Knowing the amount of moisture blown in with the blast, a proper allowance is $29,040 \div 9 = 3,227$ Calories for every kilogram of moisture thus blown in. It is probable that this moisture is all decomposed, its hydrogen appearing in the gases. In the absence of data as to the hygrometric condition of the blast, the amount of moisture entering may be inferred and calculated from the amount of hydrogen in the gases.

Heat to Separate Constituents of Bath.

We here meet the question, how much heat of combination exists between the bath and the various ingredients which are removed—carbon, silicon, manganese, phosphorus, sulphur. Le Chatelier believes manganese to exist in the bath as Mn^3C, requiring 80 Calories per kilogram of manganese to decompose it. Silicon and carbon have, as far as has at present been determined, no sensible heat of combination with iron. Sulphur requires 750 Calories to separate each kilogram from iron. Phosphorus requires, according to Ponthiere, 1397 Calories to separate each kilogram from iron, but the reliability of this datum is doubtful. Until more reliable tests are made it is perhaps better to omit this item than to use it, although it must be of great importance if as large as Ponthiere states it to be.

Heat Conducted Away by Supports.

This is a very difficult quantity to determine, being conditioned by the size of the supports, their cooling surface and the kind of connection they have with other objects. The heat which would pass to the blast pipe is practically returned to the converter by the incoming blast. The heat passing into the supports is perhaps best found by taking their temperature at different places, and calculating the heat loss from their surface by radiation and conduction to the air. This amounts practically to considering them as part of the outer cooling surface of the converter; the calculation of these surface losses is given in the two following paragraphs:

Heat Conducted to the Air.

This is a function of the extent of outside surface, its temperature, the temperature of the air, and the velocity of the air current. Measurement will give the extent of surface in contact with the air and the average velocity of the air current; the surface being rough iron, the coefficient of transfer conductivity may be taken as $k = 0.000028\ (2 + \sqrt{v})$. where v is the air velocity in c.m. per second, and k is the heat conducted per second in gram-calories, from each square c.m. of surface per 1° difference of temperature. The temperature of the outer surface should be carefully measured, so that a reliable average is obtained, and the air velocity likewise averaged, since it has considerable influence on the heat lost to the air.

Illustration: A converter has an outside surface of 50 square meters, at an average temperature during the blow of 200° C. the average air current being 1 meter per second, and outside air 30° C. What is the heat loss by conduction to the air in kilogram Calories per minute?

Solution:

Coefficient of transfer conductivity:

$$0.000028\ (2 + \sqrt{100}) = 0.000336\ .$$

Heat loss per 1° difference, per second, in gram-calories:

$$50 \times 10{,}000 \times 0.000336 = 168 \text{ calories.}$$

Heat loss per 170° difference, per minute, in kg.-calories:

$$168 \times 170 \times 60 \div 1000 = \mathbf{1714} \text{ calories.}$$

Heat Radiated During the Blow.

This is a function of the temperature of the outside shell, the mean temperature of the surroundings of the converter and the nature of the metallic surface. As the surface is oxidized iron, it would lose about 0.0141 gram-calories from each square centimeter per second, if at a temperature of 100° and the surroundings at 0°; or practically 1 gram-calorie per second from each square meter, for every 100,000,000 of numerical difference between the fourth powers of the absolute temperature of the radiating surface and its surroundings. (See Metallurgical Calculations, Part 1., p. 185).

Illustration: Assuming the surroundings of the converter at 30°, in the preceding illustration, what amount of heat is radiated per minute in large Calories?

Solution: The absolute temperatures in question are $273+30 = 303$, and $273+200 = 473$. The difference of their fourth powers is:

$$473^4 - 303^4 = 41{,}626{,}500{,}000,$$

which, divided by 100,000,000, gives 416.265 gram-calories lost per second per each square meter of radiating surface. The radiation loss for the whole surface per minute is, therefore:

$$416.265 \times 50 \times 60 \div 1000 = \mathbf{1249} \text{ kg.-Calories.}$$

While the assumption made as to the temperature of the outside shell is doubtless only approximate, yet if the temperature of the same is carefully determined the radiation loss can be accurately calculated. If the outside of the converter were polished, this radiation loss might be reduced nearly nine tenths.

Problem 68.

From the data and results of calculation of Problem 65 (see pages 310, 317 and 323,) we see that 22,500 pounds of pig iron and 2,500 pounds of spiegeleisen produced 24,665 pounds of steel, there being eliminated during the blow and recarburization:

Carbon	679.5	pounds	(140.7 to CO^2)
Silicon	203.2	"	
Manganese	197.9	"	
Iron	253.9	"	(25.3 to Fe^2O^3)

The gases contain:

CO^2	5.20 per cent.
CO	19.91 "
H^2	1.39 "
N^2	73.50 "

The slag contains:

SiO^2	63.56 "
Al^2O^3	3.01 "
FeO	21.39 "
Fe^2O^3	2.63 "
MnO	8.88 "
CeO	0.90 "
MgO	0.36 "

Make average assumptions for requisite data not given.

Required: A balance sheet of heat evolved and distributed.

Solution: The items of this balance sheet have already been discussed in detail. We will apply them to this specific case:

Heat in Body of Converter at Starting: Assuming that this is a blow in regular running, the heat may be taken at any reasonably approximate quantity, because the same quantity with only a slight deduction will be allowed as contained in the same on finishing. We will, therefore, take a figure already calculated, 8,034,970-pound Calories, as the heat in the converter body at starting.

Heat in Melted Pig Iron: We will take it at 300 Calories per pound, or a total of $300 \times 22,500 = 6,750,000$ Calories.

Heat in Spiegeleisen: $2,500 \times 300 = 750,000$ Calories.

Heat in Blast: This may safely be considered as warmed by compression and entering the converter at 60° C. The amount of blast received altogether is calculated thus:

Carbon oxidized = 679.5 pounds.

Volume of CO and CO^2 formed:

$$679.5 \times 16 \div 0.54 = 20,133 \text{ cu. ft.}$$

Volume of gases $\frac{20,133}{0.2511}$ = 80,179 "

Volume of nitrogen $80,179 \times 0.735$ = 58,932 "

Volume of air proper in blast = 74,408 "

Volume of hydrogen in gases:

$80,179 \times 0.0139 =$ 1,115 "

Volume of moisture in gases = 1,115 "

Assuming the blast at 60° C., the heat in it is:

Air	74,408×0.3046 =	22,665 oz. Cal. per 1°	
H^2O	1,115×0.3790 =	423 "	"
		23,088 "	"
	23,088×60 =	1,385,280 oz. Cal.	
	=	86,580 lb. Cal.	

Heat of Oxidation:

C to CO^2	140.7×8100 = 1,139,670	Calories
C to CO	538.8×2430 = 1,309,280	"
Si to SiO^2	203.2×7000 = 1,422,400	"
Mn to MnO	197.9×1653 = 327,130	"
Fe to FeO	228.6×1173 = 268,150	"
Fe to Fe^2O^3	25.3×1746 = 44,170	"
	4,510,800	"

Heat of Formation of Slag: The 197.9 pounds of manganese oxidized forms 255.5 of MnO. Hence the weight of the slag is 255.5÷0.0888 = 2877 pounds. The slag, therefore, contains also 2877×0.6356 = 1829 pounds of SiO^2, of which 203.2 ×60/28 = 435 pounds came from the silicon oxidized, and 1794 pounds from the lining. The lining will also have lost the Al^2O^3, CaO and MgO in the slag, equal to 2877 × 0.0427 = 123 pounds. The total iron going into the slag, 253.9 pounds, is equivalent to 326.4 pounds of FeO.

The heat of formation of the slag will therefore be:

FeO	326.4×124 = 40,474	Calories.
MnO	255.5× 76 = 19,418	"
	Total 59,892	"

Heat in Converter at Finishing: This will be the same as at starting, less the heat in 1794+123 = 1917 pounds of lining, which was corroded and entered the slag. Assuming this to have been on the inner surface, at an average temperature of 1500°, the heat in it, using the mean specific heat of silica, will have been

1917×0.2988×1500 = 851,200 Calories.

And the heat in the converter body at the finish:

8,034,970—851,200 = 7,183,770 pound Calories

Heat in Finished Steel: Taking its temperature as **1650°**, with 350 Calories per unit, we have

24,665×350 = 8,632,750 Calories.

Heat in the Slag:

2877×550 = 1,582,350 “

Heat in Escaping Gases: These have already been calculated as consisting of

Nitrogen........................	58,932	cubic feet.
Hydrogen......................	1,115	“ “
Carbon monoxide..............	15,964	“ “
Carbon dioxide.................	4,169	“ “

The first three have the same heat capacity per cubic foot, so assuming their temperature 1550°:

N^2, H^2, CO 76,011×534.5 = 40,627,900 oz. Cal.
CO^2 4,169×947.1 = 3,948,250 “
“
44,576,150 “
= 2,786,000 lb. Cal.

Absorbed in Decomposing Moisture: The 1,115 cubic feet of hydrogen in the gases represent so much steam or water vapor decomposed. Since 1 cubic foot = 0.09 ounces, the heat absorbed is

1,115×0.09×29,040 = 2,914,160 oz. Cal.
= 182,130 lb. Cal.

Heat Conducted to the Air: Assuming the conditions worked out in the illustration under this heading, this item would be approximately, for 9 min. 10 secs., in lb. Cal.

1,714×2.204×9.167 = 34,630 lb. Cal.

Heat Lost by Radiation: Making similar assumption, we have

1,249×2.204×9.167 = 25,240 lb. Cal.

Recapitulation.

	Lb. Cal.
Heat in converter body at starting	8,034,970
" melted pig-iron	6,750,500
" spiegeleisen	750,000
" blast	86,580
Heat of oxidation	4,510,800
" formation of slag	59,890
Total on hand and developed	20,192,740
Heat in converter body at finish	7,183,770
" finished steel	8,632,750
" slag	1,582,350
" escaping gases	2,786,000
Heat absorbed in decomposing moisture	182,130
Heat conducted to the air	34,630
Heat lost by radiation	25,240
Total accounted for	20,426,870

Another way of expressing this balance is to itemize the avenues of heat evolution and utilization, as follows:

	Lb. Cal.
Received from converter body	851,200
Received by oxidation	4,510,800
Received by formation of slag	59,890
Total	5,421,890

	Lb. Cal.
Used, excess of heat in gases over blast	2,699,420
Used, excess of heat in steel and slag over pig iron and spiegel	2,714,600
Decomposition of moisture	182,130
Radiation and conduction	59,870
Total	5,656,020

CHAPTER IX.

THE TEMPERATURE INCREMENT IN THE BESSEMER CONVERTER.

In the preceding chapter, we have studied the generation of heat in the Bessemer converter, and its distribution. We saw in that analysis that in a typical operation, nearly one-half of the heat generated during the blow is carried out by the hot gases, about half is represented in the increased temperature of the contents of the converter, while only about 5 per cent. is lost by radiation, etc. In the present paper we wish to analyze still further this question of increased temperature, which is so vitally necessary for the proper working of the process, and to calculate the relative efficiency of the various substances oxidized in causing this rise of temperature.

While at no time in the Bessemer operation is only one substance being oxidized, yet we can get the best basis for our computations by assuming a charge in operation and only one substance oxidized at a time. Whatever substance is in question, let us assume one kilogram burnt in a given short period of time, generating the heat of its combustion. With the bath at a given temperature, the air, at say 100° C., comes in contact with it, bearing the necessary oxygen. If nothing was oxidized, the oxygen and nitrogen would simply be heated to the temperature of the bath, and pass on and out, while the bath would be meanwhile losing heat also by radiation. It is evident then, that unless at least as much heat as the sum of these two items is generated, the bath will cool, and that only the excess of heat above this requirement is available for increasing the temperature of the bath and resulting gases. The proper procedure for us will therefore be to calculate, in each case, the chilling effect of the air entering, subtract this from the heat generated, and the residue is net heat available for raising the temperature of the contents of the converter and the gases, and supplying radiation losses. The latter are proportional to the time, and therefore to the amount of air used, assuming blast constant.

SILICON.

This is burnt out in the first part of the process, during which the temperature begins low and ends high. We will therefore assume two temperatures, and calculate the thermal increment at each. We will take 1250° and 1600°. The net heat is absorbed by the bath, slag and nitrogen.

Oxygen necessary to burn one kilogram of silicon:

1×32÷28 = 1.143 kg.
Nitrogen accompanying this oxygen = 3.810 "
Weight of air needed = 4.953 "
Volume of air = 4.953÷1.293 = 3.831 m^3
Specific heat, 100° to 1250°, per m^3 = 0.3395
Specific heat, 100° to 1600°, per m^3 = 0.3489
Chilling effect of air at 100°, bath at 1250°
= 3.831×0.3395×1150 = 1496 Cal.
Chilling effect of air at 100°, bath at 1600°
= 3.831×0.3489×1500 = 2043 Cal.
Heat generated per kilogram of silicon = 7000 Cal.

This is, however, for cold oxygen and cold silicon burning to cold solid silica. Under the conditions prevailing we have melted silicon at the temperature of the bath, oxidized by hot oxygen to hot silica, giving a slightly different heat of combination, calculated as follows:

Heat in melted silicon at 1250° = 480 Cal.
" " oxygen required, at 1250° = 334 "
" " silica, at 1250° = 750 "
Heat of oxidation at 1250°
= 7,000+480+334—750 = 7,064 "

The difference from 7,000 is so small as to be within the possible error of the 7,000 itself, and we can therefore make the calculations with all the accuracy they allow, taking the ordinary heats of oxidation from the tables.

One factor of heat generation has, however, not been mentioned, viz.: the heat of combination of silica with oxides of iron and manganese to form slag. This is 148 Calories per kg. of silica when forming iron silicate, and 90 when forming manganese silicate, which quantities would become 317 and 193 Calories respectively when calculated per kg. of silicon oxidizing. The question arises, however, whether it is fair to credit all this to the silica, because this generation of heat by slag formation is really a mutual affair, chargeable to the credit of both silica and the other oxides; we should, therefore, not charge it all up to the credit of silica formation, and we do not know what part to charge to the credit of silica if we do not charge it all. In this dilemma it may be well to remember that silicon is probably oxidized before the iron and manganese, and that the heat of formation of the slag is therefore more properly considered as being generated afterwards, and therefore may be practically credited entirely to the oxidation of iron and manganese.

Resume for oxidation of 1 kilo. of silicon:

	Cal.
Heat generated	= 7,000
Chilling effect of the blast, 100° to 1250°	= 1,496
Chilling effect of the blast, 100° to 1600°	= 2,043
Available heat, bath at 1250°	= 5,504
Available heat, bath at 1600°	= 4,957

If we assume a radiation loss proportional to the length of the blow, *i. e.*, proportional to the air blown in, we can find out from average blows that this amounts to about 50 Calories per cubic meter of blast used. The radiation loss during combustion of 1 kilogram of silicon would therefore be

	Cal.
3.831×50	= 192
Leaving net available heat at 1250°	= 5,312
At 1600°	= 4,765

The above quantity of heat is expended in raising the temperature of 99 kg. of bath, 2.143 kg. of silica, and 3.810 kg. of nitrogen gas, from their initial temperature. At the temperatures of 1250° and 1600°, respectively, the heat capacity of these products of the operation will be, per 1° C. rise:

	Specific Heat		*Heat Capacity*	
Products.	*at* 1250°	*at* 1600°	*at* 1250°	*at* 1600°
Bath, 99 kg.......	0 25	0.25	24.8	24.8
SiO^2, 2.14 kg......	0.37	0.43	0.8	0.9
N^2, 3.02 m^3.......	0.37	0.39	1.1	1.2
		Totals.	26.7	26.9

Theoretical rise of temperature:

5,312 ÷ 26.7 = 199° (bath at 1250°)
4,765 ÷ 26.9 = 177° (bath at 1600°)

Average rise, per average 1% of silicon = **188°** C.

MANGANESE.

As high as 4 per cent. of manganese may be oxidized during the blow, and therefore this heat of combustion is sometimes important. We will calculate the net heat available for raising temperature and the rise of temperature per 1 per cent. of manganese oxdized, *i. e.*, for 1 kilo. of manganese per 100 kilos. of bath.

Oxygen necessary 1 × 16/55 = 0.291 kg.
Nitrogen accompanying this = 0.970 "
Weight of air used = 1.261 "
Volume of air used = 0.975 m^3
Chilling effect of air at 100° on bath at 1250° = 0.975 × 0.3395 × 1150 = 381 Cal.
Heat generated per kg. of manganese = 1653 "
Heat of formation of $MnO.SiO^2$ 1.291 kg. MnO × 76 = 98 "
Total heat developed = 1751 "
Heat available = 1751—381 = 1370 "
Radiation loss = 0.975 × 50 = 49 "
Net available heat = 1321 "
Heat capacity of 99 kg. of bath per 1° = 24.8 "
Heat capacity of 2.4 kg. of slag = 0.7 "
Heat capacity of 0.8 m^3 nitrogen = 0.3 "
Heat capacity of products per 1° = 25.8 "

Theoretical rise of temperature:

$$1321 \div 25.8 = \mathbf{51}° \text{ C.}$$

This is, in round numbers, one-fourth the efficiency of silicon.

IRON.

While it is not desired to oxidize iron, and while it is relatively less oxidizable than silicon or manganese, yet some is always oxidized because of the great excess of iron present in the converter. The amount of iron thus lost is variable, and some of it, towards the end of the blow, may be oxidized to Fe^2O^3 instead of FeO, the larger part, however, oxidizes to FeO. We will make the calculations for both oxides, per kilogram of iron.

Formation of FeO.

Oxygen necessary $1 \times 16/56$	= 0.286	kg.
Nitrogen accompanying this	= 0.953	"
Weight of air used	= 1.239	"
Volume of air used	= 0.958	"
Chilling effect of air at 100° on bath at 1250° = $0.958 \times 0.3395 \times 1150$	= 374	Cal.
Chilling effect of air at 100° on bath at 1600° = $0.958 \times .3489 \times 1500$	= 501	"
Heat generated per kg. of iron	= 1,173	"
Heat of formation of $FeO.SiO^2$ = 1.286 kg. $FeO \times 124$	= 159	"
Total heat developed	= 1,332	"
Net heat available at 1250° = 1332—374	= 958	"
Net heat available at 1600° = 1332—501	= 821	"
Radiation losses = 0.958×50	= 48	"
Net available heat at 1250°	= 910	"
Net available heat at 1600°	= 773	"
Heat capacity of 99 kg. of bath per 1°	= 24.8	"
Heat capacity of 2.4 kg. of slag per 1°	= 0.7	"
Heat capacity of 0.8 m^3 of nitrogen	= 0.3	"
Heat capacity of products per 1°	= 25.8	"

Theoretical rise of temperature:

$$910 \div 25.8 = \mathbf{36}° \text{ C.}$$
$$773 \div 25.8 = \mathbf{30}° \text{ C.}$$

This is only about one-sixth as efficient as silicon.

Formation of Fe^2O^3.

Weight of air used = 1.859 kg.
Volume of air used = 1.438 m^3
Chilling effect of air at 100° on bath at 1600° = 1.438×0.3489×1500 = 753 Cal.
Total heat developed by oxidation = 1746 "
Heat of formation of slag = 159 "
Total heat developed = 1905 "
Heat available = 1905—753 = 1152 "
Radiation losses = 1.438×50 = 72 "
Net heat available = 1080 "
Heat capacity of products = 26 "

Theoretical rise of temperature:

$$1080 \div 26 = \mathbf{42°}\ \text{C.}$$

TITANIUM.

While titanium is an unusual constituent of pig iron, yet it is conceivable that titaniferous pig iron might be made and blown to steel. If so, the following calculation, based on an estimated but quite probable value for the heat of oxidation of titanium, will show that the titanium is a valuable heat producing substance, being, in fact, weight for weight three fourths as efficient as silicon.

Oxygen needed 1×32/48 = 0.667 kg.
Nitrogen accompanying this = 2.222 "
Air used = 2.888 " 9
Volume of air needed = 2.250 m^3
Chilling effect of air at 100° on bath at 1250° = 2.250×0.3395×1150 = 878 Cal.
Heat generated per kg. of Ti (probably) = 5000 "

Heat of formation of slag—unknown
Net heat available = 5000—878 = 4122 "
Deduct for radiation losses = 3978 "
Heat capacity of products per 1° C. = 26.5 "

Theoretical rise of temperature:

$$3978 \div 26.5 = \mathbf{150°}\ \text{C.}$$

ALUMINIUM.

This metal is also rarely found in pig iron, yet when present it would be a powerful heat producer, as the following calculations show:

Oxygen needed $1 \times 48/54$ = 0.889 kg.
Nitrogen = 2.963 “
Air = 3.852 “
Volume of air = 2.964 m^3
Chilling effect of air at 100° on bath at 1250° = $2.964 \times 0.3395 \times 1150$ = 1157 Cal.
Heat generated per kg. of Al = 7272 “
Heat of formation of slag—uncertain
Heat available = 7272—1157 = 6115 “
Deducting for radiation losses = 5967 “
Calorific capacity of products per 1° C. = 26.6 “

Theoretical rise of temperature:

$$5967 \div 26.6 = 224°\text{C}.$$

If a blow was running cold, and ferro-silicon was not on hand to add in order to increase its temperature, ferro-aluminium, or aluminium itself, would be a good substitute in the emergency.

NICKEL.

It is hardly probable that nickeliferous pig iron would be blown to steel, because of the waste of valuable nickel in the slag; yet if 1 per cent. of nickel were thus oxidized, calculations similar to the preceding would show a net rise in temperature of the contents of the bath of about **33**° C.

CHROMIUM.

Quite recently some chromiferous pig iron has been blown in the Bessemer converter, and those in charge were hampered by the lack of data as to how chromium would behave during the blow and its heat value to the converter, Technical literature has not yet been enriched by the account of the experiments, and no thermo-chemist has, as yet, determined the heat of oxidation of chromium or of formation of chromium slag. From what we know of the chemical reactions of chromium, however, it is likely that its heat of oxidation is somewhere about 3,000 Calories per kilogram. Using this, and neglecting the heat of formation of slag, we have the following approximation to its heating efficiency, assuming it to be oxidized when the bath is near to its maximum temperature:

Oxygen needed 1×48/104 = 0.462 kg.
Nitrogen entering = 1.540 "
Air used = 2.002 "
Volume of air = 1.548 m^3
Chilling effect of air at 100° on bath at 1600° = 1.548×0.3489×1500 = 810 Cal.
Heat of oxidation (assumed) = 3,000 "
Net heat = 3000—810 = 2,190 "
Deducting for radiation losses = 2,113 "
Calorific capacity of products per 1° = 26.1 "

Theoretical rise of temperature:

2,113÷26.1 = **81°** C.

CARBON.

This element commences to be oxidized in large amount only towards the middle of the blow, when the temperature of the bath is high, because of the previous oxidation of silicon. It will be about right, therefore, to estimate the bath at an average temperature of 1600° during the elimination of carbon. The product is mostly CO, but partly CO^2. We will, therefore, calculate for each of these possible products separately. The net heat available, after allowing for average radiation losses, is used to increase the temperature of the products, *i. e.*, of the bath, the nitrogen and the CO or CO^2.

Oxidation to CO^2.

Oxygen required = 1×32/12 = 2.667 kg.
Nitrogen accompanying = 8.889 "
Air used = 11.556 "
Volume of air = 8.937 m^3
Chilling effect of air at 100° on bath at 1250° = 8,937×0.3395×1150 = 3,489 Cal.
Heat of oxidation = 8,100 "

Heat available = 8,100—3,489 = 4,611 Cal.
Radiation losses = 8.937×50 = 447 “
Net heat available = 4,164 “
Heat capacity of 99 kg. bath = 99×0.25 = 24.80 “
Heat capacity of 7.05 m^3 N^2 = 7.05×0.37 = 2.61 “
Heat capacity of 1.90 m^3 CO^2 = 1.90×0.88 = 1.70 “
Heat capacity of products, per 1° C. = 29.11 “

Theoretical rise of temperature:

$$4{,}164 \div 29.11 = \mathbf{143}°\text{C.}$$

Since carbon burns to CO^2 principally at the beginning of the blow, while the bath is cold, we see that carbon thus consumed is about three-quarters as efficient as an equal weight of silicon in raising the temperature of the bath.

Oxidation to CO.

Oxygen needed 1×16/12 = 1.333 kg.
Nitrogen accompanying = 4.444 “
Air used = 5.777 “
Volume of air = 4.469 m^3
Chilling effect of air at 100° on bath at 1600° = 4.469×0.3489×1500 = 2,339 Cal.
Heat of oxidation = 2,430 “
Heat available = 2,430—2,339 = 91 “
Radiation losses = 4.469×50 = 233 “
Net heat available = 91—233 = —142 “
Heat capacity of 99 kg. of bath = 99×0.25 = 24.8 “

$$\left.\begin{array}{l}\text{Heat capacity of 3.5 m}^3\text{ of N}^2\\ \text{Heat capacity of 1.9 m}^3\text{ of CO}\end{array}\right\} 5.4\times0.39 = 2.1 \text{ “}$$

Heat capacity of products = 26.9 “

Theoretical rise of temperature:

$$-142 \div 26.9 = -\mathbf{5}°\text{ C.}$$

The result is, therefore, that when carbon burns, as it mostly does, to CO, and the temperature of the bath is high, there is practically no further rise of temperature, for the heat of oxidation is barely sufficient to counteract the chilling effect of the air and to supply radiation and conduction losses.

In the above calculations, no allowance was made for heat required to separate carbon from its combination with iron, or for the variation in the heat of combination of carbon with oxygen from the combination heats at ordinary temperatures. The former is not known, or perhaps is very nearly zero. The heat of oxidation of liquid carbon at 1250° to CO^2 or at 1600° to CO is calculated as follows:

Oxidation 1 kg. C to CO^2 at 0° = 8,100 Cal
Heat to raise 1 kg. C to 1250° = 505 Cal.
Heat to liquefy 1 kg. at 1250° = 129 "
Heat to raise 2.67 kg. O^2 to 1250° = 779 "

Heat to raise reacting substance to 1250° = 1,413 "
Heat in 3.67 kg. CO^2 at 1250° = 1,493 "
Heat of reaction at 1250° (8,100 + 1,413 − 1,493) = **8,020** "

For production of CO, at 1600°, the correction is larger, as is seen from the following:

Oxidation 1 kg. C to CO at 0° = 2,430 Cal.
Heat to raise 1 kg. to 1600° = 680 Cal.
Heat to liquefy 1 kg. C at 1600° = 156 "
Heat to raise 1.33 kg. O^2 to 1600° = 554 "

Heat to raise reacting substances to 1600° = 1,390 "
Heat in 2.33 kg. of CO at 1600° = 1,104 "
Heat of reaction at 1600° (2,430 + 1,390—1,104) = **2,716** "

The use of this corrected value makes the oxidation of C to CO give a small net heat development, with consequent slight rise of temperature, instead of the slight cooling effect before calculated. The conditions are so nearly even, however, that a slight increase of temperature or slowing up of the blow would wipe out the heat excess.

PHOSPHORUS.

This is the last important element to be considered, and is always eliminated after the carbon, at the maximum bath temperature, which we will assume, for calculation, at1600°. The heat generated, at ordinary temperatures, is 5892 Calories per kilogram of solid phosphorus. Per kilogram of liquid phosphorus it would be only 5 Calories more, or 5897 Calories. For the reaction at 1600° we would have a different value, probably some 500 Calories more, but the necessary data concerning the specific heats of P and P^2O^5 are not known, and we must omit this calculation. The heat of combination of iron and phosphorus is also a doubtful quantity. Ponthiere places it as high as 1,397 Calories per kilogram of phosphorus, but this appears altogether improbable since another experimenter could obtain no heat of combination at all. As concluded in another place, I advise for the present omitting this questionable quantity.

The phosphorus pent-oxide forms $3CaO . P^2O^5$ with the lime added, but since there is always more lime present than corresponds to these proportions ($3CaO : P^2O^5 :: 168 : 142$), the calculation of heat of formation of the slag must be based on the amount of P^2O^5 formed (1123 Calories per kilogram of P^2O^5). This amounts to a considerable item. On the other hand, the lime needed for slag is put in, usually preheated, for the sole purpose of combining with the P^2O^5. It seems, therefore, only right to charge the phosphorus with the heat required to raise this lime to the temperature of the bath. The lime added averages three times the weight of P^2O^5 formed, and is preheated usually to about 600°. Assuming these conditions, the following calculations can be made per kilogram of phosphorus oxidized:

Oxygen required = 1.29 kg.
Nitrogen accompanying = 4.30 "
Air used = 5.59 "
Volume of air = 4.32 m^3
Heat of formation of slag,
2.29 kg. $P^2O^5 \times 1123$ = 2572 Cal.
Heat of oxidation of phosphorus = 5897 "
Total heat developed = 8469 "
Chilling effect of air at 100° on bath at
1600° = $4.32 \times 0.3489 \times 1500$ = 2261 "
Chilling effect of lime (600° to 1600°)
$(2.29 \times 3) \times 0.328 \times 1000$ = 2253 "
Chilling effect of blast and lime = 4514 "
Heat available = 8469—4514 = 3955 "
Radiation losses = 4.32×50 = 216 "
Net heat available = 3739 "

Heat capacity 99 kg. of bath = 99×0.25 = 24.8 kg.
Heat capacity 3.4 m^3 of N^2 = 3.4×0.39 = 1.3 "
Heat capacity 6.9 kg. of slag = 6.9×0.3 = 2.1 "

Heat capacity of products, per 1° = 28.2 "

Theoretical rise of temperature:

$$3739 \div 28.2 = \mathbf{133}° \text{ C.}$$

If the lime were added cold, its cooling effect would be 883 Calories greater, the net heat available would be 883 Calories less, and the calculated rise of temperature 31° less, or 102° C. Using the preheated lime we can regard phosphorus as being practically two-thirds as efficient, weight for weight, as silicon; with cold lime, about one-half as efficient.

Resumé.

Heat effect of oxidizing 1 kilogram of element.

	Heat of Oxidation.	*Formation of Slag.*	*Total Heat Developed.*	*Chilling Effect of Blast, Radiation, etc.*	*Net Heat Available for Raising Temperature.*	*Theoretical Rise of Temperature.*
Silicon	7,000	...	7,000	1,688	5,312	188°
Manganese	1,653	98	1,751	430	1,321	51°
Iron (to FeO)	1,173	159	1,332	422	910	33°
Iron (to Fe_2O_3)	1,746	159	1,905	825	1,080	42°
Titanium	5,000	...	5,000	1,022	3,978	150°
Aluminium	7,272	...	7,272	1,305	5,967	224°
Nickel	1,051	159	1,210	378	832	33°
Chromium	3,000	. .	3,000	887	2,113	81°
Carbon (to CO_2)	8,100	. .	8,100	3,936	4,164	143°
Carbon (to CO)	2,430	.	2,430	2,572	-142	—5°
Phosphorus	5,897	2,572	8,469	2,477 2,253*	3,739	133°

* Chilling effect of lime added, preheated to 600°

It must be observed that the above table is for comparison only, it cannot be used for an actual case, such as when 1 per cent. of silicon, 3 of iron, 4 of carbon and 2 of phosphorus are oxidized. In such a case, the rise in temperature would be only very roughly:

From silicon	1×188 =	188°
From iron	$3\times\ 33$ =	99°
From carbon	– say =	0°
From phosphorus	2×133 =	266°
Total	=	553° C.

It is to be recommended that in each specific case the calculation be made for the specific conditions obtaining, such as temperature of the metal at starting, temperature of the blast, time of the blow (as far as this affects radiation and conduction losses), proportion of carbon burned to CO^2, free oxygen in the gases, moisture in the blast, temperature and quantity of lime added, corrosion of lining. When all these items and conditions are taken into account there will be room for only small discrepancy between the calculated and the observed rise of temperature. The chief items needing experimental research at present are: The specific heat of the melted bath, the specific heat of the slag, the heat of combination of various elements comprising the bath, the heat of formation of the slag, and the heat of oxidation of some of the rarer elements, such as titanium and chromium. Such establishments as the Carnegie Institution could not do the cause of metallurgy better service than to subsidize metallurgical laboratories for the determination of such data.

CHAPTER X.

THE OPEN-HEARTH FURNACE.

By the above title we mean to designate not only the regenerative gas furnaces for making steel but also those for reheating purposes; in other words, regenerative or recuperative reverberatory furnaces. Prominent among these is the Siemens-Martin furnace, with complete gas and air preheating regenerative chambers. In all these furnaces the charge is heated, or kept hot, partly by direct contact with the gaseous products of combustion and partly by radiation from the flame and the sides and roof of the furnace. It was the Siemens brothers who first insisted on the relatively great importance of the radiation principle, in distinction to the direct impingement of the flame on the material, pointing out that a luminous flame radiates from all parts of its volume, while a hot, solid body radiates only from its surface, and direct impingement interferes with the development of perfect combustion and communicates heat relatively slowly at best.

Gas Producers.

Gas producers are the usual adjunct for open-hearth furnaces, excepting where natural gas or blast furnace gas is available. They may be placed far from the furnace, when they deliver cool gas to the regenerators, or close to the furnace, delivering comparatively hot gas to the regenerators, or even be made part of the furnace itself, delivering their hot gas immediately to the ports of the furnace. The latter is undoubtedly the most economical arrangement where practicable.

The following generalizations concerning the relations of the gas producer to the open-hearth furnace may be made: Producers furnish 4,300 to 4,600 cubic meters of gas per metric ton of coal used (150,000 to 160,000 cubic feet per short ton); the gas produced runs 3 to 8 per cent. CO^2, 5 to 20 per cent. H^2. 20 to 30 per cent. CO, and 50 to 60 per cent. N^2; its calorific power is 750 to 1000 Calories per cubic meter (47 to 63-pound Calories, or 85 to 115 B. T. U. per cubic foot); its calorific power represents 60 to 90 per cent. of the calorific power of the fuel used; in steel-making processes, the keeping of the furnace up to proper heat requires the gasifying of 25 to 35 kilograms (50 to 80 pounds) of coal per hour, in the producers, for each ton of metal capacity of the furnace; good producers gasify 60 to 65 kilograms of coal per hour per each square meter of gas-producing area (10 to 15 pounds per hour per each square foot); a furnace therefore requires some 0.4 to 0.6 square meter (4 to 6.5 square feet) of gas-producing air in the producers for each ton of metal capacity of the furnace.

Flues to Furnace.

In conducting the gases to the furnace, the flues or conduits should be of ample size. If too small the gas must pass through them with high velocity, requiring considerable draft to give them this velocity, which the chimney, or blower may or may not be capable of furnishing. Producers are almost always worked by a steam blower, furnishing mixed air and steam and a plenum of pressure in the upper part of the producer, which suffices to send the gas through the conduits under a slight pressure, and thus avoids any sucking in of air through crevices in the conduits. With too small conduits the resulting friction and high velocity required may give the blower more work than it can do, and thus entail demands for draft upon the furnace stack. A reasonable rule is to give the flues such cross-sectional area that the hot gas which must pass through them shall have a velocity between 2 and 3 meters per second.

Regenerators.

The dimensions of the regenerators are of the first importance to the working of the furnace. They should have sufficient length in the direction the gas currents are passing, so that the gases may be properly cooled or heated; they should have sufficient cross-sectional area of free space, so that the velocity of the gases through them is not too great; they must have sufficient thermal capacity, so that they can absorb the requisite quantity of heat.

Length.—From 4 to 6 meters (13 to 20 feet) is a suitable length in the direction of the gas currents. This permits the hot products to become properly cooled before going to the chimney, and the gas or air to be properly heated before entering the furnace. The shorter length may be used when the regenerator is of large cross-sectional area, with slow velocity of gas currents through the free spaces; the longer when the regenerator is rather restricted in cross-section and the gas currents have somewhat high velocity.

Cross-Section.—The free-space sectional area should be such that the gases where hottest should not have a calculated velocity of over 3 meters (10 feet) per second, and if calculated for 2 meters (6.5 feet) will give much better results as regards transmission of heat to the checker work. In this manner, knowing how much gas must go through the regenerator and what its maximum temperature will probably be, the cross-section area of free passage space can be calculated. The relation of this to the cross-section of the entire stove must next be considered, and this is entirely a question of how the checker work is built up. If the bricks are stacked close together the free space may be reduced to as much as one-half the total; as ordinarily stacked it may be 60 to 80 per cent. of the total; if perforated bricks are used, as in blast furnace firebrick-stoves, the area of free space averages one-half the total; with ordinary bricks the average is 70 per cent. This is a question which is very variously worked out in different furnaces, and to which not as much scientific thought has been given as should be. The thickness of the bricks influences greatly the relative amount of free space and filled space, and the rate at which the generator heats up or cools off. In a regenerator of given length and cross-section closer packing of the bricks gives more heat absorbing surface, increases the velocity of the gases and diminishes the cross-sectional area of each passage and of the sum of all the passages; some of these factors increase the efficiency of the regenerator, others tend to decrease it, and there are, therefore, several independent variables to be considered in finding the best arrangement for highest efficiency. A numerical solution is indeed a possibility, but is too involved for an elementary presentation of the subject.

Relative Sizes.—The relative sizes of gas and air regenerators is a question of importance which admits of easy solution by calculation. So far we have treated the pair of regenerators together, and discussed the sum of their cross-sections as deduced from the volume of products passing through at an assumed maximum temperature and allowable velocity. The regenerators at one end of a furnace are, however, usually divided into a pair or set, one for heating gas and the other for heating air. This is not usual where natural gas is used because of the deposition of soot in the regenerator by the latter when it is heated, but nine out of ten open-hearth furnaces preheat their gas as well as the air. The heating capacity of the regenerators should be divided in proportion to the calorific capacities of the gas and air simultaneously heated. The problem is therefore to find the heat capacity per degree of the gas and air used, or, more exactly, the total heat capacity of each of these between the temperature at which they enter the regenerators and that at which it is desired that they should enter the furnace.

Problem 69.

An open-hearth furnace uses producer gas containing, by volume, at it reaches the regenerators:

CO	26.97	per cent.
CO^2	4.37	"
CH^4	0.33	"
H^2	13.00	"
NH^3	0.21	"
H^2S	0.10	"
N^2	54.01	"
Air	1.03	"

Each cubic meter, measured at 20° C. and 720 m. m. barometric pressure, is accompanied by 73.22 grams of moisture, as determined by drawing through a drying tube and weighing the moisture. The air used is at 20° C., 720 m.m. barometer, and three-quarters saturated with moisture. A maximum of 10 per cent. more air is used than is theoretically necessary to completely burn the gas (assuming NH^3 to burn to H^2O and NO^2, and allowing for the air already present in the gas). The gas and air may be both assumed as coming to the regenerators at 20° C., and to be heated in the regenerators to 1200° C.

Required.—(1) The relative volumes of gas and air passing through the gas and air regenerators.

(2) The total amounts of heat necessary to be furnished to each, per cubic meter of gas used.

(3) The relative sizes of the two regenerators.

Solution.—(1) Taking 1 cubic meter of the dry gas, as represented by the analysis, the combustion of its combustible ingredients is represented by the equations:

$$\begin{aligned}
&2CO + O^2 = 2CO^2\\
&CH^4 + 2O^2 = CO^2 + 2H^2O\\
&2H^2 + O^2 = 2H^2O\\
&4NH^3 + 7O^2 = 6H^2O + 4NO^2\\
&2H^2S + 3O^2 = 2H^2O + 2SO^2
\end{aligned}$$

And since molecules represent volumes, each unit volume of CO, CH^4, H^2, NH^3 and H^2S is seen to require respectively 0.5, 2, 0.5, 1.75, or 1.5 volumes of oxygen. The 1 cubic meter of dry gas therefore requires oxygen as follows:

$$\begin{aligned}
&CO\ 0.2697 \times 0.5 = 0.1349\ m^3\\
&CH^4\ 0.0437 \times 2.0 = 0.0874\ \text{"}\\
&H^2\ 0.1300 \times 0.5 = 0.0650\ \text{"}\\
&NH^3\ 0.0021 \times 1.75 = 0.0037\ \text{"}\\
&H^2S\ 0.0010 \times 1.5 = \underline{0.0015}\ \text{"}\\
&\qquad\text{Total} = 0.2925\ \text{"}
\end{aligned}$$

$$\begin{aligned}
&\text{Air needed} = 0.2925 \div 0.208 &&= 1.4062\ m^3\\
&\text{Add 10 per cent. excess} &&= 1.5468\ \text{"}\\
&\text{Air present in gas} &&= 0.0103\ \text{"}\\
&\text{Air to be supplied} &&= 1.5365\ \text{"}
\end{aligned}$$

Each cubic meter of dry gas, at any given conditions of temperature and pressure, would require 1.5365 cubic meters of dry air at the same conditions of temperature and pressure. This, however, is not exactly the relation required, for the reason that the gas is accompanied by considerable moisture, which in reality adds to its volume, while the air is also moist, adding to its volume. Two corrections must therefore be applied; first, to calculate the volume of the moisture accompanying 1 cubic meter of (assumed) dried gas; the second, to calculate the volume of moisture accompanying 1.5365 cubic meters of (assumed) dry air. Assuming our gas and moist air both at 20° and 720m.m. pressure, the volume of moisture accompanying 1 cubic meter of (assumed) dry gas is the volume of 73.22 grams of moisture at these conditions, which is

$$73.22 \div 1000 \div 0.81 \times \frac{273 + 20}{273} \times \frac{760}{720} = 0.1024 \text{ m}^3$$

The air being 0.75 saturated with moisture at 20°, the tension of this moisture will be 17.4×0.75 = 13 m.m. The air proper is therefore under 720—13 = 707 m.m. tension instead of 720 m.m. and the volume of the moist air containing 1.5365 cubic meters of (assumed) dry gas is therefore:

$$1.5365 \times \frac{720}{707} = 1.5648 \text{ cubic meters.}$$

The relative volumes of actual (moist) gas and actual (moist) air used are therefore:

$$1.1024 : 1.5684 = 1.0000 : 1.419 \qquad (1)$$

(2) To calculate the heat necessary to raise gas and air from 20° to 1200° per cubic meter of gas used, the best preliminary is to calculate the composition of the gas, *including* its moisture. Since 1 cubic meter of (assumed) dry gas is accompanied by 0.1024 cubic meter of water vapor, the sum being 1.1024 cubic meters, we can calculate the real percentage composition to be:

CO	24.47	per cent.
CO^2	3.96	"
CH^4	0.30	"
H^2	11.79	"
NH^3	0.19	"
H^2S	0.09	"
N^2	48.99	"
Air	0.93	"
H^2O	9.29	"

Of the above quantities the (assumed) dry gas in 1 cubic meter of (actual) moist gas is 0.9071 c.m. The air used for its combustion will therefore be:

0.9071×1.5365 = 1.3938 m^3 dry air.
0.9071×1.5648 = 1.4080 m^3 moist air.
1.4080—1.3938 = 0.0142 m^3 of moisture.

The heat required by the 1 cubic meter of (actual) moist gas is found as follows:

$$
\begin{array}{lll}
\textit{Volume} \times \text{Mean Specific Heat} & & \\
& 20^\circ\text{—}1200^\circ & \\
\left.\begin{array}{ll} \text{CO} & 0.2447 \\ H^2 & 0.1179 \\ & \\ N^2 & 0.4899 \\ \text{Air} & 0.0093 \end{array}\right\} & \times 0.3359 = 0.2895 & \text{Calories.} \\
CO^2 \;\; 0.0396 & \times 0.6384 = 0.0253 & \text{"} \\
H^2O \;\; 0.0929 & \times 0.5230 = 0.0486 & \text{"} \\
CH^4 \;\; 0.0030 & \times 0.6484 = 0.0019 & \text{"} \\
NH^3 \;\; 0.0019 & \times 0.5752 = 0.0011 & \text{"} \\
H^2S \;\; 0.0009 & \times 0.5230 = 0.0005 & \text{"}
\end{array}
$$

Mean cal. capacity per 1° = 0.3669 "
Total calorific capacity 20°—1200°
0.3669×1180 = 432.9 Calories.

The calorific capacity of the moist air simultaneously heated through the same range will be:

Air 1.3938×0.3359 = 0.4682 Calories.
H^2O 0.0142×0.5230 = 0.0074 "

Sum = 0.4756 "

Total calorific capacity 20°—1200°
0.4756×1180 = 561.2 Calories.

The air regenerator should therefore have 561.2÷432.9 = 1.30 times the heating power or cross-section of the gas regenerator; *i. e.*, 30 per cent. more. Or the combined capacity of the pair of regenerators should be divided so as to give 57 per cent. to the air regenerator and 43 per cent. to the gas regenerator. In ordinary practice it is usual to allow about 60 and 40 per cent. respectively; it is better to calculate ahead for the specific case in hand, if the composition of the gas to be used is known.

VALVES AND PORTS.

No very exact rule can be given as to the size of the gas and air valves, or those leading the products to the chimney. If made too large they are cumbersome to operate and apt to warp; if made too small they give undue obstruction to the flow of gas. A general rule is to calculate the free opening, such as to give the gases passing through a velocity between 3 and 5 meters (10 and 16 feet) per second, allowing, of course, for the average temperature of the gas or air products of combustion passing through them. It may be remarked that while water-seal valves are very convenient, the water is evaporated where in contact with gas or air, and diminishes the heating efficiency of the furnace, the use of a non-volatile oil or a fine sand would appear perferable to water.

The ports are a very important part of the furnace, and may be designed in many different styles for various ways in which a furnace is to be worked. Their cross-section, however, can be calculated when we know the volume of gas or air leaving the regenerators and their temperature, or the volume of the products of combustion entering the regenerators and their temperature. They should be so designed that the velocity of the gases through them is not over 20 meters per second, while 10 meters per second is a better velocity to use. A long furnace can admit of higher velocities at the ports than a short one; but in any case the higher the velocity the farther complete combustion will occur from the ports, and if the velocity is too high for the length of the furnace combustion may even be continued in the opposite regenerators and less than the maximum occur in the furnace. This is a condition to be scrupulously avoided if possible.

Problem 70.

Producer gas of the following composition:

CO	24.47	per cent.	NH^3	0.19	per cent.
CO^2	3.96	"	N^2	48.99	"
CH^4	0.30	"	Air	0.93	"
H^2	11.79	"	H^2O	9.29	"
H^2S	0.09	"			

is burned with 1.408 times its volume of moist air (see Problem 69). The furnace treats 50 metric tons of steel in 12 hours, using 17.5 tons of coal in the producers, from which 15 tons of carbon pass into the gas. The gas and air pass out of the regenerators at 1200°, and the products of combustion (assumed complete) pass into the opposite regenerators at 1400°. Assume a maximum velocity of the hot gas and air as 10 meters per second, as they pass through the ports.

Required.—(1) The volume of gas and air at 20° C. and 720 m.m. barometer used by the furnace per second.

(2) The areas of the gas and air ports.

(3) The velocity of the products entering the opposite ports.

Solution.—(1) The carbon in 1 cubic meter of the gas at standard conditions is

$$\begin{array}{ll} CO & 0.2447 \\ CO^2 & 0.0396 \\ CH^4 & 0.0030 \\ \hline & 0.2873 \times 0.54 = 0.1551 \text{ kg.} \end{array}$$

Gas used in 12 hours (standard conditions):

$15{,}000 \div 0.1551 = 96{,}710 \text{ m}^3$

Per second $= 2.24 \text{ m}^3$

Gas used at 20° C. and 720 m.m.:

$$2.24 \times \frac{273+20}{273} \times \frac{760}{720} = \mathbf{2.53} \text{ m}^3 \text{ per second.} \qquad (1)$$

Air used (standard conditions):

$2.24 \times 1{,}408 = 3.15 \text{ m}^3$

Air used at 20° C. and 720 m.m.:

$$2.53 \times 1{,}408 = \mathbf{3.56} \text{ m}^3 \text{ per second.} \qquad (1)$$

(2) The volume of gas used per minute, as it issues from the ports at 1200°, is

$$2.24 \times \frac{1200+273}{273} \times \frac{760}{720} = 12.8 \text{ m}^3$$

and of air $3.15 \times$ " $\times$ " $= 17.9$ "

and assuming a maximum velocity for each of 10 meters per second, the areas of the ports must be:

Gas ports	1.28 m^2
Air ports	1.79 "
Sum	**3.07** " (2)

(3) There is usually contraction when gases burn, the products having less volume than the gas and air used. Inspecting the equations of combustion of CO, CH^4, H^2, H^2S and NH^3 given in Problem 69, we can construct the following table of relative volumes concerned and the ensuing contraction:

	CO	CH^4	H^2	H^2S	NH^3
Volume used	1.0	1.0	1.0	1.0	1.0
Oxygen used	0.5	2.0	0.5	1.5	1.75
Gases combining	1.5	3.0	1.5	2.5	2.75
Volume of products	1.0	3.0	1.0	2.0	2.5
Contraction	0.5	0.0	0.5	0.5	0.25

Using 1 cubic meter of producer gas the contraction resulting from its combustion with an excess of air is

CO	0.2447×0.5	$= 0.12235$ m^3
CH^4		$= 0.00000$ "
H^2	0.1179×0.5	$= 0.05895$ "
H^2S	0.0009×0.5	$= 0.00045$ "
NH^3	0.0019×0.25	$= 0.00050$ "
	Total contraction	$= 0.1822$ "

Since the volume of gas, plus air used, is 2.408 m^3, the volume of the products, at standard conditions, is

$$2.408 - 0.182 = 2.226 \text{ m}^3$$

per cubic meter of gas used under standard conditions. The volume of products per minute, at standard conditions, is, therefore,

$$2.226\times 2.24 = 4.986 \text{ m}^3.$$

And at 1400° and 720 m.m. pressure:

$$4.986\times\frac{1400+273}{273}\times\frac{760}{720} = 32.7 \text{ m}^3.$$

Since the sum of the area of gas and air ports is 2.91 m^2, the velocity of the products in these ports will be

$$32.7 \div 3.07 = \mathbf{10.7} \text{ m. per second.} \qquad (3)$$

In both the calculations of the size of the ports and the velocity of the products we have assumed the tension of the gas, air or products in the ports to be the prevailing atmospheric tension. This may or may not be exactly true, because the air or gas may be under a slightly less tension, being drawn into the furnace by the stack draft. If the pressure inside the furnace, with doors closed, is greater or less than atmospheric pressure, the tension of the gases in the entrance ports will be correspondingly greater or less than the atmospheric pressure, while the tension of the products will probably always be less than atmospheric pressure, because of the stack draft. Under ordinary conditions these corrections are too small to need to be taken into consideration.

Laboratory of Furnace.

The laboratory consists of the open space enclosed between the hearth, sides, ends and roof. Its dimensions vary with the intended capacity of the furnace and the ideas of the designer. If a hearth is to contain, say, 50 tons of melted steel, which weighs some 7 tons per cubic meter (425 pounds per cubic foot), there will be contained in the furnace at one time 7 cubic meters, or 260 cubic feet of steel. The deeper this lies the more slowly it will be heated or oxidized by the flame, and therefore there is a limiting depth of, say, 50 centimeters, or 20 inches, which it is not advisable to exceed, while a more shallow bath will result in faster working. Assuming a depth of 40 centimeters (16 inches), the volume divided by the depth will give the area of the bath:

$$\begin{aligned} 7 \div 0.4 &= 17.5 \text{ square meters} \\ 260 \div 1.25 &= 208 \text{ square feet.} \end{aligned}$$

We can then either choose a convenient width, consistent with a practicable roof span, and derive the length, or choose a length and derive the width, or choose a certain ratio of length to width, and derive both. If the width is 3 meters the length must be 5.8; if the length is assumed 5 meters, the width is 3.5; if the ratio of length to width is 2 to 1, the length figures out 5.92 meters and the width 2.96. These dimensions are those of the bath of metal, and each should be increased by at least 1 meter to get the area of the hearth inside the walls, thus allowing 0.5 meter clear space all around the metal.

If a furnace is short it should be wide and the roof high, in order to give cross-sectional area and thus diminish the velocity of the gases over the hearth. The gases attain their maximum temperature in the laboratory, theoretically, some 1700° to 1900°, and their velocity depends solely on the vertical cross-sectional area of the laboratory or body of the furnace. In Problem 70, for instance, about 5 cubic meters of products of combustion (measured at standard conditions) pass through the furnace per second. At 1800° this volume would be 38 cubic meters, and if the laboratory were 4.5 meters wide by 1.5 meters high above the level of bath, there would be 7.25 square meters of cross-section, and the velocity of the gases would be $38 \div 7.25 = 5.2$ meters per second. This would allow barely 1 second for the hot gases to pass over the bath, which would result in a low rate of heating and probable incomplete combustion, for the gas can only burn as it gets mixed with air, and it is hardly likely that 100 per cent. of it would get mixed with air and consumed in 1 second. Such could only be attained by sub-division of the gas and air and very intimate mixture at the ports. Much of the economy undoubtedly attained by raising the roof of open-hearth furnaces is due to the slowing-up of the gas currents in the laboratory, though it is usually ascribed to avoidance of contact of flame and bath, increased heating by radiation, etc. In the writer's opinion the raising of the roof from 1 to 2 meters, let us say, thus doubling the vertical cross-sectional area, cutting in half the velocity of the gases through the furnace, and doubling the period in which they are able to combine, and to radiate or impart heat to the furnace walls and charge—is the principal reason for the increased economy observed.

An equally important improvement is lengthening the distance between ports. There is a limit to the width of the furnace, set by the practicable arch for the roof; there is also a limit to the height of roof, set by the increasing distance of the gases from the hearth; when both these factors have reached their maximum, further efficiency of utilization of the heat of combustion can only be secured, as far as the body of the furnace is concerned, by lengthening the hearth. There is no mechanical limit, and in every case the distance between the ports and the velocity of the gases should be such that complete combustion takes place in the furnace laboratory before the products pass into the regenerators.

Problem 71.

H. H. Campbell gives in the *Transactions* of the American Institute of Mining Engineers, 1890, analyses made at the Pennsylvania Steel Co.'s works, as follows:

	Gas Burned, Entering Furnace.	*Products, Leaving Furnace.*
CO^2	5.5 per cent.	3.1 per cent.
O^2	2.3 "	0.7 "
CO	8.2 "	7.1 "
CH^4	7.3 "	0.0 "
H^2	39.8 "	11.6 "
N^2	36.9 "	77.5 "

Required.—(1) The proportion of the calorific power of the fuel developed while passing through the body of the furnace.

(2) The proportion of the air necessary for complete combustion which was used.

Solution.—(1) One cubic meter of the gas contains the following weight of carbon:

$$(0.055+0.082+0.073)\times0.54 = 0.1134 \text{ kg.}$$

One cubic meter of products contains:

$$(0.071+0.031)\times0.54 = 0.0551 \text{ kg.}$$

Therefore, volume of products per 1 cubic meter of gas:

$$0.1134\div0.0551 = 2.06 \text{ m}^3.$$

Calorific power of 1 cubic meter of gas:

CO	$0.082\times3062 =$	251 Calories
CH^4	$0.073\times8623 =$	629 "
H^2	$0.398\times2613 =$	1040 "
		1920 "

Calorific power of 2.06 cubic meters of products:

CO $0.071 \times 3062 =$ 217 Calories.
H^2 $0.116 \times 2613 =$ 303 “

520 “
$520 \times 2.06 =$ 1071 “

Heat developed in the furnace:

$1920 - 1071 = 849$ Calories.

Proportion of the possible heat development:

$849 \div 1920 = 0.442 =$ **44.2** per cent. (1)

(2) The 1 cubic meter of gas needed, to burn its combustible constituents, the following amount of oxygen:

CO $0.082 \times 0.5 = 0.041$ m³
CH^4 $0.073 \times 2.0 = 0.146$ “
H^2 $0.98 \times 0.5 = 0.199$ “

Sum = 0.386 “
Oxygen present in gas = 0.023 “

Oxygen needed from air = 0.363 “
Air = $0.363 \div 0.208$ = 0.745 “

The 2.06 m³ of products of incomplete combustion require for their combustion:

CO $0.071 \times 2.06 \times 0.5 = 0.0731$ m³ oxygen.
H^2 $0.116 \times 2.06 \times 0.5 = 0.1195$ “ “

Sum = 0.1926 “ “
Oxygen present in the products = 0.0070 “

Oxygen needed from the air = 0.1856 “
Air needed to complete combustion = 0.892 “
Total air needed for complete combustion = 1.745 “

Air supplied in the furnace = 0.853 “

Percentage supplied:

$0.853 \div 1.745 = 0.489 =$ **48.9** per cent. (2)

It is almost needless to remark that with less than half the air necessary for complete combustion supplied, a high calorific intensity of flame and a high utilization of the calorific power of the fuel are impossible. More air should have been used and the furnace made longer, so as to secure perfect combustion in the furnace, and not have over half the possible development left to take place in the regenerators or stack.

CHIMNEY FLUES AND CHIMNEY.

The gases pass into the chimney flues at from 150° to 450°. If their volume at an assumed average temperature of, say, 300° is calculated, they can be given an assumed velocity of 2 to 3 meters (5 to 10 feet) per second, and thus a suitable cross-sectional area of the chimney flues obtained. The stack will work best with a velocity of 5 meters per second, and thus its cross-sectional area may be calculated. A height of 25 to 30 meters (75 to 100 feet) is sufficient for most furnaces.

MISCELLANEOUS.

Some other data useful in figuring up the dimensions and running conditions of modern open-hearth steel furnaces are the following, taken mostly from an article by H. D. Hess, in the *Proceedings* Engineering Club of Philadelphia, January, 1904:

Average coal consumption, in pounds, per hour per ton of metal capacity of the furnace, 55 to 80.

Cubical feet of space in one pair of regenerators, per ton of metal capacity of the furnace, 30 to 75.

Cubic feet of space in one pair of regenerators per pound of coal consumed per hour, 0.5 to 1.0.

A correllation and combination of data of this sort, with details as to the actual working of the furnaces, would point the way towards a general solution, which would furnish the best condition for every possible case, with strict consideration for all the variables involved.

[The next instalment of these calculations will discuss the thermal efficiency of regenerators and of the furnace as a whole, also special forms of open-hearth furnaces worked in special ways.]

CHAPTER XI.

THERMAL EFFICIENCY OF OPEN-HEARTH FURNACES.

The ordinary open-hearth steel furnace receives cold pig iron, cold scrap, warm ferro-manganese, cold limestone and cold ore, it receives cold air and moderately warm producer gas, and it furnishes melted steel and slag at the tapping heat. The larger part of the usefully applied heat is that contained in the melted steel, for it must be melted in order to be cast, and when once taken away from the furnace the latter is done with it.

The total heat available for the purposes of the furnace and which should be charged against it consists of the following items:

(1) Heat in warm or hot charges.
(2) Heat in warm or hot gas as it reaches the furnace.
(3) Heat in warm or hot air as it reaches the furnace.
(4) Heat which could be generated by complete combustion of the gas.
(5) Heat of oxidation of those constituents of the charge which are oxidized in the furnace.
(6) Heat of formation of the slag.

The items of distribution of this total will be as follows:

(1) Heat in the melted steel at tapping.
(2) Heat absorbed in reducing iron from iron ore.
(3) Heat absorbed in decomposing limestone added for flux.
(4) Heat absorbed in evaporating any moisture in the charges.

These first three items constitute the usefully applied heat, and their sum measures the net thermal efficiency of the furnace.

(5) Heat absorbed in reducing ferric oxide to ferrous oxide.
(6) Heat in the slag.
(7) Heat lost by imperfect combustion.

(8) Heat in the chimney gases as they leave the furnace.
(9) Heat absorbed by cooling water.
(10) Heat lost by conduction to the ground.
(11) Heat lost by conduction to the air.
(12) Heat lost by radiation.

(1) HEAT IN WARM CHARGES.

If the pig iron is charged melted instead of cold an immense amount of thermal work is spared the furnace, and it should be charged with all the heat (reckoning from 0° C. as a base line) which is in the melted pig iron as it runs into the furnace. This will average 275 Calories per unit of pig iron, but should be actually determined calorimetrically in each specific instance wherever possible. The net thermal efficiency of the furnace will figure out higher with cold charges than with melted pig iron, because, with a possible flame temperature of 1,900° C. in the furnace, heat is absorbed much more rapidly by cold charges than by hot ones, and a larger percentage of the available heat will be thus usefully applied.

Scrap is almost always charged cold, but if any of it is hot its weight and temperature should be known and the amount of heat thus brought in charged against the furnace. Or a small piece may be dropped into a calorimeter and its heat content per unit of weight measured directly, and thus the heat in all the hot scrap used may be estimated.

Ferro-manganese is often added cold, but usually is preheated to cherry redness (about 900°) in another small furnace, in order that it may dissolve more quickly in the bath. Knowing its weight, temperature and specific heat, the heat which it brings into the furnace can be calculated; a better plan is to drop a piece into a calorimeter and measure the actual heat in a sample of it.

Limestone and ore are almost invariably put into the furnace cold. If used warm the heat in them can be determined by the methods just described.

(2) HEAT IN THE GAS USED.

By this is meant, not the heat in the gas after it is heated by the regenerators, but its sensible heat as it reaches the furnace. This applies only to furnaces where the producers or gas supply are independent of the furnace. Where the producers are an integral part of the furnace it is impracticable to consider them separately from the furnace, and the efficiency of the whole plant, including the producers, must be considered together. But where the gas supply from whatever source comes to the furnace from outside, and reaches the furnace warm, its sensible heat is to be charged against the furnace as part of the heat which the furnace must account for. If the gas comes from producers its amount is satisfactorily found from the known weight of carbon gasified per hour, or per furnace charge, and the weight of carbon contained in unit volume of gas, as calculated from its analysis. If gas comes from a common main which supplies several furnaces, or is simply natural gas, its amount can only be roughly estimated by measuring the area of the gas supply pipe or flue and measuring the velocity of flow by a pressure gauge or Pitot tube or anemometer. None of these methods just mentioned are satisfactorily accurate, and there is great need of simple methods for determining accurately the flow of gases in flues or pipes. If the velocity of warm gas is determined suitable correction for its temperature must be made to reduce it to volume at standard conditions.

(3) Heat in the Air Used.

If the air coming to the furnace is warm its sensible heat must be charged against the furnace. If the air is warmed, however, before it goes into the regenerators by waste heat from the furnace itself, then its sensible heat should *not* be charged against the furnace, because that would amount to charging the furnace twice with this quantity of heat. Such preheating it in reality only a part of the regenerative principle, even though it may not be done in regenerators, but, for instance, by circulating air around a slag-pot or through the hollow walls of the furnace. If the air used is moist its moisture should not be omitted in the calculation.

The amount of air used is best determined by a comparison of the analyses of gas and chimney products, and a calculation based on the carbon contents of each and the known volume of gas used.

(4) HEAT OF COMBUSTION.

Under this head comes the principal item of heat available for the furnace. In reckoning it we should calculate the total heat which could be generated by the perfect combustion of the gas used, to CO^2, N^2 and H^2O vapor. If there is in reality imperfect combustion, as is shown by analysis of the chimney gases, that is a defect of operation of the furnace which should be written down against it. Problem 71 showed an actual case in which there was very incomplete combustion in the body of the furnace, but where combustion was afterwards completed in the regenerators. In such a case the same principle applies; the furnace must be charged with the total calorific power of the fuel used, and incomplete combustion can be charged against the furnace as a whole only on the basis of unconsumed ingredients in the chimney gases—the products finally rejected by the furnace. If there is poor combustion in the body of the furnace and combustion is only completed in the regenerators, the furnace will not give as high net thermal efficiency as if combustion were complete above the hearth.

(5) OXIDATION OF THE BATH.

The oxidation of carbon, iron, silicon, manganese and sometimes phosphorus and sulphur, add a not inconsiderable amount to the heat resources of the furnace. Carbon should be burnt to CO^2, iron is usually oxidized to FeO, manganese to MnO, silicon to SiO^2, phosphorus to P^2O^5, and sulphur to SO^2. All of these oxidations generate heat, and, moreover, heat which should be very efficiently utilized, being produced in direct contact with the metallic bath; it should all be charged against the furnace as part of its available heat.

(6) FORMATION OF SLAG.

The metallic oxides produced unite with each other, and with the lime and silica of ore used and lining of the hearth to produce the slag, the heat of formation of which can be calculated and counted in as available heat.

(1) HEAT IN MELTED STEEL.

This is a large item in the work done by the furnace; in fact, usually the largest single item. It should be determined calorimetrically when possible; if this is not done its temperature should be known and its composition, in order to compare it with the calorimetric experiments of others, and thus derive a probable value for its heat contents. Not many experimental values in this line have so far been published, and a very much needed investigation is one upon the total heat in melted steels of different compositions at different temperatures. Values from 275 to 350 Calories per kilogram have been observed.

(2) Heat of Reduction of Iron from Ore.

This is an item which appears whenever ore is used to facilitate oxidation of the bath. The weight and composition of the charges and the products will easily show how much iron has been reduced. The ore used is almost always hematite, less frequently magnetite; hydrated iron oxides are not used for obvious reasons. The heat absorbed is 1,746 Calories per kilogram of iron reduced from Fe^2O^3 and 1,612 Calories per kilogram from Fe^3O^4.

(3) Decomposition of Limestone Flux.

If limestone is charged raw, as is usually done in order to avoid the dusting caused by using burnt lime, then the furnace is called upon to burn this limestone in place of the lime kiln. The heat absorbed may be taken as either

451 Calories per kilogram of $CaCO^3$ decomposed.
1,026 Calories per kilogram of CO^2 driven off.
806 Calories per kilogram of CaO produced.

(4) Evaporation of Moisture in the Charges.

If the ore, flux, scrap or ore are put into the furnace wet their moisture must be evaporated. The correct figure for this evaporation is the latent heat at ordinary temperatures, viz.: 606.5 Calories per kilogram. This allows for the heat required to convert into cold vapor of water, and puts the H^2O thereafter upon the same basis as all the other gas going out of the furnace. The chimney gases carry out sensible heat, and the H^2O in them can be calculated as carrying out a certain amount of heat as gas, reckoning from zero, and thus the correct chimney loss obtained. It is incorrect either to charge the latent heat of vaporization as chimney loss or to charge the sensible heat of the water vapor in the chimney gases to heat absorbed in evaporating water in the furnace. It is also incorrect to do as is frequently done, viz.: to calculate the heat required to evaporate the moisture to water vapor at 100°—637 Calories—and say that this is the heat to evaporate the moisture. With almost no moisture in the gases, the moisture of the charges would commence to evaporate at once, while they were yet cold, and the moisture is no more evaporated at 100° or to vapor at 100° than it is to 200° or 500°. The only safe course is to confine the evaporation heat to that necessary to convert the moisture into cold vapor, and let its sensible heat as it escapes as vapor at any other temperature be reckoned in with the sensible heat of the chimney gases.

(5) Reduction of Ore Into the Slag.

While considerable of the iron in the ore used is reduced to the metallic state, yet often the larger part is reduced merely to the state of FeO, and as such goes into the slag. The amount so reduced can be determined by subtracting the iron reduced from ore from the total iron in the ore used; the differences gives the iron from the ore going into the slag as FeO. The weight of FeO corresponding is then easily calculated. The heat absorbed in this partial reduction is:

446 Calories per kilogram of FeO reduced from Fe^2O^3.
341 Calories per kilogram of FeO reduced from Fe^3O^4.

(6) Heat in Slag.

This is usually a small item in open-hearth practice, but may amount to a very considerable one in the method of running with large ore charges, as in the Monell process. The variations of composition of the slag, and especially in the temperature at which it is run off, are so large that the heat in the slag should always be determined calorimetrically for each specific case. If assumptions have to be made, 450 to 550 Calories per kilogram of slag would be assumed. The weight of slag is seldom taken, although it could in most cases be done if desired. If the weight is not known it may be calculated from the known weight of either iron, manganese or phosphorous going into it, as seen from the balance sheet and the percentages of these elements in the slag as shown by analysis.

(7) LOSS BY IMPERFECT COMBUSTION.

This is based upon the unconsumed ingredients of the chimney gases, as shown in an analysis. From this the calorific power of the unburnt gases in 1 cubic meter can be calculated. If then we know the volume of chimney gases per unit of charge, we get the heat loss by imperfect combustion per unit of charge. The volume of chimney gas is found by means of the carbon in it, which must all come from the carbon in the gas used, plus the carbon oxidized out of the charges, plus the carbon of CO^2, driven off raw limestone used as flux. Or, putting it in another way, the total carbon going into the furnace in any form, less the carbon in finished steel, must give the carbon in the chimney gases. This divided by the weight of carbon in unit volume of chimney gas gives the volume of the latter, per whatever unit of charge is used as the basis of calculations. This volume times the calorific power of unit volume of chimney gas, gives the total heat lost by imperfect combustion.

(8) SENSIBLE HEAT OF CHIMNEY GASES.

The temperature of these gases should be taken as they enter the chimney flue. Their amount is determined as explained under the previous heading. The water vapor contained should not be overlooked, being reckoned simply as vapor or gas in exactly the same category as the other gases. The analysis of the chimney gases being usually given on dried gas, a separate determination of the moisture carried per unit volume of such dried gas is necessary. If this is not done an approximation can be made by considering all the hydrogen in the gas burned to form water vapor, and add in the moisture of the air used and the moisture in the charge.

(9) HEAT LOST IN COOLING WATER.

This is a very variable amount, and must be determined for each furnace by measuring the amount of water used per unit of time and its temperature before reaching and after leaving the furnace. Doors are frequently water-cooled, also ports, where the heat is fiercest, and sometimes a ring around the hearth at the slag line.

(10) Loss by Conduction to the Ground.

This is a quantity extremely difficult to measure or to estimate. If a closed vessel filled with water were put into the foundations the rate at which its temperature rose might give some idea of the rate at which heat passed in that direction per unit of surface contact. At present, lacking all reliable data, we must put this item in the " by difference " class.

(11) Loss by Conduction to the Air.

This is an amount which can be observed and calculated with some approach to satisfaction. The *sina qua non* for this purpose is a Féry radiation pyrometer, by which the temperature of the outside of the furnace at different parts can be accurately determined. Then the velocity of the air blowing against the furnace, if it is in a current of air, is observed with a wind gauge, and its temperature before reaching the furnace. With these data and by the methods of calculation before explained in these calculations (Part I, Chap. VIII) the heat lost to the air may be calculated.

(12) Radiation Loss.

Having determined the temperature of the outer surface of the furnace and measured its extent, as above explained, the radiation loss can also be calculated, knowing the mean temperature of the surroundings, by the principles of radiation, having due regard to the nature of the radiating surface. Tables of specific radiation capacity of different substances (fire-brick, stone, iron) will be found at the reference just given above.

Problem 72.

Jüptner and Toldt (Generatoren und Martinöfen, p. 73) observed the following data with regard to an open-hearth steel furnace charge:

Weight of cold charges, at 26° C.	3,745 kg.
Weight of hot charges, at 700° C.	1,700 "
Total weight of charge	5,445 "

Average composition of charge	C =	1.07 per cent.
	Si =	0.50 "
	Mn =	1.33 "
Coal gasified in producers....................		1,980 kg.
Carbon gasified from coal....................		47.13 per cent.
Average composition of dried gas used.....	CO^2	3.81 "
	O^2	0.98 "
	CO	23.82 "
	CH^4	0.42 "
	H^2	8.75 "
	N^2	62.22 "
Moisture accompanying each m³ of gas......	=	82 grams.
Temperature of gas reaching furnace..........		165° C.
Temperature of air used......................		26° C
Moisture accompanying each m³ of air........		12 grams.
Barometer..................................		717 m.m.
Steel produced..............................		5,191 kg.
Composition of steel	C =	0.12 per cent.
	Si =	0.04 "
	Mn =	0.19 "
Temperature of steel when tapped............		1410° C.
Heat in 1 kg. steel, by calorimeter (to 0° C.)..		277 Cal.
Composition of slag	SiO^2	45.65 per cent.
	FeO	33.60 "
	MnO	18.21 "
	CaO	2.54 "
Weight of slag..............................		425 kg.
Temperature of slag when issuing..........		1,410° C.
Heat in 1 kg. slag, by calorimeter (to 0°)......		560 Cal.
Composition of the stack gases (dry)	CO^2	11.12 per cent.
	O^2	6.78 "
	N^2	82.10 "
Temperature of the gases in chimney flue.....		500° C.

Requirements:

(1) A balance sheet of materials entering and leaving the furnace.

(2) A balance sheet of the heat available and its distribution.

(3) What excess of air above what is necessary for complete combustion is used, and what per cent. of all the available heat of the furnace is thereby lost?

(4) What is the thermal efficiency of the furnace?

Solution: (1)

BALANCE SHEET OF MATERIALS.

Charges.		*Steel.*	*Slag.*	*Gases.*
Metal,	**5,445** kg.			
C,	58 "	6	...	52
Si,	27 "	2	25	....
Mn,	72 "	10	62	....
Fe,	5,288 "	5,173	115	....
Limestone,	**20** "			
CaO,	11 "	....	11	....
C,	2.5 "	....	....	2.5
O,	6.5 "	....	....	6.5
Hearth,				
SiO^2	132 "	....	132	....
Gas,	**7,884** "			
C,	933 "	....	....	933
O,	2,003 "	....	....	2,003
H,	118 "	....	....	118
N,	4,830 "	....	....	4,830
Air,	**16,026** "			
O,	3,812 "	....	80	3,732
N,	12,195 "	....	....	12,195
H,	19 "	....	....	17 9
Totals,	29,507 "	5,191	425	23,891

NOTES ON THE BALANCE SHEET.

The distribution of carbon, silicon, manganese and iron is governed by the known amounts of these elements present in the steel, the rest of the carbon going into the gases (as CO^2), and the manganese, silicon and iron passing into the slag (as MnO, SiO^2 and FeO, respectively.)

The amount of limestone used was not stated, but was deduced from the fact that the slag was said to weight 425 kilos. and to contain 2.54 per cent. of CaO, which makes the CaO 11 kilos. and assuming pure limestone, this would bring in 9 kilos. of CO^2, which appears on the balance sheet as 2.5 kilos. of carbon and 6.5 kilos. of oxygen, contributed to the gases.

The weight of silica contributed by the hearth is deduced from the fact that the slag must contain the silicon, manganese and iron oxidized from the charge, as SiO^2, MnO and FeO, the CaO of the flux and the SiO^2 contributed by the hearth, and its total weight is 425 kilos. The ingredients of the slag must, therefore, be

		Kg.
SiO^2	$25 \times 60/28 =$	53.5
MnO	$62 \times 71/55 =$	80.0
FeO	$115 \times 72/56 =$	147.9
CaO	$=$	11.0
	Sum	293
From hearth (difference)		132
Total slag		425

The gas used we find by starting with the fact that 1,980 kilos. of coal is used, from which 47.13 per cent, of carbon enters the gases. This makes carbon in the gases 933 kilos. Each cubic meter of dry gas, as analyzed, contains 0.2805 cubic meter of CO^2, CO and CH^4 added together, and therefore, $0.2805 \times 0.54 = 0.1515$ kilos. of carbon. The volume of dry producer gas used is therefore, at standard conditions, $933 \div 0.1515 = 6{,}160$ cubic meters, containing by its analysis:

CO^2	$6{,}160 \times 0.0381 =$	$235\ m^3 =$	465 kg.
O^2	" $\times 0.0098 =$	$60\ m^3 =$	86 "
CO	" $\times 0.2382 =$	$1{,}467\ m^3 =$	1,840 "
CH^4	" $\times 0.0042 =$	$26\ m^3 =$	19 "
H^2	" $\times 0.0875 =$	$539\ m^3 =$	49 "
N^2	" $\times 0.6222 =$	$3{,}833\ m^3 =$	4,830 "
		$6{,}160\ m^3 =$	7,297 "

The moisture is 82 grams per each cubic meter of gas, measured at 26° and 717 m.m. pressure; but the 6,160 cubic meters of gas at standard conditions would be 7,175 cubic meters at those conditions of temperature and pressure, and therefore be accompanied by

$$7{,}175 \times 82 = 588{,}350 \text{ grams}$$
$$= 588 \text{ kg. of } H^2O \text{ vapor.}$$

We can now enter the gas on the balance sheet either as so much CO^2, CO, H^2O, etc., or else resolve it into its essential constituents C, H, O and N, which course we have followed on the balance sheet. The carbon in the gas, is 933 kg. by assumption, the oxygen is 8/11 the CO^2, all the O^2, 4/7 the CO and 8/9 the H^2O, a total amounting to 2,003 kilos; the hydrogen is 4/16 the CH^4, all the H^2 and 1/9 the H^2O, a total of 118 kilos.

The air supplied is best found from the volume of the chimney gases. The total carbon entering these is $52+2.5+933 = 987.5$ kilos., as seen from the balance sheet. Each cubic meter of dry chimney gas contains 0.1112 m^3 of CO^2, carrying $0.1112\times0.54 = 0.0600$ kilos. of carbon. The volume of dry chimney gas at standard conditions is therefore $987.5\div0.0600 = 16{,}458$ m^3. This contains $16{,}458\times0.8210 = 13{,}512$ m^3 of N^2, and since 3,833 cubic meters came in with the gas 9,679 m^3 must have come in with the air, corresponding to 12,220 m^3 of dry air at standard conditions. This would consist of 12,195 kilos. of N^2 and 3,660 kilos. of O^2. To find the moisture present the volume of this air at 26° and 717 m.m. pressure would be 14,230 m^3, and would be therefore accompanied by

$$\begin{aligned}14{,}230\times12 &= 170{,}760 \text{ grams}\\ &= 171 \text{ kg. of } H^2O.\end{aligned}$$

This consists of 19 kilos. of hydrogen and 152 kilos. of oxygen, the latter increasing the total oxygen in the air used to $3\,660+152 = 3{,}812$ kilos.

(2) HEAT BALANCE SHEET.

Heat Available.

	Cal.		*Percentages.*
Heat in the warm charges	189,210	=	2.45
Sensible heat of air used	99,480	=	1.29
Sensible heat of gas used	360,550	=	4.68
Heat of combustion of gas	6,202,300	=	80.44
Heat of oxidation of the bath	833,600	=	10.81
Heat of formation of slag	24,200	=	0.31
Total	7,709,340	=	100.00

Heat Distribution.

In melted steel at tapping	1,437,900 =	18.65
Decomposition of limestone	9,200 =	0.12
Sensible heat of slag	238,000 =	3.09
Sensible heat of chimney gases	3,118,450 =	40.45
All other losses, not classified	2,905,790 =	37.69
Total	7,709,340 =	100.00

Notes on the Heat Balance Sheet.

The warmed charges weighed 1,700 kilos. at 700°, and the cold charges 3,745 kilos at 26°. Taking 0° C. as the base line the sensible heat in these is

	Cal.
1,700 × 0.15 × 700 =	178,500
3,745 × 0.11 × 26 =	10,710
Sum =	189,210

The air used contains, at standard conditions, 12,220 m^3 of air and $171 \div 0.81 = 211$ m^3 of water vapor. These carry at 26°, heat as follows:

	Cal.
12,220 × 0.3037 × 26 =	98,490
211 × 0.3439 × 26 =	990
Sum =	99,480

The gas used, coming in at 165° C., carries in heat as follows:

		Cal.
O^2, CO, H^2, N^2	5,899 m^3 × 0.3075 =	1,814
CO^2	235 m^3 × 0.4063 =	95
CH^4	26 m^3 × 0.4163 =	11
H^2O	726 m^3 × 0.3648 =	265
Average calorific capacity per 1° =		2,185
Heat content 2,185 × 165	=	360,525

The heat of combustion is that of the combustible ingredients of the gas used to CO^2 and H^2O vapor:

Cal.
CO 1,467 $m^3 \times 3,062$ = 4,492,000
CH^4 26 $m^3 \times 8,598$ = 223,500
H^2 539 $m^3 \times 2,613$ = 1 486,800
Sum = 6,202,300

The heat of oxidation of the bath is from the various substances oxidized:

Cal.
C to CO^2 $52 \times 8,100$ = 421,200
Si to SiO^2 $25 \times 7,000$ = 175,000
Mn to MnO $62 \times 1,653$ = 102,500
Fe to FeO $115 \times 1,173$ = 134,900
Sum = 833,600

The heat of formation of the slag is the heat of combination of 80 kilos. of MnO, 148 kilos. of FeO and 11 kilos. of CaO, with 186 kilos. of SiO^2. This will be, since the bases are largely in excess of the silica:

$$186 \times 130 = 24,200 \text{ Cal.}$$

The figure 130 is an average for the heat of combination of 1 kilo. of SiO^2 with about 2 parts of FeO to 1 part MnO.

The heat in the steel at tapping is simply its weight multiplied by its heat contents per kilo. ($5,191 \times 277$).

The heat in the slag is similarly obtained (425×560).

The decomposition of limestone represents 9 kilos. of CO^2 liberated, and the heat absorbed is $9 \times 1,026$.

The sensible heat in the chimney gases is obtained by first noting that their volume (measured dry), as already obtained, is 16,458 cubic meters. The CO^2, 11.12 per cent., becomes, therefore, 1,843 m^3; the O^2, 1,116 m^3; N^2, 13,512 m^3, while the H^2O accompanying this will be 9 times the weight of hydrogen passing into the gases, which is $9 \times (118+17) = 1,215$ kilos. $= 1,500$ m^3. A simpler way to get the volume of the water vapor is to observe that it is always equal to the volume of hydrogen going into it, and, therefore, in this case would be $(118+17) \div 0.09 = 1,500$ m^3. The heat carried out by these gases would therefore be:

N^2+O^2 = 14,628 $m^3 \times 0.3165$ = 4629.8 Cal. per 1°
CO^2 = 1,843 $m^3 \times 0.4800$ = 984.4 " "
H^2O = 1,500 $m^3 \times 0.4150$ = 622.5 " "

Calorific capacity = 6236.9 " "
Total capacity = 3,118,450 " per 500°

The heat balance sheet as a whole discloses the fact that in this furnace the fuel only supplies some 80.5 per cent. of the total heat available, and that about 10.8 per cent. is furnished by the oxidation of the bath itself. On the other hand, the melted steel accounts for 18.6 per cent., while chemical reactions absorb almost none, giving a net thermal efficiency of slightly under 19 per cent. The other important items are 40.5 per cent. of the total heat lost up the chimney, and 38 per cent. lost by radiation and conduction. Such data as these point the way to avenues of possible saving or avoidance of waste of heat.

(3) The excess of air is obtained directly from the chimney gases. The 1,116 m^3 of oxygen, unused, represents $1,116 \div 20.8 = 5,365$ m^3 of air in excess, which leaves $16,458 - 5,365 = 11,093$ m^3 of air which came in and was used. The percentage of air used in excess of that which was necessary was:

$$5,365 \div 11,093 = 0.4845 = \mathbf{48.5} \text{ per cent.} \qquad (3)$$

No properly run open-hearth regenerative gas furnace should ever have such a large excess of air, for it cuts down the temperature of the flame and leads to high chimney losses.

The air used brought in 171 kilos of water vapor, and therefore the excess air brought in

$$171 \times \frac{48.5}{148.5} = 56 \text{ kilos. of water,}$$

the volume of which, at standard conditions, would be

$$56 \div 0.81 = 61 \text{ cubic meters.}$$

The excess air, with its accompanying water, going into the chimney at 500°, carried out heat as follows:

	Cal.
$5,365 \times 0.3165 \times 500$ =	849,000
$61 \times 0.4150 \times 500$ =	12,650
	861,650

Representing 861,650 ÷ 7,709,340 = 0.112 = **11.2** per cent. (3)

(4) The thermal efficiency has been already added up as

18.65 + 0.12 = **18.77** per cent. (4)

Problem 73.

In the open-hearth furnace of the preceding problem, assume that the calculations therein made showed that, per heat of steel produced, 5,191 kilograms, there entered and left the furnace the following volumes of gases, measured at standard conditions:

Producer Gas.		*Air.*	*Chimney Gases.*
CO^2	235 m³	.....	1,830 m³
O^2	60 m³	3,833 m³	1,116 m³
CO	1,467 m³	.....	.....
CH^4	26 m³	.....	.....
H^2	539 m³	.....	.....
N^2	3,834 m³	9,679 m³	13,512 m³
H^2O	726 m³	211 m³	1,500 m³

The temperature of air used was 26°, of producer gas 165°, of chimney gases 400°. The excess of air used was 48.5 per cent. The gas and air entered the laboratory of the furnace preheated to 1,100°, and the products of combustion entered the regenerators at 1,450. Items of heat balance sheet:

Available.

	Calories
In warm charges	189,210
Sensible heat of air used at 26°	90,480
Sensible heat of gas used at 165°	360,550
Heat of combustion of the gas	6,202,300
Heat of oxidation of the bath	833,600
Heat of formation of slag	24,200
	7,700,340

Distribution.

In melted steel at tapping at 1,410°	1,437,900
In slag at tapping at 1,410°	238,000
Decomposition of limestone	9,200
Sensible heat in chimney gases at 400°	3,065,350
All other losses, not classified	2,949,890
	7,700,340

Required:

(1) The thermal efficiency of the regenerators.

(2) The thermal efficiency of the laboratory of the furnace.

(3) The temperature of the flame.

(4) The change in (3) if only the theoretical amount of air for combustion were used.

Solution:

(1) The products of combustion, entering the regenerators at 1,450°, carry into them the following amounts of heat:

		Calories.
CO^2	1,830×0.689 =	1,261
O^2+N^2	14,628×0.342 =	5,003
H^2O	1,500×0.557 =	836
Calorific capacity per 1°		= 7,100

Calorific capacity per 1,450° = 10,295,000 Calories.

The same gases entering the chimney flue at 400° carry with them the following amounts:

		Calories.
CO^2	1,830×0.458 =	838.1
O^2+N^2	14,628×0.314 =	4,593.2
H^2O	1,500×0.400 =	600.0
Calorific capacity per 1°		= 6,031.3

Calorific capacity per 400° = 2,412,500 Calories.

The gas used for combustion, entering the regenerators at 165° and leaving it at 1,100°, carried into the regenerators 360,550 Calories, as already given in the balance sheet, and carried out at 1,100° the following:

		Calories.
CO^2	235×0.612 =	143.8
CH^4	26×0.620 =	16.1
O^2, N^2, H^2, CO	5,899×0.333 =	1,964.4
H^2O	726×0.505 =	366.6
Calorific capacity per 1°		= 2,490.9

Calorific capacity per 1,100° = 2,780,000 Calories.

Heat abstracted from regenerators:

2,780,000—360,550 = 2,419,450 Calories.

The air used, entering the regenerators at 26°, carries in as sensible heat 90,480 Calories, as already given in the balance sheet, and issuing from them at 1,100° carries out the following:

		Calories.
O^2+N^2	$13,512\times0.333 =$	4,499.5
H^2O	$211\times0.405 =$	85.5
Calorific capacity per 1°	=	4,585.0

Calorific capacity per 1,100° = 5,043,500 Calories.

Heat abstracted from regenerators:

5,043,500—90,500 = 4,953,000 Calories.

The thermal efficiency of the regenerators may now be calculated from three standpoints. There is no doubt that the gas and air take from the regenerators, and return to the body of the furnace 2,419,450 + 4,953,000 = 7,372,450 Calories. This is, therefore, the usefully returned heat, and the ratio of this to the heat received by the regenerators measures their efficiency *qua* regenerators. The three figures obtained for this efficiency depend on what is to be considered as the heat chargeable against the regenerators. Are they to be charged with all the heat in the hot products at 1,450° (10,295,000 Calories), or only with the heat left in the regenerators by these products leaving at 400° (10,295,000—2,412,500 = 7,882,500 Calories), or perhaps only with the heat carried in less a certain assumed amount representing the minimum temperature to which it is desirable to cool the products before they enter the chimney?

If we charge the regenerators with all the heat *brought in* by the products their thermal efficiency figures out:

$$\frac{7,372,750}{10,295,000} = 0.72 = \mathbf{72} \text{ per cent.} \qquad (1)$$

If we charge them with the heat *left in* the regenerators, by the products, their efficiency is:

$$\frac{7,372,450}{7,882,500} = 0.94 = \mathbf{94} \text{ per cent.} \qquad (1)$$

leaving 7 per cent. of the heat chargeable against them lost by radiation from their walls and conduction to the ground.

If we think that the first calculation gives too low an efficiency, because the gases must leave the regenerators hot, in order to be used for chimney draft, and therefore some or all of the heat in the chimney gases should not be charged against the regenerators, on the other hand, the second calculation may represent too high an efficiency, because the gases may be discarded to the chimney at a higher temperature than is necessary to provide the requisite chimney draft, and this *excess of* chimney temperature and consequent heat loss is a defect of the regenerators which they should be charged with. If we assume that a chimney gives very nearly its maximum drawing capacity with the gases entering it at 300°, it would be perfectly proper to charge the regenerators with all the heat which could be given out by the products in cooling from 1,450° to 300°, heat which they should have entirely absorbed. In the case in hand, the products at 300° would contain (by calculations similar to those already made) 1,777,400 Calories, leaving 10,295,000—1,777,400 = 8,517,600 Calories chargeable against the regenerators, as the heat which they should have absorbed or intercepted. Measured by this standard, their efficiency is:

$$\frac{7,372,450}{8,517,600} = 0.87 = \mathbf{87} \text{ per cent.} \qquad (1)$$

The losses from the regenerators in this view would be 7 per cent. (about) by radiation and 7 per cent. by *unnecessary* chimney loss.

Comparing these three methods of considering efficiency, the third appears to the writer as the fairest, and the one which gives the metallurgist the most reliable criterion of the real work which his regenerators are doing for him, and the best basis of comparison when considering the work of different regenerators or of the same regenerators under different conditions.

(2) The laboratory of the furnace, the space enclosed between the hearth, roof, side walls and ports, receives from the entering preheated gas and air their sensible heat, and the heat generated by combustion. In the case in point these items total, as already calculated:

	Calories.
Sensible heat in preheated gas	2,722,300
Sensible heat in preheated air	5,043,500
Heat generated by the combustion	6,202,300
Total	13,968,100
Hot products at 1,450° take out	10,295,000
Heat left in the laboratory	3,673,100

These figures show that the laboratory of the furnace appropriates to its own purposes 3,673,100 Calories out of the 13,968,100 Calories poured into it. This part of the furnace, therefore, *qua* laboratory, has an efficiency in this respect of

$$\frac{3,673,100}{13,968,100} = 0.26 = \mathbf{26} \text{ per cent.} \qquad (2)$$

This is the datum which would be useful to the metallurgist in comparing the efficiencies of differently shaped laboratories, such as those with differently shaped hearths, differently shaped roof, differently arranged ports, etc. This conception of efficiency is that taken by Damour, and repeated by Queneau in his book on "Industrial Furnaces." We must be careful here not to compare the heat left in the laboratory with the heat of combustion alone. This would give

$$\frac{3,673,100}{6,202,300} = 0.59 = 59 \text{ per cent.}$$

But this is not the heat absorption of the laboratory alone, but is a function of the furnace as a whole, and depends largely on the efficiency of the regeneration accomplished by the regenerators. If we wish to obtain an idea of the perfection with which the laboratory of the furnace appropriates the heat passing into and through it, we must simply compare what it appropriates with what was sent into it. The percentage of this appropriation measures the efficiency of the laboratory for abstracting heat for the purpose of heating itself—a datum highly useful to know if the furnace is used simply for keeping a given working space up to a given temperature for an indefinite time. If the heating of the furnace charge to the furnace heat is only a minor part of the useful work of the furnace, and keeping it at that temperature is the chief function of the furnace, then the relation of the heat thus appropriated and utilized to the total heat available to the laboratory, is a measure of the perfection of construction of the laboratory. This is the view of Damour and Queneau, and seems in some respects plausible.

However, if we are examining this question thus in detail, it appears to the writer that the view just explained and the conclusions derived thereform may really be the very opposite of the truth of the matter, and lead to entirely erroneous conclusions. If two exactly similar open-hearth furnaces are constructed, with the sole difference that the body of one is thicker walled than the body of the other, it is perfectly true that maintaining the same temperature in each will require more gas in the thin-walled furnace, but that it will abstract and radiate a considerably larger proportion of the heat passing through it than the thick-walled furnace. Yet, according to Damour and Queneau's principle, the thin-walled furnace would be considered as being the more efficient laboratory of the two. The truth is, we must either compute the heat left in the laboratories per unit of time per cubic meter of stock space in order to compare different furnaces, or else to get absolute efficiency compute the ratio of the heat passing into the laboratory with that absorbed usefully by the charge, viz.: in this case:

$$\frac{1{,}447{,}100}{13{,}968{,}100} = 0.104 = \mathbf{10.4} \text{ per cent.} \tag{2}$$

(3) The temperature of the flame is that to which the products of combustion can be raised by the maximum heat which they contain. When perfectly consumed they contain the heat pre-existing as sensible heat in the hot gas and air, plus the heat of combustion. We have already calculated this total as 13,968,100 Calories. The mean heat capacity of the products of combustion, per 1° between 0° and t°, is:

$$\begin{array}{llcr}
CO^2 & 1{,}830\ m^3\ (0.37\ +0.00022t) & = & 677+0.4026t \\
O^2+N^2 & 14{,}628\ m^3\ (0.303+0.000027t) & = & 4{,}428+0.3950t \\
H^2O & 1{,}500\ m^3\ (0.34\ +0.00015t) & = & 510+0.2250t \\
\hline
 & \text{Sum} & = & 5{,}615+1.0226t
\end{array}$$

Therefore,

$$t = \frac{13{,}968{,}100}{5{,}615+1.0226t}$$

Whence,

$$t = \mathbf{1{,}749°} \qquad (3)$$

(4) If the excess air were not used, the 1,116 cubic meters of oxygen in the products, together with its corresponding quantity of nitrogen, 4,249 cubic meters, would be absent from the products of combustion, as would also some of the 211 cubic meters of water vapor. Since the oxygen in the air was 3,833 m³ and the unused excess 1,116, the proportion of the 211 m³ of water vapor belonging to the excess air was

$$211\times\frac{1{,}116}{3{,}833} = 61\ m^3,$$

and the final products are CO^2 1,830 m³, N^2 9,263 m³ and H^2O 1,439 m³.

The heat available will be the same as before from combustion, the same from preheated gas, but less from preheated air, because of the absence of the excess air. Since the air formerly used brought in 5,043,500, the proportion of this carried by the excess air is

$$5{,}043{,}500\times\frac{1{,}116}{3{,}833} = 1{,}468{,}500,$$

leaving heat brought in by air in the second case the difference, viz.: 3,575,000, and the total heat in the products 13,968,100—1,468,500 = 12,499,600 Calories.

The mean heat capacity of the diminished quantity of products, per 1°, is, by the same methods as previously used, $3{,}973+0.8685t$, and, therefore,

$$t = \frac{12{,}499{,}600}{3{,}973+0.8685t} = \mathbf{2{,}142°} \qquad (4)$$

a gain of nearly 400° in maximum temperature, by cutting off the 40 per cent. excess of air which was being used.

Problem 74.

The new style Siemens furnace for small plants has the gas producers built in as part of the furnace, between the two regenerators. The furnace has only one regenerative chamber at each end for preheating the air used for burning the gas, while the latter comes to the ports hot directly from the producers. This plant is compact, economical of fuel, allows high temperatures to be reached, and occupies little floor space. As compared with the old style separate furnace and producer plant, it occupies about half the floor space, costs about 60 per cent. as much to build and uses about 60 per cent. as much coal. They are largely used abroad for melting steel for castings in small foundries and for melting pig iron for castings to be subsequently annealed to malleable castings.

Such a furnace melted a charge of 3,000 kilograms of cast iron in 4 hours, using 750 kilograms of coal. The cast iron was charged cold, at 0°, and run out melted at 1,450°, containing 300 Calories of sensible heat per kilogram. The coal and gases were of the following compositions:

Coal—C 75, H 5, O 12, H^2O 2; ash 6.
Producer Gas—CO 20, CO^2 5, CH^4 2, H^2 16, N^2 57.
Chimney Gas—CO^2 19, O^2 1.8, N^2 79.2.

The air coming to the furnace is at 0° and dry; a steam blower is used to run the producer, using 1 kilo. of steam per 6 kilos. of air blown in, and the raising of this steam requires 0.1 kilo of coal used under boilers. The ashes produced weigh 75 kilos. per heat run. Temperature of the hot producer gas entering the furnace laboratory 600°, of preheated air 1,000°, of products leaving laboratory 1,400°, of products entering chimney flue 350°.

Required:

(1) A heat balance sheet of the furnace as a whole.

(2) The net thermal efficiency of the furnace.

(3) The net thermal efficiency of the laboratory of the furnace.

(4) The net thermal efficiency of the regenerators.

(5) The theoretical flame temperature in the furnace.

Solution:

(1) Heat balance sheet per charge of 3,000 kilos.

Heat Available.

	Calories.
Calorific power of coal used in producers	5,248,500
" " " " " under boilers	398,900
	5,647,400

Heat Distribution.

In melted cast iron	900,000
In chimney products	768,950
Loss by unburnt carbon in ashes	243,000
Used for raising steam	398,900
Loss by radiation and conduction	3,336,550
	5,647,400

Calculation of the Heat Balance.

The heat of combustion of a kilogram of coal is not given, therefore must be calculated from its composition:

		Calories.
C $0.75 \times 8{,}100$	=	6,075
H $\left(0.05 - \frac{0.12}{8}\right) \times 34{,}500$	=	1,208
Calorific power to liquid water	=	7,283
Vaporization heat of water formed $(0.02 + 0.45) \times 606.5$	=	285
Calorific power to vapor of water	=	6,998
Of 750 kilos. in the producers	=	5,248,500

The coal used under the boilers can only be found by first finding how much steam was used, which in its turn can be gotten from the air blown in, and the nitrogen of this can be found from the total nitrogen in the producer gas. The volume of producer gas can be gotten from its carbon content per cubic meter and the known weight of carbon gasified. Or, turning this chain of reasoning the other way, if we subtract the carbon in the ashes from the carbon in the coal, the difference is the carbon entering the gases; this divided by the carbon in 1 cubic meter of chimney gas (calculated from its analysis) gives the volume of chimney gas, and by the carbon in 1 cubic meter of producer gas gives the volume of this gas used, from which the nitrogen in it can be calculated, which divided by 0.792 gives the volume of air used, from which its weight is obtained, thence the amount of steam used, and finally from this the amount of coal necessary to burn under boilers to raise this steam.

[In working most metallurgical problems the difficulty of finding the connection or succession of steps connecting the requirements with the data given is often easiest overcome by starting with the requirement in mind and noting from what other figure its value may be calculated, and thus passing backwards from one figure to another we finally arrive at one which can be found directly from the data given. The logical sequence of operations is thus disclosed and the problem is in reality solved; the following of the thread in the reverse direction, from data to requirement, involves calculations only, not hard thinking, and is usually a matter of the simplest arithmetic.]

The operations for calculating the steam used are as follows:

Carbon in coal in producers = 750×0.75 = 562.5 kg.
Carbon in ashes from producers = 75—45 = 30.0 "

Carbon in gases from producers = 532.5 "
Carbon in producer gas per 1 m^3 = 0.27×0.54 = 0.1458 "
Producer gas per heat = $532.5 \div 0.1458$ = 3,652 m^3
Nitrogen in producer gas = $3{,}652 \times 0.57$ = 2,082 "
Air used in the producer = $2{,}082 \div 0.792$ = 2,629 "
= 3,399 kg.
Carbon in chimney gas per 1 m^3 = 0.19×0.54 = 0.1026 "
Chimney gas per heat = $532.5 \div 0.1026$ = 5,190 m^3
Nitrogen in chimney gas = $5{,}190 \times 0.792$ = 4,110 "
Nitrogen from air used = 4,110—2,082 = 2,028 "
Air used to burn gas = $2{,}028 \div 0.792$ = 2,561 "
Weight of this air = $2{,}561 \times 1.293$ = 3,311 "
Weight of air used in producer = 3,399 "
Weight of steam used in producer = $3{,}399 \div 6$ = 567 "
Weight of boiler coal used = 567×0.1 = 57 "
Calorific power of this coal = $6{,}998 \times 57$ = 398,900 Cal.

The heat in the melted cast iron is simply its weight times 300 = 300×3,000 = 900,000 Calories.

(2) The net thermal efficiency follows directly from this, as

$$\frac{900{,}000}{5{,}647{,}400.} = 0.16 = \mathbf{16} \text{ per cent.} \qquad (2)$$

(3) The gaseous products consist dry, as analyzed, of

CO^2 5,190×0.19 = 986 m^3
O^2 5,190×0.018 = 93 "
N^2 5,190×0.792 = 4,110 "

And in addition all the water formed from the coal, plus the steam used, a total of:

Water from coal = 0.47×750 = 352.5 kg.
Steam = 566.5 "

Total water vapor in gases = 919.0 "
Volume at standard conditions = 919÷0.81 = 1,135 m^3

At 350° these products carry out of the furnace heat as follows:

Calories.
O^2+N^2 4,203×0.312 = 1,311
CO^2 986×0.447 = 441
H^2O 1,135×0.392 = 445

Average caloric capacity per 1° = 2,197
Capacity per 350° = 768,950 Calories.

These same products would carry heat out of the laboratory of the furnace at 1,400° as follows:

Calories.
O^2+N^2 4,203×0.341 = 1,433
CO^2 986×0.678 = 669
H^2O 1,135×0.550 = 624

Average caloric capacity per 1° = 2,726
Capacity per 1,400° = 3,816,400 Calories.

The heat developed in the laboratory of the furnace by the combustion of the 3,652 m^3 of producer gas is

Calories.

CO $0.20 \times 3062 =$ 612

CH^4 $0.02 \times 8{,}598 =$ 172

H^2 $0.16 \times 2{,}613 =$ 418

Per 1 m^3 $= 1{,}202$

Per 3,652 m^3 = 4,389,700 Calories.

The 3,652 m^3 of gas comes into the laboratory of the furnace at 600°, and therefore carries in as sensible heat the following:

CO^2 $0.05 \times 0.502 = 0.0251$ Cal. per 1°

CH^4 $0.02 \times 0.512 = 0.0102$ " "

CO, N^2, H^2 $0.93 \times 0.319 = 0.2967$ " "

$0.3320 \times 600 = 199.2$ Cal.

Per 3,652 m^3 = $199.2 \times 3{,}652$ = 727,480 Calories.

This does not count, however, the water vapor accompanying the producer gas. This is best determined from the fact that the total hydrogen in the coal and steam used in the producer must appear as hydrogen in the producer gas in some form or other, and whatever is not present in the dry producer gas must be in the water vapor accompanying it. The amount of this and the heat it carries into the laboratory of the furnace are thus determined:

Hydrogen in 750 kg. coal = 750×0.0522 = 39.15 kg.

Hydrogen in steam used = $567 \div 9$ = 63.90 "

Hydrogen going into producer gases = 102.15 "

Hydrogen in dry producer gases, $3{,}652 \times 0.20 \times 0.09 =$ 65.74 "

Hydrogen in producer gas as vapor of water = 36.41 "

Water vapor in producer gas = 327.7 "

Volume of this vapor = 405 "

Heat in this at 600°, $405 \times 0.43 \times 600$ = 104,500 Cal.

Total heat in moist producer gas, $727{,}480 + 104{,}500$ = 831,980 "

We must also calculate the heat brought into the laboratory of the furnace by the preheated air, at 1,000°, used for combustion. This is

2,561 $m^3 \times 0.330 \times 1{,}000$ = 845,130 Calories.

It follows from the above calculations that the laboratory of the furnace receives per heat of steel:

		Calories.
From hot producer gas at 600°	=	831,980
From preheated air at 1,000°	=	845,130
From combustion	=	4,389,700
Total	=	6,066,810

Of this total there is rejected in the hot products at 1,400°, 3,816,400 Calories, leaving in the laboratory of the furnace 2,250,410 Calories.

According to the view of Damour and Queneau (Industrial Furnaces, page 56) the ratio of the heat thus left in the body of the furnace to the calorific power of the fuel used, measures the thermal efficiency of the furnace. According to that view this new style Siemen's furnace has an efficiency of

$$\frac{2,250,410}{5,647,400} = 0.400 = 40.0 \text{ per cent.}$$

This figure, however, is an illusive one. It enables us to compare two furnaces and see which regenerates the waste heat best, or which furnace laboratory is designed best so as to catch and retain most of the heat furnished to it; but the real question is the comparison of different laboratories as to their net melting efficiency. This laboratory abstracts from the heat supply furnished to it 2,250,410 Calories, and furnishes to the steel 900,000 Calories. Its proportion of usefully applied heat to heat appropriated is, therefore:

$$\frac{900,000}{2,250,410} = 0.400 = \mathbf{40.0} \text{ per cent.} \qquad (3)$$

The laboratory of the furnace therefore loses by radiation 60 per cent. of the heat which it abstracts from the gases, or 2,250,410 − 900,000 = 1,350,410 Calories. This is 24 per cent. of the calorific power of the coal used.

(4) The regenerators receive 3,816,400 Calories from the laboratory of the furnace, and return to it the heat in the preheated air at 1,000°, viz.: 845,130 Calories. If we call the ratio of these two the efficiency of the regenerators we have

$$\frac{845,130}{3,816,400} = 0.222 = 22.2 \text{ per cent.}$$

If, however, we charge them only with the heat actually left in them by the hot products, entering 1,400° and leaving at 350°, we have an efficiency of

$$\frac{845,130}{3,816,400-768,950} = 0.277 = 27.7 \text{ per cent.} \tag{4}$$

As long as the chimney gases are near in temperature to 300°, we can use the latter form of calculation as representing the real efficiency of the regenerator. The regenerators, therefore, lose by radiation and conduction to the air 2,202,320 Calories, which is 72.3 per cent. of the heat left in them by the hot gases and 39 per cent. of the calorific power of the coal used.

(5) The flame temperature is that to which the 6,066,810 Calories available in the laboratory of the furnace will raise the products of combustion. The average mean specific heat of the latter per 1° is:

$$\begin{array}{lll}
CO^2 & 986 \text{ m}^3\times(0.37 \ +0.00022t) = & 365+0.2169t \\
O^2+N^2 & 4,203 \text{ m}^3\times(0.303+0.000027t) = & 1,274+0.1135t \\
H^2O & 1,135 \text{ m}^3\times(0.34 \ +0.00015t) = & 386+0.703t \\
\hline
 & \text{Sum} = & 2,025+0.5008t
\end{array}$$

Therefore $$t = \frac{6,066,810}{2,025+0.5008t}$$

Whence $$t = 2,003 \tag{5}$$

Problem 75.

In an basic lined open-hearth furnace using the Monell process, 50 short tons of melted pig iron, at 1,300°, is run upon 30,000 pounds of Lake Superior iron ore (90 per cent. Fe^2O^3, 10 per cent. SiO^2) lying on the hearth and previously heated to 1,300°. There is 2,000 pounds of burnt lime lying on the ore to help to form slag. The ore reacted quickly, almost violently, on the melted pig iron, so that at the close of the reaction, in 20 minutes, the slag could be run off. The pig iron contained,

	On Running in.	*After the Reaction*
Carbon	3.50	3.00
Silicon	2.00	0.00
Phosphorus	0.75	0.00
Manganese	0.50	0.00
Iron	93.25	97.00

The oxidation of C, Si, P and Mn may be assumed as being produced first by reducing all Fe^2O^3 present to FeO, and completed by the reduction of *some* FeO to Fe. The carbon is assumed oxidized in the reaction to CO, although this CO may be subsequently partly burned to CO^2 by excess air in the furnace.

Required:

(1) The amount of iron reduced into the bath.

(2) The weight and percentage composition of the slag formed.

(3) The items of heat evolved and absorbed in the reaction.

Solution:

(1) We cannot make a simple, direct solution, because the weight of the metal after the reaction, analysis of which is given, is not known. The inexperienced calculator might be tempted to say that there was 3.50—3.00 = 0.50 per cent. of carbon oxidized, 2.00 per cent. of silicon, 0.75 per cent. of phosphorus and 0.50 per cent. of manganese, calculate the weights of these, reckon up the oxygen they would absorb in being oxidized, and thus get at the amount of Fe^2O^3 reduced to FeO and FeO reduced to Fe. This would be correct as far as silicon, manganese and phosphorus are concerned, because they are entirely oxidized, but incorrect for the weight of carbon, because the 3.00 per cent. not oxidized is per cent. of the final bath, which is of different weight from the original one, and, therefore, we are in error in subtracting 3.00 from 3.50. Being confronted with this dilemma we can see, however, that if we only knew the weight of the bath after the reaction we could calculate correctly how much carbon is in it, thence get the correct weight of carbon oxidized, then the correct amount of oxygen absorbed in the reaction, and from this the weight of iron reduced into the bath. We could also get the latter quantity more simply by finding the iron present in the bath

after the reaction (97 per cent.), and subtracting from it the iron in the original bath. We thus have two ways of getting the same requirement if we only know the weight of the bath. In such a case the mathematical key to the situation is, of course, to let X represent the weight of the bath, and work out the amount of iron reduced into the bath by the two methods, getting the result expressed in each case in terms of X. Since the two expressions represent the same quantity, we put them equal to each other and solve for X. Having obtained X, we substitute it in either expression and get the result asked for.

Let X be the weight of the bath after the reaction, in pounds; the bath before the reaction weighs 100,000 pounds.

Oxidized out:

Carbon (100,000 × 0.035)—X 0.03 = 3,500—0.03 X pounds.
Silicon 100,000 × 0.02 = 2,000 "
Phosphorus 100,000 × 0.0075 = 750 "
Manganese 100,000 × 0.005 = 500 "

Oxygen required:

For carbon (3,500—0.03 X) 16/12 = 4,677—0.04 X pounds.
For silicon 2,000 × 32/28 = 2,286 "
For phosphorus 750 × 80/62 = 968 "
For manganese 500 × 16/55 = 145 "

Sum = 8,076—0.04 X pounds.

Oxygen supplied:

If all Fe^2O^3 of ore (27,000 pounds) were reduced to FeO = 27,000 × 16/160 = 2,700 pounds.

If all Fe^2O^3 of ore were reduced to Fe 27,000 × 48/160 = 8,100 pounds.

We thus see that we will certainly require more oxygen than the Fe^2O^3 can give up in becoming all FeO, but not as much as would be given up if it all became Fe. If all the Fe^2O^3 were considered first reduced by the reaction to FeO, giving up 2,700 pounds of oxygen, the reaction will still require the furnishing of

(8,076—0.04 X)—2,700 = 5,376—0,04 X pounds.

of oxygen, which would have to be furnished by FeO becoming

Fe. In that reduction, however, 72 parts of FeO gives up 16 of oxygen in becoming 56 Fe. The reduced Fe will be, therefore, 56/16 of the weight of oxygen thus furnished, and therefore,

Reduced Fe = 56/16 (5,376—0.04 X) pounds.
= 18,816—0.14 X pounds.

The same quantity is obtained more directly as follows:

Fe in original bath 100,000 × 0.9325 = 93,250 pounds.
Fe in bath after reaction = 0.97 X pounds.
Therefore, Fe reduced = 0.97 X—93,250 lbs.

These two expressions represent the same thing, and, therefore,

18,816—0.14 X = 0.97 X—93,250
Whence X = 100,960

And the reduced iron = 0.97 X—93,250 = 4,681 pounds. (1)

(2) The ore used contains altogether

Fe = 27,000 × 112/160 = 18,900 lbs.
Fe reduced to metallic state = 4,681 "

Fe remaining in slag as FeO = 14,219 "
Weight of FeO = 14,219 × 72/56 = 18,282 " = 61.1 per cent.
Weight of P^2O^5 = 750 + 968 = 1,718 " = 5.7 "
Weight of MnO = 500 + 145 = 645 " = 2.1 "
Weight of CaO = 2,000 " = 6.7 "
Weight of SiO^2 = 3,000 + 4,286 = 7,286 " = 24.4 "

Total weight of slag = 29,931 " (2)

(3) The physical data available do not permit of calculating the actual heat of the reaction at 1,300°, since many of the specific heats needed are lacking. We will therefore foot up the items of heat evolution and absorption uncorrected for temperature, which is the only thing to be done under the circumstances.

	Heat Evolution.	*Calories*
Si to SiO^2	2,000 × 7,000	= 14,000,000
P to P^2O^5	750 × 5,892	= 4,419,000
Mn to MnO	500 × 1,653	= 826,500
C to CO	471 × 2,430	= 1,144,500
SiO^2 to FeO. SiO^2	7,286 × 144	= 1,049,200
CaO to 3CaO. P^2O^5	2,000 × 949	= 1,898,000
	Total	= 23,337,200

Heat Absorption.

			Calories.
Fe^2O^3 to FeO	18,900 × 573	=	10,829,700
FeO to Fe	4,681 × 1,173	=	5,490,800
Fe^3C to Fe^3+C	471 × 705 (?)	=	332,000 (?)
FeSi to Fe + Si	2,000 × 931 (??)	=	1,682,000 (??)
Fe^3P to Fe^3+P	750 × 1,400 (??)	=	1,050,000 (??)
	Sum	=	19,564,500

These calculations, therefore, show a minimum surplus of heat in the reaction of 23,337,200 − 19,564,500 = 3,772,700 Cal., an amount which would raise the temperature of the slag and resulting metal approximately 100° C. above the 1,300° at which the reacting materials came together. The quantity above marked (?) is a little doubtful in amount, but those marked (??) are very doubtful, perhaps may not exist at all. If these are omitted from the heat absorption the surplus heat is increased some 50 per cent. of its value, and the rise in temperature might be in the neighborhood of 150°. Further, some of the CO formed by the oxidation of carbon may be burned to CO^2 close to the surface of the bath, by free oxygen in the furnace, still further increasing the rise in temperature.

The conclusion from these calculations and discussions is that the pig iron and ore reaction in the Monell process is a heat evolving reaction, which, independently of the heating effect of the fuel used by the furnace, could increase the temperature of the contents of the furnace at least 100°, and possibly 150°. It would be highly interesting to have a typical heat such as this followed closely with a good reliable pyrometer, so as to check the indications of the thermochemical study of the process.

CHAPTER XII.

THE ELECTROMETALLURGY OF IRON AND STEEL.

Electrical methods may enter into the extraction of a metal from its ores either as electrolytic or as electrothermal processes. Electrolytic processes are those in which the electric current is used for its electrolytic action, *i.e.*, for its electrical decomposing and depositing properties; electrothermal processes are such as use the current merely as a source of heat, to furnish the sensible heat and high temperature necessary for melting materials or for bringing about chemical reactions. So far electrolytic processes have entered the metallurgy of iron only as used by Burgess for electrolytically refining nearly pure iron in an aqueous electrolyte and depositing chemically pure iron; the electrolysis of fused iron salts has not been practically utilized. Up to the present, electrothermal processes are in commercial use for melting together wrought iron and cast iron to make steel, also for keeping cast iron melted while its impurities are being extracted by oxidation; the electrothermal reduction of iron ores to cast iron has been proved technically possible, and may in some places prove commercially practicable.

ELECTROTHERMAL REDUCTION OF IRON ORES.

If the electric current is used to furnish the heat energy necessary to reduce iron ore, it cannot displace the reducing agent—carbon. In ordinary blast furnace practice the carbon is first burned to provide the heat necessary to smelt down the pig iron and slag, and the product of this incomplete combustion—CO—abstracts oxygen from the ore. The two equations are practically:

At the tuyeres—

$$30C + 15O^2 + 57.15\ N^2 = 30CO + 57.15\ N^2$$

Reduction:

$$4Fe^2O^3 + 30CO + 57.15\ N^2 = 12CO^2 + 18CO + 57.15\ N^2 + 8Fe$$

These equations show us that to produce 8Fe = 448 parts, 30C = 360 parts of carbon is the minimum necessary, which is first burned to CO at the tuyures, and then the producer gas thus formed (N^2 and CO) reduces the iron oxides above. If the heat for fusion is furnished electrically, the first combustion is unnecessary, all blowing in of air is dispensed with and the reaction taking place is:

$$14Fe^2O^3 + 30C = 12CO^2 + 18CO + 28Fe$$

And we have 28Fe = 1,568 parts reduced by 30C = 360 parts, a consumption of less than one-third as much carbon as is required in the blast furnace. The operation consists, therefore, in mixing iron ore and carbon so that for every part of iron present about 0.25 parts of carbon is present, using the proper quantity of limestone or other material to flux the gangue of the ore to a fusible slag, and then furnishing electrically the heat necessary to cause the chemical reaction, melt down the resulting iron and slag, and supply radiation losses. The gases resulting from this electrical reduction are combustible, just as the gases from the blast furnace, and since there is no blast to be heated they can very well be utilized to preheat the charges coming into the furnace, and thus save some of the electrical energy needed.

Problem 76.

A magnetite ore contains:

	Per Cent.		*Per Cent.*
Fe^2O^3	60.74	MgO	5.50
FeO	17.18	P^2O^5	0.04
SiO^2	6.60	S	0.57
Al^2O^3	1.48	CO^2	2.05
CaO	2.84	H^2O	3.00

It is to be mixed with pure carbon (charcoal fines) and a suitable flux; the fixed carbon being 0.25 per cent. of the iron present; the flux silica sand, so as to make a slag with 33 per cent. of SiO^2. Neglect the ash and assume 10 per cent. of moisture in the charcoal. Assume also:

(*a*) The pig iron to contain 4 per cent. C, 3.5 per cent. Si, 92.4 per cent. Fe.

(*b*) The slag and pig iron to contain at tapping 600 and 400 Calories of heat respectively.

(*c*) The heat losses by radiation, etc., to be 30 per cent. of the total heat requirement of the furnace.

(*d*) The hot gases to escape at 300° C.

(*e*) The iron to be completely reduced into the pig iron.

(*f*) The sulphur to go entirely into the slag as CaS.

Requirements:

(1) The weights of ore, flux and charcoal dust needed per 1,000 kg. of pig iron produced.

(2) A balance sheet of materials entering and leaving the furnace.

(3) A heat balance sheet of the furnace.

(4) The number of kilowatt days of electrical energy required per metric ton of pig iron produced.

Solution:

(1) The ore must supply 924 kg. of iron. But 100 parts of ore contains iron as follows:

Kg.

In Fe^2O^3 $60.74 \times 112/160 = 42.52$

In FeO $17.18 \times 56/72 = 13.36$

Sum = 55.88 (1)

Ore required per 1,000 kg. of pig iron:

$924 \div 0.5588 =$ **1,654** kg.

The slag-forming ingredients from this amount of ore are as follows:

Kg.

Al^2O^3 $1{,}654 \times 0.0148 = 24.6$

MgO $1{,}654 \times 0.0550 = 91.0$

CaO $1{,}654 \times (0.0284 - 0.0057 \times 56/32)$

$= 1{,}654 \times 0.0184 = 30.4$

SiO^2 $(1{,}654 \times 0.0660) - (35 \times 60/28) = 109.2 - 75 = 34.2$

CaS $1{,}654 \times (0.0057 \times 72/32) = 21.2$

Sum = 201.4

If x parts of SiO^2 sand are added to these, the total weight of slag will be $201.4+x$, of SiO^2 in it $34.2+x$. And since the SiO^2 is to be 33 per cent. of the weight of slag, then

$$34.2+x = 0.33\ (201.4+x)$$

Whence $$x = 48 \text{ kg.} \tag{1}$$

The charcoal dust used must contain fixed carbon equal to 0.25 of the iron present, *i. e.*,

$$924\times 0.25 = 231 \text{ kg.}$$

And since it is 90 per cent. fixed carbon the dust required is:

$$231\div 0.90 = \mathbf{257} \text{ kg.}$$

Charges.	*Pig Iron.*	*Slag.*	*Gases.*
Ore.......**1654** Kg.			
Fe^2O^3.......1004.6	Fe.......703.2		O......301.4
FeO..........284.2	Fe.......221.0		O.......63.2
SiO^2..........109.2	Si.........35.0	SiO_2.......34.2	O.......40.0
Al^2O^3.........24.6		Al_2O_3.....24.6	
CaO...........46.9		CaO.......30.4	O........4.7
MgO..........91.0		MgO......91.0	
P^2O^5...........0.6	P..........0.3	Ca........11.8	O........0.3
S..............9.4		S..........9.4	
CO_2...........33.9			CO_2.....33.9
H^2O...........49.6			H_2O.....49.6
Flux.........**48** Kg.			
SiO^2..........48.0		SiO_2.......48.0	
Charcoal....**257** Kg.			
C............231.0	C.........40.0		C......191.0
H^2O..........26.0			H_2O.....26.0
1959.0	999.5	249.4	118.1

(3) Heat available is the heat of oxidation of carbon plus that furnished by the electric current. The charge gives up to the carbon, as shown on the balance sheet, $301.4+63.2+40.0+4.7+0.3 = 409.6$ kg. of oxygen. The 191 kg. of carbon burned would take $191\times 16/12 = 254.7$ kg. of oxygen to burn it to CO, leaving 154.9 kg. of oxygen to burn CO to CO^2. This would burn $154.9\times 28/16 = 271.1$ kg. of CO to CO^2.

The heat of formation of the slag may be taken as approximately 150 Calories per kg. of contained $SiO^2+Al^2O^3$. The heat of combination of carbon with the iron is a doubtful quantity, which may be taken at 705 Calories per kilogram of carbon. The formation of CaS gives 2,947 Calories per kilogram of sulphur.

Letting the heat furnished by the electric current = x, and neglecting the heat of oxidation of the small amount of electrode carbon consumed, we have:

Heat Available.

		Calories.
Supplied by electric current:		x
Oxidation of C to CO	191×2,430 =	464,130
Oxidation of CO to CO^2	271.1×2,430 =	658,770
Formation of silicate slag	106.8× 150 =	16,020
Formation of CaS	9.4×2,947 =	27,700
Formation of Fe^3C	40. × 705 =	28,200
	Sum =	1,194,820+x

Heat Distribution.

		Calories.
Reduction of Fe from Fe^2O^3		
703.2×1,746		= 1,229,790
Reduction of Fe from FeO		
221.0×1,173		= 259,230
Reduction of Si from SiO^2		
35.0×7,000		= 245,000
Reduction of P from P^2O^5		
0.3×5,892		= 1,770
Reduction of Ca from CaO		
11.8×3,288		= 38,800
Expulsion of CO^2 from ore		
33.9×1,026		= 34,780
Evaporation of H^2O from charges		
75.6×606.5		= 45,850
Sensible heat in gases, at 300°		
CO 174.6 kg. = 138 m³		
×0.311	= 42.9	

CO^2 459.9 kg. = 232 m^3
× 0.436 = 101.1
H^2O 75.6 kg. = 93 m^3
× 0.385 = 35.8

179.8 × 300 = 53,940
Sensible heat in slag 249.4 × 600 = 149,640
Sensible heat in pig iron 1,000 × 400 = 400,000
Loss by radiation, etc., 0.30 $(1,194,820 + x)$ = $358,450 + 0.3x$

Sum total = $2,817,250 + 0.3x$

Equating the heat available and accounted for we have:

$$1,194,820 + x = 2,817,250 + 0.3\,x.$$

Whence $$x = 2,317,760 \text{ Calories.}$$

And the sum total of heat requirement is

3,512,580 Calories,

of which the electric current supplies

$$\frac{2,317,760}{3,512,580} = 0.66 = \mathbf{66} \text{ per cent.} \qquad (3)$$

(4) A kilowatt-day of electricity is equal to

$$0.239 \times 60 \times 60 \times 24 = 20,650 \text{ Calories.}$$

There is, therefore, required per ton of pig iron produced:

$$\frac{2,317,760}{20,650} = \mathbf{112} \text{ kilowatt days.} \qquad (4)$$

This figure might be materially reduced by using the waste gases to warm up the charges entering the furnace. It is also possible that in a properly designed shaft the gases passing out might contain nearly equal volumes of CO and CO^2, instead of 3CO to 2CO, as assumed in this problem, from best ordinary blast furnace practice. Any greater utilization of the heat-producing power of the carbon would decrease the electrical energy required; the above calculated value is given as a safe figure for this ore on which to base working calculations.

Problem 77.

At Sault Sainte Marie, Canada, roasted pyrrhotite ore was smelted with the addition of limestone and charcoal fines. The mixture used contained 400 pounds of ore, 110 pounds charcoal dust and 85 pounds limestone. The analyses of each of these materials was:

Roasted Ore.		*Limestone.*		*Charcoal Dust.*	
$Fe^{2}O^{3}$	65.43	CaO	52.00	Fixed C	55.90
CuO	0.51	MgO	2.10	Vol. matter	28.08
NiO	2.84	$Fe^{2}O^{3}$	0.60	Moisture	13.48
SiO^{2}	10.96	$Al^{2}O^{3}$	0.21	Ash	2.54
$Al^{2}O^{3}$	3.31	SiO^{2}	1.71		
CaO	3.92	$P^{2}O^{5}$	0.01		
MgO	3.53	SO^{3}	0.13		
SO^{3}	3.90	CO^{2}	43.15		
$P^{2}O^{5}$	0.03				
$H^{2}O$	5.57				

Using 165.65 kilowatts effective electric energy for 56 hours 20 minutes, there was produced 7,336 pounds of nickeliferous pig iron and 5,062 pounds of slag, having the following average compositions:

	Pig Iron.		*Slag.*
C	3.05	SiO^{2}	16.44
Si	5.24	$Al^{2}O^{3}$	13.86
S	0.01	CaO	42.87
P	0.05	MgO	8.80
Cu	0.81	CaS	13.34
Ni	3.94	FeO	0.84
Fe	86.90	Undetermined	3.85

Requirements:

(1) A balance sheet of materials entering and leaving the furnace.

(2) A heat balance sheet of the furnace, making necessary assumptions where data is not furnished.

(3) The thermal efficiency of the furnace.

Solution:

(1) The amount of ore used may be calculated either from the iron, the nickel or the copper. The nickel and copper are the easiest to use, because there is supposed to be none of

them in the slag, but they are the least reliable, because present in such small amount. The pig-metal contains 7,336×0.81 = 59.4 pounds of copper, and since the roasted ore contains 0.51 $\times\frac{63.6}{79.6}$ = 0.41 per cent. copper, the weight of ore used, on this basis, would be 59.4÷0.0041 = 14,493 pounds. As for nickel, the pig-metal contains 7,336×0.0394 = 289 pounds of nickel, and since the roasted ore contained $2.84\times\frac{59}{75} = 2.23$ per cent., the weight of this used should have been 289÷0.0223 = 12,960 pounds. These figures differ so much that we will make the calculation on the basis of the iron. There is iron present as follows:

	Pounds.
In the pig iron 7,336×0.8690	= 6,375
In the slag 5.062×0.0084×56/72	= 33
Total in products	= 6,408
In 100 pounds of ore 65.43×0.7	= 45.80
In 21 pounds limestone 21.×0.0060×0.7	= .08
In 27.5 pounds of charcoal 27.50 × 0.0025 ×0.7	= .04
In charge, per 100 pounds of ore used	= 45.92

Therefore, ore necessary to supply the iron in products:

	Pounds.
6,408÷0.459	= 13,961
with which will be used:	
Charcoal = 13,961×110/400	= 3,839
Limestone = 13,961×85/400	= 2,967

We are now ready to construct the balance sheet as soon as we assume probable values for the composition of the volatile matter and ash of the charcoal. The ash might be taken as containing on an average: K^2O 15 per cent., CaO 40, MgO 20, MnO 15, and Fe^2O^3 10 per cent. The volatile matter is due to insufficient charring, and the gases given off on heating may be assumed as, by volume, CO^2 25 per cent., CO 15, H^2

50, CH^4 10. This would make the volatile matter to contain, in per cents. by weight, carbon 33.7, oxygen 58.5, hydrogen 7.8 per cent. (The verification of this last statement is a nice little exercise in chemical arithmetic.) The full statement of the elementary composition of the charcoal, for use in making the balance sheet, is therefore:

	Per Cent.	
Fixed carbon	55.90	
Volatile carbon	9.46	28.08%
Volatile hydrogen	2.19	
Volatile oxygen	16.43	
Moisture	13.48	
K^2O	0.38	2.54%
CaO	1.02	
MgO	0.51	
MnO	0.38	
Fe^2O^3	0.25	

Balance Sheet, per 7,336 *Lbs. Pig-metal.*

Charges.		*Pig-metal.*	*Slag.*	*Gases.*
Roasted Ore.	**13,961**			
Fe^2O^3	9,135	Fe 6,375	FeO 25	O 2,375
NiO	397	Ni 289	NiO 28	O 80
CuO	71	Cu 59		O 12
SiO^2	1,530	Si 384	SiO^2 1,091	O 55
Al^2O^3	461		Al^2O^3 461	
CaO	547		CaO 166	O 109
MgO	493		MgO 493	
SO^3	545	S 1	CaS 490	O 327
P^2O^5	4	P 4		O 0
H^2O	778			H^2O 778
Limestone	**2,967**			
CaO	1,543		CaO 1,542	O 0
MgO	62		MgO 62	
Fe^2O^3	18		FeO 16	O 2
Al^2O^3	6		Al^2O^3 6	
SiO^2	51		SiO^2 51	
P^2O^5	0		P^2O^5 0	
SO^3	4		CaS 4	
CO^2	1,280			CO 1280
Charcoal dust	**3,839**			

Fixed C	2,146	C 224		C 1,922
Vol. C	363			C 363
Vol. H	84			H 84
Vol. O	631			O 631
H^2O	518			H_2O 518
K^2O	15		K^2O 15	
CaO	39		CaO 39	
MgO	20		MgO 20	
MnO	15		MnO 15	
Fe^2O^3	10		FeO 9	O 1
Electrode	**66**			
C	66			C 66
	20.828	7,336	4,533	8,962

There is a lack of close correspondence between the weights and compositions of slag, as observed and as calculated, due evidently to inaccurate sampling and analyses of the roasted ore and slag.

(2) From the balance sheet we can deduce the heat evolved and absorbed in the chemical reactions in the furnace. The more involved items are calculated as follows:

Oxidation of carbon to CO: All the carbon put into the furnace as fixed carbon goes out as either CO or CO^2, except that going into the pig iron. The carbon burnt to CO in the furnace may be, therefore, taken as $1,922+66 = 1,988$ pounds, evolving $1,988 \times 2,430 = 4,830,800$ pound-Calories.

Oxidation of CO to CO^2: There is given up in the furnace, by the reductions accomplished, 3,021 pounds of oxygen, of which $1,988 \times 16/12 = 2,651$ pounds would burn fixed carbon to CO, as above shown, leaving 370 pounds to burn CO to CO^2. This would oxidize $370 \times 28/16 = 648$ pounds of CO to CO^2, which would evolve $648 \times 2,430 = 1,574,300$ pound-Calories.

Heat energy of electric current: One kilowatt-second is 0.239 kilogram Calories, or 0.527 pound-Calories. The current being on 56 hours, 20 minutes, or 202,800 seconds, the heat equivalent of the current used is:

$$0.527 \times 202,800 \times 165.65 = 17,704,000 \text{ pound-Calories.}$$

Heat in escaping gases: We are here confronted with the fact that no observation of the temperature of these was given.

There is no essential reason why they should escape very hot from the furnace, if properly run and conducted, so we will assume a maximum temperature of 500° C. The gases would consist of 0,958 + 2,651 − 648 = 4,061 pounds of CO and 648 + 370 = 1,018 pounds of CO^2, from the oxidation of fixed carbon in the furnace; plus 1,280 of CO^2 from the limestone, and 666 pounds CO^2, 254 pounds CO, 97 pounds CH^4 and 60 pounds of H^2 from the volatile matter of the charcoal. To these must be added 1,290 pounds of water vapor. The heat is therefore

CO	4,315 lbs.	= 54,800 ft^3 × 0.304	= 16,650	oz. Cal.	
CO^2	2,964 lbs.	= 23,950 ft^3 × 0.480	= 11,500	"	
CH^4	97 lbs.	= 2,150 ft^3 × 0.490	= 1,050	"	
H^2	60 lbs.	= 10,700 ft^3 × 0.304	= 3,250	"	
H^2O	1,290 lbs.	= 25,500 ft^3 × 0.415	= 10,550	"	
	Sum	= 117,100 ft^3	43,000	"	per 1°
			= 21,500,000	"	per 500
			= 1,343,750	lb.-Cal.	

The other items of the heat balance sheet are almost self-explanatory, and the complete balance is as follows:

Heat Available.

	Pound-Cal.
Energy of the electric current	= 17,704,000
Oxidation of C to CO	= 4,830,800
Oxidation of CO to CO^2	= 1,574,600
Combination of C with Fe^3 224×705	= 157,900
Combination of Ca with S 220×2,947	= 648,300
Formation of silico-aluminate slag ($SiO^2 + Al^2O^3$) 1 609×150	= 241,400
Total	= 25,157,000

Heat Distribution.

Reductions:		
Fe^2O^3 to Fe	6,375×1,746 =	11,130,750
NiO to Ni	289×1,051 =	303,750
CuO to Cu	59× 593 =	35,000
SiO^2 to Si	384×7,000 =	2,688,000
SO^3 to S	218×2,872 =	626,100
P^2O^5 to P	4×5,892 =	23,550
CaO to Ca	274×3,288 =	900,900
Fe^2O^3 to FeO	50× 446 =	22,300

Expulsion of CO^2 from flux:	1,280×1,026 =	1,313,300
Evaporation of H^2O	1,290×606.5 =	783,400
Sensible heat in gases	=	1,343,750
Sensible heat in pig iron	7,336× 400 =	2,934,400
Heat in slag	4,533× 600 =	2,719,800
Loss by radiation, conduction, etc.	=	332,000
	Total =	25,157,000 (2)

(3) The essential work done by the furnace is the reductions, evaporation of moisture and decomposition of carbonates. The heat in slag, iron, gases and radiation loss are all susceptible of diminution or of being more or less returnable to the furnace. The usefully applied heat is, therefore, 17,827,050 pound-Calories. To produce this there was consumed the 25,157,000 pound-Calories actually generated, and there was wasted 13,390,000 pound-Calories, the calorific power of the gases escaping from the furnace, which should have been generated or might be utilized, making a total of 38,527,000 pound-Calories disposable.

The working thermal efficiency over all was therefore:

$$\frac{17,827,050}{38,527,000} = 0.46 = \mathbf{46} \text{ per cent.} \qquad (3)$$

PRODUCTION OF STEEL.

There are three methods of producing steel electrically which are practicable. First, the electric furnace may replace the crucible simply as a melting apparatus, in producing a cast steel from cemented bars; second, the electric furnace may replace the crucible or open-hearth furnace as an apparatus in which to melt together wrought iron and pure cast iron, such as washed pig metal, although in this operation, the electric furnace is more like the crucible method, in that there is not necessarily any oxidation of the metal or of its impurities in the operation; third, the electric furnace may be used to melt or keep melted cast iron, while its impurities are oxidized out by additions of iron ore, in this operation resembling the Uchatius method of making crucible steel or the "pig and ore" process of making steel in the open-hearth furnace.

The particular advantages possessed by the electric furnace processes are, compared with the crucible process, the larger quantities in which the steel can be made in one operation, the absence of carbon in the furnace lining, thus controlling better the carbon and silicon in the steel, and the higher temperature enabling a more basic slag to be kept fluid and the sulphur to be better eliminated; the advantages compared with the open-hearth furnace are the absence of gases of combustion in contact with the metal, and the higher temperature available, which permits of very basic, refractory slags being made and kept thinly fluid, and thus gives better control of sulphur and phosphorus. In addition to these, in both cases, may be mentioned the commercial advantages, for the saving in crucibles alone makes the electric furnace superior in this respect to the crucible process, and the electric furnace can compete successfully as regards cost with the regenerative open-hearth furnace wherever water power costs less than $10.00 per horse-power-year and coal costs over $5.00 per ton.

A particular point to be noted is, that when heating by combustion is used the efficiency of the absorption of heat by the charges decreases very rapidly as the temperature gets higher. For instance, if a cold ingot of iron is placed in a furnace the temperature of which is 1,500°, the iron absorbs heat with very great rapidity from the start up to, say, 1,000°; but with decreasing rapidity thereafter. The rate of transfer of heat from the gases to the iron is proportional to the difference of temperature, and is some fifteen times as fast when the iron is at 0° as when it is at 1,400°. If the efficiency of the heating by furnace gases is, say, 25 per cent. in bringing metal up to 1,500°, it is likely that the distribution of this efficiency is proportioned about as follows:

Heating from 0° to 500°..............45 per cent. efficiency.
Heating from 500° to 1,000°..........27 per cent. efficiency.
Heating from 1,000° to 1,500°........ 3 per cent. efficiency.

On the other hand, the conversion of electrical energy into heat in the substance of the material to be heated is not a contact or transfer phenomenon, but a thermodynamically frictionless transfer of 100 per cent. efficiency, and equally so at the highest as at the lowest temperatures. Only radiation and conduction losses need be considered, the problem is not how much heat can you *get* into a body but how much can you *keep* in; it is already all in, 100 per cent. of it, to start with. In a large, properly designed electric furnace the radiation and conduction losses of heat, even working to the highest temperatures, can be kept at 15 to 25 per cent. of the total heat generated, giving an efficiency of 75 to 85 per cent.

It may very well be, that there are places where the relative prices of coal and electric power are such that coal is the cheaper for heating to 500°, at 45 per cent, efficiency, or to 1,000° at 36 per cent. efficiency, or even to 1,500°, at 25 per cent. efficiency, but that the combination of heating by fuel to 1,000° at 36 per cent. efficiency and then by electricity from 1,000° to 1,500°, at 70 per cent. efficiency, would be the cheaper plan, or even by fuel to 500°, at 45 per cent. efficiency, and then by electricity from 500° to 1,500°, at, say, 75 per cent. efficiency, would be commercially advantageous.

Illustration: Steel bars are to be melted in an electrical furnace. It takes 300 Calories effective in the steel per kilogram to heat it to a tapping heat; the electric furnace supplies this at a net thermal efficiency of 75 per cent. To heat the bars to 750°, cherry red, without melting them, requires, 88 Calories, or 29 per cent. of the total. If the bars were heated in a coal furnace to 750°, and then transferred to the electric furnace, some 25 per cent. of the electrical power might be saved. If this heating were done by coal having a calorific power of 8,500, at a thermal efficiency of 25 per cent., there would be needed 40 grams of coal. The question is, therefore, the relative cost of $88 \div 0.75 = 117$ Calories delivered electrically, and 40 grams of coal. The former requires $117 \div 0.239 = 490$ kilowatt-seconds = 8.2 kilowatt-minutes = 0.14 kilowatt-hours. At $10.00 per kilowatt-year (8,760 hours) this would cost $0.14 \times 0.114 = 0.016$ cents. At $5.00 per metric ton the coal would cost $0.040 \times 0.5 = 0.020$ cent. Under such assumed conditions of cost of power and of coal the electrical heating, even up to 750°, would be the cheaper.

Problem 78.

In an induction electric furnace of 170 kilowatts capacity, 4.7 tons of steel is made per day by melting together cold-washed pig iron and scrap iron, the melted steel carrying 350 Calories per kilogram.

Required:

(1) The electric energy in kilowatt hours required per ton of steel produced.

(2) The thermal efficiency of the furnace.

(3) If one-third the material used were put into the furnace melted, carrying 275 Calories per kilogram, what would be the production per day and the power required per ton of steel?

Solution:

(1) Energy for 4.7 tons = 170 kw-days.
Energy for 1.0 ton = 36.2 "
Energy for 1.0 ton = 0.10 kw-year
Energy for 1.0 ton = **869** kw-hours. (1)

(2) 1 kw-hour = $0.239\times 60\times 60$ = 860 Calories
869 kw-hours = 747,340 "
Heat in 1 ton of steel = $350\times 1{,}000$ = 350,000 "

$$\text{Thermal efficiency} = \frac{350{,}000}{747{,}340} = 0.47 = \mathbf{47}\text{ per cent.} \qquad (2)$$

(3) Heat in melted material used per kilogram of steel produced = $275\times 1/3$ = 92 Calories.

Heat to be supplied by the current $350 - 92 = 258$ Calories.

Production per day under these conditions:

$$4.7\times\frac{350}{258} = \mathbf{6.4}\text{ tons.} \qquad (3)$$

Relative times for the heats = 1 to 0.74.

Energy required per ton = $170\div 6.4$ = 26.6 kw-days.
= 0.07 kw-year.
= **638** kw-hours. (3)

Problem 79.

An electric steel furnace running at full heat, and containing about 2,500 kg. of steel, loses by radiation, etc., 250,000 Calories per hour; 2,500 kg. of melted pig iron is run into the hot furnace, carrying 250 Calories per kilogram, and it is treated with 500 kg. of iron ore, previously heated to 500° C., and 50 kg. of limestone added cold. The steel produced carries 400 Calories per kilogram and the slag 600 Calories. The operation lasts 1 hour. Assume the following composition of materials used and made:

Pig Iron.		*Iron Ore.*		*Limestone.*		*Steel.*	
Fe	96.656	Fe_2O_3	85.93	CaO	53.74	Fe	99.60
C	2.700	FeO	3.96	MgO	0.17	C	0.11
Si	0.600	SiO_2	5.50	SiO_2	3.14	Si	0.11
Mn	0.025	MnO	0.63	Fe_2O_3	0.18	Mn	0.15
S	0.007	Al_2O_3	0.76	Al_2O_3	0.32	S	0.02
P	0.012	CaO	2.23	P_2O_5	0.006	P	0.01
		MgO	0.97	S	0.001		

The bath was treated by the final addition of 10 kg. of cold ferro-manganese, carrying 80 manganese, 16 iron and 4 carbon. The steel obtained weighed 2,630 kg.

Required:

(1) A balance sheet of materials entering and leaving the furnace.

(2) The weight and percentage composition of the slag.

(3) A balance sheet of the heat received and distributed.

(4) The net power required to run the furnaces and the cost of power per ton of steel made, at $25.00 per kilowatt-year.

Balance Sheet.

Charges.		*Steel.*	*Slag.*		*Gases.*	
Pig Iron....(2500 Kg.)						
Fe	2416.4	2416.4				
C	67.5	2.5			C	65.0
Si	15.0	2.9	SiO^2	24.9		
Mn	0.6	......	MnO	0.8		
S	0.2	0.5				
P	0.3	0.3				
Ore...........(500 Kg.)						
Fe^2O^3	429.7	203.1	FeO	125.6	O	87.2
FeO	19.8	......	FeO	19.8		
SiO^2	27.5	......	SiO^2	27.5		
MnO	3.2	......	MnO	3.2		
Al^2O^3	3.8	......	Al^2O^3	3.8		
CaO	11.2	......	CaO	11.2		
MgO	4.8	......	MgO	4.8		

Limestone.......(50 Kg.)				
CaO..........	26.9	......	CaO........ 26.9	....
MgO..........	0.1	......	MgO....... 0.1	....
SiO^2..........	1.6	......	SiO^2........ 1.6	....
Fe^2O^3.........	0.1	......	FeO........ 0.1	....
Al^2O^3.........	0.2	......	Al^2O^3....... 0.2	....
CO^2..........	21.2	......	....	CO_2........ 21.2
Ferro-manganese (10 Kg.)				
Fe............	1.6	1.6	....	....
C.............	0.4	0.4	....	....
Mn............	8.0	3.9	MnO....... 5.3	....
	3060.0	2631.6	255.8	173.4

(2) The slag contains:

		Per Cent.	
SiO^2......................	54.0 pounds	= 21.1	
Al^2O^3......................	4.0 "	= 1.5	
CaO......................	38.1 "	= 14.9	
MgO......................	4.9 "	= 1.9	
FeO......................	145.5 "	= 56.9	
MnO......................	9.3 "	= 3.6	
	255.8 "	= 99.9	(2)

Heat Available.

		Calories.
Electric current:		x
Oxidation of C to CO	65.0×2,430 =	157,950
Oxidation of CO to CO^2	0.9×2,430 =	2,190
Oxidation of Si to SiO^2	12.1×7,000 =	84,700
Oxidation of Mn to MnO	4.7×1,653 =	7,770
Formation of slag	22.6× 150 =	3,390
Heat in melted pig iron	2,500× 250 =	625,000
Heat in iron ore	500× 77 =	38,500
	Sum =	$x+919{,}500$

Heat Distribution.

		Calories
Heat in melted steel	2,630× 400 =	1,052,000
Heat in melted slag	256× 600 =	153,600
Reduction of Fe^2O^3 to FeO	386.7× 446 =	172,470

Reduction of FeO to Fe	$203.1 \times 1,173 =$	238,240
Separation of carbon from iron	$65 \times 705 =$	45,800
Heat in gas at 1,500°:		
$CO = 151.7$ kg. $= 120.4$ m$^3 \times 0.32 \times 500$	=	19,260
$CO^2 = 1.4$ kg. $= 0.7$ m$^3 \times 0.60 \times 500$	=	200
Loss by radiation, etc.	=	250,000
	Total =	1,931,570

Heat to be supplied by current:

$$x = 1,931,570 - 919,500 = 1,012,070 \text{ Calories.} \qquad (3)$$

(4) One kilowatt furnishes per hour 860 Calories, therefore the power required to run the furnace is:

$$1,012,070 \div 860 = 1,177 \text{ kilowatts.} \qquad (4)$$

At $25.00 per kilowatt-year a kilowatt-hour would cost

$$\$25.00 \div 8,760 = 0.2854 \text{ cents.}$$

And the power to run the furnace 1 hour would cost

$$0.002854 \times 1,177 = \$3.36.$$

And the cost per ton of steel:

$$\$3.36 \div 2.630 = \mathbf{\$1.32}.$$

4)

Problem 80.

It is desired to design a plant for the electro-deposition of pure iron by the Burgess process (see Transactions American Electrochemical Society, Vol. V., p. 201). The desiderata and data are as follows:

Output, 25 metric tons per day.

Current density, 110 amps. per square meter.

Anodes, 0.75×0.5 meters immersed ×3m.m. thick.

Cathodes, 0.75×0.5 meters immersed ×1 m.m. thick at starting.

Cathodes to be run until deposit is 1.5 c.m. thick on each side.

Anodes run until 0.9 consumed.

Tanks, 1.00 meter deep, 0.6 m. wide, 2 m. long inside, filled to within 0.10 meter of top with electrolyte.

Working distance between anode and cathode 6 centimeters at starting.

Electrolyte contains 10 per cent. $FeSO^4 . 7H^2O$, and 5 per cent. $(NH^4)^2SO^4$, specific gravity 1.1, electrical resistivity 20 ohms per centimeter cube.

Voltage *drop* in connections and conducting rods 0.3 volt per tank.

Main conductors carry 2 amps. per m.m. square of section.

Net cost of electrical power, $25.00 per kilowatt-year.

Requirements:

(1) The number of anodes and cathodes per tank and the number of tanks in the plant and their arrangement.

(2) The weight of anodes and cathode sheets, increasing the weight of immersed part 10 per cent. Specific gravity of the rolled iron 7.9

(3) The weight of ferrous sulphate and ammonium sulphate required to start the plant.

(4) The drop of potential across the electrodes at starting and at the close of a deposition; the drop of potential per tank; the total voltage needed at starting the plant and when it is in regular operation.

(5) The cross sectional area of the main conductors.

(6) The time required to consume an anode plate, *i. e.*, in dissolving iron away equal to 0.9 of its weight.

(7) The time required to deposit a full cathode plate; specific gravity of the deposit 7.6

(8) The electric power required to run the plant and its cost per ton of iron deposited.

Solution:

(1) 110 amps. per square-meter deposits per day:

$$0.00001036 \times 110 \times \frac{56}{2} \times 60 \times 60 \times 24 = 2{,}757 \overset{\text{kg}}{\text{grams}} \text{ Fe.}$$

Therefore, depositing surface required:

$$25{,}000 \div 2{,}757 = 9{,}140 \text{ square meters.}$$

Since one cathode plate has a depositing area on both sides of $0.75 \times 0.5 \times 2 = 0.75$ square meter, the number of cathode plates required in the whole plant is:

$$9{,}140 \div 0.75 = 12{,}187$$

In one tank, if there are x cathodes and $x+1$ anodes, the thickness of these plates at starting is, in millimeters, $x+3(x+1) = 4x+3$ m.m. The number of spaces between anodes and cathodes being $2x$, and each of these being 6 c.m. = 60 m m. at starting, the spaces are $120x$ m.m. The length of the tank being, inside, 2,000 m.m.:

$$124x+3 = 2{,}000$$

whence

$$x = 16.1.$$

Each tank will therefore contain 16 cathodes and 17 anodes, at a distance apart, at starting of

$$\frac{2{,}000-16-3\,(17)}{2\,(16)} = 60.4 \text{ m.m.} = \mathbf{6.04} \text{ c.m.} \qquad (1)$$

Since we need 12,187 cathode plates we need

$$12{,}187 \div 16 = 761.7 \text{ tanks}$$

Which means that we would use **762** tanks. (1)

The arrangement of the tanks in series and groups of series can be best discussed when we know the voltage drop per tank, grouping them so as to absorb either 110 or 220 volts per series in one group.

(2) An anode sheet weighs:

$$75\times50\times0.3\times7.9\times1.1 = 9{,}776 \text{ grams,}$$ kg

of which there is immersed 8,888 grams.

The 17 anodes per tank weigh altogether:

$$9.776\times17 = 166.2 \text{ kg.,}$$

and the 16 cathodes, which are one-third as thick:

$$3.259\times16 = 521.1 \text{ kg.}$$

In the whole plant, at starting, the weights will be:

Anode sheets	166.2×762 = **126,644** kg.	
Cathode sheets	52.1×762 = **39,700** "	(2)

(3) Volume of liquid in tank:

$$(1-0.1)\times0.6\times2 = 1.08 \text{ cubic meters.}$$

Weight of solution per tank:		
0.18×1,000×1.1	= 1,188 kg.	
Weight of dissolved salts:		
Copperas	= 118.8 "	
Ammonium sulphate	= 59.4 "	
Weight in the whole plant:		
Copperas	= **90.5** tons.	
Ammonium sulphate	= **45.3** "	(3)

(4) At starting the surface of the electrodes are 6.04 c.m. apart, and 110 amps. passes through each square meter of electrode surface; therefore, 110×0.375 = 41.25 amps. pass from each free side of each anode plate to the corresponding side of a cathode plate. Neglecting the small cross sectional area of electrolyte outside the plates, the resistance of each space would be

$$\frac{20\times 6.04}{75\times 50} = 0.322 \text{ ohms,}$$

and the drop of voltage across two electrodes:

$$0.0322\times 41.25 = \mathbf{1.33} \text{ volts.}$$

If we take into account the 5 c.m. free space at the sides of each electrode, and allow an equal amount as effective beneath, the cross-section of the electrolyte may be taken as

$$(75+5)\times(50+10) = 4{,}800 \text{ c.m}^2.,$$

and the resistance between two plates:

$$20\times 6.04 \div 4.800 = 0.0252 \text{ ohms,}$$

and the drop $$0.0252\times 41.25 = \mathbf{1.04} \text{ volts.}$$

This value is the more probable one of the two.

At the close of a deposition, neglecting the decreased thickness of the thin anode plates, the working distance is decreased by 1.5×2 = 3 centimeters, and the voltage drop between plates will then be:

Blech!
zwischen
2 Elektr

$$\frac{20\times 3.04}{4{,}800}\times 41.25 = \mathbf{0.52} \text{ volt.}$$

nur 6.04 − 1.5

$$\frac{20 \times 4.54}{4800} \times 41.25$$

= 0.78

In both cases the voltage drop in contacts and conductors being 0.3 volt, the working voltage per tank will be:

	Volts.
At starting	1.34
At end	0.82
Average	1.08

The voltage needed at the generators can only be calculated when we assume a plan of grouping the 762 tanks. If we assume 110 volts to be desired at the generators, we could run 102 tanks in one series, which would give 7½ series. If we used 220 volts at the generators 2 series of 190 cells and 2 of 191 would absorb at starting 255 and 256 volts respectively, but when in regular running, with tanks in all stages of deposition, 205 and 206 volts. This would be a reasonable and practicable arrangement. In reality, at least one if not two additional tanks would be slipped into each series, for at least that number would be out of circuit continuously, being cleaned and made ready for re-starting.

(5) The amperes per tank would be:

$$0.75 \times 0.5 \times 2 \times 16 \times 110 = 1,320$$

And the area of the main conductors in each series:

$$1,320 \div 2 = 660 \text{ sq. m.m.} \qquad (5)$$

(6) The part of the anode sheet immersed weighs 8,888 grams, of which 0.9 is 8,000 grams, and if the anode is an intermediate one it is corroded on both sides, and receives, therefore, 85 amps. of current. This current dissolves, per second:

$$0.00001036 \times 28 \times 85 = 0\ 024657 \text{ grams.}$$

And therefore the anode sheet will last

$$\begin{aligned} 8,000 \times 0.024657 &= 324,000 \text{ seconds.} \\ &= 90 \text{ hours.} \qquad (6) \end{aligned}$$

(7) The weight of deposit on both sides of a cathode plate is

$$75 \times 50 \times 2 \times 1.5 \times 7.6 = 85,500 \text{ grams.}$$

And the time required to deposit this, since it is deposited by 85 amps., is

$$\begin{aligned} 85,500 \div 0.024657 &= 3,467,600 \text{ seconds.} \\ &= 40 \text{ days } 3 \text{ hours.} \qquad (8) \end{aligned}$$

(8) Each series requires 1,320 amps. at 205 volts, or

$$1{,}320 \times 205 \div 1{,}000 = 270.6 \text{ kilowatts.}$$

The three series therefore require 812 kilowatts, which will cost

$$\$25.00 \times 812 \div 365.25 = \$55.68 \text{ per day.}$$

An average cost of power per ton of iron refined of

$$\$55.68 \div 25 = \mathbf{\$2.23}. \qquad (8)$$

The other items of cost in a well conducted refinery will about equal this sum, making the total cost of refining about $4.50 per ton of pure iron. With cheap soft steel used as the raw material, there is a striking possibility of such a process being commercially practicable for furnishing one of the raw materials for producing the finest qualities of steel, the other raw material being washed pig metal of standard quality. We commend this possibility to the attention of the makers of fine steel.

APPENDIX TO PART II.

PROBLEMS FOR PRACTICE.

Problem 81.

A blast furnace will require 7000 cubic feet of cold air supplied per minute, and assuming that it will be provided with **5** tuyeres, and that the pressure in the main will be kept at 8 pounds per square inch, that the back pressure in the furnace will average 2 pounds per square inch, and that the coefficient of contraction of the jet, for a conical nozzle, is 0.92—

Required:

(1) The diameter of each nozzle.

Ans.: **3** inches.

Problem 82.

A blast-furnace charge is composed of the following ingredients, in percentage composition:

Ore		*Coal*		*Ash of Coal*		*Flux*	
Fe^2O^3	71.49	fixed C	90	SiO^2	48.00	CaO	52.83
SiO^2	15.73	ash	10	Al^2O^3	41.20	CO^2	41.51
Al^2O^3	4.21			Fe^2O^3	8.00	SiO^2	5.66
CaO	5.00			CaO	2.80		
MgO	3.57						

Per ton of pig iron there is used 1.5 tons of coal. Pig iron contains 94 per cent. Fe, and 2.8 per cent. Si, 99 per cent. of the iron in the charge goes into the pig iron. Quantivalent ratio of the slag, calling both Si and Al acids, 1.882.

Required, per ton of pig iron produced:

(1) The weight of ore charged. *Ans.*: **1.88** tons
(2) " " " flux " *Ans.*: **0.48** tons
(3) " " " slagproduced *Ans.*: **0.91** tons
(4) The percentage composition of the slag.

Ans.:	SiO^2	36.95	per cent.
	Al^2O^3	15.56	"
	CaO	38.79	"
	MgO	7.40	"
	FeO	1.30	"
		100.00	"

Problem 83.

The composition of the waste gases of a blast furnace is by weight (not by volume)

Nitrogen	55.40
Carbonous oxide	28.00
Carbonic oxide	16.50
Hydrogen	0.10

From analyses of the charges and products it is known that for every 100 kg. of pig-iron made 79.52 kg. of oxygen enters the gas from the solid charges and 15.5 kg. of carbon enters the gases from other sources than the fixed carbon of the fuel. The fuel contains 90 per cent. fixed carbon; the pig-iron contains 3 per cent. carbon. In 24 hours there is produced 41,400 kg. of pig-iron; the blowing engine works 23 hours. Assume least dry.

Required:

(1) Per 100 kg. of pig iron, the weight of fuel charged.
Ans.: **114.4** kg.

(2) " " " " the carbon burned at the tuyeres.
Ans.: **87.4** kg.

(3) " " " " the carbon otherwise consumed.
Ans.: **12.6** kg.

(4) " " " " the weight of the gases.
Ans : **700** kg.

(5) " " " " the weight of the gases.
Ans.: **504** kg.

(6) The volume of blast received per minute.
Ans.: **117** m^3.

(7) The dimensions of the blast cylinder.
Ans.: l=**1.5** m, d=**1.88** m., **20** r.p.m.

Problem 84.

Four varieties of ore are used in a blast-furnace, containing by analysis:

	A	B	C	D
Fe	63.25	60.10	64.35	62.35
SiO^2	5.86	4.20	5.30	6.58
Al^2O^3	1.48	1.98	1.96	1.87
CaO	1.04	——	0.16	0.90
MgO	0.75	——	0.09	0.51
P	0.019	0.107	0.019	0.015

The flux, fuel and pig iron contained:

	Flux		*Fuel*	*Pig Iron*	
SiO^2	5.46		5.64	Fe	95.24
Al^2O^3	1.53		3.74	Si	1.40
CaO	47.00		0.56		
MgO	3.60		0.60		
P	0.010		0.020		
		FeS	1.32		

The ores are mixed in the proportions $\frac{1}{3}$ A, $\frac{1}{3}$ B, $\frac{2}{9}$ C, $\frac{1}{9}$ D. A "round" of fuel consists of 12 barrows of coke containing 520 pounds per barrow. 1885 pounds of coke is used in producing a "ton" of 2300 pounds of pig-iron. Assume $\frac{9}{10}$ of the sulphur to go into the slag, and $\frac{9}{10}$ of the phosphorus to go into the pig-iron.

Required:

(1) A corrected fluxing table, showing for each substance (100 parts) the weights of ingredients furnished to the slag, the quantivalence of each element thus contributed, and the net available acid or basic quantivalence assuming the slag to be a bi-silicate, counting Si and Al as the acid elements in the slag.

(2) The weight of each ingredient of the burden per round of coke. *Ans.*: Ore **11,640** lb., flux **1090,** coke **6240.**

(3) The weight of slag produced per 2300 lbs. of pig-iron.

(4) The percentage composition of the slag.

(5) The percentage of S and P in the pig-iron.

Problem 85.

The flux used in a blast-furnace and the slag produced by its use have the following compositions:

Flux		*Slag*	
$CaCO^3$	80.36	CaO	29.0
$MgCO^3$	15.75	MgO	4.8
SiO^2	3.00	SiO^2	53.4
H^2O	0.89	Al^2O^3	9.0
		FeO	2.6
		Na^2O	1.2

Per 100 kg. of pig iron produced there is used 28.7 kg. of flux. and there is made 50.15 kg. of slag.
Required:

(1) The quantivalent ratio of the slag.
Ans.: **2.96**

(2) How much flux would be needed to produce a uni-silicate slag. *Ans.*: **126** kg.

(3) What would be the weight of this slag.
Ans.: **184** kg.

(4) What would be its percentage composition; check the quantivalent ratio from this composition.

Problem 86.

A blast furnace works on the following materials:

Ore		*Coke*		*Flux*		*Pig Iron*		*Gases*	
Fe^2O^3	85	Fixed C	87	CaO	52.50	Fe	94.8	CO	28.41
SiO^2	9	SiO^2	6	SiO^2	6.25	Si	1.4	CO^2	10.85
Al^2O^3	1	Al^2O^3	5	CO^2	41.25	C	3.8	N^2	60.78
CaO	2.8	H^2O	2						
H^2O	2.2								

100 kg. of coke and 160 kg. of ore are used per 100 kg. of pig-iron produced.

Required: (1) The weight of flux charged, per 100 of coke, to make a slag with the quantivalent ratio:

$$\frac{\text{Quant. Si} + \text{Quant. Al}}{\text{Quant. Ca}} = 1.75.$$

Ans.: **39.1** kg.

(2) The weight of carbon burned at the tuyeres per 100 of pig-iron. *Ans.*: **70.1** kg.

(3) The weight of carbon consumed above the tuyeres per 100 of pig-iron. *Ans.*: **13.1** kg.

Problem 87.

The blast-furnace of preceding problem has 7 tuyeres, each 5 inches in diameter. Temperature of blast in blast main 819°, indicated pressure on blast-main gauge 22.08 lbs. per sq. inch, the back pressure in the furnace in the region of the tuyeres is 3.69 lbs. per sq. inch. The air jet contracts in issuing until the coefficient of contraction of area of the jet—μ—is 0.9.

Required: (1) The actual temperature of the blast entering the furnace, assuming it to be cooled only by expansion. Assume the mean specific heat of air under the above conditions as 0.40 (oz. cal. per cubic foot or Cal. per cubic meter).

Ans.: **743°**

(2) The volume of blast per minute received by the furnace, as standard conditions of measurement. *Ans.:* **48,400** ft^3.

Problem 88.

Taking the calculated data of Problems 86 and 87, and combining them, how many tons of pig-iron, at 2240 lbs. per ton, are produced per day, assuming the blast to be on the furnace 23 hours 30 minutes? *Ans.:* **700** tons.

Problem 89.

A blast furnace makes 330,000 kg. of pig iron in 24 hours. The blowing engine runs 1400 minutes per day; 3 cylinders, double acting, 2 m. diameter by 2 m. stroke, piston rod 0.1 m. diameter and passing through one end of the cylinder only; 40 strokes per minute. Temperature in engine room 27.3°; assume air dry.

Charges per 100 kg. of pig iron: Ore 155.0, flux 45.2, coke 84.0. Ore contains 62 per cent. of Fe, as Fe^2O^3, 5 per cent. H^2O and the rest SiO^2. The flux is 3 per cent. SiO^2 and the rest $CaCO^3$. The coke contains 89 per cent. fixed carbon, 1 per cent. H^2O and the rest half SiO^2 and half Al^2O^3. The pig-iron carries 3.5 carbon, 1 silicon, 94.6 per cent. iron. The waste gases contain 2.3 volumes of CO to 1 volume of CO^2. Assume all the oxygen in the CO and CO^2 to come from the blast, reduction of Fe^2O^3 and SiO^2, and the CO^2 of the flux.

Required:

(1) The weight of carbon burned at the tuyeres, per 100 kg. of pig-iron produced. *Ans.*: **57.8** kg.

(2) The weight of carbon burned above the tuyeres, in direct reduction, per 100 of pig-iron. *Ans.*: **13.5** kg.

(3) The volume of blast, at standard conditions, received by the furnace per minute. *Ans.*: **608.5** m^3

(4) The same, per ton of pig-iron. *Ans.*: **2582** m^3

(5) The efficiency of the blowing plant, *i.e.*, the ratio of air received to the piston displacement. *Ans.*: **88.9** per cent.

Problem 90.

A blast-furnace produces 300 metric tons of pig-iron per day, and is charged, per 100 kg. of pig-iron, with

156 kg.	iron ore
50 "	limestone
90 "	coke

The percentage compositions of these materials and of the pig-iron and gases produced are:

Ore		*Limestone*		*Coke*		*Pig Iron*		*Gases*	
Fe^2O^3	85	CaO	51.66	Fixed C	88	Fe	94.00	CO	26.50
SiO^2	8	MgO	2.50	SiO^2	8	Si	2.10	CO^2	13.25
Al^2O^3	4	SiO^2	2.50	FeS	2	C	3.75	N^2	60.25
H^2O	3	CO^2	43.34	H^2O	2	S	0.10		

Required:

(1) The volume of gas, measured dry, at 0° and 760 m.m. pressure, produced per 100 kg. of pig-iron made.
Ans.: **379** m^3

(2) The volume of blast, assumed dry and at 0° and 760 m.m., received per 100 kg. of pig-iron made. *Ans.*: **288** m^3

(3) The weight of carbon consumed by the blast, at the tuyeres, per 100 kg. of pig-iron made. *Ans.*: **66** kg.

(4) The weight and percentage composition of the slag.
Ans.: **49** kg.

Composition: SiO^2 32.6, Al^2O^3 12.4, CaO 49.3, MgO 2.4, FeO 1.2, CaS 2.4.

(5) The horse-power producible from one-half of the gases, assuming them used in gas-engines at 25 per cent. net thermo-mechanical efficiency. *Ans.*: **7570** h.p.

Problem 91.

A blast-furnace makes 300 metric tons of pig-iron daily, producing per 100 kg. of pig iron made 464.5 m^3 of gas of the following composition: CO 24, CO^2 12, N^2 64, and using 352.5 m^3 of blast, at 700° C. The blowing engines consume 1,000 indicated horse-power, the lift and pumps 150 h.p. The blast (assumed dry at 0°) is heated to 700° in fire-brick stoves, at an efficiency of 50% on the heat of combustion of the gas used in them.

Required:

(1) The proportion of the gas made by the furnace required to be used by the stoves. *Ans.*: **46.6** per cent.

(2) The rest of the gas being burned under boilers, and just raising the power required by the furnace, what is the net thermo-mechanical efficiency of the boilers and engines together? *Ans.*: **3.2** per cent.

(3) If these gases were used in gas engines at an efficiency of 25 per cent., what surplus power would the blast-furnace produce above its own requirements? *Ans.*: **7830** horse-power.

Problem 92.

An Alabama blast furnace uses and produces materials of the following compositions:

Ore		*Dolomite*		*Coke*		*Pig Iron*	
Fe^2O^3	72.85	CaO	30.24	C	86.00	Fe	93.54
SiO^2	9.00	MgO	20.48	SiO^2	4.00	C	3.50
Al^2O^3	3.75	Fe^2O^3	0.50	Al^2O^3	2.00	Si	2.25
CaO	0.75	Al^2O^3	0.50	Fe^2O^3	2.00	S	0.06
P^2O^5	0.90	SiO^2	2.00	S	1.00	P	0.65
SO^3	0.25	CO^2	46.28	H^2O	5.00		
CO^2	0.60						
H^2O	11.90						

Assume: Burden = 2.00 (*i.e.*, ore plus dolomite = twice coke). All the iron in the charge reduced into the pig iron.

Sulphur not in pig iron goes into slag as CaS.

Phosphorus not in pig iron goes into slag as P^2O^5.

Slag to contain 34.00 per cent. SiO^2.

Eighty-nine per cent. of the fixed carbon of the coke will be consumed at the tuyeres, by dry blast.

Required: A balance sheet of materials entering and leaving the furnace.

Solution: [N.B.—Let x = ore used, y = dolomite, then $\frac{x+y}{2}$ = coke, and the balance sheet thus constructed leads easily to a solution conforming to above conditions.]

BALANCE SHEET (per 1000 of pig iron).

Charges		*Pig Iron*		*Slag*		*Gases*	
Ore	**1792**						
Fe^2O^3	1305.5	Fe	913.9			O	391.6
SiO^2	161.3	Si	22.5	SiO^2	113.1	O	25.7
Ol^2O^3	67.2			Al^2O^3	67.2		
CaO	13.4			Ca	1.5	O	0.6
				CaO	11.3		
P^2O^5	16.1	P	6.5	P^2O^5	1.3	O	8.4
SO^3	4.5	S	0.6	S	1.2		
CO^2	10.8					CO^2	10.8
H^2O	213.2					H^2O	213.2
Flux	**411**						
CaO	124.3			Ca	13.8	O	5.5
				CaO	105.0		
MgO	84.2			MgO	84.2		
Fe^2O^3	2.1	Fe	1.5			O	0.6
Al^2O^3	2.1			Al^2O^3	2.1		
SiO^2	8.2			SiO^2	8.2		
CO^2	190.2					CO^2	190.2
Coke	**1101**						
C	946.9	C	35.0			C	911.9
SiO^2	44.0			SiO^2	44.0		
Al^2O^3	22.0			Al^2O^3	22.0		
Fe^2O^3	22.0	Fe	15.4			O	6.6
S	11.0			S	11.0		
H^2O	55.1					H^2O	55.1
Blast	**4004**						
O^2	924.					O	924.0
N^2	3080.					N	3080.0
	7308.		1000.0		485.9		5824.2

Charges		*Slag*			
Coke	1000	SiO^2	34.0%	CaS	5.7
Ore	1628	Al^2O^3	18.8%	P^2O^5	0.3
Flux	373	CaO	23.9%		
					100.2
Pig Iron	908	MgO	17.5%		

Problem 93.

A foundry cupola melts 6,000 kg. of pig iron per hour, using 480 kg. of coke containing 85 per cent. fixed carbon. Average composition of issuing gases, by volume, N^2 75, CO^2 16, CO 4. Some Fe, Mn and Si are oxidized, forming the silicate $Fe^5 Mn SiO^8$. No carbon is oxidized out of or absorbed by the pig-iron. Assume the blast dry and neglect the ash of the coke and corrosion from the lining.

Requirements:

(1) The volume of blast received by the cupola per minute.
Ans.: **59.7** m^3

(2) The percentage loss in weight of the pig-iron, assuming it to lose only Fe, Mn and Si. *Ans.*: **4.74** per cent.

(3) The proportion of the whole heat generated which is due to the oxidation of carbon and to the oxidation of the pig-iron.
Ans.: **84.5** and **15.5** per cent.

Problem 94.

Dichmann, in *Stahl und Eisen*, 1 December, 1905, gives the following data respecting the Monell open-hearth operation, as practised by him.

Charge: 1000 kg. limestone, CaO 54.1, SiO^2 1.65, MgO 0.68.
3276 " hematite ore, Fe^2O^3 95.0, SiO^2 3.7.

These were put on a basic hearth and heated nearly to melting. There was then run upon them 20,300 kg. of melted pig-iron. Starting at 2.30 P.M., the subsequent analyses showed:

	Metal				*Slag*				
P.M.	C	Si	P	Mn	FeO	Fe^2O^3	Mn	P^2O^5	SiO^2
2.30	4.61	0.84	0.15	2.20					
3.00	4.56	0.19	0.05	0.45	47.88	6.10	15.22	2.36	17.68
5.40	1.47	0.05	0.03	0.63	10.36	3.23	12.67	2.35	23.00
5.45	(819 kg. more ore added)								
6.15	0.43	0.05	0.03	0.49	11.44	2.37	12.04	2.03	22.90

Required:

(1) The weight of iron reduced into the bath during the slag-forming period—2.30 to 3.00 P.M.
Ans.: **1219** kg. = **56**% of the iron in the ore.

(2) The weight of iron reduced into the bath during the boil—3.00 to 5.40 P.M.

Ans.: 705 kg. - 32.4% of the iron in the ore.

(3) The weight of iron reduced from the additional ore added—5.40 to 6.15 P M

Ans.: 509 kg. = 93% of the iron in the ore added.

(4) The proportion of oxidation produced by the ore and by the furnace gases in each of these periods.

Ans.: 1st period **100** and **0.**
2d " **30** and **70.**
3d " **73** and **27.**

Problem 95.

A Bessemer converter is charged with 10,000 kg. of pig-iron, from which is oxidized

Si	2.8 per cent.	
C	3.3 "	1/5 to CO^2
Fe	1.12 "	

Length of blow 15 minutes, no free oxygen escapes from the converter. Temperature in engine room 0°, barometer 760 m.m., mean pressure on piston of blowing cylinder during the stroke 1 kg. per sq. centimeter. No moisture in the air. Assume a coefficient of delivery of 0.60.

Required:

(1) The volume of blast received per minute.

Ans.: **196** m^3

(2) The dimensions and speed of the blowing cylinder.

Ans.: *d* **2.4** m., *l* **2** m., **18** r.p.m.

(3) The horse-power exerted by the blowing cylinder.

Ans.: **727** h.p.

(4) If the speed of the blowing cylinder is kept constant, but the temperature in the engine room becomes 30° and saturated with moisture, how much longer will the blow last?

Ans.: **46** seconds.

Problem 96.

A Bessemer converter contains 10,000 kg. of pig-iron, from which there is oxidized by the blast: Si 1, Fe 2, C as CO^2 0.7, C as CO 2.8 per cent., while no free oxygen or H^2O vapor escapes from the converter. The blowing engines have a piston displacement of 326.5 m^3 per minute. The air in the engine room is at 27.3°, barometer 741 m.m., air saturated with moisture. The blow lasts 9 minutes 10 seconds, up to the end of the boil.

Required:

(1) The coefficient of useful delivery of the blowing cylinders and conduits. *Ans.*: **66** per cent.

(2) The average composition of the gases produced.

Ans.: CO 5.18, CO^2 20.73, H^2 3.38, N^2 70.80 per cent.

Problem 97.

The gases from a Bessemer converter had the following average composition during the slag-forming period and the boil, respectively:

	First 3 *minutes.*	*Last* 2 *minutes.*
O^2	0.6	0.1
CO^2	8.4	4.3
CO	5.2	26.1
H^2	0.6	0.6
N^2	85.2	68.9

Duration of blow 5 minutes. Weight of charge 2500 kg. Weight of carbon oxidized 3.9 per cent. of the weight of the charge. Assume the blast constant per minute throughout, and that the composition of the slag formed from the Fe, Mn and Si, oxidized is Fe Mn Si^2O^6. Neglect the moisture of the blast.

Required:

(1) The volume of the blast per minute. *Ans.*: **168.5** m^3

(2) The proportion of the total carbon oxidized passing off as CO^2. *Ans.*: **30.9** per cent.

(3) The percentage loss in weight of the charge from the oxidation of its ingredients. *Ans.*: **9.30** per cent.

Problem 98.

A Bessemer converter is charged with 8000 kg. of pig-iron. The slag-forming period lasts 6′ 20″, the boil 4′ 10″. At the end of the boil 800 kg. of spiegeleisen is added, and the converter momentarily turned up. The steel ingots obtained weigh 7900 kg. Hydrogen in gases comes from moisture in the blast.

Temperature of air in engine room 30° C., barometer 760 m.m. Assume blast constant per minute. Blast cylinder 1.5 m. internal diameter, 2 m. stroke, double acting, 90 strokes per minute, piston rod through both ends, diameter 0.15 m. Effective pressure of the blast, 2 atmospheres.

Analyses:

	Pig Iron	*End of 1st period*	*End of 2d period*	*Spiegel*	*Steel*
C	4.00	2.63	0.04	5.00	0.49
Si	2.00	0.26	0.03	3.00	0.10
Mn	1.40	0.42	0.01	15.00	0.78
P	0.05	0.05	0.06	0.12	0.06
S	0.05	0.05	0.06	——	0.05
Fe	92.50	96.59	99.80	76.88	98.52

Average composition of gases:

	In 1st period	*In 2d period*
CO	7.19	27.45
CO^2	7.19	2.60
O^2	2.60	——
H^2	2.81	2.36
N^2	80.21	67.59

Final Slag	
SiO^2	48.62
MnO	21.72
FeO	29.66

Required:

(1) A balance sheet, showing constituents of the bath at each stage of the blow.

(2) The volume of blast per minute, at the engine room temperature; the weight of blast per ton of pig-iron treated.

(3) The relative volumes of gas issuing per minute in each period.

(4) The proportion of the total carbon burned in the blow which is burned to CO and CO^2.

(5) The proportions of the carbon, silicon and manganese of the spiegeleisen lost during re-carbonization. Express these also as percentages of the weight of steel produced

(6) The total weight of the slag; the weight of silica corroded from the lining.

(7) The volume efficiency of delivery of the blowing engine.

(8) The net effective horse-power of the blowing cylinder.

Solution:

(1) Balance Sheet

	Pig Iron	*Loss*	*End 1st period*	*Loss*	*End 2d period*	*Spiegel*	*Loss*	*Steel*
C	320	120	200	197	3	40	4	39
Si	160	140	20	18	2	24	18	8
Mn	112	80	32	31	1	120	59	62
P	4	—	4	0	4	1	0	5
S	4	—	4	0	4	0	0	4
Fe	7400	60	7340	124	7216	615	49	7782
Total	8000	400	7600	370	7230	800	130	7900

(2) Volume received by converter per minute at 30°: 287 m^3

Weight per ton of pig-iron treated: 436 kg.

(3) Relative volumes of gases per minute: 1 to 1.20

(4) Proportion of carbon burned to CO: 75.7 per cent.

(5) Loss in per cent. of spiegel: in per cent. of steel

C	0.5	0.05
Si	2.3	0.23
Mn	7.4	0.75

(6) Weight of slag: 1005 kg. Loss of lining: 112 kg.

(7) Efficiency of delivery = 82.5 per cent.

(8) Net effective horse-power = 900; gross, 1000.

Problem 99.

Ten metric tons (10,000 kg.) of pig-iron is charged into a basic lined (Thomas) Bessemer converter, and blown 12 minutes. The lining is burnt dolomite, composition practically CaO, MgO. Analyses showed:

Pig Iron		*Metal at end of blow*		*Slag*	
C	3.05	C	0.1687	SiO^2	5.98
Mn	0.41	Mn	0.0973	MnO	1.39
Si	0.83	Si	———	CaS	2.49
S	0.33	S	0.0540	P^2O^5	10.08
P	1.37	P	0.0650	FeO	7.14
Fe	94.01	Fe	99.6150	Fe^2O^3	1.20
				CaO	67.05
				MgO	4.67

Assume all the Fe, Si and Mn oxidized to be removed in the first period, all the carbon in the second, $\frac{1}{5}$ to CO^2 and $\frac{4}{5}$ to CO, and all the P and S in the third period, and no free oxygen to escape from the converter.

Requirements:

(1) The weight of slag produced. *Ans.*: **2975** kg.
(2) " " " steel " *Ans.*: **9250** kg.
(3) " " " lining corroded away during the blow. *Ans.*: **333** kg.
(4) " " " lime added during the blow. *Ans.*: **1858** kg.
(5) The duration of each period, assumed as sharply defined. *Ans.*: 2′ 27″, 6′ 50″, 2′ 43″.

Problem 100.

In a basic-lined Bessemer converter, there is oxidized during the blow:

Silicon	0.84 per cent.	
Carbon	3.00 "	1/5 to CO^2
Phosphorus	1.86 "	
Manganese	0.55 "	
Iron	2.80 "	

Bath weighs at starting 8000 kg., blow lasts 18 minutes, no free oxygen escapes from the converter. Effective pressure of the blast 1.5 atmospheres, outside air at 0° and 760 m.m.

Requirements:

(1) The volume of the blast per minute. *Ans.*: **134** m^3
(2) The net horse-power of the blowing engine. *Ans.*: **313** h.p.

(3) If the slag has the formula: $3\ Ca^4P^2O^9.\ MnFe^5Ca^{12}\ Si^3O^{24}$, how much lime must be added during the blow and what is the weight and percentage composition of the slag?

Ans.: **1075** kg. CaO
1905 kg. slag.

P^2O^5	17.89 per cent.
SiO^2	7.56 "
CaO	56.46 "
MnO	2.98 "
FeO	15.11 "

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