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THE PRINCIPLES
OPERATION AND PRODUCTS
OF THE
BLAST FURNACE

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THE PRINCIPLES OPERATION AND PRODUCTS OF THE BLAST FURNACE

BY

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TO

JAMES GAYLEY

FOUNDER OF MODERN AMERICAN BLAST-FURNACE PRACTICE
INVENTOR OF THE DRY BLAST
GENEROUS AND HELPFUL FRIEND TO MANY FURNACEMEN

THIS WORK
IS RESPECTFULLY DEDICATED

PREFACE

The rational subdivisions for a work on the blast furnace are: Construction, Principles, Operation and Product.

Construction was treated in my recent book "Blast Furnace Construction in America." This volume treats of the last three subdivisions of the subject.

The treatment of a subject from several different points of view involves a certain amount of repetition exactly as the mechanical engineer in making a drawing of a machine must show it on three planes of projection and must show some of the same parts in each view. The same conditions hold in presenting a complicated subject like the blast furnace. Any adequate treatment must show it from several points of view and a certain amount of repetition is not only inevitable but is desirable to drive home important considerations.

The section on "Principles" might be called the theory of the blast furnace, but the word "theory" carries, to many minds, the unpleasant implication that it is something the opposite of practice, while it has been my greatest effort to develop a set of principles which should so thoroughly agree with practice that one would merge into the other, and that only an arbitrary dividing line could be drawn between them.

The section on "Operation" may be criticized as inadequate to the vastness and importance of the subject, but the limitations of space must not be ignored.

I have put into the chapters on operating difficulties a number of personal experiences which are to some extent representative. Many other furnacemen have had experiences which I should like better to describe, but it is virtually impossible to obtain adequate descriptions of such experiences without living through them.

It may be that some of my contentions in the section on "Products" will not be universally admitted for years to come, especially in regard to the effect of oxygen in cast iron, but the amount of proof available is so great that it has forced the acceptance of my conclusions by some of the highest authorities, and I confidently expect that others will follow.

A chapter on "Commercial Considerations" is added at the close of the book, which I hope will be found to contain valuable information of a kind not usually given in technical books.

I wish to acknowledge the help I have received in the form of facts and ideas from nearly all the furnacemen I have met. I have tried to make specific acknowledgment in the text to those who have given me

the most valuable information; undoubtedly I have missed some, but the omission was unintentional.

To Mr. D. M. Liddell, author of the *Metallurgists' & Chemists' Hand Book*, my sincere thanks are tendered for reading over my manuscript and finding in it many obscure paragraphs and errors whose presence I suspected, but, owing to too great familiarity with the text, could not see.

To Mr. Bradley Stoughton, Secretary of the American Institute of Mining Engineers, I am indebted for helpful and constructive criticisms on several of the chapters.

To the memory of my lamented friend, Dr. E. F. Roeber, late Editor of *Metallurgical & Chemical Engineering*, I make grateful acknowledgment of his unfailing helpfulness, patience, appreciation, and encouragement. This work would scarcely have been undertaken and carried through but for him.

J. E. Johnson, Jr.

New York,
January, 1918.

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THE PRINCIPLES, OPERATION AND PRODUCTS OF THE BLAST FURNACE

PART I
PRINCIPLES

CHAPTER I

INTRODUCTORY

The blast furnace challenges investigation for two reasons, one commercial, one scientific. The first comes from its enormous consumption of fuel, some 60,000,000 tons of coal per year being consumed by it in the United States alone. The second comes from the natural desire to subject to natural law an apparatus, which in operation is often so uncertain, incomprehensible and capricious as to have earned universally the human pronoun "She".

These reasons have inspired a vast number of scientific papers and some books. The authors of these have attempted to solve the riddles which the blast furnace furnishes, but, in my judgment, none of them succeeded in proposing any theory which fits or explains the important facts. Nevertheless, much credit is due to some of the earlier investigators, for they helped to lay the foundation, although not precisely for the structure which they had in mind.

Sir I. Lothian Bell in particular found time in a busy and highly successful commercial life to prosecute extensive investigations, to ponder at great length, and to record accurately the results of his labors in two large volumes. In these I believe it is admitted that the first reasonably successful attempt was made to write a heat equation of the blast furnace. Most unfortunately for him and his disciples there are not one but two heat equations of the blast furnace, and in endeavoring to square all the conditions with this one equation he was led into errors which went far to vitiate the value of his work. But as a pioneer in applying chemistry and quantitative heat values to the operations of the furnace he is deserving of his high place in the esteem of furnacemen.

Gruner also set forth in 1879 the ideal condition of working of a blast furnace; his conclusions have been too little heeded and have even been

attacked in recent years as not universally correct, but I think I shall be able to show that Gruner is right and that his critic, through not realizing all the conditions, has fallen into error.

The action of the blast furnace must be considered in three different aspects which sometimes merge into one another, but nevertheless can best be considered separately at first, the chemical, the thermal and the mechanical; in which order we shall consider them.

THE DIFFERENT REGIONS OF THE FURNACE

The "lines" of a typical modern blast furnace are shown in Fig. 1. The cylindrical straight portion at the bottom is called the hearth or crucible or sometimes the well because it serves to contain the liquid iron and slag. The divergent cone above this is called the bosh. Then comes a short cylindrical portion with a long convergent cone above it and this surmounted by another cylinder. This region taken as a whole has so far as known to me no name established by universal custom, and I have been accustomed to call it the shaft, since the furnace as a whole is a "shaft" furnace and it is obviously this portion which gives it that name.

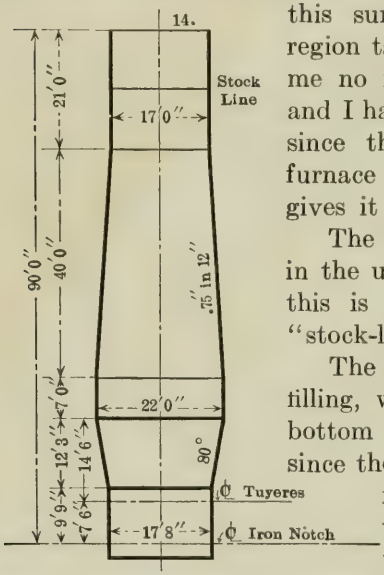


Fig. 1.—Lines of a modern blast furnace (South Chicago No. 4, 1914).

The furnace should be kept filled to the line in the upper cylinder marked "stock line" and this is the diameter which is meant by the "stock-line diameter."

The height of furnaces, in the days of hand filling, was always measured from the hearth bottom to the top of the filling platform, but since the decline of hand filling the top platform is not quite such a definite and important level, having nothing to do with the level from which filling is done in mechanical charging, so it is better now to give the height to the bottom of the supporting collar on the hopper as that corresponds more nearly to the old top platform than any other equally definite point.

The size of furnaces is given by their height and diameter at the top of the bosh, very frequently the diameter of the hearth and stock line are added in the order given.

Blast-furnace terminology suffers from one defect; the word "hearth" denotes the level at which combustion takes place and connotes the laboratory of the apparatus in which the active work is done, but the region of the furnace which corresponds to this description is really the bosh,

because the hearth, so-called, is generally filled (or largely so) with molten material, and combustion to any considerable extent cannot take place there in any event, since there is no outlet for the blast in any direction but upward, so that instantly on leaving the tuyeres the blast must pass up into the bosh, where it burns the coke and where most of the final work of the furnace is done. This should obviously be called the "hearth," if any region is to have that name. The habit of thinking and speaking of what goes on "in the hearth" is so universal among furnacemen that it is almost impossible to avoid using the word "hearth" in the sense of the laboratory of the furnace. I shall avoid confusion on this score to the best of my ability, but the reader should be on guard against the ever-present possibility of confusion from this source.

The Function of the Bosh.—In the introductory chapter of the first volume the general outlines and requirements of the blast-furnace process were set forth, and need not be repeated here. In operation the oxygen of the blast is burned by the fuel of the charge to CO in the bosh of the furnace. Theoretically oxygen first burns to CO_2 and then absorbs an additional atom of carbon which converts it into CO, since CO_2 cannot exist as such in the presence of carbon except at temperatures far lower than those in the hearth of a blast furnace. I was formerly inclined to believe that for practical purposes the formation of CO_2 might be disregarded and the subject considered only on the basis of a direct formation of CO but this is not entirely true.

I shall later set forth the opinion that combustion of the oxygen to CO is not complete until the gas (blast) reaches the top of the bosh. If this be true and there were not a zone of CO_2 formation then the temperature would be virtually the same at the tuyeres as at the top of the bosh and this we know most positively is not true. There is a zone of intensest temperature right around the tuyeres which drops rapidly at first and then more slowly as we ascend.

These statements do not, unfortunately, depend greatly upon pyrometric measurements at different levels because the conditions of temperature, pressure, and dripping iron and cinder within the furnace make such measurements in this zone almost if not quite impossible; the statements depend upon observation of the wear and the evidences of fusion at different levels in furnaces after they have been blown out, and general obsevation and experience with furnaces in operation.

Professor Howe, however, has pointed out to me that this fact of observed practice is well explained by assuming a zone of CO_2 formation at the tuyeres.

The amount of heat developed by the combustion of a given quantity of oxygen to CO is only six-tenths of that developed by its combustion to CO_2 and the reaction $CO_2 + C = 2CO$ absorbs a large quantity of heat, hence combustion to CO_2 followed by instant conversion to CO would give

a hot zone succeeded by a relatively much cooler one, the condition which we find in practice and for which we have no other adequate explanation. We are, therefore, compelled to believe that at least part of the oxygen of the blast is converted to CO_2 and remains in that condition long enough to affect the temperature of the tuyere zone, though the interval must be measured in fractions of a second, and is reflected in a corresponding reduction of temperature at a higher level.

As far as the total heat developed in the hearth and that remaining in the gas discharged into the shaft from the bosh is concerned, the combustion to CO_2 has no effect, for in coming back from CO_2 to CO the heat absorbed is precisely the excess developed by consumption to CO_2 over that to CO, and the effect in the final result is therefore zero. Whether any effect of this narrow zone of high temperature and relatively oxidizing condition can be determined, may be left for later discussion. We need only say now that the ultimate reaction between the oxygen of the blast and the fuel in the bosh is to convert both to CO, with the development of a certain amount of heat, which is needed to complete the smelting operation, the nitrogen is simply a useless load which must be carried.

The Function of the Shaft.—The CO produced in the hearth and bosh passes up through the shaft of the furnace and with more or less help from the solid carbon of the charge reduces the iron from the oxide to the metallic state according to certain reactions which we will first discuss, leaving for later discussion the question of heat development.

Functions of Hearth and Shaft Distinct.—The functions of the upper and lower portions of the furnace, the shaft and the bosh, are quite separate and distinct, so much so that we could substitute some other apparatus for one and leave the other unaffected, and each as we shall later see has its own thermal equation.

For instance, we could produce "iron sponge" by using a reducing flame in a rotary kiln, introduce the sponge into the "bosh" of a furnace with no shaft at all and there melt it to produce liquid iron and slag.

On the other hand, we could conceivably extract the iron sponge from the shaft of the blast furnace just above the bosh and then melt it down in an open-hearth or other melting furnace.

Many such processes have been tried and some of the attempts have succeeded technically although none of them have survived in actual use for they could not meet commercial conditions.

They serve a useful purpose by furnishing proof that the function of the blast furnace is not a single but a double one for the performance of two separate and distinct operations. There is in my opinion no such thing as a fundamental understanding of blast-furnace principles without a full realization of this fact.

CHAPTER II

CHEMICAL PRINCIPLES

The number of reactions which actually take place within the blast furnace is almost unlimited, but those which control its action are relatively few and simple.

These are the reactions between carbon, oxygen, and iron and its oxides, and the reactions which lead to the formation of slag, which are principally the formation of silicates and aluminates of bases, generally, in fact almost universally, lime and magnesia.

The Reactions Between Carbon and its Oxides and Iron and its Oxides.—There are three well-recognized oxides of iron which are in the order of their oxygen contents: Ferric oxide Fe_2O_3, ferric-ferrous, magnetic, or black oxide Fe_3O_4, and ferrous oxide FeO.

The former is normally blood red in color and very slightly magnetic under even the most powerful magnetic field, it is the commonest form in which iron occurs in nature. When hydrated it is brown in color and commonly known as limonite. The second is black and more highly magnetic than any other natural mineral; it is the second commonest form of iron oxide, and that to which iron oxidizes when heated.

The third, ferrous oxide FeO, is unstable under atmospheric conditions, and seizing oxygen from the air, instantly returns to the form of ferric oxide.

The oxides of carbon are two, carbon monoxide CO, and carbon dioxide CO_2, both gaseous at temperatures even far below that of the atmosphere.

These two elements and their five oxides react with one another at various temperatures according to the following equations in which the modern symbols are used to show that they are reversible:

$$3Fe_2O_3 + CO \leftrightarrows 2Fe_3O_4 + CO_2$$
$$Fe_3O_4 + CO \leftrightarrows 3FeO + CO_2$$
$$FeO + CO \leftrightarrows Fe + CO_2$$
$$3Fe_2O_3 + C \leftrightarrows 2Fe_3O_4 + CO$$
$$Fe_3O_4 + C \leftrightarrows 3FeO + CO$$
$$FeO + C \leftrightarrows Fe + CO$$

It may well be doubted whether the reduction of Fe_2O_3 to FeO takes place by way of Fe_3O_4, and for two reasons: First, the relative com-

plexity of the reaction involving 3 molecules of one oxide and 2 of the other, as compared with the extremely simple reactions

$$Fe_2O_3 + C = 2FeO + CO$$
$$Fe_2O_3 + CO = 2FeO + CO_2$$

which involve only 1 of each. Second, it is generally admitted that the magnetic oxide is less reducible in the furnace than ferric oxide, and it is difficult for me to see how this could be so if ferric oxide has to pass through the magnetic oxide stage during reduction, and I have for several years past rejected that idea.

On the other hand, it is claimed that magnetic oxide is not irreducible in itself, but only because it is extremely dense and non-porous, so that the gas gets no opportunity to work on anything but its exterior surface. That magnetite is generally very dense is certainly true, but even in an extremely fine state of subdivision like roll scale or some of the Lake ores which are composed of flakes almost like graphite this oxide has a strong tendency to scour the furnace, that is, to come through only partly reduced and uniting with the slag forms a silicate of iron which always has an extremely scouring action.

On the other hand, again, Professor H. O. Hofman of the Massachusetts Institute of Technology has told me that there are several arrests in the curve giving the relation between temperature and deoxidation of iron which indicate the existence of several intermediate oxides between those here noted, and the fact that iron in the course of reduction passes through these subordinate states of oxidation would indicate that it would also pass through the state of Fe_3O_4.

Testimony from such an authority cannot be questioned, but even admitting this as a laboratory condition it does not follow that the same thing takes place in the furnace, and certainly the reputation of magnetic oxide as an ore is not good among furnacemen on account of its well-recognized irreducibility, and I cannot believe that reduction of ferric oxide takes place principally by way of Fe_3O_4.

Carbon unites with oxygen according to three well-known equations as follows:

$$C + O_2 \leftrightarrows CO_2$$
$$2C + O_2 \leftrightarrows 2CO$$
$$2CO + O_2 \leftrightarrows 2CO_2$$

all of which are reversible.

As the two oxides of carbon occur in the blast furnace in all concentrations from CO alone to CO and CO_2 in about equal proportions and through a very wide range of temperatures, we have iron and its oxides exposed simultaneously to influences which tend to oxidize them and to those which reduce them.

The question of the temperatures and concentrations of the two oxides of carbon with which carbon is in equilibrium has been experimentally investigated by O. L. Boudouard in France, and the equilibrium condition of the iron and its oxides in the presence of varying percentages CO and CO_2 at different temperatures has been experimentally investigated by Baur and Glaessner in Germany and reported by them in *Stahl und Eisen* for May 1, 1903.

They added to the chart of their results those of Boudouard in order to show the relations between carbon and iron and the oxides of both.

The work of Baur and Glaessner was extensive and highly creditable. The data given are of great value, but must not be used recklessly, as they cannot always be applied directly to the solution of practical problems whose conditions are frequently very different from those which it is necessary to create in order to secure scientific results. In the present case the scientific investigation has sought equilibrium conditions which are only established after many hours, whereas in the blast furnace the total time of passage of the gas from its entrance at the tuyeres to its exit at the top is only a few seconds, during which equilibrium in most reactions is not even approximated.

We can, therefore, use the valuable diagram of Baur and Glaessner to show what *tends* to happen and what *cannot* happen, but we should be led far astray if we tried to use its results to show the extent to which most of these reactions actually take place.

Their results are given by Sir William Ramsay in his work on "The Phase Rule," from which the following extract is taken, as it is the only condensed and yet logical statement extant with which I am familiar, of a very complex set of conditions:

"Some of the most important systems of three components in which equilibrium exists between solid and gas phases are those formed by the three components—iron, carbon monoxide, and carbon dioxide—and they are of importance especially for the study of the processes occurring in the blast furnace.

"If carbon monoxide is passed over reduced iron powder at a temperature of about 600°, the iron is oxidized and the carbon monoxide reduced with separation of carbon in accordance with the equation

$$Fe + CO = FeO + C.$$

This reaction is succeeded by the two reactions

$$FeO + CO = Fe + CO_2$$
$$CO_2 + C = 2CO.$$

"The former of these reactions is not complete, but leads to a definite equilibrium. The result of the different reactions is therefore an equilibrium between the three solid phases, carbon, iron, and ferrous oxide, and the gas phase consisting of carbon monoxide and dioxide. We have here four phases, and if the total pressure is maintained constant, equilibrium can occur only at a definite temperature.

"Since, under certain conditions, we can also have the reaction

$$Fe_3O_4 + CO = 3FeO + CO_2$$

a second series of equilibria can be obtained of a character similar to the former. These various equilibria have been investigated by Baur and Glaessner and the following is a short account of the results of their work.

"Mixtures of the solid phases in equilibrium with carbon monoxide and dioxide were heated in a porcelain tube at a definite temperature until equilibrium was produced, and the gas was then pumped off and analyzed. The results which were obtained are given in Tables 1 and 2 and represented graphically in Fig. 2.

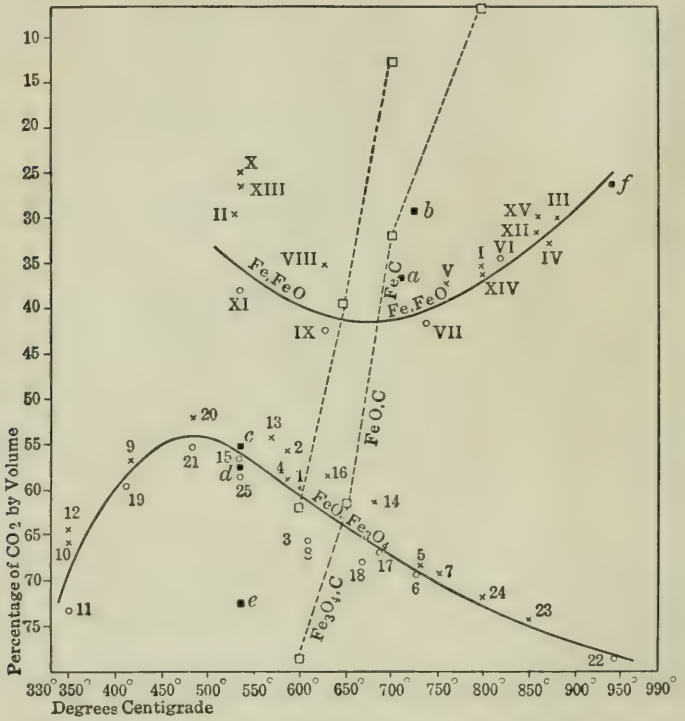


FIG. 2.—Equlibrium curve.

"As is evident from Tables 1 and 2 and from the curves in Fig. 2, the curve of equilibrium in the case of the reaction

$$Fe_3O_4 + CO = 3FeO + CO_2$$

exhibits a maximum for the ratio $CO : CO_2$, at 490°, while for the reaction

$$FeO + CO = Fe + CO_2$$

this ratio has a minimum value at 680°. From these curves can be derived the conditions under which the different solid phases can exist in contact with gas. Thus, for example, at a temperature of 690°., FeO and Fe_3O_4 can coexist with a

TABLE I.—SOLID PHASES: Fe_3O_4; FeO

No.	Tube filled with	Duration of the experiment in hours	Temperature	Percentage of	
				CO_2	CO
1	CO	14	600°	59.3	40.7
2	CO	15	590°	54.7	45.3
3	CO_2	16	590°	64.6	35.4
4	CO	24	590°	58.4	41.6
5	CO	22	730°	67.7	32.3
6	CO_2	22	730°	86.1	31.9
7	CO	22	750°	68.4	31.6
8	CO_2	22	610°	64.9	35.1
9	CO	23	420°	56.0	44.0
10	CO	47	350°	65.6	34.4
11	CO_2	46	350°	72.8	27.2
12	CO	53	350°	64.0	36.0
13	CO	18	570°	53.4	46.6
14	CO	19	680°	60.5	39.5
15	CO_2	24	540°	55.5	44.5
16	CO	21	630°	57.5	42.5
17	CO_2	17	690°	65.5	34.5
18	CO	17	670°	67.0	33.0
19	CO	24	410°	58.5	41.5
20	CO	24	490°	51.7	48.8
21	CO	23	590°	54.4	45.6
22	CO	4	950°	77.0	23.0
23	CO	15	850°	73.4	26.6
24	CO	8	800°	71.2	28.8
25	CO_2	24	540°	56.7	43.3

TABLE II.—SOLID PHASES: FeO; Fe

No.	Tube filled with	Duration of the experiment in hours	Temperature	Percentage of	
				CO_2	CO
I	CO	15	800°	35.2	64.8
II	CO	18	530°	29.1	70.9
III	CO	13	880°	30.2	69.6
IV	CO_2	24	870°	32.3	67.7
V	CO	18	760°	36.9	63.1
VI	CO_2	16	820°	34.7	65.3
VII	CO_2	18	730°	41.1	58.9
VIII	CO	18	630°	34.9	65.1
IX	CO_2	17	630°	61.6	58.4
X	CO	18	540°	25.0	75.0
XI	CO_2	25	540°	36.5	63.5

mixture of 65.5 per cent. of CO_2 and 34.5 per cent. of CO. If the partial pressure of CO_2 is increased, there occurs the reaction

$$3FeO + CO_2 = Fe_3O_4 + CO$$

and if carbon dioxide is added in sufficient amount, the ferrous oxide finally disappears completely. If, on the other hand, the partial pressure of CO is increased, there occurs the reaction

$$Fe_3O_4 + CO = 3FeO + CO_2$$

and all the ferric oxide can be made to disappear. We see, therefore, that Fe_3O_4 can exist only at temperatures and in contact with mixtures of carbon monoxide and dioxide, represented by the area which lies below the under curve in Fig. 2. Similarly, the region of existence of FeO is that represented by the area between the two curves, while metallic iron can exist under the conditions of temperature and composition of gas phase represented by the area above the upper curve in Fig. 2. If, therefore, ferric oxide or metallic iron is heated for a sufficiently long time at temperatures above 700° (to the right of the dotted line, *vide infra*), complete transformation to ferrous oxide finally occurs.

"In another series of equilibria which can be obtained, carbon is one of the solid phases. In Fig. 2 the equilibria between carbon, carbon monoxide, and carbon dioxide under pressures of 1¼ atmospheres, are represented by dotted lines.[1]

"If we consider only the dotted line on the right, representing the equilibria under atmospheric pressure, we see that the points in which the dotted line cuts the other two curves must represent systems in which carbon monoxide and carbon dioxide are in equilibrium with $FeO + Fe_3O_4 + C$, on the one hand, and with $Fe + FeO + C$ on the other. These systems can exist only at one definite temperature, if we make the restriction that the pressure is maintained constant (atmospheric pressure). Starting, therefore, with the equilibrium $FeO + Fe_3O_4 + CO + CO_2$ at a temperature of about 670°, and then add carbon to the system, the reaction

$$C + CO_2 = 2CO$$

will occur, because the concentration of CO_2 is greater than what corresponds with the system $FeO + Fe_2O_4 + C$ in equilibrium with carbon monoxide and dioxide. In consequence of this reaction, the equilibrium between $FeO + Fe_3O_4$ and the gas phase is disturbed, and the change in the composition of the gas phase is opposed by the reaction $Fe_3O_4 + CO = 3FeO + CO_2$, which continues until either all the carbon or all the ferric oxide is used up. If the ferric oxide first disappears, the equilibrium corresponds with a point on the dotted line in the middle area of Fig. 2, which represents equilibria between $FeO + C$ as solid phases, and a mixture of carbon monoxide and dioxide as gas phase. If the temperature is higher than 685°, at which temperature the curve for $C - CO - CO_2$ cuts that for $Fe - FeO - CO - CO_2$, then, when all the ferric oxide has

[1] These equilibria were obtained by Boudouard, *Annales chim phys.*, 1901 [7], 24, 5. See also Hahn, *Zeitschr. physikal. Chem.*, 1903, 42, 705; 44, 513. Rhead and Wheeler, *Jour. Chem. Soc.*, 1910, 97, 2178.

disappeared, the concentration of CO_2 is still too great for the coexistence of FeO and C. Consequently, there occurs the reaction $C + CO_2 = 2CO$, and the composition of the gas phase alters until a point on the upper curve is reached. A further increase in the concentration of CO is opposed by the reaction $FeO + CO = Fe + CO_2$, and the pressure remains constant until all the ferrous oxide is reduced and only iron and carbon remain in equilibrium with gas. If the quantities of the substances have been rightly chosen, we ultimately reach a point on the dotted curve in the upper part of Fig. 2.

"Fig. 2 shows us, also, what are the conditions under which the reduction of ferric to ferrous oxide by carbon can occur. Let us suppose, for example, that we start with a mixture of carbon monoxide and dioxide at about 600° (the lowest point on the dotted line), and maintain the total pressure constant and equal to 1 atmosphere. If the temperature is increased, the concentration of the carbon dioxide will diminish, owing to the reaction $C + CO_2 = 2CO$, but the ferric oxide will undergo no change until the temperature reaches 647°, the point of intersection of the dotted curve with the curve for FeO and Fe_3O_4. At this point further increase in the concentration of carbon monoxide is opposed by the reduction of ferric oxide in accordance with the equation $Fe_3O_4 + CO = 3FeO + CO_2$. The pressure, therefore, remains constant until all the ferric oxide has disappeared. If the temperature is still further raised, we again obtain a univariant system, FeO + C, in equilibrium with gas (univariant because the total pressure is constant), and if the temperature is raised the composition of the gas must undergo change. This is effected by the reaction $C + CO_2 = 2CO$. When the temperature rises to 685°, at which the dotted curve cuts the curve for Fe − FeO, further change is prevented by the reaction $FeO + CO = Fe + CO_2$. When all the ferrous oxide is used up, we obtain the system Fe + C in equilibrium with gas. If the temperature is now raised, the composition of the gas undergoes change, as shown by the dotted line. The two temperatures, 647° and 685°, give, evidently, the limits within which ferric or ferrous oxide can be reduced directly by carbon.

"It is further evident that at any temperature to the right of the dotted line, carbon is unstable in presence of iron or its oxides, while at temperatures lower than those represented by the dotted line it is stable. In the blast furnace, therefore, separation of carbon can occur only at lower temperatures, and the carbon must disappear on raising the temperature.

"Finally, it may be remarked that the equilibrium curves show that ferrous oxide is most easily reduced at 680°, since the concentration of the carbon monoxide required at this temperature is a minimum. On the other hand, ferric oxide is reduced with greatest difficulty at 490°, since at this temperature the requisite concentration of carbon monoxide is a maximum."

While the whole series of reactions between iron and carbon and their oxides are graphically portrayed in the chart of Fig. 2 and the accompanying explanation, the form in which the explanation exists is rather condensed and it may be well to run over some of the more important reactions in their relation to the more important phases of the operation of the furnace.

The reduction of iron oxide to iron is performed principally by carbon monoxide, but partly by solid carbon. The more complete is the reduction by CO the more efficient is the operation. The reason for this is not immediately apparent, but will be explained in detail in the next chapter. Part of the CO_2 so formed picks up carbon from the fuel and reconverts itself into CO; on the other hand, the CO is in part split up by what is supposed to be a catalytic action of the iron oxide according to the equation $2CO = CO_2 + C$. The carbon so deposited is in the form of an impalpable powder, which being a solid travels down with the stock, while the gas whose splitting up deposited it, passes on up and out of the furnace. At lower levels where the temperatures are higher and a smaller concentration of CO_2 can remain in equilibrium with carbon this carbon dust is dissolved by the reaction of $C + CO_2 = 2CO$ and passes up again with the gas. We have then a never-ending conflict of conditions in the shaft of the furnace with first one reaction occurring and then the opposite one wiping out its effects.

The effect of having deposited carbon carried down in the solid state through a given zone and carried up as gas to be deposited again at the top of this zone is to produce an excess of this carbon dust in this zone, which tends to obstruct the openings in the stock through which the gas must pass and causes the furnace to work "tight" in this zone, and most furnaces which slip with more or less regularity in normal operation do so from about the same depth, as measured by the violence of the slip and the effect on the furnace. Such slips throw out huge clouds of black dust which travels high in the air; part of this is undoubtedly partly reduced iron, but in many cases much of it is the carbon dust which caused the slip.

While discussing the subject of the conflicting conditions existing in the shaft of the furnace it is well to call attention to the fact that the stock is charged in roughly horizontal layers, first one of fuel, then one of ore and stone, one of which tends to reduce the CO_2 already formed to CO, while the other tends to oxidize the CO to CO_2. These layers are only a foot or so in thickness, and the time of the passage of the gas through them must be measured in fractions of a second, so their effect is like that of waves of alternating forces, one set trying to hinder, the other to assist, in bringing about the equilibrium which the broader conditions of temperature, etc., are trying to establish. This in itself would constitute a sufficient reason for the impossibility of predicting the conditions which will prevail under any given circumstances by the equilibrium diagram.

CONTROLLING FACTORS IN THE COMPOSITION OF THE TOP GAS

After all the laborious and painstaking investigations of this subject which have been made we come now to the astonishing fact that the

composition of the top gases is not a cause but an effect, and that important as are the detailed reactions I have so briefly described the composition of the top gas does not depend on them primarily, and at least three-fourths of all the work done on that subject has been wasted.

The reason for this will be clearer after we have discussed the heat equation of the furnace, but it will be well to explain it now and then return to it later. The reason is this: The ore to produce a ton of iron contains a definite quantity of oxygen. Fe_2O_3, the most common ore, in its pure condition contains 70 per cent. Fe and 30 per cent. oxygen. Pig iron contains about 94 units of Fe. It is obvious that this brings into the furnace 40.3 units of oxygen per 100 units of pig. Fe_3O_4, magnetite, contains in its pure condition 72.4 Fe and 27.6 O, so that 94 units of iron in this form bring into the furnace 35.8 units of oxygen per 100 units of pig. These are definite chemical relations not subject to furnace conditions or other qualifications. We shall presently see that to keep the furnace hot enough in the hearth to run, a certain amount of fuel must be burned in the hearth for every unit of iron produced, the amount having nothing to do with reduction or in a general way with chemistry at all, but being a plain matter of heat, as in the case of melting ice or any other solid. Now this carbon is burned to CO and nothing else; the CO_2 phase is, as I have explained, a transient one without effect on the final result. Thus we have a certain definite amount of carbon monoxide depending entirely upon hearth conditions and a certain definite quantity of oxygen removed from the ore added to it during the upward passage of the gas. It is obviously no problem in chemistry, but only a rudimentary one in arithmetic as to what the result will be in the composition of the gas at the furnace top.

But this statement which would settle so many problems if it were unreservedly true is subject to a certain limitation. The amount of carbon which must be burned in the hearth is not the same as the amount which is charged into the top, nor does it even bear a fixed relation with it, because the carbon charged, from the moment it enters the furnace, is subject to the solution by the CO_2 in the gas, and to direct oxidation by the oxygen of the ore and these influences, particularly the latter, as I shall presently show, are extremely variable, so that though the oxygen liberated and the carbon burned in the hearth per unit of iron produced are definite quantities which by themselves would give a top gas of a certain definite composition, they are not the sole determining factors; a secondary but none the less considerable influence is exerted by the carbon dissolved before it reached the tuyeres. This constitutes a variable addition of carbon to the definite composition of gas produced by the two main factors just outlined.

Solution of the Carbon.—The flux used for blast furnaces is universally either carbonate of lime, calcite, or carbonate of lime and magnesia,

dolomite, or a mixture of these two. These carbonates are broken up by heat, the carbon dioxide beginning to come off at a temperature of 800°F. or so, and not being all driven off, especially in the case of dolomite, until it reaches a temperature almost twice as high.

This is the range of temperature in which carbon dioxide attacks solid carbon very actively, and as a consequence the carbon dioxide liberated by the flux carries off enough carbon to restore approximately the equilibrium set by the conditions of temperature and the relative strength of the reducing and oxidizing influences in that zone.

This not only constitutes a loss of solid carbon, but a loss of heat as well, since the reaction $CO_2 + C = 2CO$ represents an absorption of heat of $14{,}750 - 2 \times 4375 = 6000$ B.t.u. per pound of carbon dissolved. The carbon dissolved would obviously be equal to that in the limestone from whence the CO_2 comes, if all the CO_2 of the flux were reduced to CO, and as carbon constitutes 12 per cent. of pure limestone (13.8 per cent. of pure dolomite) and as the ratio of CO to CO_2 to which the carbon dioxide of the stone is reduced is approximately 2 : 1 or two-thirds CO, we can see that 8 to 9 per cent. of the weight of the flux is the quantity of carbon dissolved and carried out the top of the furnace by the CO_2 of the flux. In proof of this fact gas samples taken from a point well below the stock line show a higher content of CO_2 than simultaneous samples from the furnace top showing that the CO_2 evolved by the flux was actually reduced to CO. I believe that this experiment has been made quite frequently, and I myself have made it with results which left no room for doubt.

The obvious suggestion is that the flux should be "burned" so as to drive off its CO_2 before charging into the furnace, and this has in fact often been proposed, but has never been done to any great extent. This failure may be due to inertia and the desire to avoid any additional operation at the blast furnace, but it has a certain justification in that most furnaces have a considerable excess of heat in the shaft and the limestone can be calcined with this without burning any fuel for this purpose. In many, if not most cases this results in ultimate economy in dollars and cents in spite of the fuel dissolved by the CO_2. We can discuss this subject better when dealing with heat balance of the furnace in the next chapter.

Another cause of solution loss is the contact of the ore and fuel and the direct reduction which results according to the equation $Fe_2O_3 + C = 2FeO + CO$ and $Fe_2O_3 + 3C = 2Fe + 3CO$.

These reactions take place freely throughout a wide range of temperature as shown by Fig. 2, and therefore every point of direct contact between ore and fuel is a possible point of direct reduction and solution loss. It would appear at first sight that this was precisely what we wanted, but when we come to deal with the thermal equations we shall

see that it results in a real loss, and I shall endeavor to show that the increase in the number of points of contact between ore and fuel accounts for the increase in the fuel consumption of furnaces which has often resulted when their burden has been changed largely to fine ore.

The conditions which lead to solution losses by any or all three of these methods are important and worthy of careful study, even though the theoretical laws of ore reduction do not control the action of the furnace to anything like the extent believed by some.

ACTION OF HYDROGEN AND VOLATILE HYDROCARBONS

All furnace fuels contain a certain amount of volatile combustible matter not driven off when the fuels were produced, but volatile at the temperature of the blast furnace, and as these frequently if not always contain considerable quantities of hydrogen their effect on the composition of the top gases is greater than their absolute quantity would lead one to suppose.

The quantity of volatile combustible matter in anthracite and coke is ordinarily 1 to 3 per cent., although it may go higher than this in some cases.

No analyses of this volatile combustible matter in anthracite and coke are at hand, and in ordinary cases and for ordinary purposes their quantity is not sufficient to exert an important influence. But with charcoal the case is very different; the volatile matter is in some cases about 30 per cent. of the total weight of the fuel, and by far the larger proportion of it is combustible, about 50 per cent. by volume is hydrogen and about 15 to 20 per cent. is methane or other hydrocarbon containing the same amount of carbon and hydrogen as that amount of methane; there is also some 10 or 15 per cent. CO.

This is very important because the first two of these gases are extremely active reducing agents even at quite low temperatures, and the quantity of oxygen required to satisfy them is much greater than is required for CO or carbon. Hydrogen requires eight times its own weight of oxygen to convert it to water, and methane, to convert it to water and CO_2 requires four times its weight of oxygen, as compared with one and a third times its weight to convert carbon to CO or two and two-thirds to convert it to CO_2. About 30 per cent. of the products of combustion of methane and all that of hydrogen is water vapor which mingles with the water vapor from the stock and completely disappears as a determinable quantity in the top gases. Hence extreme care is needed not to overlook their effect.

Hydrogen is active as a reducing agent at temperatures lower than those required for activity by carbon monoxide, and therefore the presence of this gas may be very beneficial in certain special cases. We have,

unfortunately, no such reliable investigations of the reducing action of hydrogen as those of Baur and Glaessner for the oxides of carbon, but it is well known that the reaction is reversible; steam passed through a red-hot iron pipe is broken up, the oxygen attacking the iron of the pipe and hydrogen being set free. On the other hand, hydrogen will reduce iron oxide to metallic iron at quite a low temperature. But no data exist, so far as known to me, on the equilibrium percentages of hydrogen and water vapor at different temperatures in the presence of iron and carbon and their oxides.

The reversibility of the action of hydrogen will appear very strikingly in the next chapter; it will be seen that a chemical balance for the ingoing and outcoming materials of a charcoal furnace cannot be made unless the very considerable proportion of the total oxygen which disappears by combination with hydrogen be brought into account, while in coke furnaces it will be seen that hydrogen is produced by the decomposition of water, not only in the hearth of the furnace but also on a much more extensive scale in the shaft.

The reactions which are probably responsible for this result are

$$H_2O + Fe \leftrightarrows FeO + H_2$$

and

$$H_2O + C \leftrightarrows CO + H_2$$

$$H_2O + CO \leftrightarrows CO_2 + H_2$$

all of which are reversible, as indicated.

The second is the typical reaction of the steam-blown gas producer.

The factors which control the direction in which these reactions take place are probably temperature and concentration of CO_2, but the indications are that temperature is the more important because hydrogen is consumed in the charcoal furnace, with its low top temperature, in spite of fairly high concentration of CO_2, while it is produced in the coke furnace, with its much higher top temperature, in spite of the low concentration of CO_2.

There is, however, much more ore and, therefore, more oxygen in proportion to the top gas in the charcoal furnace, and this may account for the oxidation of the hydrogen in that case.

These are some of the factors which affect the situation, but the conditions which control we frankly do not know.

CARBURIZATION OF THE IRON

This is a subject of the details of which we know relatively little. Iron in the solid condition absorbs carbon eagerly up to between 1 and 2 per cent. if exposed for a sufficient length of time at a high temperature, and in the liquid condition reasonable exposure to incandescent carbon will raise the latter element to about 2.5 per cent. in a neutral or

slightly oxidizing atmosphere, but it is difficult to raise the carbon contents of a bath of steel beyond this limit by any means commonly available. Even in the electric furnace difficulty has been found in commercial operation in raising the carbon to the range which is commonly found in pig iron.

The explanation for this probably is that the conditions of exposure in the blast furnace are exceedingly favorable. The iron sponge, produced by the breaking up of the iron ore into powder and the removal of oxygen under the action of the reducing gases, probably absorbs some carbon from the gas or from the fine carbon precipitated out of the gas, before the sponge reaches the zone of fusion, but not much is known about this.

After fusion the iron forms into drops presumably on the surface of the pieces of coke and then trickles down through the coke which constitutes the only solid contents of the bosh and hearth.

The progress of the iron is probably very slow at first, because until it is carburized its temperature of fusion is that of steel, several hundred degrees higher than that of cast iron, while the temperature of the upper part of the bosh is much lower than that around the tuyeres. It may even be that the iron descends through the upper part of the bosh attached to the coke and is carried down by the latter in the solid condition. Then as it becomes more thoroughly carburized and the temperature rises, it melts and completes the journey by trickling, but even this constitutes a slow descent because the surface of the coke is always porous and therefore rough, and the pieces of coke being in close contact with one another the path of the trickling iron is rough and tortuous.

Another important factor in retarding the progress of the iron and giving a chance for carburization is the high velocity of the gas upward, which must act to some extent like the up-blast through a shot tower in retarding the velocity of the liquid metal downward.

The conditions controlling carburization are not by any means thoroughly understood, and it is a lamentable fact that so little reliable work has been done on the determination of carbon in cast iron that our knowledge of the quantity of carbon in irons made under different conditions, is much less comprehensive than that of any other branch of the chemistry of iron.

We do know, however, that by the use of extremely high temperatures in the experimental electric furnace Moissan and more lately Witorff have succeeded in producing compounds of iron and carbon higher in the latter element than have ever been produced industrially. The compound Fe_2C seems to have been definitely identified as one of these products, and this contains 9.7 per cent. of carbon. It is, therefore, probably safe to say that the higher the temperature, other things being equal, the more carbon will be absorbed. It is also probably safe to say

that the more carbon in the hearth per unit of iron produced, other things being equal, the greater will be the carbon absorption.

The amount of excess heat in the hearth is probably a factor of much importance, and the nature of the fuel used may be of predominating importance since with charcoal fuel, the carbon in the iron produced under certain circumstances rises to 4.5 per cent. or more, although the temperature in the hearth is low relatively to that of a coke furnace which produces iron commonly running about 3.7 to 4.1 per cent. carbon.

This subject will be further discussed in dealing with furnace operation and the quality of iron.

THE REMOVAL OF THE SULPHUR

Sulphur may be introduced into the furnace by any of the raw materials, the fuel, the ore, or the flux, their responsibility for its introduction being in the order given.

The flux generally contains only traces of sulphur, but one case came under my observation in which the management of a charcoal furnace were greatly disturbed and equally puzzled to find the sulphur in their iron too high with no apparent reason for its being so. Analyses of the ore and then of the charcoal showing nothing out of ordinary, they finally analyzed the limestone and found enough sulphur to account for all the trouble. I think the amount was about 0.3 per cent., which was sufficient to spoil charcoal iron, because the slag on which that iron is made is so acid as to leave in the iron a considerable proportion of the sulphur in the charge.

Most of the ores of the Lake Superior region are very free from sulphur, although several of these on the Menominee range contain as much as 0.2 or 0.3 per cent. The ores of the Virginia and Alabama iron districts contain in general only the faintest traces of sulphur, as do most of those of the East, but some of the magnetites of New Jersey and eastern Pennsylvania are high in sulphur, in particular, the ore from the Cornwall mine near Lebanon, Pa., the largest and most famous single mine in the East, which has been worked continuously since revolutionary times, contains on the average about 2 per cent. of sulphur. It cannot ordinarily be used in the furnace without giving it a preliminary roast, which reduces the sulphur in unconcentrated ore to between 0.5 and 1 per cent. A large proportion of this ore is now crushed fine and magnetically concentrated, after which the fine concentrates are nodulized in a rotary kiln, and this in good practice reduces the sulphur to 0.1 per cent. or under. Some of the magnetites of Canada are also high in sulphur, running 3 to 4 per cent. in their native condition, and these are either crushed fine, concentrated and agglomerated, or treated by roasting, which reduces the sulphur to within permissible limits for furnace use.

In general if an ore is rich and pure enough in other respects to be worth the treatment it can be so roasted as to lower the sulphur within easily usable limits.

Sulphur in Fuel.—Charcoal is free of sulphur to a far greater extent than any other furnace fuel, but varies within quite wide limits. Charcoal from hardwood, exclusive of its bark, nearly always contains well under 0.1 per cent. and even down to 0.02 or 0.03 per cent., while the bark may simultaneously contain 0.2 or 0.3 per cent. or even more sulphur; but the bark is such a small proportion of the whole that good hardwood charcoal probably averages under 0.1 per cent. as a whole.

This small amount is largely absorbed even by the most acid slag, and only a small quantity enters the iron, under 0.02 with good raw materials, in ordinary practice.

This absence of sulphur and the consequent absence of need to run the furnace for desulphurization constitute the fundamental difference between charcoal and coke or anthracite practice and the irons resulting from them.

Coke contains all the way from 0.6 to 2 per cent. sulphur, which is present in two forms, ferric and ferrous sulphide, FeS_2 and FeS, and vegetable compounds.

The sulphur combined with iron occurs in the form of pyrite FeS_2 in the coal, but the heat of the coking operation drives off 1 molecule of sulphur from some of the pyrite and leaves it in the form of FeS in the coke, so that coke makers have a rule for general use that the reduction of sulphur is just about the same as the loss of weight in coking, so that the percentage of sulphur in coke is about the same as that of the coal from which it is made. I believe that the classification of coke into good and bad as regards sulphur in the minds of most furnacemen, is based on whether it is above or below 1 per cent. The original Connellsville coke had only about this and the New River and Pocohontas considerably less, but the sulphur in some of the western Pennsylvania fields outside the Connellsville basin is higher and much coke is now used running 1.25 per cent. and upward in sulphur.

I have known of a case where a plant ran for a considerable period on coke of nearly 3 per cent. sulphur, but the manager said, "I had to disregard coke consumption in order to make good iron." In another case a plant was run for a term of years on coke of 1.75 per cent. sulphur.

As the sulphur specifications for steel mill irons are "under 0.06 per cent.," and for all merchant iron "0.05 per cent. and under," or in some cases "0.03 per cent. and under," it is obvious that nearly all the sulphur brought in by the raw materials must be eliminated.

The method by which this is done consists principally, in carrying the sulphur off with the slag as calcium sulphide CaS.

It has generally been held that the sulphur from the charge was re-

moved entirely by the action of the slag, that if any sulphur were volatilized in the hearth it was caught and carried back by the descent of the charge column, and was, therefore, eventually forced to make its way out of the furnace in the slag.

Mr. James Bell, the superintendent of furnaces at the Algoma Steel Co., who has had a very extensive experience in working sulphurous ores, has told me, however, that he had investigated this subject carefully and that he had found that as much as 35 per cent. of the total sulphur in the charge could be eliminated by volatilization, but that this could be done only with a fairly acid slag, and that he could accomplish a better desulphurization with a slag of this variety than with an excessively limey slag because, while the latter had great sulphur-carrying power, it prevented the escape of sulphur in the gas and therefore increased the amount of sulphur which the slag had to carry off in greater proportion than its increased carrying capacity. Mr. Bell's experience is regard to sulphurous ores has been so extensive and his information was so positive that I am inclined to accept his view, especially as it fits in with the known fact that an excessively basic slag will produce high-sulphur iron unless it is kept very hot. This fact I had always attributed entirely to its lack of fluidity but it may be due in part also to the causes mentioned. Whether the sulphur volatilized passes off as sulphur vapor or as sulphur dioxide SO_2, I do not know.

The reactions by which calcium sulphide is formed are not very definitely known, but involve the reducing action of carbon to assist the reduction of the calcium from the oxide to the sulphide presumably by reactions somewhat as follows:

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

This is the reaction given by Professor H. M. Howe in his "Iron, Steel and Other Alloys," and is probably correct in principle if not exact in detail. The sulphur which is present as an organic compound is presumably carried off in a similar way, but nothing definite is known about the details of the reaction. It seems certain, however, that the sulphur cannot reduce lime sufficiently to form calcium sulphide without the assistance of the reducing action of carbon. As a matter of fact the reactions are probably not so simple as indicated, since the silica exerts a powerful attraction for the lime and there must be enough of the latter present to satisfy the silica before much sulphur is removed.

The conditions controlling desulphurization, and the substances involved in the operation are too numerous to permit its investigation without a vast amount of experimental work and overcoming many difficulties. We know, however, as the result of observations on operation four factors upon which desulphurization depends: First, the relative excess of bases over acids in the slag (positive); second, the temperature

of the slag (positive); third, the fluidity of the slag (positive); fourth, the concentration of sulphur in the slag (negative).

The bearing and results of these laws may be more properly discussed under the head of furnace operation and need not be further considered here.

We encounter here for the first time the fact which should be impressed upon the mind of every student of this subject and which is too little realized or taught in metallurgy:

The chemistry of the blast furnace is not a chemistry of definite atomic proportions. It is a chemistry of infinitely varying balances among conflicting tendencies.

A homely illustration is that if you place a heavy book upon the seat of a rocking chair the chair will take up a certain position; if you push the book back the chair will tip back and if you pull the book forward the chair will tip forward, its motion being roughly proportional to the movement of the book. If the rule of definite atomic proportions held the rocker of the chair would consist of only two or three straight sections of definite length and making considerable angles with each other, and the book could be removed through considerable distances without affecting the position of the chair, then when it did move it would rock instantly from one straight section to the next and remain absolutely at rest until the book had been shifted through another considerable range.

Nothing could be further from the facts of furnace operation than the last illustration, nothing be more like than the first. Each change of conditions sufficiently large not to be masked by the continual variations of operation produces its proportional effect, and these effects shade from one to the other by imperceptible gradations. It is, I think, this law which scientists have tried to capture and brand as "The Phase Rule." It is perhaps the misfortune of my generation that we had passed our student days when the existence of this rule was established and so did not grasp the new conception which it tries to codify, with the result that the simple relations which are used to illustrate the workings of the phase rule do not seem to need or receive additional light from it, and the more difficult ones whose explanation is sought by its assistance are made the harder for us to understand by the introduction of its difficult terminology. To another generation trained to think in this terminology from their collegiate years it will, we may hope, prove a benefit, but for the purposes of this work, plain statements of fact with such homely illustrations as the above must suffice.

THE REDUCTION OF SILICON, PHOSPHORUS, AND MANGANESE

These elements are all more difficult to reduce from their oxides than iron and therefore it should theoretically be possible to run the furnace so that iron would be reduced but without reducing any of these impuri-

ties. But as a matter of fact it is not possible to do so; if they are present in the charge they will be found in the iron to some extent. We can vary this extent greatly in the case of two of them, but even here we cannot exclude them altogether under practical operating conditions, if at all.

This is for the reason that iron exercises a solvent action upon all three elements and forms a definite compound with at least one of them, and probably the others also. The difference between a physical solution like that of caustic soda in water and a chemical combination like that of caustic soda with hydrochloric acid is not so great, or at least so readily distinguishable, at the high temperatures in the health of the furnace, and I do not feel qualified to distinguish between them in all cases. But it seems likely that manganese forms with iron only a solution or perhaps with the carbon in the iron a double carbide, the silicon acts as if formed silicide and a solution of this silicide in the iron, while phosphorus is known to form two or three definite phosphides, and solutions of some of these in iron.

Without attempting to pass definitely upon the question of whether the iron merely dissolves the silicon and manganese or really combines with them, we know that it has a considerable affinity for all three of these elements, and this fact has a strong influence in their reduction from the oxide to the elemental condition in which they are taken up by the iron. This is important because all of them are more difficult to reduce than iron requiring a higher temperature and a greater quantity of heat per unit of element reduced than does iron, and if the reducing action were not assisted by the affinity of iron for these substances in their elemental condition it is probable that they would not be reduced at all, or in much less degree than they are.

The case is analogous to that of copper smelting which utilizes the power of copper as a "catcher" for silver and gold. The ores of these metals are charged into the copper furnace and a very large proportion of their values is caught by the copper matte, from which they are subsequently recovered by electrolytic refining; but if the copper were not there to act as a catcher these values would largely be lost in the slag and the fumes.

It is believed that all three elements under discussion are reduced by solid carbon and not to any extent by CO.

Phosphorus is more completely reduced than either of the other two. This may be because of its stronger affinity for iron rather than to greater inherent reducibility; in any event practically all of this element present in the charge passes into the iron unless the furnace is working "cold," with a scouring slag, when as much as 10 per cent. of it may, according to Sir Lothian Bell, pass into the slag. From my own observation, I should say that even a considerably greater percentage of the phosphorus

could be eliminated with the cold scouring slag that comes from a "sick" furnace, but this is a matter of no industrial or commercial importance, and I have never gone deeply into it.

It is stated in Sexton and Primrose's "Metallurgy of Iron and Steel," pages 61 and 62, that phosphorus is not reduced by incandescent carbon except in the presence of silica in excess. The phosphorus is generally present in the ore as tricalcium-diphosphate and the reaction is said to take place according to the equation:

$$Ca_3P_2O_8 + 3SiO_2 + 5C + Fe = 3CaOSiO_2 + 5CO + FeP_2.$$

Silica is always present in excess in the charge and so the phosphorus can always be reduced even if this be a necessary condition. In the absence of any experimental data as to the reduction of phosphorus in a furnace working without silica in the charge, it is really more or less an academic, rather than a practical question whether this is a necessary condition or not. But I incline to the belief that while incandescent carbon alone may be unable to reduce phosphorus from the calcium phosphate, incandescent carbon in the presence of molten iron in excess might be able to bring about the reaction even in the absence of the silica; this is, of course, equivalent in a rough way to saying that the affinity of iron for phosphorus is probably as great as that of lime for silica so that the occurrence of the former reaction would compensate for the absence of the latter, but for practical purposes this is merely speculative.

Manganese.—The percentage of the total manganese charged which is reduced with the iron depends upon the temperature at which the furnace is worked and the basicisity of the slag, from a half to two-thirds of the whole amount charged will pass into the iron in ordinary coke pratice and less than this in good charcoal practice because those furnaces are worked both colder and with a more acid slag, though charcoal furnaces *can* be worked to throw as great a percentage into the iron as coke furnaces do. A part of the manganese is lost in the slag and a part by vaporization in the hearth, the latter can be plainly seen, at furnaces making ferromanganese, passing out the stacks of the stoves and boilers as a very heavy yellow fume.

The relative amounts lost in these two ways depend on the hearth temperature and the composition of the slag. Raising the hearth temperature tends to increase the vaporization loss and to diminish the slag loss while increasing acidity in the slag increases the slag loss rapidly without much effect on the vaporization loss. Cases are on record of unsuccessful attempts to make ferromanganese in which nearly all the manganese charged passed out into the slag, only an insignificant amount passing into the metal.

Silicon.—Silicon is generally present in the charge in far greater quantity than is needed to supply the percentage desired in the iron.

Generally the composition of the raw materials is such as to produce this condition whether we will or not, and if it is not so the furnaceman usually produces it by adding a silicious ore to the charge as it is easier to put the silicon desired into the iron when a superabundance is present, than it is to obtain it by robbing the slag of the silica it needs. In coke practice the silicon thrown into the iron is commonly less than 20 per cent. of the total silicon charged. On the other hand, I have run a charcoal furnace on rich low-silica ore and made high-silicon iron, about 3 per cent., which required more than half the silica charged for its production, but this is not good practice.

It is stated by Sexton and Primrose (*op. cit.*) that silicon is not reduced by carbon at temperatures below those of the electric arc which means that the affinity it has for iron is strong enough to make up the deficiency in the reducing power of carbon at lower temperatures, so that silicon is reduced not to the elemental state, but the state of silicide of iron. This is borne out by the limitations of the manufacture of ferrosilicon in the blast furnace. This material containing as high as 13 per cent. Si ordinarily, and higher occasionally, is regularly produced in blast furnaces using very high blast temperatures and a large quantity of fuel per ton of product, but when material containing more silicon than this is desired it is necessary to go to the electric furnace which is quite without those limitations of temperature under which the blast furnace suffers, and in that apparatus it is perfectly possible to produce a material containing from 50 to 80 per cent. Si, or higher for special purposes. This is probably explained by the fact that when the iron reaches say 15 per cent. Si, the Fe is so nearly saturated for this element that it does not exercise any affinity for any further amount and reduction of silicon accordingly ceases.

Since the above was written I have been informed by Professor J. W. Richards that silica begins to be reduced by carbon at 2750°F. and is reduced quite freely at 3250°F. Whatever may be the conditions as to silica alone the facts of practice are as above stated.

It seems likely that all these elements—phosphorus, silicon, and manganese—are reduced on the surface of the incandescent coke in a way exactly similar to the reduction of litharge to lead on the surface of a piece of charcoal by blowing on it with a blow pipe. The conditions in the furnace are exactly the same on a large scale. The trickling iron running down over the surface of the coke on which these elements are reduced is immediately at hand to take them up.

It has several times been suggested that the silicon of the iron came from the silica of the coke. This suggestion has much to recommend it and is probably largely correct for ordinary conditions, but in the manufacture of ferrosilicon in the blast furnace in which the silicon goes up as high as 13 per cent. it is obvious that this cannot all come from the

coke since ordinary coke contains less than 7 per cent. silica corresponding only to about 3 per cent. of silicon. This proves conclusively that the silica of the coke ash is not the only source of silicon and indicates the probability here as in so many other cases that the course followed is a compromise between two possible extremes, a balance between opposing influences. The reaction according to which this reduction takes place is then of the form:

$$yFe + SiO_2 + 2C = Fe_ySi + 2CO.$$

SLAG

The impurities of the fuel and of the ore must be eliminated from the furnace. In the early days this was probably done in the same way as taking the clinker out of a domestic fire by prying the clinker up from the bottom and raking it out, but in a furnace over 30 ft. in height, which the early furnaces soon came to be, it obviously could not be taken out the top and an opening was provided in the hearth with a forehearth in front of it, through which access could be had to the inside of the furnace by removing the heavy lid of the forehearth. This was only done after cast when the blast was off, as at any other time the gas formed in the hearth would have blown out the opening and made work impossible in the vicinity.

Gradually it came to be realized that the slag could be made fusible by the addition of "flux" and that when this was done it was not so necessary to open up the front and "work her down," so that practice declined and died out, but not so many years ago as might be thought, since I can distinctly remember as a very small boy seeing a jib crane, hung from the stone pier of the front arch of the furnace, to the chain of which the keepers hung in turn a huge poker, a gigantic shovel, as I recollect it about 2 ft. square, and perhaps some other tools which were laboriously operated by two or three men who were not as economical of their strength as is now customary and worked out the slag through the open front.

This was a charcoal furnace, but I am informed that the same practice was retained at the anthracite furnaces perhaps even to a later date.

The early furnaces always used charcoal fuel in which the percentage of ash is small and that present largely lime and alkali while sulphur is almost absent. For these reasons lime was little needed and its use developed slowly, but when soft coal and anthracite came into use, with a much larger amount of ash and sulphur, the latter requiring a relatively basic slag to keep it out of the iron, the use of flux came into regular use.

The principal impurity in both ore and mineral fuel is silica. Its importance comes from two sources; first, it is generally present in much larger quantity than any other substance, and second, it is by far the most active, if not the only acid of importance in common practice.

Next in quantity and importance comes alumina, which is very weak chemically, practically neither acid nor basic, but has a powerful effect on the physical characteristics of the slag.

These combine with mineral bases and the compounds so formed are far more fusible than any of the components separately. For instance, silica melts about 3180°F. and lime alone is infusible even in the oxyhydrogen blow pipe, but these two form compounds which melt about 2100°F.

Advantage is taken of this fact to convert the impurities of the charge into a fusible slag which runs from the furnace easily by adding mineral bases to the charge, even in charcoal practice where sulphur is almost entirely absent, and in coke practice the addition of lime is carried much further so as to render the slag basic enough to fix the sulphur and carry it out of the furnace.

The reaction between silica and lime is an exothermic one so that when they are heated to a temperature high enough to permit reaction between them the reaction goes forward more rapidly on account of the heat evolved. At the same time the quantity of heat evolved in this reaction is not comparable with that in many others, being only about 300 B.t.u. per pound of compound produced as against several thousand in some other reaction. Perhaps for this reason the resulting product differs less in its properties from those of its component substances and acts more like a solution than a chemical compound as compared with those substances which react more violently together.

It is generally believed that the formation temperature of slags is higher than the temperature of fusion so that if lime and silica be heated together they have to be raised to a higher temperature before combining than the resulting slag would require to remelt it.

This is a more or less obvious corollary to the fact that the melting temperatures of the ingredient are higher than that of the compound. It has been found also that the fineness of grinding and the intimacy of contact of the particles have a powerful effect on the temperature of formation which is likewise to be expected for the same cause.

These are facts which are sometimes of capital importance in understanding the operation of the furnace, and we shall have occasion to return to them in discussing that subject.

In practice only two bases are ever used, lime and magnesia. This is for two reasons: first, they occur in the greatest abundance in nature, far exceeding all the other alkalies and alkaline earths put together, and in massive geological formations close to the earth's surfaces so that they can be cheaply obtained by quarrying; and second, because they, particularly lime, are among the most powerful of all the bases chemically.

Lime alone is often used as flux, but never magnesia. This is for two reasons; first, lime carbonate, which contains only insignificant

quantities of magnesium carbonate, occurs in vast quantities in nature, but the reverse is so seldom true as to make the latter compound many times more expensive than limestone; second, the chemical activity of lime is much greater than that of magnesia. It is claimed by Sir Lothian Bell that magnesia was worthless for purposes of desulphurization; experience has proven this not to be true when both lime and magnesia are used together and whether it would be true if magnesia alone were used for flux is a purely academic question since commercial considerations prevent its use for that purpose.

Much limestone contains magnesium carbonate in quantities varying from a trace up to true dolomite, the double carbonate of lime and magnesia $CaO,MgO(CO_2)_2$, in which when decarbonated, the bases are present in the proportion of 58.3 and 41.7 per cent. owing to the difference in the atomic weights of Ca and Mg. Dolomite occurs in nature in great quantities also as does dolomitic limestone and these are used as flux, either alone or in conjunction with limestone, according to considerations which may be more appropriately discussed under the head of operation.

The combination of those bases with the silica of the charge forms the silicates of lime and magnesia which constitute in all cases more than half the total slag volume and this acts as a solvent for many other ingredients of which the alumina, in my judgment, is one; the principal one in quantity, next to the basic silicates themselves, varying from 7 to 15 per cent. in ordinary coke practice but going as high as 35 per cent. in certain special cases. The ingredient next in quantity in coke practice is calcium sulphide CaS, ranging from 2 to 5 per cent., but in normal practice from 2.5 to 3.5 per cent.

There is always present a certain amount of iron in the form of FeO. This varies from a mere trace in a white cinder made in a hot-working furnace to several per cent. in bad working, but under 1 per cent. in any normal working furnace. Manganese oxide MnO is present in quantities depending on the amount of manganese in the charge, in ordinary irons running under 1 per cent. in manganese the MnO in the slag should be under 0.5 per cent. and from this down to a trace. On the other hand when high-manganese irons, spiegel and ferromanganese are being made there are always several per cent. of MnO in the slag, even in best practice.

In general the rule that one-fourth of the manganese charged will go into the slag even if the furnace be operated to throw as much as possible of it into the iron, will define the minimum amount to be expected in the slag, and this may be increased up to a large proportion of the whole amount charged by different furnace operation. This does not necessarily apply in making spiegel and ferromanganese.

Titanium.—Some ores and fuels contain other elements in small quantities which go into the slag or into the iron in varying proportions.

One of the most common of these is titanium, which occurs in some cokes in fractional percentages and in many ores in amounts varying from a trace up to 15 or 20 per cent. in the form of titanic acid TiO_2.

This is extremely irreducible and infusible, and its presence complicates the operation of the furnace materially, for reasons some of which are not understood. One of these is rather unusual in a chemical sense. Titanium forms with nitrogen and cyanogen, titanium-cyano-nitride, a highly infusible compound, which builds up on the walls and in the bottom of the hearth, reducing the area of the latter to an objectionable extent if too great a percentage of titanium be maintained on the furnace for a long period.

The crystals of this material are copper-colored with a brilliant metallic luster. They are often found in and around the salamander when furnace hearths are being cleaned out for rebuilding.

This action has been understood for a long time and, in fact, has been given as the scientific reason for the practical objections to titanium. Mr. Bachman has told me, however, that in the course of his experimental run on the blast furnace at Port Henry, to be mentioned later, he saw reason to believe, both in the operation of the furnace and from the physical evidence discovered on cleaning out the hearth at the end of the blast, that a material which he found built up on the walls had been present during the blast in a liquid condition. He did not say so definitely, but I assume this to mean a variety of slag too viscous to flow out through the cinder-notch.

It was long held that the presence of a small quantity of titanium rendered ore entirely unfit for use in the blast furnace, but the whole question has recently been attacked anew and methods will probably be found whereby it can be fluxed. There is much reason to believe that the former verdict against it was on insufficient grounds.

In some cases the principal impurity in the ore is lime instead of silica, but there is seldom a sufficient excess to do more than flux the ash of the coke. When there is it is not customary to add silica by itself to the charge, but to use a portion of some other commercially available ore with an excess of silica, thereby avoiding the addition of barren material, either acid or basic, to the charge and so killing two birds with one stone.

The red hematites of Alabama and the Minette ores of Lorraine and Luxembourg are the two most notable cases of ores of this kind.

The Formation of Cyanides.—This is a subject concerning which not much is known.

The intimate contact of the nitrogen of the blast with the incandescent coke near the tuyeres in an absolutely reducing atmosphere furnishes the condition of high temperature necessary to carry out the highly endothermic reaction between those two elements while there is always present a certain amount of alkali from the ash of the coke with which the cyanogen

can unite to form alkaline cyanides, the presence of which around the hearth and bosh has often been noticed.

Several years ago an attempt was made to draw these cyanides from within the bosh and turn them to commercial use and while this attempt met some degree of technical success it was not continued and it is safe to say that commercially it was unsuccessful.

It has been suggested that these cyanides played an important part in the final reduction of the ore and it is entirely possible that this is so, since cyanogen is a powerful reducing agent and most of the cyanides formed in the hearth must be volatilized and rise through the charge with the gas column until they are either broken up or condensed and carried back by the charge. But so far as I know no critical investigation of this subject has ever been carried, on so that little of value is known about it.

Sir Lothian Bell investigated the subject more thoroughly than any one else of whom I have knowledge; his results were published in his "Chemical Phenomena of Iron Smelting," but did not go further than to establish the fact that cyanide occurred in considerable quantities in the hearth and bosh of the furnace.

Calcium Carbide.—All the literature dealing with calcium carbide states that its temperature of formation is so high that this can be reached only in the electric furnace, but in tearing out the hearths of furnaces blown out for repairs and wetting down the material left in them, I have several times noticed the smell of acetylene so plainly that it was unmistakable, and considering that lumps of lime are often found in the hearth under such conditions, when the furnace has been running on a basic slag and that this lime must have come down in contact with incandescent coke at a very high temperature, it does not seem unlikely that a certain amount of calcium carbide should form. It is impossible to say to what extent this reaction takes place, but it has a certain interest in view of the calcium carbide theory of steel purification in the electric furnace, which is receiving quite general acceptance, and as showing that reactions which are commonly stated to take place only at the temperature of the electric arc, do really occur in a limited way at lower temperatures when the conditions are favorable, furnishing a further illustration of the general law of varying equilibrium between contending forces depending on the conditions of temperature, chemical concentration, etc.

There are probably many, if not many hundreds of other reactions, which go on in the hearth under the condition of extremely high temperatures and intensely reducing atmosphere which prevail there, but the above are the principal ones necessary to an understanding of the action of the blast furnace.

THERMAL PRINCIPLES—I

CHAPTER III

THE TWO THERMAL EQUATIONS

The doctrine of the conservation of energy and the interconvertibility of its forms was well established about the middle of the last century, but the latter was well in its third quarter before any systematic effort was made to apply that doctrine to the blast furnace.

This was first done by Sir Lothian Bell, who had made in his works-laboratory countless experiments conducted with a degree of scientific skill and breadth of vision rare in that day. With the results of these and the data on thermal capacities, heats of reaction, etc., so carefully and laboriously determined by the physicists of various countries, particularly France, he prepared a heat balance of the furnace showing the quantity of heat developed and the amounts utilized and lost in various ways, which was the beginning of any comprehensive knowledge of the subject, for, without a knowledge of the theoretical amount of heat necessary to bring about the desired reactions in the furnace, it is impossible to say whether we are obtaining a reasonable efficiency from the fuel or not. Since that time heat balances without number have been prepared and used to prove any contention that it might please the fancy of their makers to uphold, but frequently without carrying much conviction.

The reason for this condition was that while taking careful account of the quantity of heat they ignored the quality factor, that is, temperature-head or intensity. It was as if a hydraulic engineer tried to calculate the water power obtainable at a given site by accurate and painstaking determinations of the quantity of water passing, without any regard to the head, or an electrician were to try to figure the power of a given circuit from the amperes of current without respect to its voltage, or more accurately still as if a steam engineer tried to figure the power he could obtain from a definite quantity of steam without knowing its pressure, which depends on the temperature.

This condition is all the more curious because in the case of the other great application of heat, the steam engine, the importance of the intensity factor was worked out and stated in mathematical language many years before the doctrines of the conservation and convertibility of energy

were discovered, and both of these were known and the theory of the steam engine was complete, virtually in its present form, about the time Sir Lothian Bell's work on the heat balance of the blast furnace was begun.

This theory of the steam engine was completely enunciated by two laws known as the First and Second Laws of Thermodynamics. These may be expressed for our purpose as follows:

1. The quantity of work produced by transformation of heat bears a definite and unchanging ratio to the quantity of heat transformed.

2. The proportion of any given quantity of heat which can be utilized for conversion into work depends upon the temperatures at which the heat is applied and discharged.

The first of these laws is simply a special form of the law of conservation of energy, and by substituting "chemical change" for "work" it would express the law of the blast furnace which Sir Lothian Bell and his followers understood. But that the blast furnace depended also upon a similar "second law" was totally beyond their knowledge, although it is just as important in this case as in that of the steam engine. This accounts for the failure of the elaborate calculations based on the first law alone, to explain many of the well-recognized phenomena of blast-furnace practice.

For instance, the introduction of the hot blast reduced the fuel consumption of soft-coal furnaces more than a half, although the heat of the blast introduced was only about 18 per cent. of the total produced—a preposterous state of affairs viewed only in the light shed by the heat balance—and Sir Lothian Bell spent not pages, but chapters, in trying to prove that the benefit of the hot blast was strictly limited, and was, in fact, smaller than it was generally known in practice to be, because he could not make the facts square with his incomplete theory.

This is a subject with the later development of which I have had some connection, and it may not be amiss to treat this portion of it from a somewhat personal point of view.

The explanation of the hot blast given in Sir Lothian Bell's works did not seem to me to explain, and I had, moreover, been puzzled by the action of moisture in the blast, a subject treated by him in a similar way, because I had for a number of years been studying that subject carefully and keeping records of humidity in the engine room, which showed that the moisture present in summer above that present in winter was sufficient to account on that basis for only 4 or 5 per cent. difference in fuel consumption, whereas the furnace records over a number of years showed 20 per cent. difference. In 1899 it began to appear to me that there might be a critical temperature in the blast furnace above which some of the heat had to be supplied, and that as the range between this temperature and the theoretical combustion temperature was only a fraction of the latter, a

change in the latter would have an effect on this range (which obviously measures the amount of such heat available), several times as great as the effect on the theoretical combustion temperature. I did not then know what the critical temperature was nor what controlled it, but calculations on this basis with assumed critical temperatures based on the best information obtainable as to the temperature inside of the furnace, seemed to show a better agreement with the facts than did Bell's figures, and this idea grew in strength.

In 1901 a "Lunette" optical pyrometer was procured and observations of temperature made through the tuyeres, and in every other way thinkable, to determine what the critical temperature really was, because as long as it was only assumed it could be arbitrarily chosen so as to bring results which would agree with practice, but which would mean nothing.

The results of these observations revealed the fact that there was a critical temperature, that it was controlled exclusively by the free-running temperature of the slag, and that this temperature for the furnaces under observation was about 2750°F. A totally different investigation revealed the fact that the result of the removal of the moisture from the blast was identical in principle with that of the hot blast, and that its effects could be figured in exactly the same way.

Calculations of heat available above this critical temperature of 2750° under different conditions of blast temperature and humidity agreed with the relative coke consumption under those conditions so well as almost to arouse suspicion of the possibility of self-deception, but the same principle seemed to work quantitatively under the most diverse conditions and to explain many facts not adequately explained before, and I became convinced it was correct.

The conception is so simple that it seemed almost sure to have occurred to some one else long ago, and I made the best search I could through the blast-furnace literature of four countries to see if this were true, without finding a trace of it anywhere.

I wished to obtain certain patents based on this principle so kept it secret for 3 years, until the summer of 1904.

At that time the patents desired were allowed and the preparation of a paper to set forth this new theory of blast-furnace action was begun.

In that autumn Mr. James Gayley published his paper describing the actual results he had obtained at the Isabella Furnaces by the application of his system of drying the blast.

This was most fortunate for me, as it supplied authentic data strongly confirmatory of the new theory which were totally inexplicable by the old, and would, as I supposed, hasten the acceptance of the former, for it never occurred to me that the publication of Mr. Gayley's results would arouse any doubts of their correctness or any other sentiment except admiration for the solution of a problem of which all furnacemen must

be aware and for which they must desire a solution. As a matter of fact, the announcement of Gayley's results set the whole metallurgical world into a furore, many furnacemen and near-scientists refused to accept the results, and even went so far as to question the correctness, not to say truthfulness, of the furnace records.

My paper entitled "Notes on the Physical Action of the Blast Furnace" was submitted to the American Institute of Mining Engineers in the autumn of 1904, soon after Mr. Gayley's paper was read, but was held up in the secretary's office for almost a year. It was, however, presented orally at the Washington meeting of the Institute in May, 1905.

It was with great trepidation that I attacked the old theory as so incomplete as to be utterly misleading, expecting to be savagely criticized for my temerity and to see efforts made to riddle the new theory. It was proportionately surprising to see it accepted without a single protest by American furnacemen and metallurgists, *because it explained Mr. Gayley's results.* Thus instead of his facts being used to sustain the new theory, as would surely have been expected, the new theory was quite generally accepted because it sustained Mr. Gayley's facts.

It is proper to say that while the acceptance of the new theory seems as far as one can judge to be quite general in America, there are many indications that it has made little or no impression in Europe, and it seems, as far as I can gather, to have been definitely rejected in Germany.

After the lapse of 10 years, during which this theory has been used as a tool for the investigation of many of the problems of the blast furnace, the original presentation seems to me to be as good as anything I can offer now, though it is no more than proper to state that it has been presented in slightly different form by various other furnacemen and metallurgists, some of whom seem to regard it as entirely their own.

The original presentation from the paper above-mentioned (*Transactions* of the American Institute of Mining Engineers) Vol. XXXVI, p. 454, follows.

THE RESULTS OF HEATING AND DRYING THE BLAST

"The explanations offered by writers on the blast furnace to account for the economic effect of heating the blast are non-quantitative and therefore inadequate. The following paragraphs, translated from Ledebur, give perhaps the best example:

" 'When, later, systematic investigations of the influence of the hot blast began to be made, the surprising fact was frequently observed that by heating the blast more fuel could be saved than was necessary for the production of the heat brought in by the hot blast. Moreover, it was very generally observed that the top of the furnace became cooler the more the blast was heated.

" 'The two phenomena bear a close relationship to each other. The furnace requires, for each kilogram of iron produced, a certain quantity of heat, and the production of this heat, as has been mentioned earlier, is the primary purpose of

the combustion of the fuel by the blast. Each kilogram so burnt furnishes a definite quantity of gas which ascends into the furnace.

"'But now, if a part of the required heat, instead of being produced by the combustion of carbon, be brought in by the heated blast, the resulting quantity of gas must be as much smaller as corresponds to the saving in fuel; the smaller quantity of gas gives up its heat more quickly and completely to the counter-current of descending solid material than does the larger quantity of gas resulting with the cold blast.

" 'The heat is accordingly more advantageously utilized in operating with hot blast, and, by this means, a secondary saving in fuel is made. The consequence of this is that the gas leaves the furnace in a cooler condition, and the top temperature falls.'

"Bell's explanation is not very different and no more satisfactory.

"A simple explanation, which affords a basis for quantitative estimates in close accord with the actual facts, is afforded by considering the temperature at which a part of the total heat must be applied.

"In the application of heat to the generation of power, it was realized more than a century ago that the temperature of application was of equal importance with the quantity of heat; and it seems remarkable that, in metallurgy, attention is rarely paid to the temperature at which the heat must be applied for the accomplishment of a given purpose, and that quantitative data bearing on this subject are practically unknown.

"Calculations of the total quantity of heat imparted to the furnace by the combustion of 1 lb. of carbon, have often been made; and in a few cases calculations have also been made as to the maximum temperatures obtainable under various conditions, but if there have ever been any calculations as to the quantities of heat available at different temperatures, I have never heard of them.

"The point of view from which this subject should be considered differs so slightly, but so radically, from the common one, that the distinction is not easy to make clear, but may perhaps be best approached by the conception of a "critical" temperature. It may be said without reservation that for every set of furnace conditions there is a certain critical temperature, above which only certain necessary operations of the process can be carried out. It is not necessary to know what the operations are, and no attempt will be made to enumerate them here, further than to say that they probably comprise the removal of the final traces of oxygen from the ore, the formation and subsequent superheating of the cinder, and the melting, carbonization and superheating of the iron—"superheating" being used in the sense of heating above the point of fusion.

"Given the existence of such a critical temperature, it is easy to see that where the heating is done by direct contact with the combustion and its products, as in the bosh of a blast furnace, the only heat available for performing the operations which must take place above the critical temperature is the portion left after deducting the amount necessary to raise the products of combustion to that temperature. Or, to state the proposition in another way, if all the heat developed by combustion passed into the products of combustion, there would be available for the work of the hearth only that portion, the removal of which would suffice to reduce the products of combustion themselves to this critical temperature.

"It is obvious that the nearer the critical temperature is to the theoretical temperature of combustion, the smaller will be the quantity of such available heat. If the critical temperature is, say, four-fifths of the theoretical combustion-temperature, then the available heat is only one-fifth of the total; and while the other four-fifths are useful for other purposes, they are lost for those under consideration.

"The critical temperature varies in the same furnace with varying conditions, but for certain conditions it was determined to be about 2750°F., as a probable average, and results obtained from calculations made on this basis were in such close agreement with the results, that the series was extended to cover other conditions, namely, two other critical temperatures, and varying quantities of moisture in the blast.

"Such calculations are extremely simple and involve no uncertain assumptions, the method being as follows:

"The combustion receives heat from three sources: the heat of combustion of carbon to CO; the heat brought in by the blast, and the heat brought in by the fuel. The latter may reasonably be assumed to be brought up to the critical temperature by the gas leaving the bosh, as the heat exchange is a true counter-current one, and the contact is intimate.

"The heat brought in by the coke is therefore $2750 \times 0.21 = 577.5$ B.t.u., the heat of combustion of 0.9 lb. of carbon is $4450 \times 0.9 = 4005$ B.t.u., and the heat brought in by the air at 70°F. (cold blast) is $5.22 \times 0.2375 \times 70 = 86.8$ B.t.u., a total of 4669.3 B.t.u.

"The products of combustion are 4.02 lb. of nitrogen and 2.1 lb. of CO; to heat these to 2750° requires respectively $4.02 \times 0.2438 \times 2750 = 2695.2$, and $2.1 \times 0.2479 \times 2750 = 1431.6$ B.t.u., a total of 4126.8 B.t.u., which deducted from 4669.3 leaves 542.5 as the available heat above 2750°.

"Now assume the blast to be heated to 1000°; the heat brought in by the blast becomes 1241.8 B.t.u., or 1155 B.t.u., more than before; the other items of heat brought in remain the same, as do those of heat removed by the products of combustion; consequently, the available heat is increased by this amount, which is a little more than twice the original amount, making the available heat in this case 1697.5 B.t.u., or more than three times that in the previous case.

"A series of calculations were made on this basis for different blast-temperatures, and also for different critical temperatures; these are given in graphic form in Fig. 3.

"It is perfectly obvious that the higher the critical temperature the less the available heat will be for a given blast-temperature, and *vice versa*.

"The modification introduced by variable moisture content in the blast is not quite so simple, but not in the least complicated.

"By way of preliminary it may be explained that the unit of moisture in the blast here adopted is 1 lb. per 1000 cu. ft. of air, since the latter is the unit of blast measurement. There being 7000 grains in a pound the commonly used unit of grains per cubic foot may be reduced to that here used by simply dividing by 7.

"I had for several years past investigated the subject of the amount of the moisture in the atmosphere as measured by local determinations of the dew point, and as taken from the records of the Weather Bureau, with a view of determining the effect of a given weight of water vapor on the economy of the furnaces, the

ultimate object being to find the relation between the cost of removing the moisture and the value of the saving so made.

"Curves of fuel consumption for the year, taken from the furnace books for the corresponding weeks in several years and averaged, were of exactly the same general shape as the curve of annual humidity, but, calculations of the effect of the humidity, on the basis given by Bell, failed to account for more than a small part of the effect produced.

"No adequate explanation was forthcoming until an analysis of the top gases was made, which should have showed a very considerable quantity of hydrogen based on the moisture contents of the blast, but which actually showed very little. This proved very clearly that the hydrogen formed at the tuyeres by the dissociation of the moisture took oxygen from the ore at a higher level in the furnace, where the temperature was sufficiently low to permit the simultaneous existence of water vapor and carbon, and that in this operation the hydrogen restored as much heat as the original water vapor had absorbed for its dissociation, so that the explanation of the loss caused by the presence of water, mentioned above, was not the true one at all.

"It then became clear that the heat was absorbed at the tuyeres or in the bosh during the process of combustion (it being entirely impossible for water vapor to exist in the presence of incandescent carbon) and, being a first charge on the assets of the combustion, was deducted from the already scanty supply of available heat so that its effects were of the same order and degree, but of opposite kind from those produced by hot blast.

"The calculations of available heat with moisture present have to be modified from those of dry blast, because part of the oxygen required for the combustion of the carbon is furnished by the moisture, and the air required per pound of fuel is accordingly diminished.

"To illustrate, let us take the case of air containing 0.75 lb. of moisture per 1000 cu. ft., or (on the basis previously explained) per 75 lb. of air, corresponding to spring and fall conditions, with blast and critical temperatures as before, 1000°F., and 2750°F., respectively.

"The oxygen in 75 lb. of air is 17.25 lb., and in 0.75 lb. of water is $\frac{8}{9} \times 0.75 = 0.667$ lb.; that is, $17.25 \div 17.917 = 96.28$ per cent. of the total oxygen comes from the air.

"The air per pound of coke is therefore $0.9628 \times 5.22 = 5.022$ lb., and the heat brought in by it is 1192.7 B.t.u.

"The total heat of water vapor per pound at 1000° is 1552 B.t.u., and the water vapor being just 1 per cent. of the air by weight, the quantity brought in is 0.0502 lb., so the total heat brought in by it is 78 B.t.u. The heat of combustion and that brought in by the coke remain the same, so the total assets of the combustion become 6152.6 B.t.u.

"The heat taken out by the nitrogen is 2594.6 B.t.u., that by the hydrogen is 52.4, and that by the dissociation of 0.0502 lb. of water is $\frac{0.0502}{9} \times 61{,}560 = 342.5$ B.t.u. The heat removed by the CO is, as before, 1431.6, or a total thermal expenditure of 4421.1 B.t.u., leaving as the heat available 1431.6 B.t.u. against 1697.5 B.t.u. with dry blast; all other conditions remaining the same. This is a

reduction of 15.6 per cent., just about the difference in fuel consumption that is found in practice under the given conditions. If the same loss were referred to the

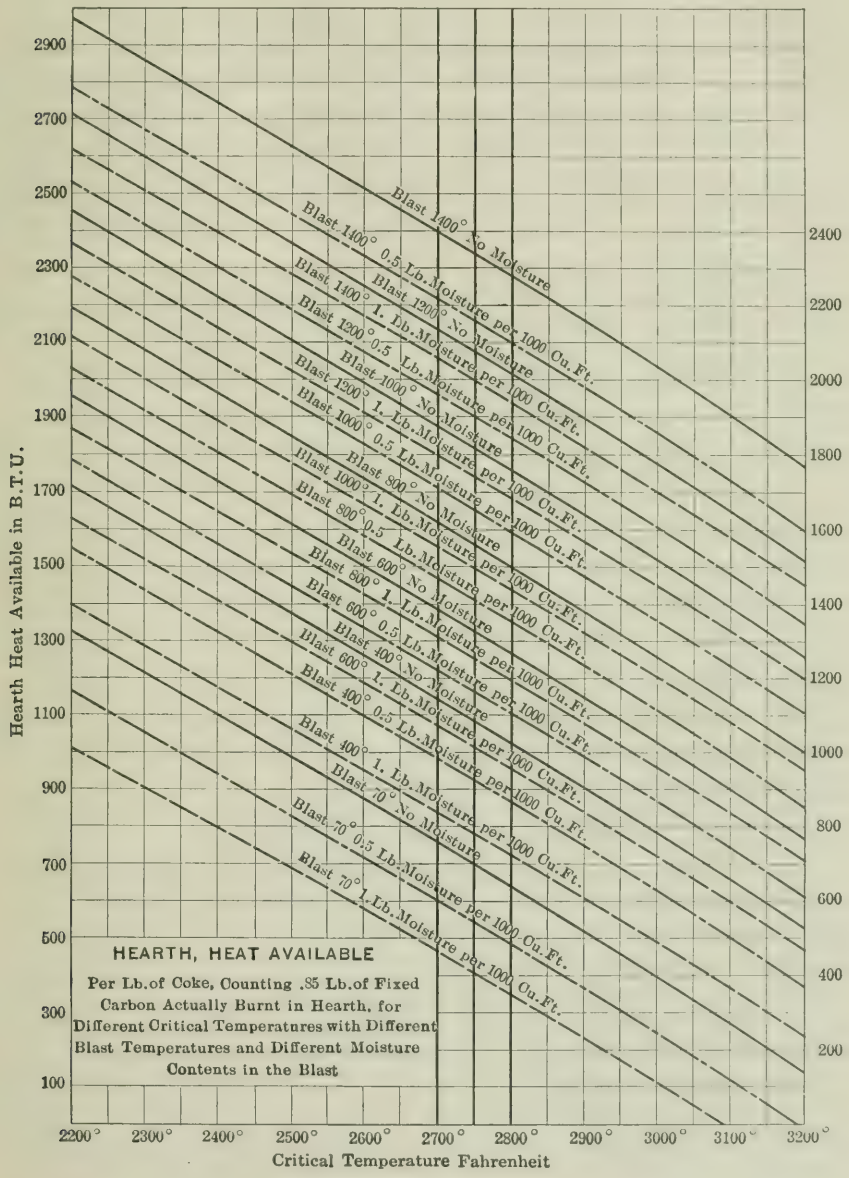


FIG. 3.

6000 B.t.u., which represent the approximate total heat development from 1 lb. of fuel, the loss would be 4.4 per cent., which is an insignificant fraction of the actual results in practice.

"The results given in Fig. 3 were obtained by a series of calculations similar to the above.

"It is hoped that these diagrams will have more than an academic interest to furnacemen, as they furnish an easy means of determining the probable results in fuel economy of any change in the temperature or humidity of the air. They also furnish the means of determining the increase in blast-temperature necessary to counteract the effects of a given variation in moisture. While it does not now seem likely that we shall ever obtain stovemen who will determine the moisture from hour to hour, and proportion the blast temperature to meet it, the thing is not impossible; and if some genius would kindly invent a recording and direct-reading instrument for measuring the humidity of the atmosphere, this result might be achieved in fact.

"These results, being based on what is supposed to be a new theory of the action of heat and moisture in the blast, will naturally be viewed with some skepticism, so that proofs of their substantial accuracy are in order.

"Fortunately the data supplied by Mr. Gayley furnish an admirable opportunity. The critical temperature alone is lacking, but from the kind of iron made may be assumed to have been 2750°F. The humidity, before the dry blast was used, averaged about 5.25 grains per cubic foot, or 0.75 lb. per 1000 cu. ft., and the blast-temperature was 720°F. After the application of the dry blast the humidity was about 2 grains, or, say, 0.3 lb. per cubic foot, and the blast-temperature was 870°F. By interpolation on the diagram we find the available heat in the two cases to be 1090 and 1420 B.t.u. per pound of fuel respectively. The coke consumption before the change was about 2140 lb. and, to be in inverse proportion to the available heats, should have been 1640 lb. after the change. Actually it was 1700 lb., a difference which is certainly no larger than might reasonably be expected, considering the many other factors varied. Notable among these is the increased ratio of CO_2 to CO in the top gases, with the correspondingly increased tendency of these gases to dissolve carbon from the fuel in the upper part of the furnace, and prevent its reaching the hearth.

"This feature, of which, obviously, the diagrams can take no cognizance, is of the first importance in an exact determination of results.

"At many works the effects of the higher humidity of the summer are masked by the fact that the furnaceman carries a higher heat in summer than in winter, either deliberately and for purpose of neutralizing the effect of the humidity, or simply because he finds that the furnace will stand more heat without sticking or other objectionable results. But at the furnaces with which the writer is connected, a constant temperature of 850° is carried the year round, and under these conditions the variation in fuel is clearly apparent, the fuel per ton of iron being about 20 per cent. more in the most humid weather than in the dryest. The critical temperature at these furnaces is known to be about 2750°F., the average low humidity is about 0.25 lb. water vapor per 1000 cu. ft., and the average high humidity is about 0.95 lb. For these conditions we find from the diagram that the available heats are 1400 and 1160 B.t.u., which are in the ratio of 1.20 : 1, or precisely the same as the fuel consumption in the two cases.

"In order to obtain a wider range of comparison, I have taken the work of a 2 weeks' period in 2 successive years (at precisely the same season in each) done by a small charcoal blast furnace, working with cold blast one year and hot the next.

"The comparison is not very satisfactory, because the critical temperature could only be obtained approximately in one case and estimated in the other, the percentage of lime used being twice as great for hot blast as for cold, with a correspondingly great influence on the critical temperature (as will be explained presently). Moreover, in the cold-blast campaign a considerable quantity of cold slag was charged, to overcome the tendency to work "dry," which was not done in the hot-blast campaign.

"The recorded fuel consumption in the two cases was in the ratio of 1.7 : 1, while the available heats based on the probable critical temperatures in the two cases and without allowance for the remelting of the additional slag in the cold-blast campaign are as 1 : 2—a reasonable correspondence, considering the circumstances.

"I recently found what appeared to be an authoritative statement, that at the Clyde Iron Works (England) the fuel consumption in January-August of 1829, 1830 and 1833, with cold, warm (300°), and hot (600°) blast respectively, was 8 tons, 1 cwt., 1 qr.; 5 tons, 3 cwt., 1 qr.; and 2 tons, 5 cwt., 1 qr., or fuel consumption in the ratio of 3.42 : 1.56 : 1, while the available heats, with a critical temperature of 2750° and average moisture, are as 1 : 1.73 : 2.63, a correspondence which is not by any means accurate, but considering the magnitude of the saving and the probable effects of secondary results is not at all to be despised.

"Other considerations of the same general kind in which the data are not available for quantitative comparisons will be given later, but will best be preceded by some remarks on the determination of the critical temperature.

Determination of Critical Temperature.—The paucity of published data of definite character on this subject led me to attempt direct experimental determinations.

"This seemed a field in which a radiation pyrometer might be employed more conveniently than any other, and with the advantage of absolutely self-luminous bodies to observe. Accordingly, a Mesuré & Nouel 'lunette' pyrometer was obtained. This instrument is not exact, and, for wide ranges of temperature, particularly at the upper or lower extremities of the scale, could not be trusted very far; but for a limited range near its center results obtained by any reasonably careful observer are closely comparable.

"Many thousand observations were made with this instrument upon the iron and the cinder, where they flowed over their respective dams, at every stage of many hundred casts.

"At first no connection whatever could be observed between the condition of the furnace, the kind of iron being made, and the reading of the pyrometer. Sometimes, it would show much higher temperatures with white iron than with gray, and, again, it would give the opposite result, until I almost gave up hope of getting any information as to the action of the furnace from it. But, finally, I observed that the readings were influenced almost solely by the relative calcareousness or siliceousness of the slag, and the difficulty of interpretation then disappeared.

"One or two things were eventually brought out with great clearness which are not recorded elsewhere, so far as I know, and are therefore given here, since, though they may be known to others, their publication may still serve to bring out valuable discussion.

"The first point noticed was the absolute collapse of the old notion that gray iron was always made in a hot furnace, and white iron in a cold one. (The furnaces were working on basic iron, and the silicon was therefore limited to 1 per cent., so that gray iron in this case means iron with only about this percentage of silicon.)

"The next observation was that, in spite of the common statement that black cinder is made because the furnace gets too cold, the black cinder, in reality, was very frequently much hotter than the light.

"On the other hand, the old founders' saying that 'lime gives heat to the furnace' was confirmed completely, the cinder being without exception hotter in proportion, as it was more limy, as long as the furnace continued to make good iron. Even when the iron became hard, the cinder might still be at its very hottest if very limy.

"It was also noticed that the cinder always controlled the temperature of the iron, and that as long as no cinder came through the tap hole the temperature of the running iron remained practically constant, but as soon as the cinder came the temperature of the iron went up considerably and became the same as that of the cinder, which was always decidedly higher than the previous temperature of the running iron.

"These observations, confirmed so many times that their accuracy for the given conditions could not be questioned, made it plain that, since the cinder became less fusible as it became more calcareous, it remained longer in the bosh, exposed to the heating action of the ascending gases, before acquiring the high fusion temperature at which it could flow down into the hearth, while less calcareous slags melted sooner and ran down out of the range of action of the products of combustion.

"The cinder, moreover, exercises a deterrent action on the iron as it drips down through the bosh, and by delaying its passage longer, as well as by direct contact, heats the iron nearly to its own temperature, a process which is completed as the metal passes through the layer of slag on top of the iron in the hearth.

"The cinder requires not only to be heated up to its temperature of fusion, but far enough beyond this point to give it sufficient fluidity and consequent activity to remove the sulphur coming from the coke, and permit the dissolved oxide of iron to separate out.

"So long as sufficient heat is produced in the hearth to impart to the cinder the temperature necessary to give this fluidity, the iron oxide is reduced and separates out; the cinder remains bright; and silicon can be reduced and can stay in the iron, making it gray. But when the temperature required is so high that sufficient heat for this purpose is not furnished in the hearth, the cinder becomes too thick and viscous to permit the operations mentioned; the oxide of iron remaining in it makes it black and, acting as a powerful oxidizer, prevents silicon from going into the iron.

"This condition may arise in any one of three ways: (1) By an increase in the lime-content of the slag, raising its fusion temperature; (2) by a reduction in the quantity of available heat, due to decreased temperature of the blast or increase of moisture; or (3) by a slip, bringing down into the hearth a quantity of improperly digested material.

"It thus becomes evident that the temperature necessary, not only to melt the

cinder, but to make it sufficiently fluid to perform its functions properly, is the 'critical temperature,' since the slag and iron must be brought to this temperature, and the final reduction of the ore must be performed above it (and, most probably, other reactions). What may for convenience be called the free-running temperature of the cinder is therefore taken in this paper as the critical temperature.

"Facts of Practice Explained by the Critical Temperature.—One of these is the fact that furnaces working on rich ores do not commonly show the low fuel consumption as compared with those working on siliceous ores, which might be expected in view of the large quantity of heat required to melt the slag. The explanation seems to be that in smelting the richer ores the much smaller slag volume available for carrying off sulphur, requires a much more calcareous slag, and therefore a higher critical temperature, which reduces the available heat per pound of fuel enough to offset largely the advantage of having less slag to melt.

"The extremely low fuel consumption of charcoal furnaces furnishes an illustration of the opposite kind. Having practically no sulphur in the fuel to contend with they can run on a very siliceous and fusible cinder, so that their critical temperature is several hundred degrees lower than that of coke furnaces smelting the same ore—which largely increases the amount of available heat.

"The fuel consumption of furnaces making ferromanganese is, on the other hand, out of all proportion to that of iron furnaces in view of the fact that the heat required for the reduction of MnO_2 is only 25 per cent. more than for that of F_2O_3; but this again becomes explicable when we consider the temperature necessary in the two cases, which, though not definitely known, is known to be much higher for manganese than for iron. In the case of iron, nearly all the reduction is effected before the charge reaches the critical temperature; but with manganese this is far from being the case. The quantity of "available heat" required is therefore much higher, as well as the temperature of its application, and the fuel consumption per pound of manganese is therefore much greater.

"Similarly the fuel consumption in the production of iron with 3.5 per cent. silicon is probably at least 20 per cent. greater than that required for 1.5 per cent. silicon iron, though the difference in the heat actually required for its reduction is only 7 per cent. But the silicon cannot be reduced at all except at high temperatures and the critical temperature is therefore raised, as well as the quantity of heat required above it, so that the fuel consumption is augmented in correspondingly higher ratio.

"It is interesting in this connection to consider why in order to make high-silicon iron with a reasonable fuel expenditure a small hearth is necessary. The reason probably is that since the necessary high temperature may not be secured by the use of calcareous slag (because such a slag does not allow the silica to leave it and be reduced to silicon) it can be secured only by a longer exposure of the charge to the products of combustion, and for this purpose the currents of both gas and dripping iron must be of smaller cross-section, thereby virtually lengthening them and increasing the number and duration of the contacts of the dripping iron with the incandescent fuel—the condition most favorable to the reduction of silicon and its absorption by the iron.

"If the claim here made for the existence and position of a 'critical' temperature be admitted, it follows that the attainable economy of fuel is subject to a double limitation: (1) By the total development of heat produced in the furnace

per pound of fuel; and (2) by the proportion of this heat available above the critical temperature.

"A legitimate corollary to this proposition is, that the work done in the process may be divided into two parts, that done below the critical temperature and that done above it, corresponding approximately to the work done above the zone of fusion and that done below it, or, roughly, to that done in the shaft of the furnace and that done in the bosh and hearth. We may for convenience call these respectively the preliminary and the final work. The total heat introduced into and developed in the furnace being H_t and the part expended in the bosh and hearth in the final work being H_a (the 'available' heat), the heat necessary for the performance of the preliminary work is $H_t - H_a$.

"From the investigations of Bell and others we know with considerable accuracy the total quantity of heat required for the production of a unit weight of pig iron, and from the diagrams herewith given we can determine approximately the proportion of this which must be applied above the critical temperature. In view of the preceding discussion it is apparent that there must be a reasonably definite ratio between these two quantities or between the latter and their difference—in other words, between H_a and $(H_t - H_a)$.

"This can be put in the form of an equation which will help to make the matter clear. If we call the total heat required to produce a unit of iron R_t, and the fuel required per unit of iron (calculated on this basis) n_1 (H_t being, as before stated, the total heat developed in the furnace by the unit of fuel), we have

$$\frac{R_t}{H_t} = n_1 \qquad (A)$$

or $R_t = n_1 H_t$, the equation, of which both sides were so magnificently and completely analyzed by Bell.

"If, however, we denote by R_a the heat required, above the critical temperature, per unit of iron produced, H_a being the available heat and n_2 the fuel consumption determined on this basis, we have

$$\frac{R_a}{H_a} = n_2 \text{ or } R_a = n_2 H_a \qquad (B)$$

"Both (A) and (B) must be satisfied if the reduction is to be complete.

"If we should increase the degree of oxidation of the fuel, and thus increase H_t without affecting H_a we would effect no fuel economy since we should do the preliminary work upon a larger quantity of ore than the available heat could take care of in the bosh. The furnace would consequently become cold and an increased quantity of fuel would have to be used to make good the deficiency in available heat.

"If, on the other hand, we increased the available heat H_a without increasing the total heat H_t we should either change the grade of the iron enough to absorb the heat-excess or drive the heat up to the higher zones of the furnace, with those disastrous results which furnacemen know under the caption 'too hot and sticking.' But no fuel would be saved, because no more heat being produced for the preliminary work no increase in the quantity of ore prepared for final reduction could take place, hence no increase of output for the same fuel.

"It is thus seen that it is necessary to increase the two quantities of heat in the same ratio if any economy is to be achieved."

It should be particularly noted that, as mentioned above, the mere conception of a critical temperature without determining what this temperature is and what controls it, is of little use and the determination that it depends upon the free-running temperature of the slag is almost as important and as useful in understanding the action of the furnace as the conception of the critical temperature itself.

In fact, the French metallurgist, M. A. Lodin, published in *Comptes Rendus,* Nov. 28, 1904, a brief note suggesting the critical-temperature theory to account for the results of the dry blast, but used the fusion temperature of the slag instead of the free-running temperature as the critical temperature. He did not connect the theory with the effect of hot blast or the broad facts of practice, or give any quantitative results, and the suggestion did not receive any attention, so far as known to me. My own "disclosure" of the idea was made in patent applications filed April 9, 1903 (see U. S. patent 783,044), and my original chart of "available heats" was dated and witnessed 1902.

Since that time it has become evident that the term "available heat" is too loose, since heat not "available" in the hearth passes up into the shaft of the furnace and does useful work there, so becoming available. I have therefore substituted the terms "hearth heat" for this and use the corresponding term "shaft heat" for that developed or carried into the shaft.

The first requisite to making and understanding such calculations is a table of thermochemical data and specific heats and I give below tables III, IV and V of these quantities, taken from Professor J. W. Richards' "Metallurgical Calculations" and where necessary, converted to Fahrenheit temperatures and British thermal units instead of calories.

This excellent work had not been published at the time the calculations in the article above quoted were made and the data available to me were not so accurate as those given by Professor Richards.

I have recently recalculated the hearth heats under different conditions in accordance with these more accurate data, using also the heat of combustion of the carbon at the given critical temperature in each case instead of the heat given as reduced to atmospheric temperature. The results are shown in the chart, Fig. 3. This is substituted for the original chart, as the results it gives are the same in principle but somewhat more accurate and the range of conditions covered is wider.

It will be noticed that the chart is based on 85 per cent. fixed carbon burned in the hearth which may seem strange as all good coke is much higher than this in fixed carbon. The reason is that the iron made takes up about 4 per cent. of its own weight of carbon so that on the basis of a pound of coke of 89 per cent. fixed carbon per pound of iron, 0.85 lb. carbon represents approximately the actual amount burned in the hearth with no solution loss, but when much of the coke is lost by solution, it is

TABLE III

Element	Compound	Molecular weight	Heat of formation, B.t.u.			
			Per lb. molecule	Per lb. element	Per lb. oxygen	Per lb. compound
Fe....	Fe_2+O_3	112+48	352,000	3,145	7,330	2,200
	F_3+O_4	168+64	487,500	2,905	7,625	2,100
	Fe+O	56+16	118,300	2,115	7,390	1,480
C.....	C+O	12+16	52,500	4,375	3,280	1,875
	$C+O_2$	12+32	175,000	14,750	5,470	3,980
	CO+O	28+16	122,500	CO 4,375 C 10,400	7,650	2,790
H.....	H_2+O to vapor	2+16	109,000	54,500	6,530	5,806
Mn...	$Mn+O_2$	55+32	226,000	4,110	7,060	2,600
	Mn_3+O_4	165+64	591,000	3,580	9,250	2,680
	Mn+O	55+16	163,600	2,985	10,230	2,308
Si.....	$Si+O_2$	28+32	324,000	11,580	10,130	5,400
P.....	P_2+O_5	62+80	657,500	10,600	8,210	4,630
Ca	Ca+O	40+16	236,600	5,910	14,780	4,220
	(Ca+O)+(C+O_2)	40+12+48	493,000	.....	.....	814
Mg...	Mg+O	24+16	258,000	10,740	16,130	6,450
	(Mg+O)+(C+O_2)	24+12+48	486,000	.....	.....	662

TABLE IV.—SPECIFIC HEATS OF GASES

Substance	Temperature range F.	Specific heat		Volume of 1 lb. in cu. ft.	Weight of 1 cu. ft. in lb.
		Per lb.	Per cu. ft.		
H.....	0°–3,600°	$3.37+0.00017t$	$0.0189+0.0000009t$	178.230	0.00561
O.....	0°–3,600°	$0.2104+0.0000104t$	$0.0189+0.0000009t$	11.209	0.08920
N.....	0°–3,600°	$0.2405+0.0000119t$	$0.0189+0.0000009t$	12.752	0.07840
CO.....	0°–3,600°	$0.2405+0.0000119t$	$0.0189+0.0000009t$	12.804	0.07810
CO_2.....	0°–3,700°F	$0.19+0.00006t$	$0.023+0.000008t$	8.102	0.12340
Air.....	.....	$0.234+0.0000111t$	$0.0189+0.0000009t$	12.387	0.08070
CH_4 "Kent"....	.....	0.5929	.....	22.301	0.04488
Carbon.....	0°–482°F.	$0.1567+0.0002t$	.....	Gas 29.850	0.03350
Carbon.....	482°–1,832°	$0.2142+0.00009t$			
Carbon.....	Over 1,832°	$0.5-\frac{216}{t}$			
H_2O, gaseous.....	Up to 3,600°	$0.42+0.000103t$	$0.021+0.000005t$		

TABLE V.—SPECIFIC HEATS, ETC., SOLIDS

Substance	Temperature range F.	Sm.	Melting point	Latent heat fusion, B.t.u.
SiO_2	0°–t°	$0.1833+0.000042t$	3,450°	243
CaO	(Est.)	$0.1715+0.000004t$		
MgO	Any	$0.2420+0.00001t$		
$CaOCO_2$	68°–212°	0.2086		
CaO, MgO } $2CO_2$	68°–212°	0.2179		
Al_2O_3	Any	$0.2081+.0000487t$	About 4,000°	917
Fe_2O	.....	$0.1456+0.0001t$		
——	.....	$0.1447+0.0001t$		
FeO	(Assumed)	0.1460		
MnO	.....	0.1570		
MnO_2	.....	0.159		
$Mn_2O_3H_2O$	.....	0.1760		
Silicates:				
Mg_2SiO_4	32°–212°	0.220	2,550°	234
$MgSiO_3$	32°–2,200°	0.301	2,375°	207
$CaSiO_3$	32°–2,200°	0.288	2,280°	180
$CaAl_2Si_2O_8$	32°–2,200°	0.294	2,230°	180
$Ca_2MgSi_4O_{12}$	32°–2,200°	0.264	2,190°	170
$CaMgSi_2O_6$	32°–2,200°	0.281	2,400°	180

necessary to determine the actual weight of fixed carbon burned in the hearth. The results taken from the chart can be applied to this actual weight (in pounds) by dividing by 0.85.

We shall later revert to this matter of solution loss and its consequences at greater length.

Need often arises to figure quickly the total heat imparted to the furnace by the coke under different conditions, allowance being made for the CO_2 from different proportions of limestone, for different top temperatures, and different ratios of CO to CO_2 in the top gas; for this purpose, a chart, also from "Notes on the Physical Action of the Blast Furnace," is reproduced as Fig. 4, from which this quantity may be directly taken. $L = 0$ means the conditions when no limestone is charged and $L = 1$ means 1 lb. per pound of coke; intermediate quantities can easily be interpolated by eye with sufficient accuracy. A supplementary diagram at the top gives the heat brought by the blast for a pound of coke at different temperatures which should be added to the other for the total. This diagram saves much tedious figuring, but must be used with discretion because it takes no account of the presence of any hydrogen which is often produced by the decomposition of moisture from the charge and the oxygen from this moisture oxidizes CO to CO_2 and gives a very distorted impression of the true conditions, unless its source be taken into considera-

tion, because the decomposition of the water absorbs almost as much heat as the corresponding oxidation of CO to CO_2 gives out.

This diagram is based on 0.9 lb. carbon while Fig. 3 is based on 0.85 lb. The discrepancy arose when Fig. 3 was recalculated, both having been based on 0.9 lb. originally; 0.85 is undoubtedly more correct, but

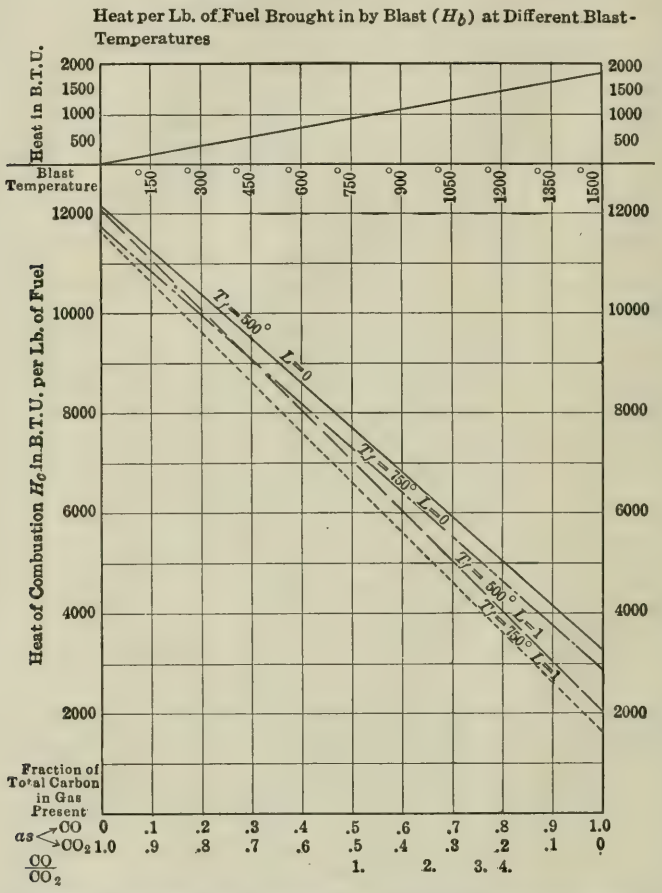


FIG. 4.—Diagram showing heat imparted to stock, by combustion of 1 lb. of fuel (90 per cent. C.) with different ratios of C. to CO_2., Top temperatures, and weights of limestone per lb. of fuel, also (above) heat brought in by blast, H_b.

Fig. 4 can only be used for rough approximations, and it is hardly worth while to recalculate it merely for the sake of uniformity.

Returning now for a moment to the comparison of the theory of the blast furnace with thermodynamics it may be shown that what may be called the availability factor can be expressed in the same mathematical terms in both cases.

The second law of thermodynamics is expressed by the formula

$Q \times \frac{T_1 - T_2}{T_1}$, in which Q is the total quantity of heat concerned in the transformation, T_1 is the temperature at which it is applied and T_2 is that at which the unused portion is rejected.

Now in the blast furnace if the whole quantity of heat developed in the hearth be Q, the theoretical combustion temperature be T_1 and the critical temperature be T_2, since the heat given out by a gas in cooling is nearly proportional to the temperature drop $T_1 - T_2$, the portion of the whole which can be utilized in the hearth is $\frac{T_1 - T_2}{T_1} \times Q$, the same as in the case of steam engine.

This is in one sense only a matter of casual interest, but in view of the increasing connection recognized between chemistry and thermodynamics it is highly suggestive.

Not One But Two Thermal Equations Control.—It will be noted that the idea that there are two heat balances for each furnace, one for the shaft, the other for the hearth and bosh, is set forth very plainly in the quotation before given from "Notes on the Physical Action of the Blast Furnace," but the difficulty of getting at the debit side of the account seemed almost insuperable, and on this account I did not for several years use the chart of hearth heat for any but comparative purposes, to show the heat obtainable per pound of coke with different blast and critical temperatures and different percentages of moisture in the blast, because the furnaces of which I had the management were coke furnaces on relatively lean ores, and in such cases the hearth heat obtainable per pound of coke exercises exclusive control of the economy of the furnace when other details of operation receive proper attention.

A few years ago when I undertook the management of a charcoal furnace using rich ores I attempted to apply the same principles and methods of calculation to it, but soon found that there were many features of its operation which could not be explained on that basis.

For instance, covering in the ends of the blowing cylinder and piping the air to it from out of doors in a very dry climate yielded no better results than taking the air from the engine room, although figures from the chart of hearth heat based on the humidity in the engine room indicated that a considerable saving should result. Similarly, changes of blast temperature exerted little or no influence on the running of the furnace compared with what similar changes would do on a coke furnace, and in particular it seemed impossible to save the furnace by the use of more blast heat when it started to run cold. It was absolutely necessary to put more fuel down into the hearth.

Finally it occurred to me that the hearth heat per pound of iron generated in that practice might be greater than was needed, and that a comparison of that developed in charcoal practice with that developed

in coke practice might be illuminating. I had been taking observations of the free-running temperature of the slag, so I knew approximately what it was; this, with the blast-temperature and the fixed carbon in the charcoal per pound of iron, supplied the necessary data for the calculation, which showed 1300 B.t.u. of hearth heat developed per pound of iron, while that developed in coke practice at the Isabella furnaces in Gayley's test was only about 1000 B.t.u.

This astonishing result was the more remarkable because about 1200 lb. of slag per ton of iron were made in the coke practice and only about 500 in the charcoal. This could only be interpreted in one way, that more hearth heat was being developed than the furnace needed, and the excess was passing up into the shaft of the furnace and finding utilization there, but only in doing relatively low-temperature work. This in turn could only mean that the heat developed in the shaft was deficient in comparison with the hearth heat, and that if means could be found to increase the shaft heat the increase would prepare for final smelting in the hearth a greater proportion of ore, of which the excess of hearth heat could take care, so that the burden could be increased and the fuel consumption reduced, and incidentally, as we shall later see, the quality of the iron improved.

The ore used was a clayey Gogebic ore carrying normally 13 to 14 per cent. of moisture, and a preliminary calculation showed that the abstraction from the small volume of gas which a charcoal furnace produces of the heat required to evaporate this moisture must lower the temperature of the gas about 400°, and as it was being discharged at about 200°F., it seemed as though the gas temperature would be high enough to do considerably more reduction, especially as the gas was amply rich for this purpose, if it did not have to drive off this water.

This seemed then to be a case in which the fuel economy of the furnace was controlled exclusively by the shaft heat developed per pound of fuel, the hearth heat playing a purely secondary rôle.

In order to ascertain whether this could be true detailed calculations were made covering the operation of the furnace as it was running and as it was believed it could run with dry ore. A similar set of calculations was then made covering the operation of a coke furnace which had made an excellent run to see how the existing and assumed charcoal cases compared with it.

The results of the whole investigation, which covered several months of laboratory work and all my time which could be spared from other work for 3 months or more, were embodied in a report to the executive of the company.

The major portion of this report is given here, as it covers the situation better than can be done in any other way.

THE EFFECT OF WET ORE ON CHARCOAL-FURNACE PRACTICE

"The conception that the great quantity of moisture present in the soft ores used in the charcoal practice of this district might affect the working of the furnace by undue cooling of the top gradually took shape in my mind from observing the top temperatures at a time when our fuel consumption was high.

"According to all previous experience high fuel goes with a high top temperature, but last fall when we were having fuel consumptions of 95 to 100 bu.[1] our top temperature was down around 200° to 250°.

"A brief calculation based on the volume of gas and the quantity of moisture in the ore showed that the heat required to evaporate the water was sufficient to lower the temperature of the gas 300° to 400°. We had also found, by a good many analyses, that our top gases were as rich in CO as those of a coke furnace, although burning as we do much less fuel per ton of iron than in coke practice this should not be the case. An analysis of the conditions was begun, based on three considerations:

"1. The ability of the gas to carry off all the oxygen of the ore with a given fuel consumption. This depends on the extent to which CO can be oxidized to CO_2 in the presence of iron ore at different temperatures.

"2. The total amount of heat developed in the furnace by the oxidation of the fuel to the extent at which it passes out in the top gases.

"3. The development of a sufficient amount of heat in the hearth to carry on the reactions which can take place only above the temperature at which the cinder runs freely.

"The importance of this last point rises from the following consideration: The fuel, say at the free-running temperature of the cinder, is burned by the blast at its incoming temperature with the development of a certain amount of heat, which, in the absence of burden, would heat the gases to a temperature known as the theoretical combustion temperature. When the burden is present, these gases are cooled down by it and give out their heat as they cool, but it is obvious that they cannot supply any heat at or above the free-running temperature of the slag (known as the critical temperature) after they are cooled down to that temperature. The amount of heat which they give out in cooling from the theoretical combustion temperature to the critical temperature may therefore be called the hearth or high-temperature heat. In coke practice the amount of this heat developed is generally smaller proportionately to the needs of the furnace than the total heat developed, and, consequently, it is the amount of this heat available which limits the fuel economy of a coke furnace. But in charcoal practice the critical temperature, that is, the free-running temperature of the slag, is so much lower than that of coke furnaces that the range from theoretical combustion temperature to critical temperature is much greater, and, therefore, the amount of hearth heat developed per pound of carbon is much higher, and it has been found by calculating the amount of high temperature heat developed per hundred pounds of iron in good coke practice, and the amount developed in our practice, that the latter was considerably *higher* than the former, although the slag volume to be melted and other work to be done in the hearth is much lower in our case.

"This indicated to my mind that we were developing more hearth heat than we needed, and making our iron hotter and of poorer quality in consequence, and I

[1] A "bushel" is 20 lb. of dry hardwood charcoal.

thought at that time that we should have some way of increasing the oxidation of the top gases so that we could increase the amount of heat in the upper part of the furnace, which, for lack of a better term, I call the shaft heat—shaft being the only name I know of for the portion of the furnace from the bosh to the top.

"After I had made the calculation showing how much the temperature of the gas was lowered by having to evaporate the moisture in the ore, it seemed to me that if the ore were thoroughly dried the top temperature would go up so much that the gases would be oxidized a good deal further, which would develop more heat per pound of carbon in the shaft, and as we had a surplus in the hearth this would enable more burden to be carried.

"In order to make reasonably accurate calculations, it was necessary to investigate along three lines as a preliminary: (1) the free-running temperature of the cinder; (2) the exact composition of the charcoal; (3) the extent to which the CO could be oxidized in the presence of iron ore at given temperatures.

"1. We have been carrying on, to the best of our ability, investigations of temperature of the running iron and cinder for over 2 years, and while they have not been completely satisfactory, they seem to indicate a temperature of 2300°F. as that at which a normal charcoal slag will run sufficiently freely for the furnace to work. Similar observations on coke furnaces several years ago indicated a temperature of about 2700°F. as that of a good slag in Bessemer practice.

"2. The composition of the charcoal. This was a matter on which we had made experiments in the past, but they were not successful enough to be considered reliable. We, therefore, put a piece of charcoal in an alundum boat in a silica tube heated by an electric furnace, surrounded it with an atmosphere of CO and heated it until no more gas came off. The gas was caught in rubber bags, its volume measured and its analysis obtained. The volume of CO used to fill the furnace was deducted from the total volume and the analysis of the gas was figured back to what it would have been if the CO had not been added in advance. Such a determination was made for birch and one for maple. The results checked exceedingly closely. As a further check the specific gravity of the gas was taken by weighing a small gas bag full of it, and this was compared with the specific gravity calculated from its analysis. The check was excellent. The charcoal remaining was weighed and then burned. The weight as taken from the electric furnace less the weight of the ash was considered to be the fixed carbon of the coal. From the analysis and volume of the gas evolved the weight of each gaseous component was figured and these were reduced to percentages by weight of the original sample of charcoal. The variations between birch and maple were very slight, and were averaged to obtain the figures given in Table VI.

Table VI.—Average Charcoal Analysis for Birch and Maple

	Per cent
CO_2	4.50
O_2	0.67
CO	11.10
H_2	1.65
CH_4	3.40
N_2	7.77
Fixed carbon	68.50
Ash	1.00

"3. The extent to which the CO could be oxidized in the presence of iron ore at given temperatures. After overcoming the worst of the difficulties in this determination, we were unable from lack of time to get a long series of these determinations at different temperatures, as we had hoped, but we demonstrated by several runs that at a temperature of about 700°F. 62 per cent. of CO_2 were in equilibrium with 38 per cent. of CO. This means that if sufficient time were allowed it would be possible to oxidize the top gases so that the CO_2 would hold this ratio to the CO at this temperature. We also proved conclusively that the equilibrium percentage was much higher in CO_2 as the temperature arose. At 800° it is about 70 to 75 per cent., and at about 900° it is around 80 per cent. CO_2, but these figures are not exact.

"These were the data on which our calculations had to be based. It was decided first to take the conditions which prevailed with this furnace at the time these calculations were started. Ninety-five bushels of coal, 50 per cent. ore yield, 13.50 per cent. moisture in the ore, 400 lb. of limestone per ton of iron. From the tonnage made and the revolutions of the blowing engine the amount of blast per 100 lb. of iron was obtained, and by temperature observations of the air going into the cylinder and coming out it was possible to get a rough check on the displacement of the air cylinder. All gas volumes are reduced to 30 in. barometer and 32°F. The specific volumes of gas are those given in Kent, and heats of combustion are taken from the same source, but the specific heats of the different components in the operation are taken from Richards' "Metallurgical Calculations." The specific heats given in Kent are not exact for high temperatures.

"It is necessary to call attention to one fact of much importance. The charcoal gas contains appreciable quantities of hydrogen and methane. Hydrogen requires for its combustion eight times its weight of oxygen, and methane for combustion to water and CO_2 requires four times its weight of oxygen. These are both very active reducing agents and will take up oxygen from the ore with great rapidity at a reasonably high temperature, 600° to 800°, but with the conditions under which the furnace works the top temperature is so low that they pass off largely without action on the ore. Our analyses have repeatedly proven them to be present in top gases. The quantity of oxygen which they can absorb is so great that the question whether they are oxidized completely or not affects the composition of the top gas tremendously.

"I have assumed that in a furnace using wet ore and 95 bu. of coal three-fourths of the hydrogen was burned and none of the methane, because this gives results which check out well with the actual gas analyses we obtained from the furnace, but, unfortunately, we did not get any during the exact period covered by the above assumption. However, the analysis of the gas in both CO_2 and CO, as well as in hydrogen and methane, is so close to what we actually found that no material error can be introduced into the heat calculations by any inaccuracy in these assumptions.

"A further fact is that the heat developed by combustion of CO and that developed by hydrogen per pound of oxygen consumed is nearly the same. Therefore, it is a matter of slight importance in regard to the development of heat whether the oxygen to be disposed of is consumed by hydrogen or by CO.

"Having made the calculation for 95 bu. of coal, I then made an exactly similar one assuming 75 bu. of coal with the ore thoroughly dried, and in this

calculation I assumed that the gases would pass off at 400° higher temperature than in the other, 632° as against 232°, assumed as a fair average of the actual temperatures for 95 bu. with wet ore. This assumption was made because of the fact before mentioned that the amount of moisture present in the ore is sufficient to cool down the gases about 400°. In this case I assumed that the hydrogen and methane were completely oxidized because previous investigation on a furnace with a moderately warm top had shown this to be the case.

"In order to get some comparative figures from another source, I have made a similar analysis of the run of a coke furnace described by A. K. Reese, in vol. 27 of the *Transactions* of the American Institute of Mining Engineers. This was a 6 months' run on the furnace at Canal Dover, Ohio. In order to check out the quantity of wind blown with the gas analysis given, it was necessary to assume that the volatile matter in the coke in this latter case consisted of methane and hydrogen, and that these were oxidized in the top of the furnace, as above described.

"Before proceeding to discussion of the results obtained in the three cases, it will be well to point out that the method of calculation of the total heat developed in the furnace is the time-tried and accepted one. The method of calculating the heat in the hearth has been used for the last 7 or 8 years, and has proven itself so reliable in giving relative figures in comparative cases that it is now generally accepted.

"In regard to the degree of oxidation of the gases in any given case, it is not commonly realized that this can be figured with considerable accuracy. The amount of blast blown supplies a given quantity of oxygen and the ore charged supplies another quantity. A slight additional amount comes from the gas given off by the charcoal, and a somewhat larger amount from the CO_2 of the limestone. All these have to come out of the stack, combined with the carbon which enters in the form of fuel and in the form of CO_2 in the limestone, except for that which comes out combined with the hydrogen of the fuel. This, of course, is in the form of water and disappears in the gas analysis.

"As we know, with considerable accuracy, all of these weights of carbon, and hydrogen, and of oxygen, the degree of oxidation of the products of combustion can be accurately calculated and the heat developed determined with corresponding accuracy.

"All of the ores in this district are hematites, and therefore each 70 units of iron contain 30 units of oxygen, and the oxygen combined with the iron can be accurately figured from this. To this must be added the oxygen which comes from the silicon going into the iron, and due account must be taken of the fact that iron contains only about 95 units of Fe. I have assumed about 1.00 to 1.25 per cent. silicon, and have neglected the manganese in all cases, as the amount of oxygen accompanying it is too small in proportion to the possible variations in the larger quantities to be given serious consideration. This gives 42 lb. of oxygen released from the ore and silica per 100 lb. of iron. (It is very desirable to have a symbol which shall represent pig iron as distinguished from chemically pure iron, Fe, and for this purpose I have used the letter "I," because iodine does not enter into the discussion and no confusion can result.)

"The volume of blast blown was estimated from the displacement of the blowing cylinder, some allowances being made for the suction in the cylinder when the

TABLE VII.—
1667 lbs. of Cok
(Canal Dov

HEARTH and BOSH

COMPONENT	Line Nos.	SOURCE	In Hearth and Bosh	Product	Disposal	Temp. at Ent'nce	Heat per lb. at Temp. of Ent'nce	Heat Brot to Hearth per 100 lb. Iron	Heat Comb per lb.	Heat of Comb per 100 lb. Iron	Total Heat in Hearth	Temp. at Exit	Heat per lb at Tem Exit
		Column Letters	A	B	C	D	E	F	G	H	I	J	K
O	1	From Blast	76.			1100°	238.5	18200			18200		
C	2	Burnt by O from Blast	57.						4450	253800	253800		
	3	C O Produced		133.								2700°	728.
	4	C for I & lost in Hearth	4.										
	5	Total of C used in Hearth	61.			2700°	1120.	68300			68300		
	6	Total fixed C in Furnace	61.										
	7	C burnt in Shaft with O from Ore	—										
	8	C O Produced	—										
N	9	N from Blast	254.5										
	10	N from Fuel											
	11	Total N	254.5			1100°	272.	69200			69200	2700°	725.
H2	12	H2 from Fuel											
	13	H2 Burnt											
	14	O for H2 Burnt											
	15	H2O produced											
	16	H2 remaining											
CH4	17	CH4 from Fuel											
	18	O for CH4 to H2O + CO2											
	19	Product CO2											
H2O	20	H2O Produced											
	21	H2O from Ore											
	22	Total H2O											
O	23	O from Fe + Si											
	24	O from Fuel											
	25	Total O											
	26	Deduct O for CH4 + H2 Lines 18 & 14											
	27	Deduct O for fixed C not burnt by Blast											
	28	Net O for CO											
CO	29	CO from fixed C											
	30	CO from fuel gas											
	31	Total CO											
	32	CO oxydized by net O, Line 28											
	33	CO remaining											
CO2	34	CO2 from CO + O											
	35	CO2 from Fuel gas											
	36	CO2 from Stone											
	37	Total CO2											

Total	409500
Removed by CO + N	281400
" " Dissoc H2O in Blast	9300
" " H2 from " " "	1800
" Total	292500
Net Heat used in Hearth	117000

KE PRACTICE
er Ton of Iron
Ohio, 1897)

SHAFT

eat ken t of arth t.u.	At Top of Bosh per 100 lb. Iron	Released in Shaft	Before Re-Action	Re-Action	Product in Top Gas Lbs						Gas Total	Heat from 32 to 432° per lb.	Heat Car out Top	Heat of Comb per lb.	Heat Comb per 100 lb. Iron	Heat Brot in at 2700	Total Hts. in Sh'ft	Cu. Ft.	Vol. of Top Gas
					N	CO	CO2	H2	CH4	H2O									
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE
580																			
	254.5																		
600					254.5						254.5	98.3	25000			184600	184600	32.50	63.7
		0.55																	
		0.55												61500	33800		33800		
			4.4																
										4.95									
		2.2												23500	49500		49500		
			8.80																
							6.05												
										4.95									
										10.80									
											20.70	1260	26500						
		42.0																	
			42.0																
			13.2																
			28.8																
	133.															96800	96800		
			133.0																
			50.4												4350	219200	219200		
			82.6			32.6					82.6	98.6	8140					1055	20.7
							79.2												
							12.8												
							98.05				98.05	87.0	8525					795	16.6
1400																			

Total 68300 583800
Heat Removed by Top Gases 68300
Net Heat used in Shaft 515600

(*Facing page 53*)



TABLE VIII.—C

Wet Ore,

95 Bushels C

HEARTH and BOSH

COMPONENT	Line Nos.	SOURCE	In Hearth and Bosh	Product	Disposal	Temp. at Ent'nce	Heat per lb. at Temp. of Ent'nce	Heat Brot to Hearth per 100 lb. Iron	Heat Comb per lb.	Heat of Comb per 100 lb. Iron	Total Heat in Hearth	Temp. at Exit	Heat per lb at Tem Exit
		Column Letters	A	B	C	D	E	F	G	H	I	J	K
O	1	From Blast	62.1			1000°	212.	13200			13200		
	2	Burnt by O from Blast	46.6						4450	207000	207000		
C	3	C O Produced		108.7								2300°	608.
	4	C for I & lost in Hearth	4.										
	5	Total of C used in Hearth	50.6			2300°	922.	46600			46600		
	6	Total Fixed C in Furnace	58.1										
	7	C burnt in shaft with O from Ore	7.5										
	8	C O produced		17.5									
N	9	N from Blast	207.9			1000°	243.5	50600			50600	2300°	606.
	10	N from Fuel											
	11	Total N											
H2	12	H2 from Fuel											
	13	H2 Burnt											
	14	O for H2 Burnt											
	15	H2O produced											
	16	H2 remaining											
CH4	17	CH4 from fuel											
	18	O for CH4 to H2O + CO2											
	19	Product CO2											
	20	H2O produced											
H2O	21	H2O from Ore											
	22	Total H2O											
O	23	O from Fe+Si											
	24	O from Fuel											
	25	Total O											
	26	Deduct O for CH4 +H2 Lines 18 & 14											
	27	Deduct O for fixed C not burnt by blast											
	28	Net C for CO											
CO	29	CO from fixed C											
	30	CO from fuel gas											
	31	Total CO											
	32	CO oxydized by net O, Line 28											
	33	CO remaining											
CO2	34	CO2 from CO+O											
	35	CO2 from fuel gas											
	36	CO2 from stone											
	37	Total CO2											
							Heat Removed by CO+N				317400		
							Net Heat Used in Hearth				191900		
											125500		

RCOAL PRACTICE
tual Case
Per Ton Iron

SHAFT

eat ken t of arth t.u.	At Top of Bosh per 100 lb. Iron	Released in Shaft	Before Re-action	Re-action	Product in Top Gas Lbs. N	CO	CO_2	H_2	CH_4	H_2O	Gas Totals	Heat from 32 to 232° per lb.	Heat Car out Top	Heat of Comb per lb.	Heat Comb per 100 lb. Iron	Heat Brot in at 2300°	Total Hts in Sh'ft	Cu. Ft.	Vol % of Top Gas
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE
200																			
5700	207.9															125700	125700		
		5.8																	
			214.5	→	214.5						214.5	47.2	10100					2740	58.8
		1.4																	
		1.05												61500	64600		64600		
			8.4																
				→						9.45									
		0.35						0.35			.35	.660	200					62	1.3
		2.89		→					2.89		2.89	82.5	240					65	1.4
			—																
			—				—												
										—									
										27.0									
											36.45	1160	42300						
		42.																	
		.57																	
			42.57																
			8.4																
			10.0																
			24.17																
	108.7	17.5														66200	172[illegible]		
		9.3																	
			135.5																
			42.3											4350	183900		183900		
			93.2			93.2					93.2	47.3						1193	25.5
				→			66.5						4600						
							3.8												
							8.0												
							78.3				78.3	40.5	3170					835	13.5
1900											425.7	60610					440409	4695	
											36.45	Heat Removed by Top Gases					60600		
											389.2	Net Heat Used in Shaft					379800		

(*Following Table* VII)

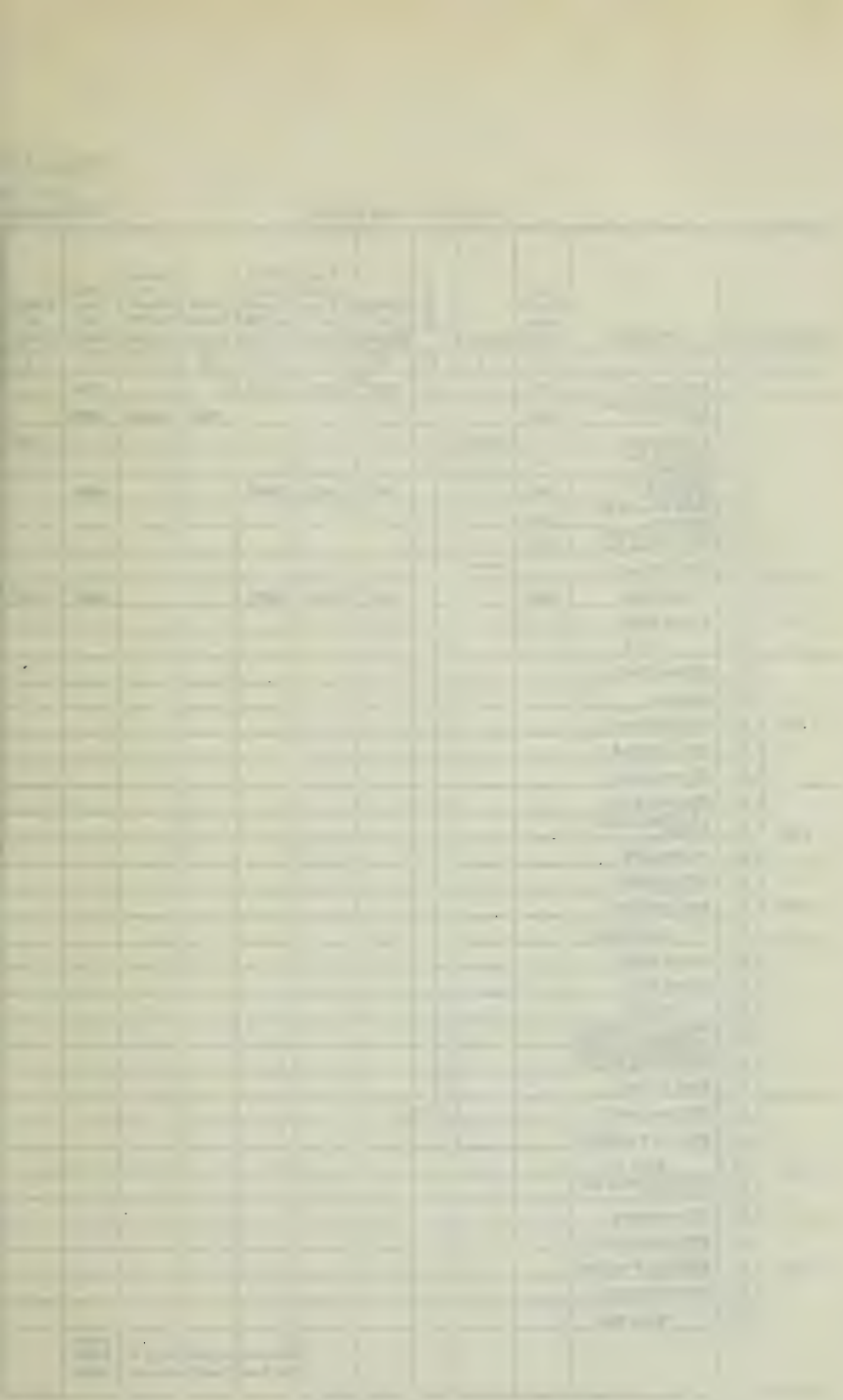


TABLE IX.—(

Dry Ore, E

75 Bushels of (

HEARTH and BOSH

COMPONENT	Line Nos.	SOURCE	In Hearth and Bosh	Product	Disposal	Temp. at Ent'nce	Heat per lb. at Temp. of Ent'nce	Heat Brot to Hearth per 100 lb. Iron	Heat Comb per lb.	Heat of Comb per 100 lb. Iron	Total Heat in Hearth	Temp. at Exit	Hea per l at Tem Exi
C			A	B	C	D	E	F	G	H	I	J	K
	1	From Blast	56.			1000°	212.	11900			11900		
	2	Burnt by O from Blast	42.						4450	186800	186800		
	3	C O produced		98.0								2300°	608.
	4	C for I & lost in Hearth	4.										
	5	Total of C used in Hearth	46.			2300°	922.	42400			42400		
C	6	Total Fixed C in Furnace	46.										
	7	C burnt in shaft with O from Ore	—										
	8	C O Produced		—									
	9	N from Blast	187.5			1000°	243.5	45600			45600	2300°	606.
N	10	N from Fuel											
	11	Total N											
	12	H2 from Fuel											
	13	H2 burnt											
H2	14	O for H2 Burnt											
	15	H2O produced											
	16	H2 remaining											
	17	CH4 from Fuel											
CH4	18	O for CH4 to H2O + CO2											
	19	Product CO2											
	20	H2O produced											
H2O	21	H2O from Ore											
	22	Total H2O											
	23	O from Fe+Si											
	24	O from Fuel											
	25	Total C											
O	26	Deduct O for CH4 + H2 Lines 18 & 14											
	27	Deduct O for fixed C not burnt by Blast											
	28	Net C for CO											
	29	CO from fixed C											
	30	CO from Fuel Gas											
CO	31	Total CO											
	32	CO oxydized by net O, Line 28											
	33	CO remaining											
	34	CO2 from CO+O											
CO2	35	CO2 from Fuel Gas											
	36	CO2 from stone											
	37	Total CO2											
								Heat Removed by CO+N			286700		
								Net Heat Used in Hearth			173200		
											113500		

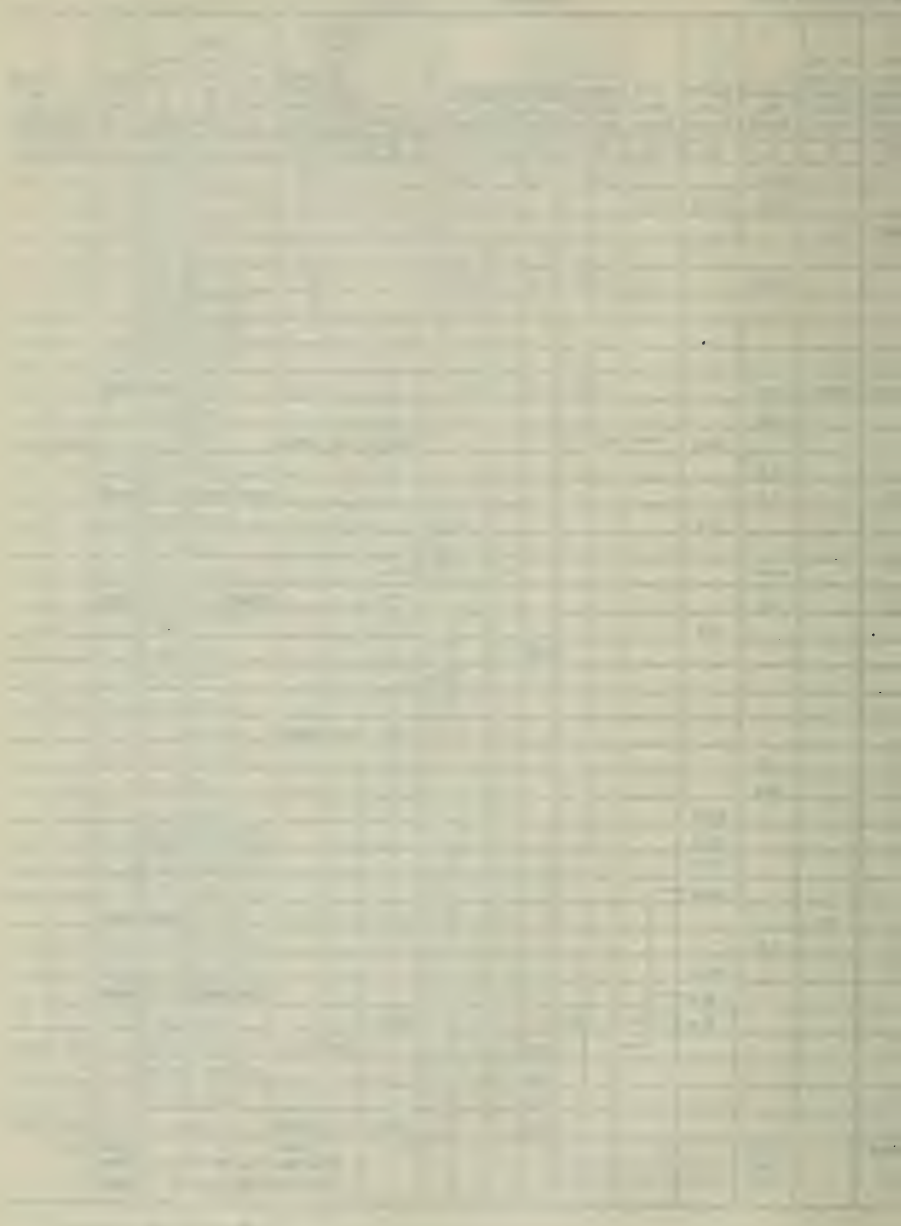
nated Results

Per Ton of Iron

SHAFT

Heat Taken Out of Earth B.t.u.	At top of Bosh per 100 lb. Iron	Released in Shaft	Before Re-Action	Re-Action	Product in Top Gas Lbs. N	CO	CO2	H2	CH4	H2O	Gas Totals	Heat from 32 to 632° per lb.	Heat Car out Top	Heat of Comb per lb.	Heat Comb per 100 lb. Iron	Heat Brot in at 2300°	Total Hts in Sh'ft	Cu. Ft.	Vol % of Top Gas
L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE
9600																			
			•																
3500	187.5															113600	113600		
		5.2																	
			192.7	→	192.7						192.7	149.	28700					2460	62.3
		1.1																	
		1.1												61500	67700		67700		
			8.8																
										9.9									
		—						—			—								
		2.3									—			23500			54100		
			9.2																
							6.33												
										5.17									
										—									
											15.1	1380	20600						
		42.																	
		0.44																	
			42.44																
			18.00																
			—																
			24.44																
	98.															59600	59600		
		7.4																	
			105.4																
			42.8											4350	166000		136000		
			62.6	→		62.6					62.6								
							67.2					149.5	5400					802	20.4
							3.												
							8.												
							84.5				84.5	136.	11500					685	17.3
3200													70400				481600	3917	
													Heat Removed by Top Gas				70100		
													Net Heat Used in Shaft				111200		

(*Following Table* VIII)



valves close and for the reëxpansion of the compressed air into the clearance space, both of which tend to reduce the actual pounds of air blown. The temperature of the air being discharged from the cylinder was taken at the discharge head, and simultaneously that of the outside air, with which the engine was supplied. The heating of the discharge air was about 20° higher than the theoretical for the pressure blown at the time, 6 lb., and this was assumed to take place before compression began and to make a further reduction of the weight of air delivered. The weight of air blown, derived from the displacement, with these corrections and with slight allowances for the loss in changing stoves and leakage, was used in the gas calculations, and checked out very satisfactorily with the actual analysis of top gas found. It may be well to remark here in passing that if incorrect assumptions be made, the calculated top gas will vary widely from the actual top-gas analysis, and will at once indicate that something is wrong.

"It will be noticed that in the tables the weight of fixed carbon in the fuel per 100 lb. of iron is given, and from this is made a deduction of 4 lb. to correspond with the 3.50 or 4.00 per cent. of carbon combined with the iron and some slight loss of solid carbon at cast and at flush time.

"The result of the calculations are each represented on a separate table, Tables VII, VIII and IX, in which it has been attempted to epitomize the calculation and to indicate the various reactions that lead to the top gas as finally discharged. In a general way the table gives, in its upper left-hand corner, the details of what goes on in the hearth and bosh, and works gradually toward the final result in gas composition and heat development at the right-hand end and bottom of the table. It is feared that these charts may not be perfectly comprehensible at first glance, but no effort has been spared to make them as logical and clear as possible, so as to save the reader an enormous amount of effort in going over written details of these calculations.

"Coming now to the final results in heat development, we find that Table VIII, giving the actual conditions with wet ore, shows a development of hearth heat of 125,500 B.t.u., and a development of shaft heat of 379,800 B.t.u., a total per 100 lb. of iron of 505,300 B.t.u.

"The coke furnace in which, by the way, the theoretical gas analysis checks remarkably well with the actual results, shows a development of hearth heat of 117,000 B.t.u. and of shaft heat of 515,600 B.t.u., a total of 632,600 B.t.u. The assumed case, Table IX, dry ore and 75 bu. of coal, shows a development of hearth heat of 113,500 B.t.u., of shaft heat of 411,200 B.t.u., a total of 524,700 B.t.u. These are arranged in condensed tabular form below:

TABLE X

	Coke practice, 1664 lb. coke	Actual practice, wet ore, 95 bu. coal	Assumed case, dry ore, 75 bu. coal
Hearth heat	117,000 B.t.u.	125,500 B.t.u.	113,500 B.t.u.
Shaft heat	515,600 B.t.u.	379,800 B.t.u.	411,200 B.t.u.
Total heat	632,600 B.t.u.	505,300 B.t.u.	524,700 B.t.u.

"Before proceeding to a discussion of these figures, it should be stated that in the case of the coke furnace it was assumed that the air blown contained 0.4 lb.

of moisture per 1000 cu. ft. of air, all of which moisture was dissociated in the hearth with corresponding absorption of heat. Further, that the hydrogen evolved by the dissociation of the water passed out of the top of the bosh at the same temperature as the other gases and abstracted a corresponding amount of heat from the hearth. The dissociation absorbs 9300 thermal units and the hydrogen absorbs 1800, a total of 11,100 thermal units. This assumption as to the amount of moisture present is based on previous experience of the moisture in engine houses during the winter months. It is not probable that the air was taken from outside the engine room, as no mention is made of that fact and it was not customary at that time (1897).

"To be strictly accurate, allowance for the oxygen from this source should be made in the gas calculations, and as the hydrogen generally recombines in the top of the furnace with oxygen from the ore, the 11,100 thermal units subtracted from the hearth heat might, with propriety, be added to the shaft heat. These corrections have not been made because their magnitude is not of sufficient importance to affect the general result, and it would greatly complicate the tables to show them. No allowance for moisture is made for our practice, because we take our air from out of doors and the amount of moisture present in the air in winter time in this climate is a negligible quantity.

"Comparing first the two actual cases, coke and 95 bu. of charcoal, we see that the heat developed in the hearth with the charcoal is considerably greater, while the heat developed in the shaft is very much less than with coke. The difference in the latter condition of over 100,000 thermal units is very striking. The explanation of the major part of the difference lies in higher temperature to which the materials must be heated in the shaft of the coke furnace than in the charcoal, and also the much greater amount of limestone to be decarbonated in the coke than in the charcoal. Only approximate calculations are possible on this subject for lack of accurate data as to specific heats of the materials at these high temperatures, but such calculations indicate that most of the difference can readily be accounted for in this way.

"Turning now to the high temperature, or hearth heat, the conditions are extraordinary. The coke furnace, with a considerably greater quantity of slag, greater radiation losses and every disadvantage compared with a charcoal furnace, develops about 7 per cent. *less* high-temperature heat than the charcoal furnace. Moreover, an examination of the table will show that while 58 lb. of fixed carbon are brought into the furnace by the charcoal, only about 50 lb. are consumed in the hearth—4 by absorption in the iron and 46 by combustion with the blast. This shows that about 8 lb. out of 58, or 14 per cent. of the total fixed carbon are dissolved by the oxygen of the ore. If this carbon came down into the hearth as it should, the excess of high-temperature heat for the charcoal furnace would be very much greater than it is.

"It seems well to point out here one curious fact. When CO is oxidized to CO_2, by oxygen taken from the ore, heat is given out by the reaction; but when carbon is burnt to CO by oxygen from the ore, an enormous amount of heat is *absorbed* for every pound of oxygen which is transferred from the ore to the carbon. This is because a unit of oxygen develops over twice as much heat in burning CO to CO_2 as it does in burning C to CO. Knowing the amount of carbon which is thus burnt directly, we can easily figure the heat absorbed. This amounts to

33,000 thermal units per 100 lb. of iron. We do not know where this reaction takes place, but the action of this furnace and the frequent observation of forge cinder at or below the level of the tuyeres when the furnace is in normal operation causes the belief that a great portion of this combustion of fixed carbon with oxygen from the ore takes place in the hearth itself, and thereby robs the hearth of the excess heat which it develops.

"Extensive investigations have been made in Germany on the equilibrium between FeO and Fe_3O_4 with CO and CO_2. These investigations proved that at temperatures of 1800° to 2000° CO could contain a considerable percentage of CO_2 and still deprive FeO of all its oxygen; but if the temperature went higher than this the affinity of the iron for oxygen increased so much that pure CO or incandescent carbon would be required to deoxidize it completely. This means that at the top of the bosh where the combustion of the blast to CO is complete the temperature should not be too high, as high temperature prevents complete deoxidation by the CO, and requires the use of solid carbon for that purpose, with consequent waste of fuel. Thus it may actually be that excess fuel leading to high temperature in the hearth exercises an unfavorable action on the final reduction of the ore.

"It is perfectly obvious that the effect of wet ore on the gas is to cool it down with extreme rapidity as it approaches the top of the furnace, and while the physical heat thus lost is of some importance, a condition of vastly greater importance results from it. This is that the temperature of the gas is so far reduced that it can no longer react on the ore. This means that oxygen which should be removed from the ore near the top of the furnace with decided evolution of heat descends to lower levels, and that which should be reduced in the central zone descends to or above the top of the bosh before it is finally removed. This involves the reaction with solid carbon, above pointed out, and the destruction of fuel economy.

"The effect of the excess heat in the hearth I believe to be bad also for the quality of the iron, because in the region around the tuyeres the temperature developed is excessive, this temperature being given up by the gas to the stock in a slightly higher zone, in order to overcome the cooling effect produced through the direct reaction of the oxygen of the ore by the incandescent fuel. These high temperatures at the tuyeres tend strongly to superheat the iron as it drips down through this zone. This increases its affinity for carbon, which the presence of an excess quantity of carbon permits it to satisfy. Therefore, the tendency of this working is to produce a hot-made high-carbon iron, although the silicon may not be high, due to the scouring action of the oxide which comes down to, or nearly to, the zone of the tuyeres.

"Turning now to the assumed case of correct top conditions and a fuel consumption of 75 bu. of coal, we find that the heat developed in the hearth is the same, or virtually the same, as that in the coke furnace (although the requirements, as above pointed, out are not so great), while the heat developed in the shaft of the furnace is very materially greater than with 95 bu. of coal and wet ore, about 407,000 thermal units against 378,000.

"The critical point in this assumption is the ratio of CO to CO_2 in the top gases. It will be seen that this works out to 17 per cent. of CO_2 and 20.3 per cent. of CO, as compared with the actual results in the coke furnace of 15.6 per cent. of CO_2 and 20.7 per cent. of CO, a ratio of 0.75 : 1 for the coke

furnace to 0.84 : 1 for the assumed charcoal conditions. This is not a very much higher ratio of CO_2, and is far lower than the equilibrium ratio, which is 1.63 : 1; that is, 62 CO_2 to 38 CO. In other words, it is possible for ore to oxidize the carbon gas to a very much higher degree than would be required for 75 bu. of coal under the given conditions.

"In regard to the time allowed for this reaction, it is well to note that the volume of the furnace in proportion to the volume of gas passing through it is very much greater in the charcoal furnace than in the coke one, which allows a correspondingly longer time for reaction.

"The development of more heat in the shaft of the furnace with over 20 per cent. less fuel than in the actual case may appear to indicate erroneous figures, but this is not the case if we admit the possibility of the degree of oxidation just explained. The amount of oxygen from the ore for 100 lb. of iron is virtually constant. For the same analysis of iron and same kind of ore it is exactly constant.

"This constant quantity of oxygen would oxidize the same quantity of CO to CO_2 in either case and develop the same amount of heat in doing so if all the fixed carbon were burnt to CO by the blast, but the smaller the quantity of fuel burned in the hearth per pound of iron, the greater the proportion of this which is oxidized to CO_2, and therefore the greater development of heat per pound of fuel. Moreover, in cases where all the carbon is not burnt to CO in the hearth by the blast (the case of wet ore, for instance), a part of this oxygen from the ore is expended in burning C to CO, which, as explained above, generates less than one-half the heat per pound of oxygen consumed that is generated by the oxidation of CO to CO_2, hence not only a less porportion of the total CO is oxidized in the case of the larger fuel consumption, but the total supply of oxygen available for this purpose is reduced about one-fourth to satisfy the fixed carbon of the fuel, hence only three-fourths as much is available for oxidation of CO to CO_2 as in the case of smaller fuel consumption. Thus not only the relative but also the absolute oxidation of CO to CO_2 is much smaller with the larger fuel consumption. This, of course, is true only within the limits of possible oxidation of carbon gas above described.

"It might be thought that this whole line of argument was fallacious because it was the hearth heat which limited the fuel economy, as it undoubtedly is in most coke practice. If this were so we could produce an enormous change in the burden-carrying capacity by changing the temperature of the blast. The heat brought in by the blast for 95 bu. of coal at 800° is 50,000 thermal units, at 1000°, as given in the table, 63,700, and at 1200° 78,700. The high-temperature heat being 124,800 B.t.u. for 1000°deg. blast-temperature would become 111,100 for 800° and 138,800 B.t.u. for 1200°; therefore, raising or lowering the blast-temperature 200° would produce a difference of about 11 per cent. either way, or there would be an economy with 1200° deg. of blast-temperature over that at 800° of about 24 per cent. As a matter of fact, the difference which we find in fuel consumption for such a change in blast-temperature is about 5 per cent. This corresponds approximately to the difference in total heat supplied to the furnace in the two cases, which figures about 5.50 per cent.

"It may be taken as established, therefore, that the amount of hearth heat produced is not the limiting condition in regular charcoal practice, but that this limitation comes from the amount of shaft heat developed per pound of carbon

burnt. This depends, as already pointed out, on the degree to which the top gases can be oxidized by the ore, and this, in its turn, depends on the temperature of the gases. If they remain hot they will continue to react on the ore until they are discharged, but it would be as unreasonable to expect them to do this when chilled with water and diluted with steam as to expect a fire to burn as freely with a hose turned on it as without."

As a result of this investigation arrangements were made to dry 500 tons of ore for a trial and while this amount was sufficient for only 2 days, run, the results bore out in the most striking manner the conclusions derived from the calculations. The fuel consumption was decreased about 12 per cent., and this threw the deficiency of heat into the hearth, with the result that the furnace responded to changes in blast-temperature to an extent that was almost incredible, in view of previous experience. Everything indicated, as far as so short a trial could, the complete agreement of practice with this theory of two thermal equations instead of a single one, as in the older theory, and that both of these must be satisfied before the furnace would function, even though the satisfaction of one involved a great surplus of heat above the requirements for the other.

THERMAL PRINCIPLES—II

CHAPTER IV

THE DETAILS OF HEAT PRODUCTION AND CONSUMPTION IN HEARTH AND SHAFT

In the preceding chapter, Thermal Principles—I, I have explained that the heat balance of the blast furnace must be considered not as one, but as two; that there are, in fact, two sets of thermal requirements, one for the preparation of the ore for its descent into the hearth, the other for the production of thoroughly reduced and melted pig iron from the ore so prepared. The present Chapter will show how these amounts may be calculated in detail and analyze the effect of solution on fuel consumption.

The disposition made of the two kinds of heat had seemed until recently, impossible to determine, largely on account of lack of data of actual furnace operations, particularly of accurate average analyses of top gases, since a variation of a few per cent. of CO_2 makes a vast difference in the heat developed. Very recently, however, two excellent sets of such data have been published, one by Mr. Walther Mathesius in his paper before the American Institute of Mining Engineers on "The Use of High Blast Heats in Mesabi Ore Practice," the other by Mr. Sidney Cornell in an article, entitled "The Heat Balance of the Blast Furnace," in *Metallurgical and Chemical Engineering* for December, 1914.

In the latter the unit of weight used is the furnace charge which yielded in that case 15,260 lb. of iron, in the former the unit used is the ton of iron, but I have reduced them both to the pound basis to which the charted results of Reece's work (Table VII) are directly reducible by simply pointing off two places, it being on the basis of 100 lb. of iron.

In order to reach comparative results we must decide what heat to consider as consumed by the furnace and what as simply developed and then carried out of it. I have adopted the rule that the heat brought in plus that developed less that taken out as sensible heat, should be charged to the furnace as consumed.

A curious oversight has crept into the work of both Messrs. Mathesius and Cornell which it has been necessary to correct. They have given

the furnace credit for the heat of dissociation of the moisture in the blast, but they have ignored the much larger quantity of heat required for the dissociation of moisture of the charge in the upper portion of the furnace.

Mr. Mathesius takes cognizance of 69 lb. of moisture dissociated per ton of iron from the blast, but the analysis he gives of top gas shows that 240 lb. of water in all are dissociated, there being 27.3 lb. of hydrogen per ton of iron in the top gases. This arises, as pointed out by A. N. Diehl in his paper "Data Pertaining to Gas Cleaning," from the dissociation of the moisture in the ore in the upper part of the furnace. It seems at first sight surprising that this should take place, but it is not when we consider that CO burnt to CO_2 develops 7650 B.t.u. per pound of oxygen, while H_2O to $H_2 + O$ absorbs only 6350 B.t.u. per pound of oxygen.

The heat necessary for this latter reaction has been entirely overlooked by both these writers, with the result that in one set of data the "loss by radiation and unaccounted for" is much larger than it should be. On the other hand, the oxygen arising from this reaction is similarly ignored and the gas analysis given does not account for all the oxygen which must have been present in the top gases.

Calculations based on operating data give us the only means we have of investigating what occurs inside the furnace, and the method of making these is of much importance to show this and simultaneously to obtain the correct figures for the heat developed. We may, therefore, give the calculations based on the excellent data of Mr. Mathesius.

His "Calculations of Operating Results," which contain the data we need, are reproduced here.

"Calculation of Operating Data

Analysis of Top Gases

	By volume	By weight	
CO_2	14.9	22.3	
CO	23.5	22.4	
H_2	4.1	0.3	(1)
CH_4	0.2	0.1	
N_2	57.3	54.9	

"On the basis of above data 1 ton of this gas contains:

$$\frac{22.3 \times 3}{100 \times 11} = 0.0608 \text{ ton of carbon as } CO_2 \qquad (2)$$

and

$$\frac{22.4 \times 3}{100 \times 7} = 0.0960 \text{ ton of carbon as CO.}$$

"This carbon originates from:

(*a*) The carbon charged, minus the amount of carbon transferred to the iron and the amount carried off with the flue dust.

(*b*) The CO_2 content of the raw materials.

These items are calculated below:

(*a*) The total amount of coke charged during the period under consideration was

13,006 tons, (3)

which analyzed:

Fixed carbon	Ash	S	P	Volatile matter	(4)
89.00	9.40	0.59	0.008	1.35 per cent.	

The coke as weighed averaged 2.30 per cent. moisture, making the weight of dry coke charged: (5)

12,707 tons (6)

The amount of fixed carbon charged is thus:

$$\frac{12{,}707 \times 89.00}{100} = 11{,}310 \text{ tons} \quad (7)$$

"From this total is to be deducted:

(*a*1) The carbon carried off with the iron, which is calculated as follows: The carbon content of the metal was 4.20 per cent. and (8)

17,146 tons of iron were produced, besides (9)

173 tons of scrap (ladle skullings and pig-machine scrap); therefore (10)

17,319 tons of iron (17,146 + 173) carried off (11)

$$\frac{4.20 \times 17{,}319}{100} = 727 \text{ tons of carbon} \quad (12)$$

"Besides the regular burden, the furnace remelted 276 tons of scrap iron, which contained:

$$\frac{276 \times 4.20}{100} = 11 \text{ tons of carbon} \quad (13)$$

"Therefore the net amount of coke carbon carried off with the metallic product is:

$$727 - 11 = 716 \text{ tons} \quad (14)$$

(*a*2) During the month 628 tons of flue dust were taken out of the dust catcher of the furnace. Assuming that the gas carried over an additional 10 per cent. of this beyond the dust catcher, the total amount of flue dust produced by the furnace was,

691 tons (15)

Since the average carbon content of the flue dust was 8.25 per cent., the amount of carbon carried from the furnace with the dust amounted to (16)

$$\frac{8.25 \times 691}{100} = 57 \text{ tons} \quad (17)$$

"Consequently the net amount of carbon gasefied in the furnace is:

$$11{,}310 - (716 + 57) = 10{,}537 \text{ tons} \quad (18)$$

(*b*) The only burden constituent containing CO_2 in large quantities was limestone, of which 6154 tons were charged. It averaged 43.1 per cent. CO_2 (19)

making the amount of CO_2 charged with the limestone $\frac{43.1 \times 6154}{100} = 2652$ (20)

tons which is equivalent to $\frac{2652 \times 12}{44} = 723$ tons of carbon (21)

"The CO_2 content of the other burden constituents (ore, scale and cinder) averaged about 1 per cent., giving off an additional (22)

$$\frac{31{,}372 \times 1}{100} = 314 \text{ tons } CO_2, \text{ which is equivalent to} \quad (23)$$

$$\frac{314 \times 12}{44} = 86 \text{ tons of carbon} \quad (24)$$

The total amount of carbon which escaped from the furnace during the month in the shape of CO_2 and CO is, therefore (see 18, 21 and 24),

$$10{,}537 + 723 + 86 = 11{,}346 \text{ tons} \quad (25)$$

"Each ton of the top gases containing 0.568 ton (see 2) of carbon, the total weight of the dry top gases for the month is:

$$\frac{11{,}346}{0{,}1568} = 72{,}360 \text{ tons} \quad (26)$$

"The total weight of water, which was charged into the furnace with the ore, coke and limestone, and which subsequently had to be evaporated, leaving the furnace together with the top gases, was, according to the analysis of the burden constituents,

$$4665 \text{ tons} \quad (27)$$

"The nitrogen content of the dry top gases (see 1) originating exclusively from the blast, and the nitrogen content of the air being known, the weight of the dry air which entered into the furnace through the tuyeres can be calculated as follows:

$$\frac{72{,}360 \times 54.9}{77} = 51{,}592 \text{ tons} \quad (28)$$

"The average moisture of the atmosphere was 5.49 grains per cubic foot at 70°F., making the weight of natural air blown into the tuyeres (29)

$$51{,}592 + 539 = 52{,}131 \text{ tons} \quad (30)$$

"The slag volume according to the daily burden calculations averaged (31)
45.5 per cent., making the total amount of slag produced, 7811 tons. (32)

"The weight of materials passed through the furnace was as follows:

Material	Total tons	Per ton of product including scrap produced	
		Tons	Pounds
Burden	31,645	1.827	4,093
Limestone	6,154	0.355	795
Coke	13,006	0.751	1,682
Product (including scrap)	17,319		
Slag	7,811	0.451	1,010
Flue dust	691	0.040	89 (33)
Blast (excluding moisture)	51,592	2.979	6,673
Moisture in blast	539	0.031	69
Top gas (excluding moisture)	72,360	4.173	9,359
Moisture in gas	4,665	0.269	603

"According to the average monthly analysis the product consisted of,

C	Si	S	P	Mn	Fe	
4.20	1.35	0.032	0.071	0.74	93.61 per cent.	(34)

The iron content originated from the following amounts of burden constituents:

Material	Group 1	Group 5	Pewabic Genoa	Pit cinder	Steel scale	Scrap	Coke	Total	
Iron, per cent.....	52.00	49.00	35.00	50.00	66.00	75.00	0.80		
Stage of oxidation	Fe_2O_3	Fe_2O_3	Fe_1O_3	Fe_3O_4	Fe_3O_4	Fe	Fe		
Pounds per ton of product.....	2,819	755	219	58	207	36	1,682		(35)
Pounds minus 1 per cent. loss...	2,791	748	217	57	205	35	1,665		
Pounds iron per ton of product.	1,451	366	76	29	136	26	13	2,097	

Consequently the iron content of 1 ton of product originated from the following stages of oxidation:

Fe	Fe_3O_4	Fe_2O_3	
39	165	1,893 lb.	(36)

"In the same manner it results that 1 ton of product contained 0.74 per cent., or 16.6 lb., of manganese; 16.3 lb. of which have been reduced from MnO, while 0.3 lb. were contained in the scrap charged. (37)

The phosphorus of the product amounts to 1.6 lb. per ton and has been reduced practically all from P_2O_5. (38)

The 1.35 per cent. of silicon is equivalent to 30.2 lb. per ton, of which 29.7 lb. were reduced from SiO_2, while 0.5 lb. were contained in the scrap charged. (39)

Heat Balance

(a) *Heat Generation*

"The total weight of carbon contained as CO_2 in the top gases per ton of product is (see 2 and 33):

$$0.0608 \times 9359 = 569.0 \text{ lb.} \quad (40)$$

The weight of carbon per ton of product, equivalent to the amount of CO_2 originating from the limestone and burden and contained in the top gases is (see 21, 24 and 33):

$$\frac{809 \times 2240}{17{,}319} = 104.6 \text{ lb.} \quad (41)$$

Deducting item (41) from (40) gives the weight of coke carbon burned to CO_2 per ton of product:

$$569.0 - 104.6 = 464.4 \text{ lb.} \quad (42)$$

One pound of carbon through combustion to CO_2 generates 14,543 B.t.u.; (43) the above 464.4 lb. generated, therefore, 6,754,000 B.t.u. (44)

The amount of carbon per ton of product burned to CO is (see 2 and 33):

$$0.0960 \times 9359 = 898.5 \text{ lb.} \quad (45)$$

One pound of carbon through combustion to CO generating 4446 B.t.u., (46)
the above 898.5 lb. generated 3,995,000 B.t.u. (47)

The specific heat of the air blast being 0.248 and the average hot-blast (48)
temperature 1248°F., the heat brought into the furnace with the blast (see (49)
33) per ton of product is:

$$1243 \times 0.248 \times 6.663 = 2{,}057{,}000 \text{ B.t.u.}$$

In the same manner the amount of heat brought into the furnace per ton of product with the moisture (specific heat, 0.49) content of the blast (see 33) is:

$$1243 \times 0.49 \times 69 = 42{,}000 \text{ B.t.u.} \quad (51)$$

(*b*) *Heat Consumption*

"The following data were used in these calculations:

	B.t.u.	
Heat required to reduce Fe_2O_3 to 1 lb. of Fe	3,240	
Heat required to reduce Fe_3O_4 to 1 lb. of Fe	2,970	
Heat required to reduce MnO to 1 lb. of Mn	2,970	(52)
Heat required to reduce SiO_2 to 1 lb. of Si	14,090	
Heat required to reduce P_2O_5 to 1 lb. of P	10,620	

The reduction of 1 ton of product therefore requires the following heat (see 34, 36, 37 and 38):

	B.t.u.	
1,893.0 lb. of Fe from Fe_2O_3	6,133,300	
165.0 lb. of Fe from Fe_3O_4	490,000	
16.8 lb. of Mn from MnO	48,400	
1.6 lb. of P from P_2O_5	17,000	(53)
29.1 lb. of Si from SiO_2	418,500	
Total	7,107,200	

"The weight of CO_2 produced by the calcination of carbonates per ton of product is, according to (20, 23 and 33):

$$\frac{(2652 + 314) \times 2240}{17{,}319} = 384 \text{ lb.} \quad (54)$$

practically all of which was contained in the burden in the form of $CaCO_3$. The heat necessary to decompose $CaCO_3$ into CaO and CO_2 is 1830 B.t.u. (55) per pound of CO_2. The driving off of above 384 lb. required

$$1830 \times 384 = 702{,}000 \text{ B.t.u.} \quad (56)$$

"The amount of heat carried from the furnace by the slag and iron was not determined. The figures used represent the average results of former tests under similar conditions. According to these the heat carried off by 1 lb. of iron amounted to 510 B.t.u. and per pound of slag to 900 B.t.u. (57)

The heat carried off per ton of product with the iron amounts to

$$510 \times 2240 = 1{,}142{,}500 \text{ B.t.u.} \quad (58)$$

and with the slag

$$900 \times 1010 = 909{,}000 \text{ B.t.u.} \quad (59)$$

"The dissociation of the moisture as carried into the furnace with the blast requires, per pound of water vapor, 5760 B.t.u.; per ton of product. the heat required for this reaction was (see 33): (60)

$$69 \times 5760 = 397{,}000 \text{ B.t.u.} \quad (61)$$

"The dry top gases carried off the following amount of heat per ton of product. (The average top temperature was 325°F., (see 1) for the gas analysis and (33) for the weight of gas)

	Gas analysis	× Weight of gas	× Top temperature	× Spec. heat	= B.t.u.	
CO_2	0.223	9,359	325	0.2169	147,100	
CO	0.224	9,359	325	0.2426	165,300	
H_2	0.003	9,359	325	3.4090	31,100	(62)
CH_4	0.001	9,359	325	0.5930	1,800	
N_2	0.549	9,359	325	0.2438	407,100	
Total					752,400	

The moisture carried out by the top gases entered the furnace at a temperature of 70°F., *i.e.*, with a heat content (see 33) per ton of product of

$$(70 - 32) \times 603 = 22{,}900 \text{ B.t.u.} \qquad (63)$$

"Since the moisture was heated in the furnace to 212°F., and evaporated, and the resulting steam superheated to 325°F., the heating of the water required

$$(212 - 32) \times 603 - 22{,}900 = 85{,}600 \text{ B.t.u.} \qquad (64)$$

The evaporation required

$$964.8 \times 603 = 581{,}800 \text{ B.t.u.} \qquad (65)$$

The superheating required

$$0.48 \times (325 - 212) \times 603 = 32{,}700 \text{ B.t.u.} \qquad (66)$$

Therefore the total heat carried off with the top gases per ton of product amounts to

B.t.u.	
85,600	(see 64)
581,800	(see 65)
32,700	(see 66)
700,100	(67)"

In the following calculation the letter M followed by a number indicates the item bearing that number in the quotation from Mathesius.

Let us start with the fundamental fact that carbon in the gaseous condition whether CO_2, CO or CH_4 has a volume of 29.85 cu. ft. per pound.

The total carbon gasified (M25) is 11,346 tons per month and the iron produced (M33) is 17,319 tons per month, or 0.655 lb. C per pound of iron. Therefore, the carbon gas per pound of iron is $0.655 \times 29.85 =$ 19.57 cu. ft. The carbon gas in percentage of the total (M1) is CO_2, 14.9 per cent., CO 23.5 per cent. or 38.4 per cent. for both. (We can disregard the CH_4 because no account is taken of the volatile matter of the coke, which undoubtedly contains some carbon.) 19.57 being the volume of carbon in cubic feet and 38.4 in percentage, the total volume

of gas is $\frac{19.57}{0.384}$ or 50.9 cu. ft. per pound of iron. The nitrogen is (M1) 57.3 per cent. of this or 29.2 cu. ft. and as all this comes from the blast of which it constitutes 79.3 per cent., the blast blown must have been 36.8 cu. ft. per pound of iron. This weighs 0.0807 per cubic foot or 2.97 lb. of which 23 per cent. by weight is oxygen or 0.683 lb. The oxygen from the charge may be obtained most easily from M53 and 54.

1,893.0 lb. Fe as Fe_2O_3 carries	$\frac{3}{7}$	× 1,893.0	=	810.0 lb. O
165.0 lb. Fe as Fe_3O_4 carries	$\frac{64}{168}$	× 165.0	=	62.9 lb. O.
16.3 lb. Mn as MnO carries	$\frac{16}{55}$	× 16.3	=	4.8 lb. O.
1.6 lb. P as P_2O_5 carries	$\frac{80}{62}$	× 1.6	=	2.1 lb. O.
29.7 lb. Si as SiO_2 carries	$\frac{32}{28}$	× 29.7	=	33.9 lb. O.
				913.7

From (M54) we find 384 lb. of CO_2 carrying $32 \div 44 \times 384 = 279$ lb. per ton, a total from these sources of $913.7 + 279 = 1192.7$ lb. per ton or 0.5325 lb. per pound of iron. To this must be added the oxygen of the blast 0.683 lb.

The moisture in the blast is dissociated in the hearth and its oxygen is added to that from the other sources and Mr. Mathesius has added this, which is quite proper as far as it goes, but it takes no account of the oxygen which comes from the dissociation of the water in the *upper* portion of the furnace. The moisture in the blast is 69 lb. per ton of which one-ninth or 7.68 lb. per ton or 0.0034 lb. per pound of iron is hydrogen. The hydrogen in the top gas is, however, 4.1 per cent. by volume, while the carbon gas is 38.4 per cent. and 19.57 cu. ft. therefore the volume of hydrogen is $4.1 \div 38.4 \times 19.57 = 2.09$ cu. ft. or $2.09 \div 178.23 = 0.0117$ lb. or over *three times* as much as the moisture of the blast accounts for. This hydrogen can come from only one source, the dissociation of water. The volatile matter of the coke would not account for all of it if the latter were *all* hydrogen, and such analyses as we have show it to contain little or none of that gas. We must, therefore, take account of the heat absorbed by this reaction and of the oxygen as well as the hydrogen produced by it. This oxygen is obviously $0.0117 \times 8 = 0.0936$ lb. per pound of iron. We have then finally

Oxygen from oxides of charge	0.4070
Oxygen from carbonates of charge	0.1240
Oxygen from blast	0.6830
Oxygen from dissociation of water of charge	0.0940
	1.3081

Oxygen required for oxidizing 0.655 C to CO is $0.655 \times 1\frac{1}{3} = 0.874$ lb. $1.308 - 0.874 = 0.434$ lb. O left to oxidize CO to CO_2 which suffices to convert 0.326 lb. of C from CO to CO_2. Of this C $12 \div 44 \times 384 \div 2240 = 0.047$ lb. came from the carbonates as CO_2 and therefore generates no heat. We have therefore $0.326 - 0.047 = 0.279$ lb. C burnt to CO_2 and $0.655 - 0.326 = 0.329$ C burnt to CO.

0.279 C to CO_2 at 14,750 B.t.u..... =4,115
0.32 C to CO at 4,375 B.t.u..... =1,437
Brought in by blast and moisture (M)
$\frac{2,099,000}{2,240}$ ..... = 937

6,489 B.t.u. per lb. of iron

The heat taken out may be considered in various ways: Cornell considers all the heat taken out whether sensible, latent or potential as having been developed in the furnace and then abstracted, while Mathesius considers the latent heat of evaporating the water of the charge as generated and taken out but that the heat of the unburned gases is not generated. On the basis previously adopted of considering only sensible heat as taken out, I consider that the latent heat of the water of the charge represents part of the heat consumed in the furnace which is what we are trying to determine. On the other hand, the heat which the gas can develop by further combustion obviously plays no part in the operation and should not be considered. On this basis the rule is that sensible heat taken out should be credited to the furnace, but not latent heat, in order to determine its actual heat consumption.

For convenience the sensible heat of the water vapor is taken as starting at 0°F. although, of course, it is not actually evaporated until many degrees above that point. The error so produced is immaterial especially as there are necessarily many other errors of greater extent due to uncertainties in our data.

The heat removed on this basis is then found as follows:

The specific heat of furnace gas is ordinarily 0.02 B.t.u. per cubic foot, but in this case, on account of the large percentage of CO_2, it is about 0.0205. The volume of the top gases is 50.9, the top temperature is 325°, and the heat removed per pound of iron by dry gas is $50.9 \times 325 \times 0.0205 = 340$ B.t.u., and the sensible heat of the water vapor is 0.269 lb. per pound of iron $\times$ 0.46 $\times$ 325 = 40 B.t.u. a total deduction of 380 B.t.u.

The net heat consumed, therefore, is $6489 - 380 = 6109$, say, 6110 B.t.u. per pound.

To this we should add the heat brought in by the raw materials at, say 60°. Their weight is about $3\frac{1}{2}$ lb. per pound of iron, and their

specific heat about 0.18, so the heat introduced in this way is about 35 B.t.u., which is not worth bothering with.

Before proceeding to the discussion of heat utilization we may compare the analysis derived from these figures with those given in the paper. The total carbon gas remains the same as does its percentage of the whole; we have therefore only to divide the total percentage of carbon gas 38.4 per cent. in the ratio of 0.326 and 0.329, the weights of carbon as CO_2 and CO respectively, which gives 19.2 per cent. CO_2 and 19.3 per cent. CO, as against the initial figures given by Mathesius of 14.9 and 23.5. In the data given by Cornell there are included an estimate and an actual gas analysis, and the CO_2 in the estimate is 12.50 per cent. and in the test 13.06 per cent., while my estimate made as above is 14.2 per cent.

We have therefore a considerable discrepancy which we can only account for in one of two ways:

(*a*) The analyses are wrong as to the subdivision of the carbon gas, due to some error of not absorbing the CO_2 completely before proceeding to determine the CO or the like.

(*b*) The hydrogen does not arise from the dissociation of water, but is driven off as such from some portion of the charge, presumably the volatile matter of the coke, though this, as before stated, is hardly possible.

Fortunately for the correctness of our estimate of heat development, this uncertainty makes very little difference, strange as this may seem, for if the hydrogen *does* comes from the dissociation of water we obtain the corresponding oxygen which must oxidize the carbon to the extent shown, with the corresponding development of heat, six-sevenths of which must be applied to the dissociation of the water. On the other hand, if the hydrogen does *not* come from this source, this heat of dissociation is not required and the oxygen resulting therefrom is not produced to cause the oxidation of the carbon to the corresponding extent.

We find then that the total heat consumption per pound of iron in the three cases is as follows:

Mathesius	Cornell	Reece
6,110	6,860	6,440

Reece's furnace had a considerably smaller output than the others; in fact, not much over half, while the external dimensions of the shell in his case were not very much smaller than theirs, so that the radiation loss is probably considerably larger per pound of iron. On the other hand, no hydrogen is given in his gas analysis, and if this were correct (which the use of a large proportion of hard ore in his practice renders probable), we have a considerably larger consumption of heat per pound of iron than in Mathesius' case.

The total heat consumed in the Cornell example is greater than in

Mathesius' by about 10 per cent., of which a part is to be accounted for by the evaporation of more water and the dissociation of more coke in the shaft, but proper allowance for these items still leaves a discrepancy of 7 or 8 per cent. for which we are frankly unable to account except on the basis of errors in the gas analyses which underlie the whole structure and which are easily possible.

It should be noted that this variation of 8 per cent. corresponds with one of nearly 40 per cent. in fuel consumed in the two cases, and is in a broad way a confirmation of the fact that the heat consumption of furnaces working under very different conditions varies but little, as compared with variations in the fuel consumption.

It is a matter of interest also that the heat consumption in the cases of Reece and Cornell are almost identical if we omit from the latter the heat charged to it for the dissociation of water in the shaft, for which nothing has been charged in the case of Reece for the reasons given.

As to the radiation loss per square foot of furnace surface at different temperatures we know little or nothing; the difficulties in the way of investigation are great, and as we do not know how to improve our construction from the point of view of reducing radiation losses it has not seemed worth while to investigate them, and it has apparently never been thoroughly done.

It is well to point out that in those coke furnaces in which the deficiency of heat is in the hearth—that is, those which need more blast heat than they can obtain—the heat carried off from the hearth and bosh is the only portion whose loss affects the economy of the furnace, because it represents a loss of that portion which is already deficient, whereas any heat lost by radiation from the upper part of the stack represents only the loss of a surplus which would pass off as additional sensible heat in the gas, if it were not lost by radiation. One proof of this is the fact that at a number of plants the stock going into the top of the furnace is thoroughly watered down to reduce the flue dust losses, and in some cases the top temperature is frankly controlled by the amount of water used. This water has all to be evaporated in the upper regions of the furnace, which requires a great quantity of heat; but no additional fuel is charged for the purpose, merely the sensible heat in the top gases is reduced.

This condition is so familiar to coke furnace operators that it is hard for them to realize that the opposite condition can ever prevail and that the economy of the charcoal furnace is sometimes, at least, limited by the heat developed in the shaft. But no one who considers the results of the calculations and experiment given in the last chapter need ever feel any doubt of this.

Since this was written I have been told by one of the best furnacemen in the country that when the thin-lined furnace was used the cooling of the top was so considerable that the wetting of the ore to keep down

flue dust had to be discontinued as it reduced the economy of the furnace. This would seem to be a direct confirmation of my results with charcoal.

We find here a smaller development of hearth heat per pound of iron in the more economical furnace than in the less economical exactly as we found in a considerably greater degree in the charcoal furnace with wet and with dry ore, for while the dry ore figures were theoretical when made, their results were so remarkably confirmed by practice as to give them complete validity.

We have practically proven in the case of the charcoal furnace that the surplus hearth heat was utilized for relatively low-temperature operations; we shall presently see that the same is almost certainly true in the case of the coke furnace having the excess of hearth heat.

The development of hearth heat in the three cases is obtained from the actual carbon burnt in the hearth multiplied by the heat per pound of coke for the given conditions taken from chart Fig 3 (page 37) and divided by 0.85, the chart being for 0.85 carbon burnt.[1]

The carbon burnt at the tuyeres is simply three-fourths the weight of the oxygen of the blast dry plus that of its contained moisture. We omit that reduced from the Si, Mn, and P, which enter the iron, although these are admittedly reduced only with incandescent carbon in the bosh because the reduction of these does not generate but absorbs heat.

The results are as follows:

Mathesius

$$\frac{0.512}{0.85} \times 1670 = 1005$$

Cornell

$$\frac{0.78}{0.85} \times 1360 = 1250$$

Reece

$$\frac{0.57}{0.85} \times 1740 = 1170.$$

It will, I think, be conceded that these show a very fair agreement, especially as the slag volume in the data by Mathesius was exceedingly small.

Turning now to the method by which the hearth heat is developed we find that practically 50 per cent. more carbon is burnt in the hearth in No. 2 (Cornell) than in No. 1 (Mathesius), but that only 15 per cent. more hearth heat is developed by it, and the reasonable assumption is

[1] The hearth heats given in the balance of this chapter were not taken from Fig. 1 but from a similar chart which ignored the increase in the heat of combustion of carbon at high temperatures and was therefore not correct. The hearth heats used here are about 100 to 150 B.t.u. per pound of iron too low. These have not been corrected on account of the immense labor of recalculating all the results in Section II of Thermal Principles and because the correction would only strengthen the important conclusions to be drawn from the calculations. It is these conclusions rather than the detailed figures which are of interest, the figures are of use only to show the method of reaching the conclusions.

that if No. 2 had been given enough blast heat to increase the hearth heat per pound of coke to that of No. 1, *and if the distribution of the charge had been good*, so that the furnace would take advantage of the increase, it would have done as good work as No. 1.

The clause in italics is very important. Cases are numerous enough in which a change in the stock distribution had produced an improvement of 30 per cent. in fuel economy. The exact cause of the excess fuel required with bad distribution we do not know, and undoubtedly it varies in different cases, but broadly we may be sure that generally, if not always, it is *the result of having to do work in the hearth that should have been done in the shaft*, and this must necessitate the development of a surplus of hearth heat, precisely as it did at the charcoal furnace above cited, though in that case this condition was not due to bad filling.

It would seem well worth while in cases where the fuel economy is poor to make a brief analysis of the conditions and determine the amount of hearth heat developed per pound of iron. If it exceeds 1100 B.t.u. when making, say, 1200 lb. slag per ton of iron it is more than likely that the cause will be found in bad filling. In one case in my own experience the removal by better filling, without any other change whatever, of a cold core in the center of the furnace which was not properly heated and reduced by the gases in their ascent, resulted in a decrease of fuel consumption of 20 per cent. and an increase in tonnage of 25 per cent.

THE HEAT CONSUMPTION

In order to analyze the consumption of heat in detail in both hearth and shaft, let us assume that under average conditions the total heat consumed is 6500 B.t.u., and that of this the hearth heat is 1100 B.t.u., then the net heat used in the shaft is 5400 B.t.u. Let us assume that the slag volume is 1120 lb. per ton of iron (half the weight of the iron), and that the limestone charged is 1000 lb. per ton.

Our fundamental "second law" states that the heat above the critical temperature is supplied by the hearth heat, and the obvious corollary follows that the heat required below that temperature is derived from the shaft heat.

With this foundation we can make a subdivision of the gross heat consumption by remembering that, excepting the heat which passes out with the top gases, the only heat taken out of the shaft is that carried down by those portions of the charge which are discharged from the shaft down into the bosh, the volatile elements of the charge are heated to various temperatures in the shaft before they are detached from the non-volatile portion of the charge with which they enter, but the heat so absorbed is all given back to the charge again when they are ascending as a part of the gas column, excepting, of course, that heat which they take out as part of the top gas.

In other words, we have only to consider as credits to the shaft heat the amounts which it imparts to the iron and the slag-forming materials in raising them to the critical temperature before delivering them into the bosh, and may disregard the temperature to which their gaseous components are heated when the latter are driven off, because the sensible heat so absorbed is restored to the stock column or credited as sensible heat of the gases.

In considering the heat absorbed by the chemical reactions which take place in the shaft we do not need to consider the complex steps through which they pass, but only the final result, and from this point of view they are few and simple; the reduction of the iron ore, the decarbonation of the stone, the decomposition of the water vapor. In addition we have to evaporate the water of the charge and provide for the radiation loss. The shaft must supply the heat to raise to the critical temperature that portion of the coke which is burnt in the hearth, but the shaft recovers all this heat exactly as it does that expended on the volatile components of the charge. The quantities of heat required for these purposes in the case we have assumed are as follows:

Reduction of the Fe counting 95 per cent. Fe in iron	2,970
Decarbonization of stone	405
Heating slag forming materials to critical temperature	300
Heating Fe to critical temperature	480
Heating carbon in iron to critical temperature	45
Decomposition 0.1 lb. of H_2O from charge	580
Radiation deduced from Cornell and Mathesius	440
Evaporation of moisture of charge (¼ lb.)	280
Total consumption in shaft	5,500

But our original figures based in practice were 6400 total and 1100 hearth heat, leaving 5300 shaft heat, an amount considerably below the actual requirements as above given.

In order to find the discrepancy let us consider next the utilization of the hearth heat. This is expended in reducing the silicon, in imparting to the iron and slag that portion of their total heat not imparted in the shaft, including the latent heat of fusion, supplying the heat lost by cooling water, radiation, and conduction through the bottom.

We know from Cornell's data that the amount of the loss from cooling water is 170 B.t.u. per pound and I have assumed that the other two would equal this amount which is probably a liberal assumption. I have assumed the silicon to be 1.5 per cent. and assumed the phosphorus and manganese to be included in this.

No attention is paid to the heat of formation of the slag and the carbide of iron since both those reactions *give out* heat in small quantities instead of absorbing it.

We have then the following consumption of heat in the hearth:

Reduction of silicon	180
Heat of slag not imparted in shaft (900 − 600) ½	150
Heat of iron not imparted in shaft (600 − 480)	120
Cooling water	170
Radiation and conduction through bottom	170
	790

No allowance is made for the heat required to decompose the moisture of the blast because that has been taken care of by deducting it from the gross hearth heat.

Adding this figure to 5500 consumed in the shaft we have 6290 which is a very satisfactory check with the totals based in practice, but the distribution is obviously erroneous; we utilize in the shaft more than we produce there, and in the hearth less.

Going over the matter carefully we see that the error can lie only in one place. We have assumed that *all* the reduction of iron was done in the shaft and none in the bosh, an assumption which, as we shall later see, is contrary to the observed facts of practice and to the indication of the equilibrium diagram in Chapter IV which shows that the final traces of oxygen are removed from iron oxide only in an atmosphere almost free from CO_2 and at a very high temperature; conditions which are only obtained in the hearth.

We see, therefore, that a considerable percentage of the oxygen of the ore is removed only in the bosh of the furnace and from the consumption of hearth heat and the figures given above we can fairly estimate how much.

The data concerning the hearth heat are the most accurate, for the difference, which is a measure of the correction to be made, depends on the smaller number of items and the best-established data.

The 790 B.t.u. accounted for, fall short of the 1100 we know to be consumed by 310 B.t.u., the total heat of reduction of the ore is 2970 B.t.u., 310 B.t.u. are about 10 per cent. of this, and we can thus feel reasonably well assured that under such conditions 10 per cent. of the oxygen of the ore is removed in the bosh. This 300 B.t.u. subtracted from the original figure of 5500 consumed in the shaft leaves 5200 which is at least as good a check with the 5300 based on practice as we have any right to expect.

THE TOTAL HEAT OF SLAG

The figure used for the total heat of slag is high, but is taken from the best sources obtainable and enables us to account for the facts of practice in regard to the effect of increased slag volume on coke consumption, something it is not possible to do in any other way. The heat imparted to the slag-forming materials up to the critical temperature as given in

the table, 600 B.t.u., is obtained by adding the heats of the principal ingredients SiO_2, CaO, Al_2O_3, as taken from Richards' data, and is therefore fairly accurate. Deducting this from the total heat of the slag 900 we obtain a difference of 300 B.t.u., which must be imparted in the hearth by the hearth heat. The quantity of the latter per pound of coke charged (not that burned in the hearth only) is in ordinary practice about 1000 B.t.u. so that 0.3 lb. of coke should be required per pound of slag. The figure commonly used is 0.25 lb., but my observation of practice in different districts where very different quantities of slag per ton of iron are made, leads me to believe that the correct figure is really about 0.33 lb. This is in good agreement with the figure just deduced on the basis of the critical-temperature theory, but cannot be squared with any other theory by any possibility. For instance, we see that the combustion of a pound of coke develops altogether under such conditions as we have been discussing about 6500 to 9000 B.t.u.; taking even the smaller figure and the same high figure for the total heat of slag 900 B.t.u., 0.14 lb. of coke would be required per pound of slag, which has no relation whatever with practice.

I call particular attention to this in order to reiterate once more that the basis on which the critical-temperature theory rests is not its reasonableness or agreement with accepted principle in other sciences, but that it accounts *quantitatively* for the facts of practice, something which no other theory hitherto proposed can even attempt to do.

The shaft heat has so far been found merely by difference, subtracting from the total the hearth heat which we can calculate quite accurately and whose quantity so calculated checks well with fuel consumption over a wide range of practice, so that a number of furnacemen have come to have much confidence in the results so obtained. But while this is a small fraction of the total heat, to obtain the shaft heat merely by subtracting this small figure from the large one of total heat developed does not seem very convincing. We shall be able to show that the heat consumed in the shaft checks well with that imparted to that region; for this purpose we can use the results of calculations made for showing the results of solution loss, which are given in the next chapter.

There it will be seen that the heat developed and that brought into the shaft by the hot gases from the hearth supply enough for the requirements of the shaft with sufficient left over to heat the top gases to the temperature at which they are actually discharged in practice under those conditions. The radiation loss may have been assumed a little higher than it should and there are undoubtedly minor errors of constants used and assumptions made but it seems inconceivable that so involved a series of calculations could be made on the basis of authentic data and check so accurately as these do with themselves and with the conditions of practice unless they were substantially correct. Granting this we

may surely say that here is a confirmation of the twofold thermal balance of the furnace which cannot be denied since we see not only that the total heat must equal a certain quantity but that a certain portion cannot possibly be applied except above that temperature; also that the two quantities bear a definite ratio to each other, depending upon the conditions of the operation.

THE DETERMINATION OF THE CRITICAL TEMPERATURE

The early work done for this purpose has been described in the quotation in Section I of Thermal Principles and the critical temperature used in the coke-furnace calculations of this chapter is taken at 2750°, the same as the figure used for the early work, not for the sake of consistency but because the considerable amount of work done since seems to indicate that for the conditions of ordinary coke practice that figure is approximately correct.

In a valuable paper by F. E. Bachman before the American Iron and Steel Institute in October, 1914, he gives the results of pyrometric observations made by an expert from the Bureau of Standards which agree better than could have been expected with this figure taken as representing average condition of coke practice.

It is greatly to be hoped that more work will be done along this line, particularly on furnaces working under varying conditions, those making ferromanganese, ferrosilicon and the like, as well as furnaces in different varieties of coke practice and in charcoal practice, both cold and warm blast.

When this is done we may have more correct figures for the various kinds of practice, but in the mean time 2750° for most coke furnaces seems to be reasonably accurate, though on some rather lean slags the critical temperature is probably as much as 100° lower.

THERMAL PRINCIPLES—III

CHAPTER V

THE THERMAL EFFECT OF LOSS OF FUEL BY SOLUTION

This is a subject which has been little understood, although as early as 1879 Gruner stated that the condition of ideal working required the fuel burnt by the blast at the tuyeres to be a maximum and that dissolved by the oxygen of the charge a minimum.

Professor J. W. Richards in a brief paper before the International Congress at Düsseldorf in 1910 has attempted to refute this theorem in regard to furnaces requiring little hearth heat such as charcoal furnaces working on rich ores and therefore producing little slag. In this case Professor Richards claims that Gruner's "ideal working" would be wasteful, and that greater economy is obtained by departing from it as far as possible. I am unable to accept this conclusion for two reasons. First, I have myself run a charcoal furnace on rich ores, and it is a matter of sad experience with me that when the departure from Gruner's ideal working is considerable, as shown by the small quantity of blast required to burn a pound of fuel, the fuel economy is poor, and when the quantity of blast to burn a pound of fuel goes up the fuel economy increases in the same proportion, in exact accordance with Gruner's theorem. Second, Professor Richards' conclusions are contrary both to the double thermal equation, which I have outlined above, and to the old-style heat balance, even for conditions entirely outside those of present practice.

Twofold Function of the Carbon.—Just why Gruner's theorem should be true is not apparent on the surface. We naturally think that as the purpose of the blast furnace is to reduce iron ore with carbon, the sooner the carbon starts on its task the better. The reason this is not true depends fundamentally upon the fact that the carbon has to perform two functions and that its capacity for the two tasks is very different. One of its duties is to reduce the iron ore by carrying off the oxygen, the other is to supply the heat for this reaction, which is highly endothermic and for the other requirements of the process which are just as important. Referring to Table III it will be seen that when carbon burns to CO_2 it develops 5470 B.t.u. per pound of O consumed, while the dissociation

of iron oxide absorbs about 7500 per pound of O removed, this varying slightly with the oxide. If the carbon is burnt only to CO the conditions are much worse since in that case the heat developed per pound of oxygen is only 3280 B.t.u.; less than half as much as the removal of the same quantity of oxygen from the ore requires, so that for purely thermal reasons we must have in this case about twice as much carbon as would suffice for reduction.

From the thermal balances already given it may be seen that the total heat required is about twice as great as the reduction heat, and on this basis the surplus of carbon required for heat development over that for oxygen removed is still greater. The greater includes the less, and our problem is then one of heat development, not of oxygen removal.

Turning then to the heat developed, that per pound of carbon burnt to CO is 4375 B.t.u. and per pound burnt to CO_2 is 14,750, more than three times as much. We have already seen that the carbon necessary for heat development is two or three times as large a quantity as can be oxidized by the oxygen of the ore, therefore in order to burn it with any degree of completeness we must have oxygen from some other source. This source must obviously be the blast.

We have seen that the heat developed for one unit of oxygen per unit of carbon (producing CO) is less than one-third of the heat developed for two units of oxygen per unit of carbon (producing CO_2). Turning this statement around we may say that the second unit of oxygen develops over one-half more heat than the first or that the rate of heat development after consuming the first unit of oxygen is much more rapid, in proportion to the oxygen used, than the rate up to that point. In other words, the more oxygen we deliver to carbon the more heat we shall get in an increasing degree right up to the point of saturation, CO_2.

These facts are all the results of a single cause, that the addition of the first unit of oxygen to carbon results in its conversion from the solid state into the gaseous with the absorption of a large amount of latent heat of vaporization exactly as when ice is converted to water and the water to steam. The second unit of oxygen develops 10,400 B.t.u. per pound of carbon, if the first did as much the heat developed per pound of carbon burnt to CO_2 would be 20,800 B.t.u., instead of the 14,750 actually developed; the 6050 B.t.u. which disappear represent the latent heat of gasification of the carbon.

The Oxygen Which can be Imparted to the Carbon is Limited.—Now we are strictly limited in the amount of oxygen we can impart to the fuel in the hearth by the fact that CO_2 cannot exist at all in the presence of incandescent carbon, therefore if we burn *all* the carbon of the fuel to CO at the tuyeres we have reached the limit, and any carbon which is dissolved in the upper part of the furnace and fails to reach the tuyeres deprives us of the power of imparting a corresponding amount

of oxygen, which deficiency can never be made up and represents a net loss of heat development when the gas is discharged from the stack.

Minimum Amount of Carbon has Sufficient Oxygen-carrying Power.—In order to confirm this conclusion, let us take a case at the limiting condition. Let us suppose that CO could be oxidized entirely to CO_2 by oxygen of the ore, then the heat developed per pound of carbon would be 14,750 B.t.u., and let us assume that the minimum heat requirements are 75 per cent. more than the heat of reduction which for Fe_2O_3 is 3145 B.t.u. per pound of iron, so that the total requirements per pound of iron would be 5500. Then 0.373 lb. of carbon would be required per pound of iron, and if this were all burnt to CO at the tuyeres (Gruner's ideal working) it would take up $0.373 \times 4 \div 3 = 0.479$ lb. of oxygen there and would require as much more from the ore to saturate it, producing all CO_2 at the top of the furnace. The oxygen per pound of pig iron in Fe_2O_3 is $0.95 \times 0.428 = 0.406$ lb., which would convert the CO formed at the tuyeres to 82 per cent. CO_2 and 18 CO, about the equilibrium ratio for 900° as we have already seen. In other words, the theoretical minimum of carbon would have oxygen-carrying power sufficient to reduce the ore completely, and if *any* of the possible oxygen be lost by the failure of a part of the carbon to reach the hearth and take up its share there, the total supply would be insufficient for the oxidation of the carbon to this equilibrium ratio, still more so for oxidizing all to CO_2, as assumed.

Comparative Results with Varying Solution Loss.—In order to show the facts in regard to this question graphically I have made an analysis of it by taking the solution loss as the independent variable which brings out some facts that are the exact opposite of generally accepted opinion.

For simplicity I have assumed that the iron produced contains no manganese and phosphorus and that the silicon is 1.5 per cent., this assumption gives results practically identical with those which would result from the use of the actual percentages of these three metalloids in ordinary steel-making irons.

Let us assume as the basic case a furnace working with a slag volume of 50 per cent. and making a ton of iron containing 1.5 per cent. Si with a ton of coke (2240 lb.) and blown in four different cases with 50, 55, 60 and 65 cu. ft. of actual air at 70°F. Let us assume that the coke contains 2000 lb. of fixed C and that 80 lb. of this are required for carbonizing the iron, leaving 1920 lb. for combustion. Let us disregard the work done in the hearth altogether and consider the materials which descend to the hearth as discharged from the shaft in the solid condition at the top of the bosh. We have already seen that such a calculation is possible in spite of our complete ignorance of the temperatures at which the gases in the charge are driven off and consequently of how much heat it required to raise them to this unknown temperature. We charge against the total heat received plus that developed in the shaft, the heat required for the

chemical reactions of the shaft and that discharged from the bottom of the shaft and by radiation, the balance is then credited to the top gases, and from it we can readily figure the temperature of the latter. The temperatures found by this method in the different cases will evidently give us a measure of the effect of solution loss in the shaft of the furnace.

Effect of Solution Loss on Hearth Heat.—The effect of solution loss on hearth heat is simple, almost obvious. The chart, Fig. 3, gives hearth heats developed not per pound of coke charged, but per pound of coke burnt in the hearth, with oxygen from the blast. Obviously any coke which does not reach the hearth can furnish no such heat at all, and it is further obvious on reflection that oxygen from other sources than the blast even if set free in the hearth does not count in the development of hearth heat because any such oxygen involves the dissociation of other compounds, FeO, SiO_2 and the like, and there is not enough heat developed by the combustion of such oxygen with carbon to keep these reactions going without additional heat from some other source, so of course there is none available above the critical temperature, therefore no hearth heat is developed.

Obviously the hearth heat developed per pound of fuel is directly proportional to the cubic feet of blast required to burn that fuel, other things being the same, that is, the more blast we blow per pound of coke the more hearth heat per pound of coke we develop in exactly the same proportion.

In making the calculation, I have assumed that the blast was dry since this saves much complication in regard to the shaft heat calculations, and the comparative results are not affected thereby.

Now our calculations in detail become as follows:

Case 1.—1920 lb. of carbon for combustion (by blast and ore together) equals 0.857 lb. per pound iron; 50 cu. ft. of blast at 75 lb. per 1000 cu. ft. equals 3.75 lb. and 23 per cent. of this gives 0.864 lb. O. Assume the ore to be Fe_2O_3 and the iron to contain 95 per cent. Fe then we obtain 0.407 lb. of O per pound iron from this source.

0.015 lb. Si carries with it 0.017 lb. O, and assuming that 0.1 lb. of H_2O is decomposed in the shaft, which is about in accordance with Mathesius' and Cornell's figures, we obtain 0.089 lb. O from this source. Then the total O per pound of iron is as follows:

From blast (dry)	0.864
From SiO_2 reduced	0.017
From Fe_2O_3	0.407
From H_2O decomposed in shaft	0.089
Total O =	1.377
O required for 0.857 C to CO = $0.857 \times \frac{16}{12}$ =	1.143
O left for CO to CO_2 = 1.377 − 1.143	0.234
Carbon to CO = (1.143 − 0.234) × ¾ =	0.681 lb.
Carbon to CO_2 = 0.234 × ¾ =	0.175 lb.

Assuming that 10 per cent. of the oxygen of the ore is removed by solid carbon in the hearth in accordance with our previous conclusion we have the oxygen in the hearth as follows:

From blast	0.864 lb.
From SiO_2	0.017
From 10 per cent. of O in ore	0.041
	0.922

The carbon consumed in the hearth is therefore $0.922 \times \frac{3}{4} = 0.691$ lb.

The CO resulting from the combustion of this is $0.691 \times 29.85 = 20.6$ cu. ft.

The nitrogen of the blast is $0.79 \times 50 \times 492 \div 530 = 36.9$, add 20.6 cu. ft. CO and we have 57.5 cu. ft., total gas coming into the shaft from hearth.

The sensible heat of this gas at 2750° = 58.8 B.t.u. per cubic foot.

Heat brought into shaft by gas from hearth $57.5 \times 58.8 = 3380$ B.t.u.

Of the 0.857 lb. carbon charged there is consumed in the hearth 0.691 lb. leaving 0.166 lb. to be consumed in the shaft by oxygen from the ore.

This requires $0.166 \times 1.33 = 0.222$ lb. oxygen. The ore contains 0.4070, but 10 per cent. is not available in the shaft, so all we have available is $0.407 \times 0.90 = 0.366$ lb., deducting 0.222 lb. from this we have left 0.1440 O from the ore to which we add $0.1 \times 8 \div 9 = 0.089$ lb., the oxygen from the water dissociated in the shaft, making 0.233 lb. O for converting CO to CO_2.

This checks with the total oxygen calculation given before, which is much simpler but does not separate the C into the two portions, that burnt to CO and that to CO_2 in the shaft.

The Shaft Heat Developed.—We can now figure the heat developed in the shaft very simply.

0.166 lb. C burnt to CO develops $0.166 \times 4{,}375 =$	727 B.t.u.
$0.233 \times \frac{3}{4}$ C as CO burnt to CO_2 develops $0.175 \times 10{,}400 =$	1,820 B.t.u.
Add to this the heat brought in from the hearth	3,380 B.t.u.
Total heat for operations in the shaft	5,927 B.t.u.

To reduce 0.9 of ore, the heat consumed is	2,670 B.t.u.
To decarbonate ½ lb. limestone	405
To heat slag forming materials (½ lb.) to 2,750°F.	300
To heat iron (1 lb.) to 2,750°F	480
To heat carbon in iron	45
To evaporate 0.25 lb. H_2O to steam	280
To decompose 0.1 lb. H_2O from steam	580
	4,760 B.t.u.

On the basis of our assumption that the water evaporated decomposed is a certain percentage of the weight of the iron these items all depend upon the weight of iron produced and vary with it, when we assume the weight of iron produced per pound of coke to vary as we presently shall.

In addition we have radiation which, on the basis of our previous data is 440 B.t.u. per pound of iron under these conditions but is constant and does not increase with the iron per pound of coke; and the heat required to bring up to the critical temperature the coke that goes down out of the shaft into the hearth which, of course, changes with the weight of coke consumed in the hearth.

In this case it is 0.691 C × total heat of coke, 1159 B.t.u. = 800 B.t.u.

Adding these items we have as the total heat required in the shaft

Constant heat required for pound of iron as above	4,760
Required for heating coke	800
Required for radiation	440
	6,000
Total heat for operation in shaft	5,927
Balance (B.t.u.)	−73

This is 73 B.t.u. *more* than the heat developed in the shaft, but let us ignore this fact for the present and say that it merely corresponds to the fact that furnaces never run with so small an amount of blast as 50 cu. ft. per pound of coke, in other words solution loss is never so bad as we have assumed. Presently we shall see that this is not necessarily true, but we will not consider that now, merely assuming for the present that this represents the impossible case.

To compute the temperature of the top gases we can figure their volume and take their specific heat per cubic foot as 0.02 since this is extremely close and the error introduced by that assumption is not important enough to justify an accurate calculation of this factor.

The total carbon from the coke is 0.857 lb. or $0.857 \times 29.85 =$	25.6 cu. ft.
Nitrogen as above	36.9 cu. ft.
CO_2 from ½ lb. of stone (12 per cent. C) $= 0.06 \times 29.85$	1.8 cu. ft.
H_2 from 0.1 lb. $H_2O = 0.1 \times 1/9 \times 178 =$	2.0 cu. ft.
	66.3 cu. ft.

The specific heat of this at 0.02 B.t.u. per cubic foot is 1.33, hence we get -73 B.t.u. $\div$ 1.33 $= -55°$F.

This temperature is normally measured from 32°F., but if we do that we must take account of the heat of the materials charged and it is simpler to reckon the temperature of the top gas from that of the raw mate-

rials which makes no appreciable error. Taking this temperature at 60° we have the top gas passing off in this case at 60° − 55° = +5°F.

The gas analysis in this case is as follows:

CO_2 from combustion $0.175 \times 29.85 =$	5.3 cu. ft.	
CO_2 from stone as above	1.8 cu. ft.	
	Cu. ft.	Per cent.
Total CO_2	7.1	10.70
CO from combustion of $0.857 - 0.175 = 0.682$ C $0.682 \times 29.85 =$	20.3	30.66
Nitrogen as above	36.9	55.60
Hydrogen from dissociation of H_2O as above	2.0	3.10
	66.3	100.00

Case 2.—We now assume that the solution loss is less, so that 55 cu. ft. of blast at 70° are required to burn a pound of coke, 10 per cent. more than in the previous case, other conditions remaining as before.

The oxygen in the blast now becomes $0.864 \times 1.1 = 0.95$, and the other sources of oxygen remaining the same, the total becomes $0.017 + 0.089 + 0.407 + 0.95 = 1.463$, and the oxygen to burn all the coke to CO remaining as before 1.143 lb., the oxygen available for CO to CO_2 is $1.463 - 1.143 = 0.32$ lb., which burns 0.24 lb. C as CO to CO_2.

The coke burnt in the hearth is $\frac{3}{4}$ $(0.95+0.017+0.041) = \frac{3}{4} \times 1.008 =$	0.756 lb.
CO formed by this is $0.756 \times 29.85 =$	22.6 cu. ft.
The nitrogen is $36.9 \times 1.1 =$	40.6
Total gas coming in from hearth =	63.2 cu. ft.
Heat brought in by this at $2{,}750° = 63.2 \times 58.8 =$	3,710
C burnt to CO in shaft $= 0.857 - 0.756 = 0.101$	
Heat produced by this $0.101 \times 4{,}375 =$	438
C as CO burnt to CO_2 in shaft as above $0.32 \times \frac{3}{4} = 0.24$ lb.	
Heat produced by this $0.24 \times 10{,}400 =$	2,495
Total heat available in shaft	6,643
Heat required per lb. of iron as before	4,760
To bring coke burnt in hearth to $2{,}750° = 0.756 \times 1{,}159 =$	877
For radiation =	440
	6,077
Total heat available for shaft	6,643
Surplus for gas $= 6{,}643 - 6{,}077 =$	566 B.t.u.
Gas volume is as before except the nitrogen is increased 10 per cent. $= 3.7$ cu. ft., $66.3 + 3.7 =$	70 cu. ft.
Heat required to raise gas 1° at 0.02 B.t.u. per cubic foot specific heat of gas $= 70 \times 0.02$	1.4

$566 \div 1.4 = 404° + 60° = 464°$ discharge temperature of the gas.

The gas analysis in this case is as follows:

Total carbon gas from fuel as before is 25.6 cu. ft., the $CO_2 = 0.24 \times 29.85 = 7.26$ cu. ft. and the CO is 18.4. The carbon dioxide from the limestone is 1.8 which added to 7.2 gives 9 cu. ft., the H_2 as before is 2 cu. ft. and the nitrogen is $36.9 \times 1.1 = 40.6$.

Then the percentages are

		Per cent.
CO_2	$9.0 \div 0.70 =$	12.8
CO	$18.4 \div 0.70 =$	26.3
H_2	$2.0 \div 0.70 =$	2.9
N	$40.6 \div 0.70 =$	58.0

Case 2A.—Now let us assume that since the hearth heat as already shown is increased in proportion to the blast per pound of coke we increase the burden of ore and stone by 10 per cent. also. The oxygen from the blast is 0.95 lb. and that from other sources is increased 10 per cent. so becomes

From SiO_2	0.019 lb
From ore	0.448
From H_2O	0.097
	0.564 lb.

which added to 0.95 gives 1.514 lb. total. Deducting from this the oxygen for 0.857 C to CO, 1.143 lb. we have left 0.371 lb. O for CO_2, which suffices to burn 0.278 C as CO to CO_2.

The oxygen available in the hearth is $0.95 + 0.019 + 0.045 = 1.014$, which burns $1.014 \times \frac{3}{4}$ C = 0.76 C, leaving $0.857 - 0.76 = 0.097$ lb. C to be burnt to CO in shaft.

0.097 C to CO produces $0.097 \times 4{,}375 =$		424 B.t.u.
0.278 C as CO to CO_2 gives $0.278 \times 10{,}400 =$		2,895 B.t.u.
CO from hearth $0.76 \times 29.85 =$	22.7	
N from hearth as before	40.6	
	63.3	
Heat carried from hearth to shaft by gas 63.3×58.8		3,720
Total heat for shaft =		7,039
Heat required:		
For iron, etc., as before $\times 1.1 = 4{,}760 \times 1.1 =$		5,236
For heating coke $0.76 \times 1{,}159$		881
For radiation		440
Total		6,557

Excess available for heating gas 7039 − 6557 = 482 B.t.u. The volume of gas and its analysis are as follows:

Total carbon gas from fuel as before	25.6 cu. ft.		
Carbon as CO_2 from fuel $0.278 \times 29.85 =$	8.3 cu. ft.		
CO by difference		17.3 cu. ft.	24.6 per cent.
CO_2 from stone 2 cu. ft.			
Total $CO_2 = 2.0 + 8.3 =$		10.3 cu. ft.	14.7 per cent.
$H_2 = 2 \times 1.1 =$		2.2 cu. ft.	3.1 per cent.
$N =$		40.6 cu. ft.	57.6 per cent.
		70.4 cu. ft.	100.0 per cent.

The specific heat of this volume of gas at 0.02 B.t.u. per cubic foot is 1.41 and the discharge temperature of the gas is 482 ÷ 1.41 = 340, which added to 60, gives 400°.

Case 3.—Solution loss is so much decreased that 60 cu. ft. of blast are required per pound of coke, other conditions being as in Case 1.

Oxygen in blast is $0.864 \times 1.20 =$		1.037
Other oxygen as in Case $1 - 0.017 + 0.407 + 0.089 =$		0.513
Total oxygen		1.550 lb.
Oxygen for 0.857 C to CO as before		1.143
Oxygen left for CO to CO_2		0.407
C as CO to $CO_2 = 0.407 \times \frac{3}{4} =$		0.305 lb.
Oxygen in hearth $0.017 + 0.041$ (as in Case 1), $+1,037 =$		1.095 lb.
Carbon burnt with this		0.823 lb.
Carbon left to be burnt to CO in shaft $0.857 - 0.823 =$		0.034 lb.
Heat developed by this $0.034 \times 4,375 =$		149
Heat developed CO to CO_2 $0.305 \times 10,400 =$		3,171
Volume of CO from hearth $823 \times 29.85 =$	24.6 cu. ft.	
Volume of N from hearth $36.9 \times 1.2 =$	44.3 cu. ft.	
Total volume of gas from hearth	68.9 cu. ft.	
Heat brought in by this $68.9 \times 58.8 =$		4,050
Total heat for shaft		7,370
Heat required:		
For iron, etc., as in Case 1		4,760
For heating coke $823 \times 1,159 =$		955
For radiation		440
Total heat required in shaft		6,155
Heat available for gas $7,370 - 6,155 =$		1,215 B.t.u.

Volume and composition of gas.

Total carbon gas from fuel as before	25.6	
CO_2 from fuel $0.305 \times 29.85 =$	9.1 cu. ft.	
CO from fuel $25.6 - 9.1 =$	16.5 cu. ft.	22.5 per cent.
CO_2 from stone 1.8		
Total CO_2 $1.8 + 9.1$	10.9 cu. ft.	14.8 per cent.
H_2 as in Case I	2.0 cu. ft.	2.7 per cent.
N_2	44.3 cu. ft.	60.0 per cent.
Total	73.7 cu. ft.	100.0 per cent.

Specific heat of this at 0.02 per cubic foot = 1.47.

Temperature of top gas = 1215 ÷ 1.47 = 826 + 60 = 886°F.

Case 3A.—Blast as in Case 3 and burden increased in same proportion, 20 per cent.

Oxygen from blast 1.037	1.037
Other oxygen as in Case 1, $\times 1.2 = (0.017 + 0.407 + 0.089) \times 1.2 =$	0.616
	1.653
Oxygen for 0.857 C to CO	1.143
O for CO to $CO_2 =$	0.510
C as CO to CO_2 $0.51 \times \frac{3}{4}$	0.383 lb.
O in hearth from blast	1.037 lb.
From other sources as in Case 1, $\times 1.2 = 0.058 \times 1.2$	0.070 lb.
Total O in hearth	1.107

This burns 0.832 C to CO and leaves $(0.857 - 0.832) = 0.025$ C to burn to CO in shaft.

Heat from this $0.025 \times 4{,}375 =$		110 B.t.u.
Heat from 0.383 C as CO to $CO_2 = 0.383 \times 10{,}400 =$		3,980 B.t.u.
CO from hearth $= 0.832 \times 29.85 =$	24.8	
N_2, as in Case 3	44.3	
Total gas from hearth to shaft	69.1	
Heat brought in by this 69.1×58.8		4,060
Total heat available in shaft		8,150

Heat requirements:

For 1 lb. iron as in Case 1 $\times 1.2 = 4{,}760 \times 1.2 =$	5,710
For heating coke $0.832 \times 1{,}159$	965
For radiation	440
	7,115

Heat available for gas 8,150−7,115 =			1,035 B.t.u.
Total volume of gas:			
Carbon gas from fuel =	25.6		
$CO_2 = 0.382 \times 29.85$ =	11.4		
CO = 25.6 − 11.4 =	14.2 cu. ft.	19.0 per cent.	
CO_2 from flux $1.8 \times 1.2 = 2.2$			
Total CO_2 11.4 + 2.2 =	13.6 cu. ft.	18.3 per cent.	
$H_2 = 2.0 \times 1.2$ =	2.4 cu. ft.	3.2 per cent.	
N_2	44.3 cu. ft.	59.5 per cent.	
	74.5 cu. ft.	100.0 per cent.	

Specific heat of this at 0.02 = 1.49.

Temperature of gas 1035 ÷ 1.49 = 0.695 + 60 = 755°F.

Case 4.—Solution loss reduced to zero so that 65 cu. ft. of blast are required to burn a pound of coke, other conditions as in Case 1.

Oxygen in blast 0.864×13. =	1.123		
Other oxygen, as in Case 1, 0.017 + 0.407 + 0.089 =	0.513		
Total oxygen	1.636		
Oxygen for 0.857 C to CO	1.143		
Oxygen left for CO to CO_2	0.493		
C as CO burnt to CO_2 with this =	0.370		
Heat developed in shaft by this $0.37 \times 10,400$ =			3,850
No oxidation of C to CO in shaft, hence no heat from this			
Vol. of CO from hearth 0.857×29.85 =	25.60		
Vol. of N from hearth 36.9×1.3 =	48.00		
Total gas from hearth to shaft	73.60		
Heat brought in from hearth by this 73.6×58.8			4,330
Total heat available in shaft			8,180
Heat requirements:			
For iron, etc., as in Case 1			4,760
Heating coke $0.857 \times 1,159$ =			995
Radiation			440
			6,195
Heat available for gas 8,180 − 6,195			1,985 B.t.u.
Total gas volume:			
Carbon gas =	26.5 cu. ft.		
$CO_2 = 0.37 \times 29.85$ =	11.1 cu. ft.		
CO	15.4 cu. ft.	19.7 per cent.	
CO_2 from stone 1.8			
Total CO_2 1.8 + 11.1 =	12.9 cu. ft.	16.4 per cent.	
H_2 =	2.0 cu. ft.	2.6 per cent.	
N_2 =	48.0 cu. ft.	61.3 per cent.	
	78.3 cu. ft.	100.0 per cent.	

Specific heat of this at 0.02 = 1.566.

Temperature of top gas 1985 ÷ 1.566 = 1266° + 60 = 1326°.

Case 4A.—Same as last except burden increased in same proportion as blast to burn a pound of coke, 30 per cent., above Case I.

Oxygen from blast	1.123	
Other oxygen, as in Case 1, ×1.3 =	0.666	
Total oxygen	1.789	
Oxygen for 0.857 C to CO	1.143	
Oxygen for CO to CO_2 in shaft =	0.646	
C as CO burnt to CO_2 with this	0.485 lb.	
Heat developed by this 485×10,400		5,040
No oxidation of C to CO in shaft, hence no heat from this		
Gas from hearth to shaft as before 73.6		
Heat brought in by this as before		4,330
Total heat available in shaft		9,370
Heat requirements:		
For iron, etc., as in Case 1, ×1.3 = 4,760×1.3 =		6,190
Heating 0.857 coke as before		995
Radiation		440
Total		7,625 B.t.u.
Available for gas heating 9,370−7,625 =		1,745 B.t.u.

Total gas volume:			
Carbon gas from fuel	25.6 cu. ft.		
CO_2 0.485×29.85 =	14.5 cu. ft.		
CO	11.1 cu. ft.	14.2 per cent.	
CO_2 in stone 1.8×1.3 = 2.3			
Total CO_2 2.3+14.5	16.8 cu. ft.	21.4 per cent.	
H_2 = 2×1.3	2.6 cu. ft.	3.3 per cent.	
N_2, as in Case 4	48.0 cu. ft.	61.1 per cent.	
	78.5 cu. ft.	100.0 per cent.	

Specific heat of this at 0.02 per cu. ft. = 1.570.

Temperature top gas = 1745 ÷ 1.57 = 1110° + 60 = 1170°F.

The results in graphic form: Fig. 5 shows these results graphically. Above the zero line we have the heat developed and that required in each of the four cases and the three subcases, but in order to have the total correct the heat required to bring the coke up to the critical temperature is deducted from both sides alike. This is perfectly correct, for we could, if we liked, have deducted from the heat brought in by the gases rising from the hearth, the heat required to heat the coke to the critical temperature, and counted the balance as that available for heating the rest of the charge and the gas. We have in fact virtually done this by adding

the heat for the coke to the requirement side instead of subtracting it directly from the heat available side. If we left this in on both sides we should be counting the heat required for the coke twice and should not get a correct total by adding the hearth heat to the above quantities.

We can readily plot the hearth heat downward from the zero line and the total distance between this and the lines of shaft heat requirements gives the total requirements for the given case. We may obviously

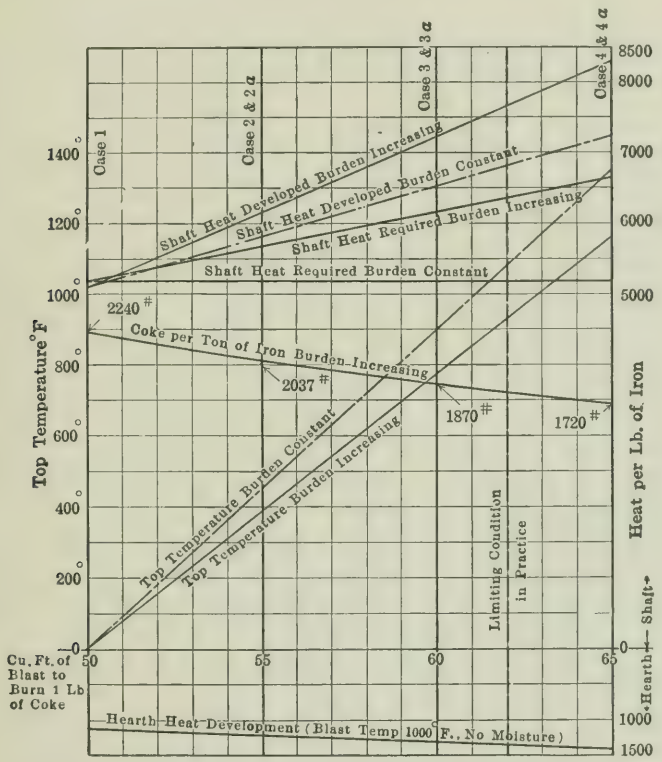


Fig. 5.—The effect of solution loss on heat development and top-temperature.

assume for Case 1 representing 1 lb. of iron that the hearth heat developed is 1100 B.t.u. in accordance with the actual data of operation given above. This is derived by the combustion of that coke which is burnt with the oxygen of the blast or $\frac{3}{4} \times 0.864 = 0{,}648$ lb. C.

Our diagram of hearth heat is based on 0.85 lb. C burnt with blast and 1100 B.t.u. for 0.648 lb. C corresponds to 1440 B.t.u. per 0.85 lb.; assuming 0.5 lb. moisture per 1000 cu. ft. of blast we find that 1000° blast-temperature produces the required amount of hearth heat. Assuming these conditions to remain the same, the hearth heat increases in

proportion to the blast per pound of coke as explained above, and starting at 1100 B.t.u. in Case 1 it rises to 1430 B.t.u. in Cases 4 and 4*a*.

Let me reiterate here that these calculations show what the thermal condition *would be*, if we could have the amount of solution loss assumed in each case, without asserting that this is possible. We can now proceed to interpret these results.

ANALYSIS OF RESULTS

High Solution, the Left Side of the Diagram.—Let us return now to the impossible top temperature in Case 1, 55° below the temperature of the entering charge which might seem to indicate that a furnace could not operate under conditions even approximating these.

As a matter of fact furnaces can and do operate under conditions very similar to these and strange as it may seem they do it by increasing the blast-temperature. Since the blast constitutes about 80 per cent. of the gas, an increase of 200° blast-temperature will give an increase of about 160° top temperature and so raise the temperature of the top gas to 165° which is still below the top temperature at which furnaces run. But referring to the diagram we find that for 51.25 cu. ft. of blast the top temperature rises to 100° and adding the 160° for a higher blast-temperature we obtain 260° for these conditions, which correspond very closely in all important particulars to those under which many furnaces operate when using much Mesabi ore. It is necessary to emphasize the fact that in such a case more heat is developed in the hearth than is needed there, and that the excess passes up into the shaft and does work there which should have been done by heat of lower temperature under more correct conditions of working. This would leave this hearth heat to be utilized for the final smelting of a larger burden.

This is precisely the condition described above, under which the charcoal furnace was working on wet ore.

The chart shows quite plainly that only about one-fifth to one-fourth as much hearth heat per pound of fuel is generated as of shaft heat, so it is obviously a waste of fuel to employ this hearth heat for use in the shaft just as it would be to employ water from hydraulic pumps under 1200 lb. pressure to feed boilers at 200 lb. pressure.

This is in accordance with the general law of thermodynamics that any application of heat at a temperature lower than that at which it is developed results in an increase of entropy and a decrease of availability.

Obviously this corresponds to the case of Cornell as against that of Mathesius. In the latter's case only 1000 B.t.u. of shaft heat were developed per pound of iron, in the former's case 1250 B.t.u., because it was doing work in the hearth that should have been in the shaft and this surplus of high-temperature hearth heat was being largely wasted on low-

temperature operations. Probably this was due to incorrect filling or a scaffold causing irregular descent of the charge into the hearth since if it were due to excessive solution loss there would be a deficient development of heat in the shaft whereas there is really an excess so far as our figures give reliable indications.

Low Solution Loss the Right-hand Side of the Diagram.—Passing now to the other side of the diagram, Cases 4 and 4*A*, the oxygen from 65 cu. ft. of blast plus that from the silicon is exactly enough to burn all the coke without leaving any for the 10 per cent. of oxygen from the ore which we have already seen is removed only in the hearth and we may therefore safely admit that this case is beyond the limit of present possibility.

From the detailed calculation it appears that 62 cu. ft. of blast is about the maximum that still leaves carbon enough for the removal of the last 10 per cent. of oxygen in the ore and a vertical line on the diagram through this quantity of blast indicates approximately the practical limit in this direction of the amount of blast per pound of coke that can be blown for these conditions, but, of course, if the quantity of fixed carbon in the coke were greater than that assumed as the basis of the calculation, then the theoretical maximum limit of blast per pound of coke would be proportionately raised.

We find in this the probable explanation for the excess hearth heat in the case of Reece, for in my first work on this subject (see the report quoted before) I did not realize that at least 10 per cent. of the oxygen of the ore was necessarily removed in the hearth, and since my figures for blast volume based on piston displacement indicated that enough blast was blown to burn all the coke I assumed this to be the case; but these figures for blast volume depend on several allowances and the results are not absolutely positive. They must, therefore, give way to the small extent required by the later deduction founded on more accurate data; that 10 per cent. of the oxygen of the ore is removed by direct carbon in the hearth with a corresponding loss of carbon.

The minimum loss is represented by the difference between 65 cu. ft. and 62 cu. ft. of blast per pound of coke or 5 per cent., but as a matter of fact the solution loss is probably never less than 10 per cent. and a deduction of 10 per cent. from the hearth heat in Reece's case, 1170 B.t.u., would bring it down to 1053 B.t.u., virtually identical with that of Mathesius. This reduction in the amount of total oxygen would also reduce the shaft heat to a figure as close to that of Mathesius as such calculation will ever come *honestly*.

The better agreement, brought about by this correction, between the results of two cases varying widely in time, place, and conditions, seems to me to confirm both the correctness of the thermal calculation as a whole

and the accuracy of our conclusion, as to the removal of the final fraction of the oxygen of the ore in the hearth.

I believe it will be generally admitted that these theoretical maximum and minimum limits of blast blown are in exceedingly close agreement with the facts of practice.

It will be seen that the coke consumption for this high limit of blast blown is about 1800 lb. whereas the results reported by Mathesius are considerably lower than this, 1682 lb., and the more recent work of Howland at the plant of the Wisconsin Steel Co. has produced a still lower figure, about 1640 lb.

These facts, however, do not in the least controvert our diagram, but rather confirm it, for we have assumed only 1000° blast temperature, whereas these remarkable results were obtained with blast temperatures of about 1250° corresponding to the production of 23 per cent. more hearth heat per pound of coke burnt with blast. Sixteen hundred and forty pounds being only 8 per cent. less than 1800 lb., it is obvious that enough hearth heat could be developed with about 15 per cent. less coke burnt by blast than in our limiting case with 62 cu. ft. of blast; which would correspond to about 53 ft. of blast; this was in fact the precise amount used by Mathesius. Moreover the total carbon in Howland's practice is 93 per cent. against 89 per cent. as assumed above, while the sulphur in his coke was so low that the critical temperature was probably lowered by the use of a more siliceous slag.

Conditions of Practice to Which the Diagram Corresponds, Hearth Heat.—The condition represented by Cases 1 to 4 in which the blast per pound of coke increases without any increase of burden may be compared with either of two conditions in practice. First, we may assume that the blast temperature falls or the humidity rises as the solution loss decreases so that while more coke is burnt in the hearth only the same amount of hearth heat is developed from it.

Second, we may assume that the weight of slag increases as the solution loss decreases and that as the hearth heat increases the heat required above the critical temperature for slag increases in the same proportion, so that left for iron and other hearth requirements is still the same. In either case no more iron could be smelted per pound of coke with low than with high solution loss, thus producing the conditions as to shaft heat which we have assumed.

The latter condition of larger slag volume and lower solution would correspond with lean lump ores, such as are used in the South as compared with the fine sandy but much richer Mesabis.

Such data as I have of cases with approximately the same fuel consumption in these two dissimilar cases confirm the results of the diagram absolutely, the top temperature being much higher in the case of the low solution loss.

The former case is approximately that of a furnace on Old-Range ores but with higher humidity and lower blast temperature, so developing less hearth heat per pound of coke but receiving more coke in the hearth on account of low solution loss and these cases also confirm in a qualitative way the results of the diagram, the top temperatures being much higher under such conditions than in Mesabi practice on the same fuel consumption. This brings our diagram into absolute agreement with practice as regards hearth heat and we may now turn to the question of shaft heat development.

Conditions of Practice to Which the Diagram Corresponds. Shaft Heat.—The chart shows that the temperature of the top gases rises almost as fast when the burden is increased in proportion to the blast blown as it does when the burden is not increased at all. This is without any allowance for the fact that the limestone needed would be reduced in proportion to the increased iron produced because of the smaller amount of coke, ash and sulphur to be fluxed. With reasonable allowance for this factor the temperature would be almost the same with the increased burden as without. This seems very surprising and the reason for it has an important bearing on the whole subject of thermal principles. This reason is that *the heat generated by the oxidation of CO to CO_2 with oxygen from the ore develops more shaft heat than is required for the preparation of the ore from which the oxygen comes.*

We have already seen that the reaction $Fe_2O_3 + 3CO = 2Fe + 3CO_2$ is slightly exothermic—7330 B.t.u. + 7650 B.t.u., but in this case it is much more than slightly so, for the CO brings with it a very large quantity of sensible heat due to the high temperature of itself and its accompanying nitrogen; these contribute far more than enough heat for all the other operations outside of reduction and the net result is that *if the solution loss remained the same* the top temperature in any given case would drop little or not at all by the addition of more ore, *always provided that enough additional hearth heat were furnished to take care of the added burden in the hearth.* As a matter of fact the solution loss does not stay the same, because the approximate equilibrium between the concentration of CO_2, the fuel and the quantity of ore is disturbed and the increased CO_2 dissolves more coke, this solution is a highly endothermic reaction and it cools off the gas quite appreciably. Our diagram shows quite unmistakably, that if the solution loss be diminished so that the coke burnt in the hearth is correspondingly increased and the burden increased in this same proportion, the top gas will become hotter and not colder.

Solution loss can be affected in two principal ways: first, by changing the characteristics of the coke itself by differences in coal used, method of coking, etc.; and by changing the type of ore used. I have never had

the opportunity to make a test of the top temperature on cokes of different solubility, but I believe it is well established that top heats on low-fuel runs were higher with Old-Range ores than they are to-day with large percentages of fine Mesabis producing high solution loss, on the same fuel consumption.

Of course, we do not find in actual practice the top heats shown by the diagram for low solution loss, because as the temperature tends to rise the solution loss rises also and automatically checks it.

Recapitulation.—Let me reiterate here that this diagram is not intended to show what *does* happen under all conditions, but only to show what *would* happen if starting with given conditions we had a varying solution loss.

The exact conditions assumed are impossible at both ends of the scale as already explained, but the indications of the diagram are certainly in good agreement with the facts of practice in the region of the diagram between 51 and 60 cu. ft. of air per pound of coke. The value of the diagram comes not from any claim to arithmetical exactness, for such a claim would be ridiculous, but from the fact that, starting with the best data obtainable, results have been obtained which are at least truly comparative for the conditions and which are certainly in good agreement with the results of practice within the legitimate range of the diagram. This diagram makes it clear that solution has two effects, the results of both of which are to diminish the economy of working of the furnace.

First, it prevents a portion of the coke from ever reaching the hearth and thereby reduces the production of hearth heat directly in the same ratio.

Second, it reduces the total amount of oxygen which can be imparted to a given weight of coke and thereby diminishes in a greater degree, proportionally, the oxidation of CO to CO_2 in the shaft, which is the principal source of heat in that region, so that the development of shaft heat with increased solution loss drops more rapidly than that of hearth heat.

If we were to use some method different from any we now have in operation but nevertheless conceivable, whereby the development of hearth heat per pound of fuel could be noticeably increased we should be under the necessity of increasing the shaft heat just as much, in order to take advantage of it, since we have seen that these requirements for any given case bear a definite relation to each other. The only way we could secure this increase would be by a further oxidation of the top gases and this in turn could only be done by diminishing the solution loss below what it now is.

We seem therefore to be perfectly safe in saying that *for any conditions of which we can conceive the higher the solution loss the poorer the fuel economy.*

The Oxygen of the Ore as an Asset.—These considerations demonstrate that the oxygen of the ore instead of being a detriment to the smelting process is an asset of great value, for it alone is available to oxidize the CO formed in the hearth to CO_2, the reaction on which the shaft must depend for the major portion of its heat supply. This is a conception which has as far as I know never been advanced before and is worthy of some reflection.

It is interesting to note the possibility that the greater fuel consumption required for magnetite than for hematite ores under similar conditions may be due to the smaller quantity of oxygen per unit of iron carried by that ore, 0.381 instead of 0.428, while the resulting deficiency of heat accompanies heat requirements per pound of oxygen transferred, greater than those of hematite, so that a smaller development coincides with a larger demand. There are, of course, other conditions, the probability of a greater heat requirement in the hearth and of more oxygen to be removed by incandescent carbon in the latter region, and these may readily be the controlling factors. Nevertheless the other consideration is worthy of thought.

There are authentic cases on record in which furnaces have been working badly and apparently too cold in the hearth but not yielding to any of the customary treatments for that condition, which have responded perfectly when the burden was increased. At first sight this seems preposterous and I confess that I formerly listened to such stories with scepticism, but in the light of the above reasoning this becomes more comprehensible; if a furnace, admittedly lightly burdened, and therefore with a surplus of hearth heat passing up into the shaft, received an increase of burden the additional oxygen in the shaft would cause a development of shaft heat more than sufficient for the increased burden and would permit the surplus hearth heat to do its proper work on the additional ore with steadying and generally beneficial results. This is an exaggerated case of the general rule well known to most furnacemen that a heavily burdened furnace generally works better than a lightly burdened one, as long as regular conditions are maintained.

Hearth and Shaft Heat Requirements: The diagram, Fig. 5, designed in the first place merely to show graphically the results calculated above, is believed to have possibilities of wider use. It brings out, as nothing else I have found could do, the direct relationship between the heat requirements of the hearth and of the shaft under different conditions. These have a definite and practically unchanging ratio to one another, for any given set of conditions, and if an increase is to be made in the quantity of either kind of heat produced, it must be accompanied by a proportional increase in the other kind if a corresponding saving is to be made.

The original diagram is drawn to show the effect of solution loss and that is accordingly made the independent variable. Cases 1, 2*A*, 3*A* and

4*A*, however, also correspond to an increase in the iron per pound of coke proportional to the decrease in solution loss and as this now becomes the independent variable whose effect we wish to examine I have drawn a separate diagram, Fig. 6, of which abscissæ represent a wide range of iron-coke ratios, from 0 to 2:1. Ordinates above and below the zero line represent hearth and shaft heat requirements as before.

The quantities of these for 1.1 lb. of iron per pound of coke (corresponding approximately to 2000 lb. of coke per ton of iron) have been taken from Fig. 5 and lines drawn through each from the zero point, *OS* and *OH*. It is evident that the ordinates of these lines for any other iron-coke ratio give the requirements of each kind of heat from each pound of fuel for those conditions (and, of course, those only).

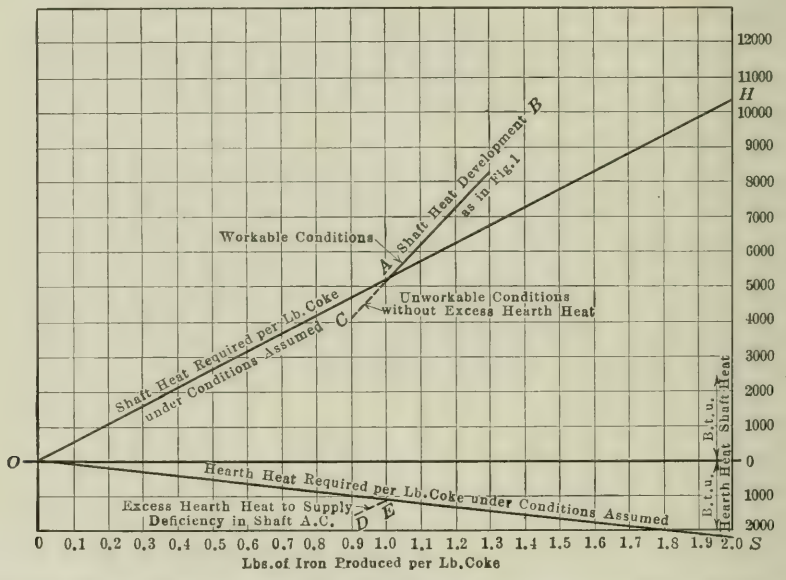


FIG. 6.—Diagram showing hearth and shaft heats necessary under normal conditions to produce different weights of iron per lb. of coke.

It is evident that if the lines of heat development be outside these lines in *both* cases or coincide in one and lie outside in the other, we shall have a workable case; but if *either* line of heat development lies inside the line of corresponding requirements that case is unworkable. I have added to the diagram the line of shaft heat development *BAC*; the line of hearth heat development with increasing burden, of course, coincides with the line of *OH* of Fig. 6.

The cases represented by the portion of the line *AB* outside the line of requirements are workable cases, but those represented by the portion *AC* inside the requirement line are not workable.

There is one exception to this latter statement to cover the case already described of a surplus of hearth heat utilized to make up a deficiency of shaft heat.

This corresponds to the condition we should have if we increased the hearth heat for cases *AC* as shown by the dotted line *DE* as far below the line of hearth requirements as the shaft heat development for those cases is below the shaft requirements.

The slope of the line indicates how impossible it is to go far in this direction.

This corresponds to an equal distortion of both lines of the diagram downward relative to the zero line. The cases so represented are not economical, but are workable, but the cases represented by the distortion of the diagram *upward* corresponding to the utilization of shaft heat for hearth purposes are not workable, being contrary to the second laws both of thermodynamics and the blast furnace.

There is, of course, a possible limitation to the development of shaft heats which must never be forgotten, though it is further from the furthest limits of practice than we have been accustomed to think, this is the limiting concentration of CO_2 in the presence of ore, irrespective of the presence of carbon, these limits being approximately given above. We must under no circumstances draw our line of shaft heat developed per pound of fuel, beyond the limits set by this limiting ratio; to do so would be to assume that the carbon gas could be oxidized to a degree which is not possible and would lead to a fundamentally incorrect result.

There is no doubt much good work being done with quite high solution loss and some furnacemen are inclined to take the stand that high solution loss is not detrimental, but in view of the foregoing demonstration of the facts I believe we are justified in saying that no matter how good work may be done under any given conditions *with* high solution loss, better could be done *without*, and the only limit to this statement comes when we reach the limiting concentration of CO_2 for the given ratio of carbon gas and ore, in the absence of fuel.

It is well to repeat that furnaces which under given conditions could not run for a deficiency of shaft heat may have this deficiency made good by an excess carried over from the hearth. I have run a furnace under such circumstances myself and know it to be true, but it is also true that it is a very uneconomical way to operate and that the hearth heat so utilized is only about one-fifth as valuable as it would be for its proper work in the hearth.

Returning now to Gruner's theorem, remembering that the lower the solution loss the greater the quantity of air required per pound of coke, we may express it tersely as follows: "The lower the solution loss the greater will be the economy of the furnace."

This is the conclusion to which our long and somewhat tiresome in-

vestigation has irresistibly led us and we can only pay a tribute of respectful admiration to Gruner for his early discovery of a most important law, whose consequences have been too much neglected. Professor Richards' criticism of it may perhaps be said to have erred in laying too much stress on oxygen-carrying power and too little on the necessity of developing heat, which can only be successfully done by utilizing the oxygen-carrying power of the fuel to the maximum possible extent.

Conclusions.—It may be well to recapitulate briefly the conclusions reached in this chapter:

For maximum fuel economy there are two principal laws.

First: Each pound of fuel must develop the maximum possible amount of heat.

Second: A certain irreducible proportion of this must be developed above the critical temperature, which is the free-running temperature of the slag.

To accomplish these results we must work along the following lines.

A. Impart as much total oxygen as possible to each unit of carbon before it leaves the top of the furnace.

B. Burn the largest possible proportion of the carbon with oxygen from the blast.

C. Heat the blast as hot as possible.

D. Remove the moisture from the blast as fully as possible.

E. Keep the free-running temperature of the slag as low as possible since a decrease in the critical temperature has a greater effect than an equal increase in blast-temperature.

F. Keep hearth requirements low by keeping down slag volume and avoiding excessive cooling for protective purposes.

G. Above all secure a stock distribution which will insure minimum solution loss with uniform preparation and descent of the charge column, so that no work which can possibly be done in the shaft will be left to be done in the hearth.

H. Even following these rules, the hearth heat is generally deficient as compared with the shaft heat and, therefore, except in certain special cases, the heat consumption of the shaft can be increased within reason without much, if any, loss of efficiency by the furnace as a whole.

It has been my endeavor to present here as simply as possible the fundamentals of the thermal action of the blast furnace, but the interrelations between chemical action and thermal action are so numerous that it is not possible to reduce the subject to short and simple unqualified statements.

In conclusion it may be well to warn those who desire to make thermal calculations for the purpose of investigating possibilities of improvement and the like, never to predict the ultimate consequence of a given change until they have followed it all the way through to see if it involves any

chemical or thermal impossibilities. For such purposes sheets of the general form used in Tables VII to IX may be recommended. They are the outcome of days of effort to record the result of such calculations so that their chemical and thermal effects could be followed to the correct conclusions. But this form does not remove the necessity for a quantity of detailed, painstaking, and tiresome work for the accomplishment of such purposes.

CHAPTER VI

MECHANICAL PRINCIPLES

The opinion has been quite generally held that the mechanical principles of the blast furnace are insignificant in number and importance, and the subject has been correspondingly neglected, but in my judgment this attitude is founded on superficial observation, since the proper mechanical action of the furnace is the key to its successful commercial operation. There are two main requirements of mechanical action, of equal importance since the fulfillment of both is vital to the process. These are: first, that the stock must settle uniformly over the whole area of the furnace and at as regular a rate as possible; second, that the gas formed by the combustion in the hearth must rise with similar uniformity of distribution and velocity so that each portion of the charge shall receive its share of the action of the gas.

In the early days of blast-furnace operation there was little or no conflict between these two requirements, but with the increase in the rate of driving previously described, they have become to a certain extent conflicting, because of the resistance to the descent of the stock column offered by the ascending current of gas. The gas is driven through the furnace by mechanical power, and the amount of pressure which we can put upon it is in recent years virtually unlimited, so that the gas (blast) pressure has risen as fast as there was any need for it to do so; in some cases, one might almost say, faster. But the force causing the descent of the charge column is simply that of gravity, which we cannot increase except by increasing the height of the furnace, and the net result of that remedy, as I shall presently show, is to make conditions much worse instead of better.

Our first care must obviously be so to distribute the charge in the top of the furnace that the resistance of all portions of the charge column shall be the same, as already pointed out in the chapter on filling the furnace.[1] We know but little about the theory of stock distribution further than the necessity of placing a considerable part of the fine material against the walls on account of the greater proportion of voids at the surface of the wall. Under the head of operation we shall discuss this a little more fully, but there is not enough known on the subject to be of use in this discussion, further than the above.

[1] See Blast Furnace Construction in America.

THE BLAST PRESSURE

Within quite recent years, and perhaps even now, there is a very considerable misapprehension on the subject of the cause and function of the blast pressure. This is made up of three parts, the pressure required to drive the air through the tuyeres, that required to force it up through the charge column, and that to force it from the top of the furnace out through the downcomer and flues. These three items make up the total blast pressure just back of the tuyeres, while to obtain the engine-house pressure the pressure due the resistance of the hot-blast main, the stoves, and the cold-blast main must be added, the sum of which should not exceed ½ lb. in good practice.

Many furnacemen have thought that the greater portion of the whole pressure was expended in driving the blast through the tuyeres, and that the resistance of the stock column was almost a negligible quantity, but nothing could be further from the facts. The pressure required to drive the blast through the tuyeres is in ordinary practice only about 10 per cent. of the total pressure, and almost all the rest is expended in overcoming the resistance of the stock column. Finally from 1 to 3 per cent. of the total is required to drive the gas through the down comer, flues, and burners.

In a paper published by me before the American Institute of Mining Engineers in 1905, entitled "Notes on the Physical Action of the Blast Furnace," there was given a discussion of this subject which, in the light of 10 years' further experience, does not seem to require much modification and is quoted here.

"**The Top Pressure.**—This is so simple that misconception would have seemed impossible had the attempt not been made to deduce results as to the quantity of flue dust carried over at different furnaces from their top pressures. The truth is that the top pressure depends on the volume and density of the top gases, and on the frictional resistance of the flues or mains through which they are forced, and on nothing else. The frictional resistance depends on the clear area, the length and the roughness of the mains.

"Considering that the condition of the latter is generally a matter of entire uncertainty, as they vary in normal operation from perfectly clean to almost completely blocked with flue dust and coke, calculations of the frictional resistance during operation are entirely worthless, as are also deductions as to the furnace work from the gas pressure. If the top pressure rises, the blowing engine automatically blows a little more pressure (never in good practice over ½ lb.), so as to maintain the same difference between the pressure at the tuyeres and that at the top. As these variations are much smaller and much slower than those due to other causes, they are naturally never noticed at the engine."

Pressure Required for the Tuyeres, Penetration.—We may well quote further here from the paper above mentioned:

"The pressure drop through the tuyeres has also come in for its share of misunderstanding. Within a few years the assistant to the superintendent (now superintendent) of the largest blast-furnace plant in the world contended with me strongly that the blast pressure was nearly all expended in forcing the blast through the tuyeres, and that the pressure at the top of the bosh would not be over 2 or 3 lb. in a furnace driven with about 15 lb. He was at that time making experiments bearing on this subject, and soon found his error. This is, in fact, a matter on which we can make calculation with certainty, Fliegener, Zeuner and Weisbach having made experiments on the flow of air through orifices, and established formulas therefor which are authoritative.

"The formula for this case is:

$$W = 63.6A\sqrt{\frac{P_2(P_1 - P_2)}{T_1}} \qquad (1)$$

W being the weight in pounds of air passing each tuyere per minute; A, the area of the tuyere; P_1, the absolute pressure outside the tuyere; P_2, the absolute pressure in the furnace; and T_1, the absolute blast-temperature (= deg. F. + 460).

"One thousand cubic feet of air at normal pressure and 70°F. weigh exactly 75 lb. Since this is about an average normal condition, the conversion of volume to weight can be conveniently made on this basis. Moreover, since the tuyeres are usually circular in section, we can convert the above formula to a more convenient form for immediate use, as follows:

$$P_1 - P_2 = 2.4\left(\frac{T_1V^2}{P_1d^4}\right)$$

where V_2 is the volume of blast (free air) passing each tuyere per minute, measured in thousands of cubic feet, and d is the diameter of the tuyere in inches. This latter formula is not quite exact, being too high for low tuyere velocities and too low for high ones; but it is accurate enough for the present purpose, under ordinary conditions.

"For a furnace blown with 40,000 cu. ft. of blast per minute at 15.20 lb. pressure and 1000°F. through twelve 6-in. tuyeres, we have $P_1 - P_2$ = difference of pressure passing through the tuyeres =

$$2.4 \times \frac{1000 + 460}{15.2 \times 14.7} \times \frac{(3.3)^2}{6^4} = 1.0 \text{ lb.}$$

"This is the difference in pressure required to give the necessary velocity through the tuyeres, and is, of course, fixed by the temperature, pressure, and volume of the blast, and the size of the tuyeres.

"It will be seen that this pressure varies as the fourth power of the diameter of the tuyeres, so that it requires over twice the pressure to force the blast through 5-in. tuyeres under given conditions as to force it through 6-in. ones.

"Other things being equal, the loss of pressure in passing the tuyeres varies as the square of the velocity, and the energy of the blast jet also varies as the square of its velocity, hence the energy varies directly as the difference in pressure. This energy represents the ability of the blast jet to overcome resistance in its line of action—in other words, its penetration; hence the penetration is proportional to the difference in pressure between the bustle pipe or tuyere stocks and the

interior of the furnace. This explains the failure of many schemes of alternate small and large tuyeres, and tuyeres with flattened nozzles adapted to deliver a fan-shaped jet of air, which will cover the whole tuyere plane equally (Gaines tuyeres). The difference of pressure, under given circumstances, within and without the tuyeres, is determined by the area of all the tuyeres, and hence the penetration in front of each of them is the same. Consequently, when alternate large and small nozzles are used, instead of the small ones throwing the air to the center and the large ones filling in the dead spaces between them, they all penetrate in figures of the same shape in the tuyere plane; but the larger tuyeres make a larger and therefore longer one than the smaller—an effect the opposite of that intended.

"Similarly the Gaines tuyeres distribute the blast so that the proper amounts are started in each direction to fill the area in that direction, but as some of these areas are much longer than others, while the difference in pressure is the same within and without the tuyeres in all directions, the penetration is either insufficient in some directions or too great in others.

"For each diameter of hearth, number of tuyeres and general conditions as to blast pressure, kind of cinder, etc., there is a given diameter of tuyeres which will throw the blast to the center sufficiently,without allowing great dead spaces on the walls between the tuyeres. If the tuyeres be made smaller than this, the force of the air jet straight ahead will take an excess of blast to the center of the furnace and allow pilasters, so to speak, of dead material to form on the walls between the tuyeres, so reducing the active area of the hearth and making the furnace work too hot at the center. If, on the other hand, the size of the tuyeres be increased, the blast jets fail to reach the center, but spread out laterally to such an extent that they may even cut the walls between the tuyeres, while a cone of dead material forms in the center.

"One of the best furnacemen in the country once told me that he had banked his furnace, cut through the jacket, and put in additional tuyeres; that in cutting in for these they had found something like 3 ft. of perfectly dead material on the walls, and that after starting up they had made nearly 50 per cent. more iron than the best they could do before. Naturally, he was a believer in multiple tuyeres, though not extreme in his views.

"On the other hand, many illustrations could be gathered in which the results were slight or even ojectionable, under circumstances at first sight not very different.

"The explanation is not difficult. In the first case the size of the tuyeres had probably been increased until they were as large as the blow stocks and bustle-pipe connections could supply, and the velocity of the blast into the furnace could not be reduced by further increase in size of the tuyeres, although it was very much too high; with the blast all going up the center, and very heavy pilasters built up between the tuyeres on the bosh walls, as shown by the depth of dead material cut through, before fire was reached.

"When the increased number of tuyeres was put to work the velocity of the air jets was diminished, and they were able to spread out laterally so as to melt off the pilasters, and increase the effective area of the hearth very materially. But if the bustle-pipe connections and tuyeres had been enlarged so that the proper quantity of air at the required temperature and pressure could have gone through

them at the proper velocity, the results would have been in all probability almost if not quite as good as those attained by the use of a greater number of tuyeres.

"If now, thinking to profit by this example, some furnaceman whose furnace was already equipped with a proper size of tuyeres, had followed a similar course, he would have so far reduced the velocity of the blast jets that their penetration would have been insufficient; and they would have spread out sidewise, scouring the walls between the tuyeres and allowing a cone of cold material to form on the bottom in the center. In such a case, unless the area of the individual tuyeres had been reduced in proportion as their number was increased, the condemnation of multiple tuyeres would have been as hearty as its praise was in the first case.

"It is not to be overlooked, however, that, other things being equal, the area of the pilasters on the walls varies nearly as the square of the distance between consecutive tuyeres or inversely as the square of the number of tuyeres. On the other hand, it must be remembered that the saving in hearth area obtained by increasing the number of tuyeres increases much more slowly with each increase in their number, and that the difficulty and expense of maintenance of the tuyeres increases with each increase in their number. It is therefore not strange that the best opinion tends more and more strongly to a moderate number of tuyeres.

"Before leaving this subject, I wish to call attention to a simple means of determining the activity of the different portions of the tuyere plane, which is, of course, a direct measure of the penetration, and therefore of the correctness of the nozzle area. This method consists in passing a ¾-in. or ⅞-in. rod through one tuyere, and pushing it through the column of stock as quickly as possible, until it strikes the far side of the hearth, leaving it from 20 to 50 sec., and quickly withdrawing it. The relative temperatures it has reached at different points will be a correct measure of the activity of the hearth at the corresponding points.

"I am indebted to Mr. Austin Farrel of the Cleveland Cliffs Iron Co., for this simple but effective expedient. When he told me of it 3 years ago, I believe it was very little known, though it has since come into use to some extent, but is probably still unknown to some who will be as glad to hear of it as I was.[1] The results shown by this test are sometimes surprising. I have seen a rod which had been put into a furnace, blown with about 11,000 cu. ft. of wind through six 6-in. tuyeres, come out almost dead black for 5 ft. in the center, and so nearly burnt in two at the noses of the tuyeres that it broke at those points when it hit the ground. (The tuyeres were 8 ft. from nose to nose.)

"On the other hand, a reduction of the size of the tuyeres to 4 in., while it showed much better results on the rod and lowered the bottom of the furnace (which was high before), was succeeded after a few weeks by a considerably greater loss of tuyeres and coolers. This is believed to have been caused by the tops of the pilasters which formed on the bosh walls, making gutters, which led all the dripping iron and cinder down on top of the tuyeres and caused their more speedy destruction. The pilasters, of course, were formed by reason of the too great velocity and penetration of the blast jets, as before explained.

"It seems very probable, therefore, that where furnaces have a small number

[1] Since writing the above, I have been informed by Mr. Frank Firmstone that this expedient has been described by French and German writers—in some cases, several decades ago.

of tuyeres, it is, on account of this secondary effect, unsafe to increase the penetration so much as to bring the test rod to a uniform temperature clear across the hearth. In furnaces with more tuyeres, the pilasters, in consequence of their smaller cross-section, do not extend so far up on the bosh walls, consequently this sdanger is much less serious. This is a point in favor of a larger number of tuyeres than six; but the necessity for this is now everywhere admitted, if large product be aimed at."

During the interval since this was written practice in regard to tuyeres has now settled down to a very moderate number of tuyeres for hearths even larger than were dreamed of at that time. Mr. H. A. Brassert stated in a paper before the American Iron and Steel Institute, May, 1914, that furnaces with hearths as large as 16½ ft. or 17 ft. in diameter gave as good results with ten tuyeres as with fifteen, a statement which, in view of his experience, is authoritative.

The formula for the drop in pressure quoted above has been quite extensively used for penetration under different conditions. Mr. E. B. Cook of Cleveland in particular has made a careful study of this matter and has been good enough to communicate the results to me. He has found that the pressure drop for small hearths ranges in good practice from 0.5 to 0.75 lb., and on large furnaces from 0.8 to 1.2 lb., except on the furnaces with very large hearths above mentioned, in which the figure is about 2 lb., a fact to which we shall refer later.

What is meant by penetration is not always easy to grasp at first sight. We think of the furnace as being merely filled with gas rather than as containing a violent current of gas, particularly in the hearth where the blast comes in horizontally and must quickly take a vertical direction.

In order to make the state of things plainer let us conceive of a tube of glass, 6 in. in diameter, filled with broken coke, with say six jets of water coming into it near the top and flowing down through the coke under the influence of gravity.

Assume that the quantity of water per minute remains constant under all conditions and that first the nozzles of the jets are quite large so that the water flows into the tube with a very low velocity. We shall obviously have a condition such as I have tried to portray in Figs. 7, 8, and 9, the current of water running principally down the sides of the tube and reaching the center only after it has travelled down a long way.

Imagine now that while the quantity of water remains the same, the jets are very much reduced in size so that their velocity under the influence of a higher pressure is very great. We shall obviously have the condition shown in Fig. 8 in which the water, in spite of the resistance of the coke, is driven very largely to the center, where the jets are stopped by impact upon one another. Here we shall have the greater portion of the water flowing down the center, and the sides not receiving their proportion for quite a distance down the tube.

Obviously now we can establish an intermediate condition in which the

velocity of the jets is considerable but not excessive, as shown in Fig. 9. They are given sufficient energy so that by the time they reach the center the energy is all exhausted by the resistance of the broken coke, and there is no surplus to pile up the water in the center and cause a disproportionate flow in that portion of the tube. At the same time the velocity is sufficient to permit only that quantity of the water to flow down the space next the walls which is proportionate to the area of that region. These are precisely similar to the conditions of deficient, excessive, and correct penetration in blast-furnace practice.

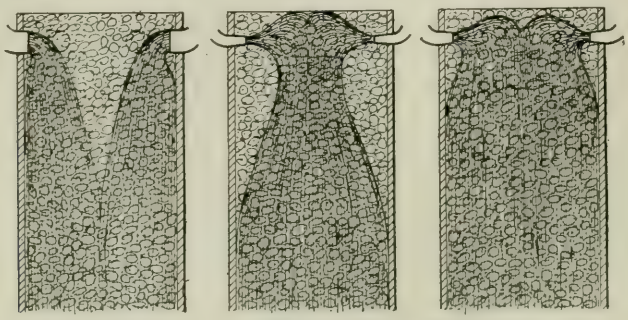


FIG. 7. FIG. 8. FIG. 9.

FIGS. 7, 8, AND 9.—Constant quantity of water discharged through nozzles of different size into tubes filled with broken material, illustrating the variations in blast penetration.

The penetration test in the quotation above given, in which the rod was absolutely black all over except for a couple of feet near the ends where it was white hot, was made on a furnace with tuyeres very large in relation to their number and to the amount of blast blown; this furnace formed a hugh "onion" of solid iron on the hearth which remained throughout the blast. The molten iron lay in the annular space between the onion and the crucible walls, and on account of the small area of this space stood at a considerable height therein at cast time; when the furnace was cast the iron flowed with the greatest violence for 1 or 2 min. and was then followed by the cinder, the cast being over. When the furnace was blown out this hugh onion was found welded fast to the salamander, and rising some 2 ft. or more above the bottom of the hearth. There can be no possible doubt that this furnace worked continually with a cold center—a central column of stock which was not traversed by the gas, and which was only eaten away by a slow process of solution in the iron and cinder, stood like a cold poultice on the bottom. In subsequent blasts smaller tuyeres were used and the same conditions never arose again.

The operation of testing the penetration with an iron rod, described above, as generally carried on is rather unsatisfactory, because no matter how excessive the supply of blast in the center may be it is obvious that

there is no deficiency of blast supply near the walls in that space immediately in front of the tuyeres which the rod must traverse when the test is made through the tuyeres, the condition being somewhat as roughly indicated in Figs. 10 and 11, which show the conditions in the tuyere zone of a furnace having six tuyeres with deficient and excessive penetration, respectively. Obviously the lines on which we should test are AB and not CD. This we can easily do, if there are cooling plates between the

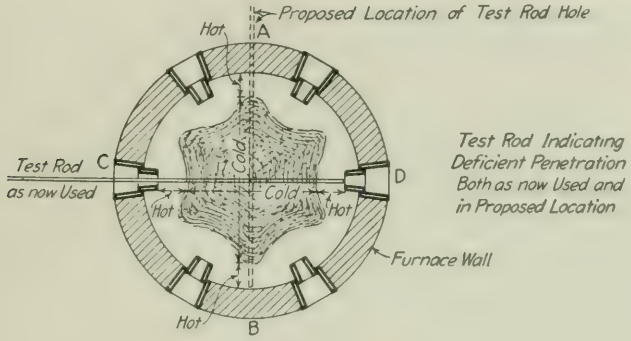


FIG. 10.

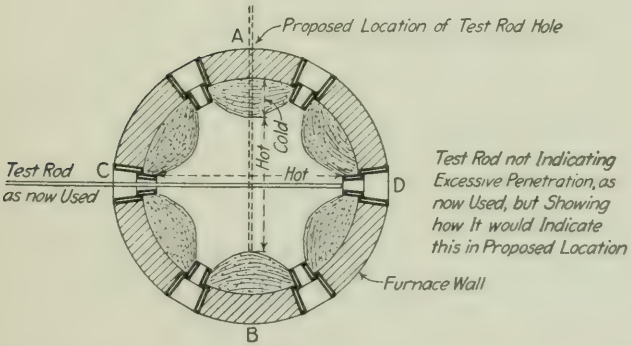


FIG. 11.

FIGS. 10, AND 11.—Location of test rod holes in penetration tests.

tuyeres and approximately on the level of the tuyere centers, as there should be, by fitting the cooling plates half way between the tuyeres with a copper pipe, passing from the butt of the plate through into its nose, carefully screwed into the latter surface and pened over, the butt end of the cooling plate being caulked up against the copper pipe to make a tight joint.

This would give a water-cooled opening of sufficient size to admit a test rod and a penetration test made here would quickly show excessive penetration. These holes, of course, would be plugged with clay or could be closed with a screw plug, when not in use.

I have never tried this method of testing myself, but I see no reason to anticipate that it would not be perfectly successful, and it should certainly give much more accurate information than testing through the tuyeres.

THE BLAST PRESSURE REQUIRED TO OVERCOME THE RESISTANCE OF THE CHARGE COLUMN

This is obviously a subject not open to accurate mathematical investigations of the kind that Fleigner was good enough to make, which supply the means for determining the pressure drop through the tuyeres. We can never hope for such a solution since from the nature of the case the conditions are not only of infinite variety but change from instant to instant, and the pressure required to blow a given furnace is something in which no rule has ever been suggested for even approximate guidance. Nevertheless this also follows a natural law, and in spite of the variation in the conditions is amenable to mathematical expression, the constant, of course, being derived entirely from practice.

Volume and Velocity of the Gas in Different Zones.—Let us consider first the relative velocities of the gas column at different zones of the furnace as affected by its volume and by the area of the furnace at the corresponding zone. The three zones of which we have any knowledge are the tuyeres' plane; the top of the bosh, where we assume that combustion to CO is complete and that the gas has cooled down to the critical temperature; and the stock line of the furnace. The volume of the gas is determined by three circumstances, its chemical condition, its absolute temperature, and its absolute pressure.

Let us assume that the tuyere pressure is 15.3 lb. or 30 lb. absolute, that the top pressure is 0.3 lb. or 15 lb. absolute, and that the pressure at the top of the bosh has dropped in the same proportion as the fraction of the total height traversed, let us say one-fifth, to 12 lb. or 27 lb. absolute. Let us assume further that the blast-temperature is 1200°F. and the top temperature 400°F., the critical temperature prevailing at the top of the bosh, as before stated, being 2750°, the absolute temperatures corresponding to these are 1660°, 860° and 3210°. Let us further assume in accordance with average practice that the top gas contains 60 per cent. nitrogen.

At the tuyere plane the blast obviously enters as air; at the top of the bosh the oxygen of the air has become CO which increases the gas volume, as compared with air, from 1 to 1.207. At the stock line the nitrogen which is the same in absolute amount has fallen from 79.3 to 60 per cent., so that the total volume must have increased by chemical action, additions, etc., to 1.32. Multiplying together the results of these three conditions we find that the relative volume at the tuyeres is

$1 \times {}^{1660}\!/_{30} = 55.4$; the volume at the top of the bosh is $1.207 \times {}^{3210}\!/_{27} = 143$, and the volume at the stock line is $1.32 \times {}^{860}\!/_{15} = 75.5$.

If the gas is to travel at a uniform velocity the area at these levels must be proportional to its absolute volume at these points, and in a circular column the diameter of the column must be proportional to the square root of these volumes. These square roots are: 7.46, 11.95 and 8.67. Multiplying all of these by a constant factor to bring them to recognizable dimensions they become 16.1 25.6, and 18.6. These are not very far from the diameters at the tuyeres, the bosh and the stock line of a 90-ft. furnace though the bosh diameter is too large and the hearth a little small.

We see, therefore, that if the furnace were empty the gas column would pass through it at an approximately constant velocity from top to bottom; the same would also be true if the percentage of voids in all portions of the furnace were the same. It is impossible for us to assert that this is true but I am unable to perceive any reason why we should not expect that it is approximately true since as we shall presently see the variation at the top of the bosh is explained by changes in other conditions.

A heterogeneous mixture of materials of different sizes must, by mixing, reach a sort of irreducible minimum of voids depending on the size and kind of the materials. From the top of the bosh down to the tuyeres the coke is burned, and as the process is necessarily progressive the average sizes of the pieces at the tuyere zone must be much smaller than those at the top of the bosh which in a general way leads us to expect a proportional decrease of the voids, which would naturally necessitate a diameter of hearth larger than the gas volume alone would account for.

The materials other than coke which have existed as solids down to the top of the bosh are liquefied as they pass below that zone with a considerable diminution of volume, and a much greater diminution of their resistance to the passage of the blast, on account of the closeness of their contact with the coke when in the liquid form, hence the available volume of voids is greater than in any other zone of the furnace either above or below and the area may be proportionally smaller than the gas column estimate would lead us to expect.

Considering these various conditions we may tentatively assume that the velocity of the gas column upward through the furnace is constant, though this is not necessary to the correctness of the formula for blast pressure, presently to be developed.

LAW OF THE FLOW OF AIR THROUGH PIPES

Turning now to the matter of the resistance to the passage of the gas offered by the stock column it will perhaps be as easy to approach it by the path I first followed as by any other.

A number of years ago there was an active controversy in one of the technical journals concerning formulas for the flow of compressed air in pipes. Numerous formulas were proposed and the results obtained by applying them to the same problem were truly startling. It finally reached the point where one correspondent declared that the initial pressure for a given flow in a long pipe line could be dropped from 180-lb. to 100-lb. gage pressure by the simple expedient of *raising* the terminal pressure of the air leaving the pipe line from atmospheric to 40-lb. pressure.

At this point I began to wonder if there might not be something wrong with the formula which all the parties were using, in one shape or another and with one set of constants or another. This formula was merely the mathematical expression of the statement that the friction of a fluid through a conduit is proportional to the length of the conduit to the square of the velocity, to the "wetted perimeter" of the conduit, divided by its area, and to a coefficient depending on the fluid. This is a fundamental law and is absolutely correct, but a little consideration showed that when the air in the above example dropped from 180-lb. pressure absolute to 15 lb. absolute, its volume and therefore its velocity increased twelve times, and as the friction is by the law proportional to the square of the velocity, the friction in this part of the pipe would obviously be 144 times as great per unit of length of pipe as in the high-pressure portion, except for the effect of the density.

To see what effect this consideration would have on the results I took one of the examples quoted and divided the length of pipe given into ten sections, figured the drop of the first section, then with the new velocity consequent on the increased volume due to the decreased pressure calculated the pressure drop for the second section, and so on, finally reaching a reasonable result. It presently became obvious that this was a legitimate field for a little calculus.

It is well known that the friction of gases is proportional to their density, as it obviously should be, other things being the same, so we must introduce this factor into the fundamental law which may be expressed as a formula by putting:

P_1 = the initial pressure, absolute.
P_2 = the final pressure, absolute.
L = length of pipe.
D = diameter of pipe.
W = weight of air passing per minute.
S = density of air.
V = volume of free air per minute.
v = velocity in pipe per minute.

$$(\pi D) \Big/ \left(\frac{\pi}{4} D^2\right) = 4/D = \text{wetted perimeter} \div \text{area.}$$

k is a constant determined by experiment, all the constant factors in the final form are included as K.

Then we have

$$V = W/S$$

and

$$v = V \Big/ \left(\frac{\pi}{4}D^2\right) = W \Big/ \left(\frac{\pi}{4}D^2 S\right)$$

Then the fundamental law for a short section of pipe becomes

$$P_1 - P_2 = \frac{4kLSv^2}{D} = \frac{4kLS}{D} \times \frac{W^2}{(\pi/4)^2 D^4 S^2} = \frac{64kLW^2}{\pi^2 S D^5}$$

but S is proportional to P and we can put

$$P_1 - P_2 = \frac{64kLW^2}{\pi^2 D^5 \times P}$$

For the very short length of pipe dL we have

$$P_1 - P_2 = dP \text{ and } P = (P_1 + P_2)/2$$

so that we have

$$dP = \frac{64kW^2}{\pi^2 D^5 P}\, dL \text{ or } PdP = \frac{64kW^2}{\pi^2 D^5} dL$$

whence by integration

$$P_1^2 - P_2^2 = K\frac{W^2 L}{D^5}$$

By applying the results of the extensive experiments on the flow of compressed air in pipes at the Mont Cenis tunnel I derived the necessary constant and the formula took the final form of

$$P_1^2 - P_2^2 = 0.0006\frac{W^2 L}{D^5}$$

in which form it has been very widely used, and extensive experiments made in the natural-gas lines have completely verified its correctness when the proper factor for the density of natural gas is used.[1]

I had made a number of attempts to understand the relations of changes in blast volume to changes in pressure on a given furnace, and also the relation between the pressure required for a given volume of blast on two furnaces of different sizes, but I had never been able to obtain any results at all in accordance with the facts. Gradually it began to seem that the same laws might be applied in this case as in the case of the friction in pipes. That is to say, it was a case of gaseous friction with

[1] I subsequently found that this formula had been developed at least once and probably several times before, but apparently the earlier investigators did not take the trouble to determine the constant, without which the formula is practically valueless, and it had never come into general use.

all the consequences of changes in velocity due to changes in pressure, but with this important difference that the friction in case of the round conduit comes only from the perimeter of the pipe, whereas in a furnace shaft filled uniformly with solid material the ratio of surface to volume of interstices is the same over the entire area, and therefore the factor for wetted perimeter is not needed.

Let us consider two furnaces of the same relative proportion, one, A, 50 ft. high by 12½ ft. bosh diameter, of 4000 cu. ft. capacity and blown with 8000 cu. ft. of wind per minute. This would require, we know by experience, about 3½ lb. pressure. The other, B, 100 ft. high by 25 ft. bosh diameter, of 32,000 cu. ft. capacity and blown with 64,000 cu. ft. of wind, what pressure will be required for it?

Let us assume that the two furnaces are each divided into fifty equal zones, those of A being similar to those of B, though only half as high. It is obviously reasonable to assume that the specific resistance of the stock to the passage of the gas will be the same in the corresponding zones; that is, that the ratio of interstices to surface of stock exposed will be the same in corresponding zones in each. Let us assume for the present that the shape of the furnaces is such that the velocity of the gas through them is constant in all zones, or if not, that it varies similarly in the two stacks so that this variation can be eliminated from consideration. This reduces the fluid friction of the gas current down to the same basis as that for flow in a uniform conduit.

Then proceeding as in the previous case we put:

D = furnace diameter.
H = furnace height.
P_1 = absolute pressure at the tuyere zone.
P_2 = absolute pressure at the stock line.
W is the wind blown per minute measured under atmospheric conditions.
S = density of the air (proportional to the pressure when the temperature is the same).
V = velocity of gas through the furnace proportional to $\frac{W}{SD^2}$

Proceeding as before we find for a short section dH that

$$dP = K\frac{W^2S}{S^2D^4} \times dH = K \times \frac{W^2}{SD^4} \times dH$$

If we substitute P for S, to which it is proportional, we have

$$PdP = K\frac{W^2}{D^4} \times dH$$

and by integration

$$P_1^2 - P_2^2 = K\frac{W^2}{D^4}H$$

The constant K we determine from the pressure assumed from general experience in the case of the small furnace, and with this value of K we determine the pressure in the large furnace to be 19.4 lb. as follows:

For our small furnace, $P_1 = 18.5$, $P_2 = 15$, $W = 8000$, $H = 50$, and $D = 12\frac{1}{2}$, from which we can find K as follows:

$$(342 - 225) = K\frac{64{,}000{,}000 \times 50}{24{,}400} \text{ or } K = 0.00089$$

and for the large furnace using the same value of K we get

$$P_1^2 - 225 = 0.00089 \times \frac{64{,}000^2 \times 100}{390{,}625} = 1{,}050{,}000 \times 0.00089 = 935$$

$$P_1^2 = 225 + 935 = 1160, P_1 = 34.1 \text{ absolute} = 19.4 \text{ gage.}$$

It must be thoroughly understood that the value of K is derived entirely from experience. There is no known method by which we can even attempt to determine its value mathematically. We must therefore determine a value for it which will fit established practice reasonably well before we can safely use the formula or compare the pressure of different furnaces with its aid. By comparisons with actual results I reached the conclusion that the proper value of K was 0.00070, and in order to make the formula easy of application I prepared a diagram, shown at Fig. 12, with the aid of which, with the accompanying explanation for its use, problems involving furnace pressure may be solved in 1 minute.

Through the kindness of a number of furnacemen this formula has been checked against practice on a number of furnaces, with the result that I believe its indications are about a pound too low in the region of 15 lb. pressure, and it is probable that the value of K should be 0.0008. While there are variations, the correspondence between the results of this formula and the pressures actually found at furnaces of different sizes and operating under different conditions is very much closer than might be expected, so that I believe it may be safely assumed to be founded on correct hypotheses, and in the absence of knowledge based on practice, to give a reasonably reliable indication of the actual pressure that may be expected under any given conditions.

It will be noted that this pressure includes both the stock-column resistance and the tuyere pressure. It would be possible to subdivide it so as to give stock-column resistance only, but this is not worth while for two reasons: First, the variations of tuyere pressure drop are smaller than the normal variations in blast pressure. Second, the tuyere pressure drop increases with the size of the furnace, as stated above, so that its variation is roughly the same as that of the stock-column pressure. It is therefore not worth while to differentiate them, but is simpler and is exact enough for all practical purposes to include both in the one formula.

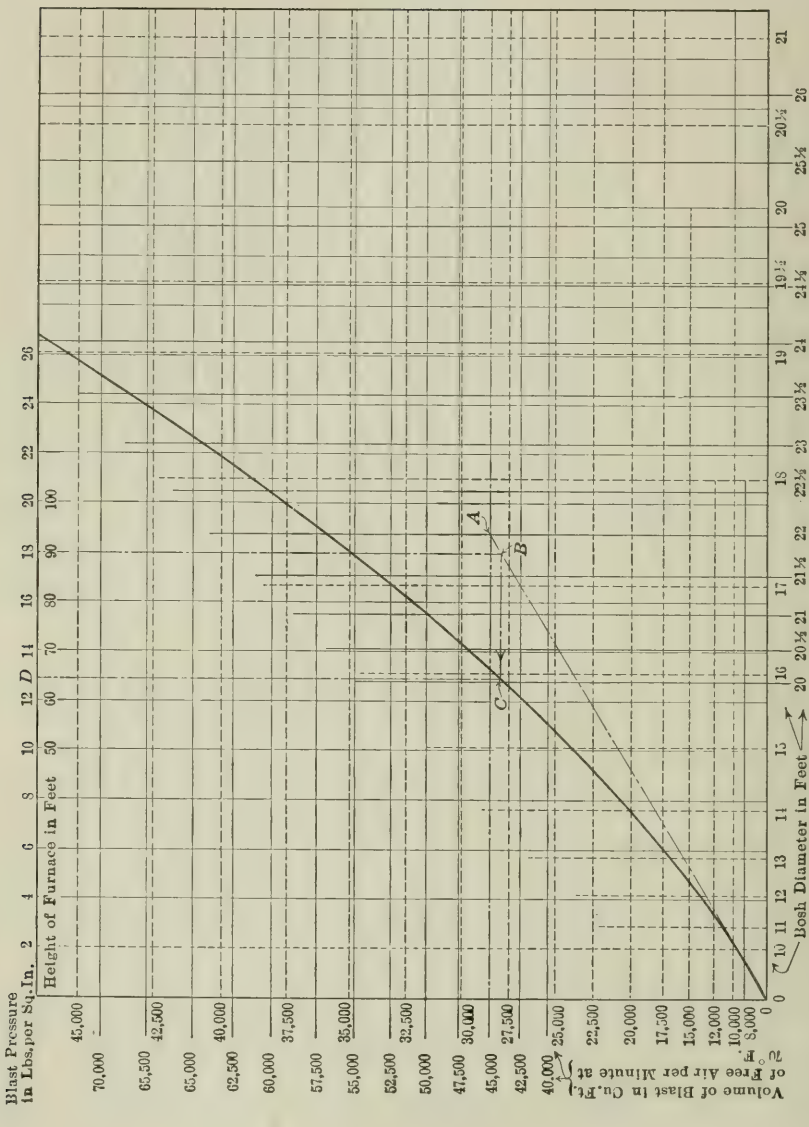


FIG. 12.—Blast-pressure chart.

For description of Fig. 12, see foot of page 113.

The top pressure assumed for the chart is that of the normal atmosphere, 14.7 lb., on the basis that most of the furnaces in the country are located several hundred feet above tide level, and the actual atmospheric pressure is about enough lower than that at sea level to allow for the top pressure required to drive gas through the flues.

It should be noted that variations from this formula tend to be, to a certain extent, self-compensating. That is to say, if owing to any condition the pressure rises, this in turn increases the density, which reduces the velocity and thereby tends to keep down the pressure drop. This may be illustrated by the electrical resistance of the tungsten lamp as compared with the carbon. The resistance of carbon decreases with temperature, therefore a slight rise in voltage, driving more current through the filament, heats it hotter, reduces its resistance and tends to let still more current pass, whereas with the tungsten lamp the resistance increases with temperature, so that an increase in voltage results in an increase temperature, and this in turn in an increase in resistance, thereby tending to cut down the increased flow of current and reduce the variation due to its effect. As a result tungsten lamps show much smaller variations of luminosity with a given variation in voltage than do carbon lamps under the same conditions. So owing to the nature of gaseous friction variations in blast pressure due to variations in resistance are much smaller than they might be expected to be.

This fact probably has something to do with the comparative correctness of the blast-pressure chart over wide range of conditions.

It should be clearly understood that the pressure given by this formula is only the normal working pressure. The furnace may get into a condition in which the gas blows through easily, due, perhaps, to a scaffold on one side above and another on the opposite side below, or something of that kind, and in such comparatively rare cases the actual pressure will be lower than that shown by the chart.

On the other hand, very many causes may make the furnace work with a considerably higher pressure than that given by the formula; there is, in fact, no limit in this direction except the power of the engines.

INSTRUCTIONS FOR USE OF BLAST-PRESSURE CHART.

Note first of all that there are two rows of figures along the bottom giving bosh diameters, and two rows along the left-hand end giving blast volumes. The inside rows of these must always be used together, or the outside rows; never figure from the inside in one row and from the outside in the other row. Some of the figures are duplicated in the inside and outside rows. This is to extend the scale and flexibility of the chart. As long as the corresponding rows are used together it makes no difference which one is taken.

Take the vertical through the figure at the bottom giving the bosh diameter and the horizontal through the figure at the left giving the blast volume in cubic feet of piston displacement. From the intersection of these draw a diagonal through the origin and extend it until it cuts the vertical through the height of the furnace given just inside the cross-sectioned area of the diagram at the top. From this intersection draw a horizontal to the curve, and from the point of intersection draw a vertical to the top of the diagram and read the pressure in the figures along the top edge of the cross-sectioned area. For instance, find the normal working pressure of a furnace, 22 ft. bosh diameter by 90 ft. high, blown with 45,000 cu. ft. of wind piston displacement per minute. The vertical through 22 in the outside row intersects the horizontal through 45,000 in the outside row at the point *A*. Through this draw a diagonal toward the origin until it cuts the vertical through 90 ft. furnace height at *B*. From this draw a horizontal to its intersection with the curve at *C*, and from this draw a vertical to the point *D* at the top of the diagram, which shows a little less than 13 lb. pressure.

First, the furnace may form a ring scaffold which forces all the gas to go through a sort of nozzle much smaller than the diameter of the furnace, and consequently with a much increased velocity and resistance. Second, the slag may become tough and stringy, and therefore be blown by the blast into the interstices of the coke, greatly obstructing them instead of running in quiet trickles down over the surface. Third, the hearth and bosh, in case of serious trouble, may become almost frozen solid, with the result that only very small passageways are left through which the blast can find its way, and the slag in those is excessively tough and stringy. Fourth, and probably most common of all, the deposition of carbon (described in the chapter on chemical principles), which is sometimes extremely voluminous, in cases amounting to several times the bulk of the ore, may be deposited in the interstices of the stock in such quantity as greatly to obstruct the flow of the gas. These are all conditions which we have difficulty in proving; to measure them quantitatively is, of course, impossible. We cannot therefore hope to fit a formula to these diverse variations.

Leaving abnormal conditions aside it has been found at a number of plants that the formula coincides with the results of normal-working furnaces with a degree of accuracy which is fairly satisfactory in so approximate a matter, though, as before stated, it is perhaps a little low. It should be stated that the quantity of air given on the chart is that measured by piston displacement in normal practice. This is indefinite to a certain degree, but unfortunately we have nothing else, and with the great improvements of blowing engines which have occurred in recent years this is sufficiently accurate for our purpose. It is probable that the actual air corresponding is less by about 12 per cent. under the ordinary conditions of good practice.

It will be noted that this formula takes no account of difference in the condition of the ore, which varies from the fine sand of the Mesabi to the all-lump ore of Southern practice. There is probably a slight variation due to this cause, but owing to the self-compensating nature of the action described above, it is very much less important than might be expected, or at least the formula fits furnaces under Southern conditions about as well as it does those running on Lake ore, which means generally from 50 to 90 per cent. Mesabi.

This formula is presented here because of the absolute lack of any other means of reaching the desired end, and because the results of its application were found to coincide so much more broadly with practice than was expected when the formula was developed.

THE EFFECTS OF BLAST PRESSURE

The pressure of the blast tends to retard and make more difficult the descent of the stock. It is curious that this idea is not more generally

held (a few years ago it was almost entirely ignored), but on the basis of Newton's first law of motion, that "action and reaction are always equal and in opposite directions," it seems impossible to escape the conclusion that if the stock column resists the ascent of the blast at the rate of so many pounds per square inch, then necessarily the ascent of the blast resists the descent of the stock by an equal number of pounds per square inch.

This view has not always been admitted from the theoretical side, but practically it has been recognized by the century-old practice of slacking the blast when the charge column was "hung" and refused to settle properly.

From this consideration it is very evident that to secure free and regular settling of the charge one of the prime conditions is to have the blast pressure low in relation to the weight of the charge column, and this, with the great expense involved in compressing the blast to a higher pressure than is absolutely necessary, would lead us to believe that high pressure was an unmitigated evil, and that in general the lower the pressure with which a furnace will work, the more satisfactory its work will be. But while this is a fundamental consideration, and should be the controlling one, there is another condition brought about by high pressure which is worthy of careful consideration, as first pointed out to me by George G. Crawford. This consideration is that the velocity of combustion is greatly augmented by pressure, and as most modern furnaces are driven to the limit set by their ability to burn the carbon in the space available for that operation, that is a consideration not lightly to be neglected. Moreover, quick combustion means a decided localization of the zone of highest temperature, which in turn means lowering the zone of fusion and bringing more closely under control that region of the furnace at which scaffolding due to pastiness is likely to arise.

THE SUPPORT OF THE CHARGE COLUMN

The support of the charge column is made up of at least four elements: First, the upward pressure of the gas; second, the friction of the charge on the sides of the shaft; third, the vertical upward thrust against the charge from the downward converging slope of the bosh walls; fourth, flotation in the molten mass of iron and cinder in the hearth. To these we might almost add a fifth, the dragging of the pasty zone against the walls at the top of the bosh, but this may be counted as a part of the friction, especially as we have no means of measuring either.

The weight of the charge column is very generally overestimated by those who have not made calculations upon it. It is ordinarily assumed that this weight is 50 or 100 lb. per square inch, but obviously this is not true. If we estimate that three-fifths of the charge by volume is coke

with a specific gravity of 0.45, and two-fifths ore and stone with a specific gravity of 2.5, we shall have a column 1.18 times the specific gravity of water. Taking the height from the tuyeres to the stock line of a modern furnace as 70 ft., the water pressure corresponding to this height is 30 lb., which would correspond to a weight of charge column of 35 lb., if the materials descended to the hearth in the condition in which they are charged, but as a matter of fact we shall presently see that they do not. Moreover, in many cases the bulk of the ore is vastly increased by the great volume of extremely light, flocculent carbon deposited upon it by the action of the gas. As a net result the weight of the charge column is greatly diminished, while considering only that part of it down to the base of the shaft, its diameter and area are greatly increased by the outward batter of the furnace still further reducing its weight per square inch.

In my paper "Notes on the Physical Action of the Blast Furnace" before referred to, I have embodied some calculations on this subject which are probably just as applicable to present conditions as they were to the conditions on which they are based, and are therefore quoted.

"In order to have a concrete example on which to base calculations, let us take, as representative of present conditions, the Isabella furnace, of which the more important data are given in Mr. Gayley's paper on the dry blast. The lines of this furnace are shown in that paper.

"Let us assume for an average of summer and winter conditions, that the output is 400 tons per day and the burden per 10,000 lb. of coke is 22,000 lb. of ore and 5500 lb. of limestone; the coke per ton of iron is 1900 lb. and the ore per cent. through the furnace, to agree with the above assumption, 53.6 per. cent.

"The total content of 18,090 cu. ft. are divided as follows: 1193 cu. ft. in the hearth, 3087 in the bosh, and 13,810 in the shaft above the bosh.

"Assume that coke weighs 28 lb., ore 135 lb., and limestone 90 lb. per cubic foot—figures sufficiently exact for our purpose, then the volume of a charge will be 357 cu. ft. of coke, 163 of ore, and 61 of stone, or 581 cu. ft. in all. Each charge weighs (as charged) 37,500 lb.; hence the initial average weight per cubic foot is 64.5 lb.

"The weight of stock in the shaft of the furnace can easily be calculated from the weight and volume of the charge given abvoe, but the result so obtained is entirely too high for several reasons. In the first place, the ore swells enormously in volume under the action of the gas and the deposition of carbon. Secondly, the oxygen of the ore is nearly all removed, lightening it about 30 per cent. Thirdly, all the CO_2 of the limestone is driven off, lightening it 44 per cent.

"It is impossible to express the sum of all these effects with quantitative accuracy, but if we assume that the ore doubles in volume, and that the limestone decreases 44 per cent. in weight by the time the charge has reached the top of the bosh, and neglect all the other conditions, we shall certainly be on the safe side in estimating the total lightening effect.

"This gives a final reduced weight of 47.2 per cubic foot, and if we assume the change to have occurred uniformly as the charge descended, we can calculate the weight of stock in the shaft, which will be, on this basis, 755,000 lb."

THE UPWARD PRESSURE OF THE BLAST

"The difference of pressure between the tuyere zone and the stock line is 14 lb., and this is evidently all used up in forcing the gas formed at the tuyeres through the column of stock.

"In the absence of knowledge as to the rate at which the pressure falls, we may reasonably assume that it is proportional to the distance traversed.

"The pressure of 11.4 lb. on an area of 21 ft. diameter gives a total pressure of 568,000 lb.; but the difference of pressure is all that counts, and each zone is a little larger than the one above, so that the whole difference of pressure only acts on a central area equal to that of the stock line. A deduction of 184,000 lb. must therefore be made from this 568,000 lb., and the net resistance offered to the descent of the stock by the blast is thus 384,000 lb., which is more than half of the entire weight of the column of stock. From the unbalanced remainder must be deducted the weight necessary to overcome the friction of the stock on the walls, which it is not practicable to estimate in figures. Probably it is not less than from 10 to 20 per cent. of the weight of the column, and may easily be more. Assuming it to be 15 per cent., it amounts to 113,000 lb., which added to 384,000 gives 497,000, or about two-thirds of the total weight of the stock column."

The resistance of the gas column to the descent of the charge has been treated above as if it existed only above the top of the bosh, though as a matter of fact it exists all the way down to the tuyeres, but has not as great an effect in the bosh as it has above that region for the reason that in the latter region the area on which the smaller blast pressure acts is greater than that on which the larger pressure acts, that is to say, the pressure at the top of the bosh is smaller but the area of this zone is larger, while the hearth pressure is larger but its area is smaller. Therefore, the difference in the products of these two is much less important than it is in the case of the bosh zone and the stock line where the greater pressure exists over the greater area and the smaller over the less.

It may be remembered that one of the approved methods of lifting grain consists in delivering it into a vertical pipe up which a current of air is traveling at a high velocity. This is not in any way connected with lifting water by suction, through the removal of air, which is limited to 34 ft.; but may be carried on practically without reference to the height. But when we find even approximately what the actual velocity of the gas current is, we realize that the present action is only roughly similar to this.

We have already seen that the velocity through the shaft is approximately constant so we can determine it roughly by reference to the hearth conditions only.

Assume a furnace of ordinary dimensions with a 16-ft. hearth blown with 45,000 cu. ft. of blast as measured by piston displacement or, say, 40,000 cu. ft. actual at atmospheric temperature, compressed to 15 lb. pressure, and heated to 1200°. The absolute volume becomes 40,000 ×

$\frac{1660}{530} \times \frac{15}{30}$ = 62,600 cu. ft. The area of the hearth empty is 200 sq. ft. but this is filled with coke, the blast can pass through the voids only. Assuming these conservatively as one-fourth of the total (see below) we have a net area certainly not to exceed 50 ft., through which all the blast must pass. This would give a velocity of $\frac{62,600}{50}$ = 1250 ft. per minute, but it must be remembered that this refers to the voids in the coke by itself and takes no account of their obstruction by molten iron and slag which as we shall later see is very great. If we assume that they amount to 50 per cent. of the original area we shall probably be safe and this would double the velocity, making it 2500 ft. per minute or approximately 30 miles per hour and it may well be that this figure is too low rather than too high.

This velocity alone, however, is not sufficient to account for the drop in pressure in so short a distance but there is another factor of great importance; the roughness of the passage through which the gas column must pass, the "wetted surface" of the conduit (the stock column) is almost infinite and when we remember the vast effect of a slight increase in the roughness of any conduit on the friction of the fluid passing through it we have no difficulty in understanding the pressure drop even though the velocity be no more than 30 miles per hour, and, of course, the pressure drop is the direct measure of the lifting power on the charge rather than the velocity. In other words the action in this case is rather that of a leaky piston than the transportation of loose material by a rapid air current.

The Friction on the Walls.—The effect of the friction on the walls is very great and must not be ignored though we have no means of estimating it accurately. It has been found in cylindrical grain bins that something like two-thirds of all the weight of the grain is taken on the side walls, but we cannot expect so large a percentage to be carried this way in case of the blast furnace because the stock is kept in a more or less violent state of agitation by the current of gas rising through it. A strong upward current of gas produces a tremendous effect in the internal friction of a loose mass of solid matter, particularly one containing much fine material, the agitation of the smaller particles makes them act almost like a liquid and exercise a corresponding influence on the larger particles. A mass of dry sand which might stand at a slope of 20° when quiescent would not stand on one of 5° if agitated by a current of air from below. On the other hand, the pressure of the charge column against the sides may be very much greater than we should expect from its weight alone, that is to say, the pressure which the walls would receive if considered as a vertical retaining wall for an embankment. This is because of the tremendous swelling which frequently takes place in the ore due to carbon deposition.

These conditions make it exceedingly difficult to apply even our slight knowledge of the internal friction of such materials as compose the furnace charge to determining the effect of wall friction quantitatively, but we do know that the charge sometimes hangs in the furnace at a height far above the beginning of the pasty zone and sometimes remains hanging even when the blast is taken entirely off. This can be due only to wall friction and indicates that this may sometimes exceed 100 per cent. though undoubtedly its normal amount is very much smaller.

Support due to the Upward Component of the Reaction of the Bosh Walls.—Obviously if the bosh walls were continued down until they met in a point the inverted cone so formed would support the stock column completely, and the portion of this cone which actually exists furnishes its portion of support; this, of course, ignores all questions of flotation from the liquid in the hearth, which we may exclude for the present. Thinking only of the steep slope of the bosh and of what a small frustum of a complete cone it is, we might be inclined to dismiss as insignificant the amount of this support, especially in view of the modern tendency to build furnaces with large hearths and extremely steep, short, bosh slopes. But even in the most extreme of these furnaces this would not be correct, for the amount of this support is obviously proportional, other things being equal, to the difference in the area of the zones projected into a horizontal plane. Even with a 22-ft. bosh and 17-ft. hearth this difference is 40 per cent. of the bosh area and it seems reasonable to assume that 40 per cent. of whatever unbalanced pressure may exist down to the tuyere zone is taken by the bosh slope even in this case. Incidentally this indicates that a change in hearth diameter of 1 or 2 ft. may have a considerably greater effect in the mechanical operation of the furnace than we might at first glance suspect. That this is true we have an abundance of experimental evidence.

In considering the shape of the furnace we shall presently note that as blast pressures have risen supplying more support for the charge column, hearth diameters have increased leaving the bosh area smaller and so supplying less support. This at least suggests that the proper descent of the charge column takes place only when the sum of the resistances thereto does not exceed a certain total.

Support of the Charge Column by Liquid.—This is an exceedingly complicated question. It is rather illuminating to consider the volume of molten material in the hearth at its maximum. Let us assume that a 500-ton furnace casts four times per day and that one-fourth of the total cinder, or 300 lb. per ton, is in the furnace before cast, and that the hearth is 16 ft. in diameter which gives an area of 200 sq. ft., all about in accordance with modern practice.

We may assume that the volume of iron at the high temperature at which it exists in the furnace is 5 cu. ft. to the gross ton, and that molten

slag weighs 150 lb. to the cubic foot, so that 300 lb. of slag have a volume of 2 cu. ft., which added to the 5 cu. ft. of molten iron makes a volume of 7 cu. ft. per ton. One hundred and twenty-five tons of iron would therefore correspond to a volume of liquid of 875 cu. ft., or sufficient to fill the hearth to the depth of a little less than 4½ ft., in other words not very much over half way up to the tuyeres.

On this basis we could dismiss the idea of flotation altogether if we considered the charge column to end at the tuyeres, but as a matter of fact we know that it does nothing of the kind, and that it must settle until it rests upon the hearth bottom, or until it is floated by the liquid in the hearth. Of course, if the stock column were only 8 or 10 ft. high it would readily be floated by the liquid, but when we consider the great height of superincumbent stock resting upon it, and forcing it down, we realize that it may be forced to the bottom of the bath at least in furnaces with a small blast pressure and shallow bath.

The result of forcing the stock column down into the bath is to raise the level of the liquid very greatly since the latter can occupy only the interstices in the coke. We do not know what these amount to exactly, but some careful experiments I made several years ago showed that the voids in thoroughly mixed crushed ore were about 33 per cent., while the percentage of voids existing between spheres closely packed is about 35 per cent. of the volume of the spheres or about one-quarter of the volume of the space occupied. We may therefore assume without chance of great error that the percentage of voids in the coke as it exists in the hearth and bosh do not exceed 33 per cent. of its net volume, or one-quarter of the total, which means that the height of the liquid must be four times as great as that estimated above or nearly 18 ft., which would bring the liquid well above the tuyeres if the coke column extended down to the bottom of the hearth. This is at least partly in accordance with the facts, since, of course, we know that the cinder will flow back into the tuyeres and rise in the penstocks to a considerable height if the blast be taken off before first "flushing" the cinder out of the furnace.

It is instructive to make an estimate of the floating effect of the liquid bath even though we must use approximate figures.

Assume coke to weigh 28 lb. per cubic foot loose and to contain 25 per cent. of voids, then its weight "solid" is 37 lb. per cubic foot. The weight of slag per cubic foot is as above given about 150 lb. and of iron 450 lb.; on the basis of the weights of these in the hearth and their combined depth of 17½ ft. in the interstices of the coke, the depth of slag alone would be 5 ft. and that of the iron 12½ ft. The buoyancy of the coke in slag per cubic foot of space is three-quarters of (150 − 37) or about 85 lb. and for the whole depth of the slag it is 425 lb. per square foot upward thrust, for the iron it is three-quarters of (450 − 37) or about 300 lb. per cubic foot and would be twelve and one-half times as

much if the coke were submerged to the bottom of the hearth in the iron, or 3750 lb. per square foot, this added to the 425 lb. per square foot due the submersion in the slag makes 4175 lb. per square foot or 29 lb. per square inch, which added to the 12 lb. due the blast pressure above the top of the bosh would make 41 lb. per square inch of total upward pressure on the base of the stock column or *considerably more than its total weight* without any allowance whatever for friction on the walls or support on the slope of the bosh. It is perfectly clear therefore that the weight of the stock column is not sufficient to force it to the bottom of the hearth when the latter contains much molten material but that it is submerged only to such a depth as supplies the upthrust not furnished by the other three forces. That the buoyancy of the base of the charge in the liquid in the hearth is a decided factor is proved by the fact that furnaces always settle immediately after cast very much more than they do at any other time. Very frequently a furnace will settle perceptibly even as a result of flushing, and there is no reason to doubt that this is due to the removal of a portion of the buoying action of the liquid.

That the charge column does not rest on the bottom at least before cast-time, a very interesting proof has recently been given by Mr. F. L. Grammar.[1] If gaging prove that a furnace is settling regularly at the rate of 30 in. per half hour previous to cast and if during the half hour occupied by cast it settles 60 in., then obviously it could not have been resting on the bottom at the beginning of cast.

There is much reason to believe that the liquid slag not only stands in the furnace above the level of the tuyeres but that it is blown up through the interstices in the coke to a level many feet higher. The slag is decidedly viscous and the blast has difficulty in making its way through it. This, of course, means that the high velocity of the gas up through the furnace tends to carry the slag up and blow it about through the interstices of the stock. We know that if the blast be taken off the furnace too quickly, even though the slag be below the level of the cinder notch when it comes to rest, we are more than likely to have the cinder come back in the tuyeres, which, of course, can only happen if at least a part of the slag has been well above their level.

Mr. D. N. Liddell has called my attention to the fact that this may be due to the settling of the charge column when it is no longer sustained by the blast pressure. This settling of the stock does undoubtedly force it down into the slag to a greater extent and by displacement forces the latter to a higher level. This action undoubtedly occurs but does not, in my judgment, account for the fact stated, that the slag may come back into the tuyeres if the blast be taken off quickly, even though the slag level be below the tuyeres when it has come to rest.

[1] Private communication.

Many experiences encountered in operation have left on my mind a strong impression that slag in important quantities is carried up well above the level of the tuyeres by the action of the blast.

In order to form a picture in more easily comprehensible terms I have sometimes thought that we might take a glass tube some 2 in. in diameter, and insert into it, 1 in. from the bottom, some ⅛-in. nozzles piped to a supply of air under slight pressure, fill the tube with water to a level half way up to the air nozzles, pour in sufficient granulated cork or other light substance to fill the tube for a height of 10 or 12 in., and then blow air through the nozzles air in sufficient quantity to keep in a lively state of agitation the water which is raised up around them by the descent of the cork. It is obvious that the cork would be supported partly by this flotation in the mass of bubbles into which the water would be converted, and partly by the ascent of the air through its interstices, and perhaps some of its weight would rest on the bottom of the tube.

Such a mental picture shows us how impossible it is to estimate exactly the value of each component in supporting the column of cork.

The Cause of Slips.[1]—Under normal circumstances that (approximate) one-third of the weight of the charge not supported by the blast resistance and wall friction as above described is enough to bring the column of stock down; but if any local derangement takes place, and the pressure ceases to fall at a regular rate, we have a condition the trouble-producing power of which is cumulative, for owing to the increased resistance, the flow past the obstructed point is reduced, and with it the friction and counter-pressure above, while owing to the damming action of the obstruction, as the engine continues to blow the same quantity of blast, the pressure soon runs up, and as the velocity is reduced the high pressure that normally exists only in the lower part of the furnace extends up toward the obstruction. This compresses the obstruction more, and forces it more tightly against the furnace walls, while at the same time, by reason of the greater pressure, it becomes denser, and offers still greater resistance to the passage of the gas, which in turn augments all the other effects, until the furnace is "stuck" tight. The "plug" is in a conical passage and cannot yield upward, and things remain in this condition while the stock below continues to settle until a cavity is formed underneath the "plug." Finally, through some accidental weakness in the obstruction, or through the slacking of the blast and reduction of the pressure under it, which allows the plug to come loose, the condition is broken, and the suspended mass falls.

As to the cause of the violent ejections of stock, some of which take the bell along, there has been much speculation, and various explanations have been made, none of which have seemed adequate. The true ex-

[1] This section is taken from "Notes on the Physical Action of the Blast Furnace."

planation seems to be that the whole furnace below the plug is a reservoir of compressed gas (this being especially true of the cavity formed under the obstruction), and when this latter gives way it is like knocking out the keystone of an inverted arch under pressure—the instant the arch is broken the compressed gas has ample energy to carry away, in its sudden escape, part of the overlying stock.

The greater the cavity the longer the "blow;" while the further down in the furnace the obstruction lies the higher the pressure under it is likely to be, and the greater is likely to be the mass of material above it through which the gas must make its exit and portions of which it will carry along.

To the initial increase in resistance to the passage of the gas several causes may contribute; but, if the furnace is not scaffolded, the most important one is the deposition of carbon dust through the splitting up of the CO into CO_2 and C. Both the extent of this action and the time of its beginning vary greatly with the character of the ore through which the gas passes, as has been shown in various papers read before the Institute and elsewhere. It has also been shown that the action proceeds with great rapidity when it has once begun, thus localizing it in some cases to a certain restricted zone in the furnace, both below and above which the charge is more open—below, by reason of its downward movement and the increased shaft diameter reached thereby; above, because no carbon has yet been deposited in it. The slips thus tend to be localized in this zone; and hence most of the slips from a given furnace, which slips habitually, should have about the same degree of violence. Practice shows this to be the case.

LIMITATIONS TO THE SIZE OF THE FURNACE

The use of the formula for blast pressure as a tool of investigation enables us to discover the reason for certain facts of practice not otherwise easily understood. If furnaces be built larger they must obviously be blown with a proportionately increased quantity of wind if they are to yield results commensurate with their size, and in fact this is always expected of them. There are a few furnacemen who have built furnaces much larger than is customary for the tonnage which they desired to produce, but this practice is very rare though extremely sensible and advantageous. Considerations of corporation policy generally force the manager to produce an amount of iron approximately proportional to the volumetric contents of his furnace. Proceeding on the assumption that this condition must be met, we obtain the following results: W, the quantity of blast per minute, to be proportional to the capacity of the furnace, must vary as D^2H; with the 22 by 90-ft. furnace and 45,000 cu. ft. of wind $\frac{W}{D^2H} = 1.03$, and any other furnace with dimensions D_1 and

H_1 must be blown with 1.03 $D_1^2 H_1$ cu. ft. of wind to maintain this proportion. Then from the general formula we have

$$P_1^2 - P_2^2 = 0.0008 \frac{(1.03)^2 (D^2 H)^2 H}{D^4} = 0.00085 H^3.$$

That is to say, if the shape and relative dimensions remain the same, the difference of the squares of the absolute top and bottom pressures increases as the cube of the height.

For the 22 by 90-ft. furnace the pressure figures out as follows:

$$P_1^2 = 216 + 0.0008 \times \frac{(45{,}000)^2 \times 90}{22^4} = 216 + 0.0003 \times \frac{2{,}025{,}000{,}000 \times 90}{234{,}000} = \frac{80 \times 202.5}{26} + 216 = 624 + 216 = 840$$

$\therefore P_1 = 29$ abs. $- 14.7 = 14.3$ lb., which is just about the actual pressure for these conditions.

For a furnace one-half larger and blown with proportionately more wind we should have then $P_1^2 = 216 + 624 \times (1.5)^3 = 216 + 2100 = 2316$ or P_1 abs. $= 48.1$ or a gage pressure of 33.4 lb. Therefore, if we build a furnace 50 per cent. larger in all its dimensions than the present 90 by 22-ft. furnace, and blow it with a proportionately increased volume of wind, we shall have a blast pressure of 33.4 lb. as against the normal pressure of the present size furnace of 14.3 lb., or nearly two and one-half times as much for an increase of 50 per cent. in height.

The result of this is twofold. First, we receive no return whatever for the power expended in compressing the blast. It is a necessary evil and nothing else. Therefore, the power expended for this purpose is wasted. Moreover the investment required to blow higher pressures increases all along the line, not quite in the same proportion, but still at a very rapid rate, and the interest and depreciation on this excess investment is therefore an absolute loss. Second, the regular descent of the stock is made increasingly difficult and a point would soon be reached where it would become impossible.

Referring to the detailed calculation of the Isabella furnace given above it will be seen that the pressure per square inch of the stock column, referred to the area of the top of the bosh, figures out to about 15 lb., or to put it a little more accurately, that the blast pressure in this case is just half of the total stock-column pressure without undue allowance for expansion of the ore. A greater height from the top of the bosh to the stock line may reasonably be assumed to yield a proportionately increased pressure of the charge column. This in our assumed furnace 50 per cent. larger in all dimensions than the modern 90 by 22-ft. furnace would give a stock-column pressure at the top of the bosh of about 22.5 lb., while the blast pressure at that point, on the basis of a uniform drop in pressure

from top to bottom, would be one-fifth less than the tuyere pressure of 33.4 lb. or about 27 lb. In other words, the gas pressure alone at this point would be materially more than the weight of the charge column, and the latter would therefore be unable by any possibility to descend regularly, since we have seen that there are three other important forces resisting it.

It is easy to see then that there are natural laws which prevent building furnaces of more than a certain height and corresponding diameter, and it is a matter of record that furnaces over 100 ft. high have been less successful than furnaces of about 90 ft. high, so that in one case furnaces 106 ft. high were cut down to 90 ft., and at another plant which started with furnaces 100 ft. high, the next ones, built after several years' experience, were made 90 ft.

These facts taken in conjunction with the blast pressure and stock-column figures given, indicate that 90 ft. is about the limit of the size of furnaces which may be blown to full capacity. If larger furnaces were built it would be necessary to blow them with less than the proportionate amount of wind. This would probably be a wise move within moderate limits since the larger furnace blown with the same quantity of wind, of course, requires a smaller pressure and allows a longer time in preparation for the stock, while the initial cost is nothing like proportional to the increase in capacity, and the smaller pressure required means a smaller investment in power plant.

Against this on the other hand is the fact that the radiation from a given furnace is practically constant, and therefore the faster the furnace is driven the less the radiation loss per pound of iron. From the data given in the article on thermal principles we know that the radiation and cooling water losses are 10 or 12 per cent. This means that if we made only half as much iron in the same size furnace these losses would run up to about 20 or 25 per cent.

Looking again at the other side we have reason to believe that in present practice furnaces are often probably blown a little harder than the rate at which the coke consumption is a minimum. A little fuel is sacrificed for the sake of increasing the output since this keeps down capital and labor costs to some extent.

THE SHAPE OF THE FURNACE

This is a subject which should properly be treated under operation, but the considerations we have discussed here exert certain influences upon the shape of the furnace, and some of these we may now consider.

We may well ask ourselves why has the furnace the shape which a slow and painful evolution has given it in all parts of the world: a cylinder at the top and bottom, the latter surmounted by an inverted cone of quite

rapid outward batter, and this in turn by a frustrum of an upright cone of a much slower inward or convergent batter?

We have already seen that the shape of the furnace is approximately that which gives a uniform velocity of ascent to the gas column, its shape has been worked out upon purely empirical grounds, so that while this condition may be due to a coincidence it is more probably due to a relation of cause and effect entirely unknown during the development. There are certain other considerations of great importance and while we cannot attach quantitative values to them, and do not know all of their effects, we can point out some of their influences at least in a qualitative way.

The common base of the two conical portions of the furnace or the base of the short cylinder which connects them is universally known as the top of the bosh. What is this point?

It is in my judgment the zone in which the combustion of the oxygen of the blast to CO is complete, or viewing it from the opposite direction, it is the point at which the coke in its descent begins to be burnt by the blast. I have already discussed to some extent the fact that the lower part of this region is hotter than the upper, which at first sight it should not be if the combustion of the carbon to CO were going on uniformly throughout the zone, and I have given Professor Howe's explanation to me of this fact, that in the lower part of this region the coke was burned in the local and temporary excess of air partly to CO_2 with resulting high temperature, but that as this CO_2 rose through the excess of fuel in the bosh it was deprived of one atom of its oxygen by another atom of carbon, the whole forming CO instead of CO_2, and this reduction of CO_2 to CO is a distinctly cooling reaction. It is, therefore, to be expected that the upper portion of the bosh should be cooler than the lower portion, and this idea is not only not in conflict with, but is a confirmation of the conception that combustion of coke to CO is going on throughout the bosh, that being in fact the region of the furnace devoted to that purpose, in other words the combustion chamber. (Since the above was written I have been informed by John N. Reese of Youngstown of the results of some extensive investigations carried on by him, in which analyses of gas taken from the bosh at increasing heights showed contents of oxygen gradually diminishing and finally disappearing just about the top of the bosh. This is an independent experimental confirmation of the view here given far stronger than I had dared to hope for, and in my judgment forms convincing proof of its correctness).

Above the top of the bosh we may assume that the material is in a "dry" condition. That is to say, neither the slag-forming materials nor the iron have begun to soften and become sticky. They then pass through a zone in which the sticky condition prevails, and finally as they become hotter and as the different slag-forming materials become more intimately mixed and therefore more fusible, both they and the iron pass

out of the sticky condition into that of complete fusion with consequent liquidity and freedom of movement. It is obvious on a little consideration that this sticky zone is likely to obstruct both the passage of the gas upward and that of the stock downward, and in order that these shall not be prevented from moving in their appropriate directions it is obviously desirable that more room and slower velocity of travel should be provided at this point than at any other. This then should be the top of the bosh.

Granting that the top of the bosh is the point where the combustion of the blast to CO is complete and is also the point at which the solid materials enter the pasty state, this is obviously also the point where the gas generated in the hearth ceases to expand by combustion and drops below the critical temperature (since that is by definition the free-running temperature of the slag). From this zone upward it must contract by cooling through contact with the stock, and while, of course, it receives some increase in volume from the CO_2 of the limestone, this is much less than the contraction due to cooling.

From the top of the bosh downward the considerations which affect the shape are the decrease in the volume of the gas current as we approach the tuyeres (that is to say, its increase in volume as it rises from them), and the shrinkage, and eventual disappearance, of the coke.

We have then at the top of the bosh conditions which reverse within a short distance, first we have an increase in diameter necessitated both by the volume of the gas and the conditions of the stock column and then a decrease in diameter necessitated by opposite conditions, but it is evident that this reversal cannot occur instantly and that instead of the two cones meeting at a fairly sharp angle, as it was once customary to have them do, there should be a transition zone either barrel-shaped as was once the custom, or a cylindrical section as is now the general practice.

Mr. Reese has recently pointed out to me that there is another reason for a cylindrical zone in this region which is that on some irons and some some ores the furnace works on a very much more refractory slag than on others, and in consequence the pasty zone will be reached at a much higher level in one case than in the other and the maximum diameter at both heights can be obtained only by a cylindrical section.

To this Mr. Reese adds the valuable general law that the more infusible the slag the lower the bosh must be, which is borne out in a very broad way by all practice, both coke and charcoal.

Charcoal furnaces are ordinarily run with a very acid and fusible slag as compared with normal coke furnaces. Owing to its fusibility this slag melts at a higher relative elevation in the furnace than do ordinary coke slags. For this reason the top of the bosh of these furnaces should be higher relative to their height than that of coke furnaces. It has been found by experience that the height of the bosh of a charcoal furnace above the hearth level should probably never be less than 25 per cent. of its

total height and may be 28 or 30 per cent., whereas that of modern coke furnaces is considerably less than 25 per cent.

It is probable also that the cylindrical section in the pasty region has an advantage for another reason. The pasty zone must be penetrated by the charge column from above and by the gas from below; as long as this zone remains flat and horizontal, these actions can go forward without difficulty, but if the zone becomes arched either upward or downward due to greater or less activity in the center than at the side, as is easily possible, then we have a condition of danger. For if the edges of the zone abut against a conical surface converging on the concave side of the curved pasty zone we shall have an arch formed which will tend to close up under the action of either the gas current or the stock column and obstruct the action of the furnace, perhaps even scaffolding it. But if the edges of the curved pasty zone abut against a cylindrical surface there is no "skewback" or support for such an arch and its chances of doing harm are much reduced.

Conditions Affecting the Size of the Hearth.—We can most conveniently consider the development of the size of the hearth from the chronological point of view.

In cold-blast charcoal furnaces, the earliest type developed, the hearths are extremely small, being only 2 ft. to 3 ft. in diameter for a corresponding bosh diameter of 8 ft. or 9 ft. In these furnaces the pressure of the blast is nearly always low so the shape of the gas column as affecting its resistance to the descent of the charge is less important than in furnaces with higher pressures. I am led to believe that this small hearth is necessary to obtain a sufficient concentration of heat to melt the iron and slag, for as shown by Fig. 3 on page 37 these furnaces produce a very small amount of hearth heat per pound of fuel in spite of their low critical temperature. Even with very high fuel consumption they are barely able to avoid freezing up, in other words their theoretical combustion temperature is but little above the free-running temperature of the iron and cinder.

In warm and hot-blast charcoal furnaces the theoretical combustion temperature is brought well above the melting temperature of the iron and slag, and the furnaces, therefore, are not forced to concentrate their heat in a very small space as is the cold-blast furnace. On the other hand, larger outputs are demanded of them, and this means a larger hearth in which to burn the fuel; it also means a greatly reduced outward batter of the bosh, and a much closer approximation of the hearth and bosh diameters to that required by a constant gas velocity.

In coke furnaces we go a step further in the same direction, hotter blast is used and more heat developed per pound of fuel. Therefore, we have a higher theoretical combustion temperature and less need for concentrating heat in the hearth, much larger outputs are demanded and

consequently a larger hearth is necessary to burn the fuel, while, owing to the higher temperature of the blast entering the hearth, the ratio of increase in volume at the top of the bosh is smaller and the hearth can therefore be relatively larger. This is the general line along which furnace development has actually taken place.

The concentration of heat in the hearth is a factor often ignored in modern practice although so vital to success in the cold-blast charcoal furnace, but in spite of this neglect it is a factor which must receive consideration when foundry and high silicon irons are to be made. We desire a high temperature of the iron so that it may take up a high percentage of silicon, and we are not at liberty to obtain this high temperature by making a limey and therefore relatively infusible slag, because the lime would resist the entrance of the silicon into the iron. Some other way must therefore be found of securing a concentration of heat in making such irons, and this is done by making the hearth of relatively small diameter which gives a corresponding concentration of heat in that region with a comparatively small and therefore hot and active column of gas rising from it, down through which the iron must pass and be correspondingly heated on its path into the hearth.

Considerations Affecting the Stock-line Diameter.—The considerations affecting the diameter of the stock line are: first, the relative volume of the gas there as compared to that at the top of the bosh, on the constant velocity theory; second, the swelling of the charge due to chemical action as it descends; third, the necessity of providing sufficient disengaging surface for the gas so that its velocity may be kept down, to prevent the carrying over of an excessive amount of the fine portion of the charge.

The small gas volume of cold-blast furnaces causes little or no trouble by carrying over fine ore and fuel from the top of the furnace, and therefore the latter can have a relatively small area and the shaft of the furnace can be given a rather sharp outwardly descending batter, 1½ in. to the foot, or even more.

The top diameter of warm and hot-blast charcoal furnaces is not increased as much proportionately as might be thought, for the smaller quantity of fuel used produces a proportionately smaller quantity of gas as compared with the total charge which it is required to heat up; the consequence is that most of the sensible heat is taken from the gas so that it is discharged from these furnaces quite cold, relatively speaking. I have seen top temperatures on a hot-blast charcoal furnace run for weeks below 212°F. The contraction of the gas due to this cooling offsets to a considerable extent the increased rate of blowing of such furnaces as compared with cold blast practice, and makes a relatively small stock line sufficient in this case also.

In coke furnaces using Mesaba ore the controlling factor in stock-line diameter is the velocity of the gas issuing from the surface of the charge.

If this exceeds a certain rate fine particles of ore and other materials are picked up bodily and carried over with the gas current, causing very serious inconvenience and loss in utilizing the gas and a loss of ore which is normally important and may easily become excessive.

If the output be great, clearly the gas volume must be so proportionate within narrow limits, and the only way to reduce its velocity is to increase the area of the throat.

A. N. Diehl has stated that the surface of the charge in ordinary practice using a large percentage of Mesaba ore is constantly in agitation with particles rising and falling all over the surface and this is obviously the limit of gas velocity permissible.

The condition is precisely similar to that in a steam boiler where it has been found absolutely necessary to provide a given amount of disengaging surface for each cubic foot of steam produced under penalty of having the steam pick up and carry over such quantities of water as to make the operation of the boiler dangerous if not impossible.

This necessity of keeping within a certain limiting top velocity has exercised a potent influence on furnace lines, for irrespective of all other conditions the top diameter must be large enough to keep the issuing velocity below the danger line. I am inclined to believe that this consideration has forced the use of larger stock lines on hard-driven furnaces than other considerations demanded and that if we were satisfied to blow a little slower on a given furnace we could probably contract its stock line to the benefit of the operation as a whole.

In some ores the swelling action is slight and in others very great. In the experiments of O. O. Landig (*Transactions* of the American Institute of Mining Engineers, vol. xxvi) some ores caused a deposition of carbon from CO five or six times the original volume of the ore, this being a sort of catalytic effect. The effect of such an increase in the volume of the ore tends to swell the whole charge and as it cannot secure more room above or below it must have room to expand laterally if it is not to become jammed in the furnace by this action. The furnace should therefore expand downward at quite a rapid rate to prevent the possibility of such jamming.

The diameter of the bosh being controlled by hearth and bosh conditions we are not at liberty to secure expansion by enlarging that and in consequence we have only one method of increasing this batter which is by carrying the stock-line diameter of the furnace down as close as we dare to the point where the swelling of the charge begins or roughly to the bottom of the warming and drying zone, so concentrating the outward batter into a shorter zone and making it more rapid. This is the line along which the modern development of furnace lines has taken place. At the same time I have never felt perfectly sure that it would not be safe to increase the bosh diameter and so secure greater batter. It is

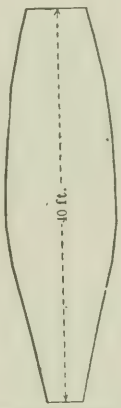
worth noting also that too large a stock line defeats its own end, as far as keeping down flue dust is concerned, for nothing makes so much flue dust as irregular descent of the charge, "slipping," and if the furnace works "tight" in the zone of carbon deposition this will result in top slips and the production of much flue dust, while if the stock line be somewhat reduced the resulting increase in outward batter supplies more room for expansion and relieves the "tight" zone, so tending to reduce slipping.

Considerations Affecting the Bosh Diameter.—We have already seen that the diameter of the gas column at the top of the bosh for constant velocity is larger than the actual bosh diameters in common use and



Blown-in, Mar. 15, 1844.
Blown-out, July 17, 1844.
Iron per week, tons, 52.30.
Average grade of iron, 1.68
Fuel per ton pig, tons, 2.28
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 3.

Fig. 13.—
Furnace No. 1.



Blown-in, Sept. 5, 1844
Blown-out, May 16, 1846.
Iron per week, tons, 57.46.
Average grade of iron, 1.89.
Fuel per ton pig, tons, 2.04.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 3.

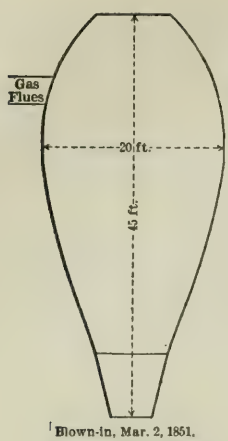
Fig. 14.—
Furnace No. 1.



Blown-in, May 25, 1845
Blown-out, Aug. 24, 1847.
Iron per week, tons, 68.36.
Average grade of iron, 3.27.
Fuel per ton pig, tons, 1.95.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 4.

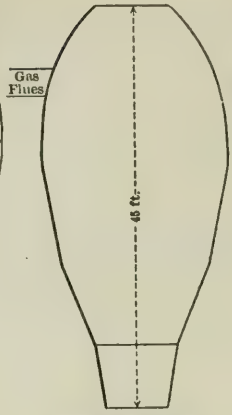
Fig. 15.—
Furnace No. 2.

have indicated certain conditions affecting this, but the conditions are many and complicated and we do not know positively enough about them to permit drawing very definite conclusions. We do know that in earlier days boshes were very much larger, particularly in relation to hearth diameter, than they are now (see Figs. 13 to 21 and following); the rapid batter of the shaft and flat bosh slope were continued until they intersected, with no intervening cylindrical section (see Fig. 19), so that they made rather a sharp internal angle where they met and it seems to be abundantly established by the experience of the furnacemen of that day that this was a very inactive region. Its area was so great that the gas velocity through it was very low; accordingly it was a fruitful



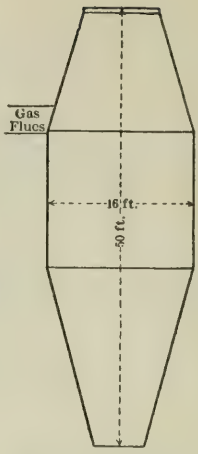
Blown-in, Mar. 2, 1851.
Blown-out, July 24, 1853.
Iron per week, tons, 114.04.
Average grade of iron, 3.42.
Fuel per ton pig, tons, 1.82.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 5.

FIG. 16.—
Furnace No. 1.



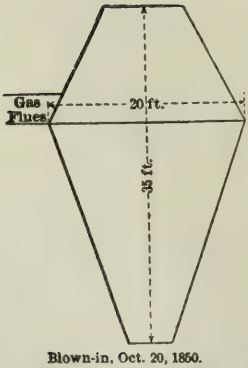
Blown-in, Sept. 20, 1853.
Blown-out, Mar. 28, 1855.
Iron per week, tons, 140.69.
Average grade of iron, 4.14.
Fuel per ton pig, tons, 2.03.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 5.

FIG. 17.—
Furnace No. 1.



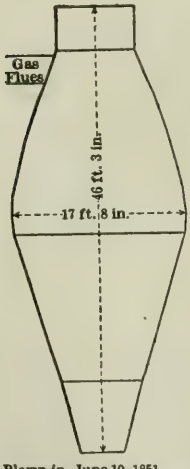
Blown-in, July 1, 1855.
Blown-out, July 1, 1857.
Iron per week, tons, 131.47.
Average grade of iron, 2.72.
Fuel per ton pig, tons, 1.91.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 5.

FIG. 18.—
Furnace No. 1.



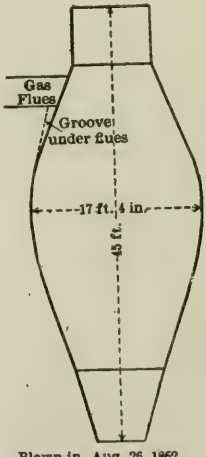
Blown-in, Oct. 20, 1850.
Blown-out, Mar. 31, 1851.
Iron per week, tons, 103.96.
Average grade of iron, 3.34.
Fuel per ton pig, tons, 2.30.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 5.

FIG. 19.—
Furnace No. 3.



Blown-in, June 10, 1851.
Blown-out, Aug. 7, 1853.
Iron per week, tons, 109.12.
Average grade of iron, 3.97.
Fuel per ton pig, tons, 2.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.
Number of tuyeres, 5.

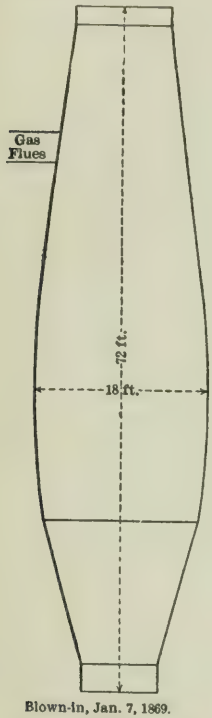
FIG. 20.—
Furnace No. 3.



Blown-in, Aug. 26, 1862.
Blown-out, Apr. 21, 1865.
Iron per week, tons, 154.69.
Average grade of iron, 4.19.
Fuel per ton pig, tons, 1.82.
Blast-temp., 500°-600°.
Blast-pressure, pounds, 4.5.
Number of tuyeres, 5.

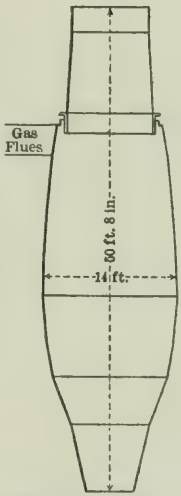
FIG. 21.—
Furnace No. 3.

zone for the establishment of scaffolds which might content themselves with filling up the useless space, but once formed, were likely to grow too large and were certain to be irregular, so that their influence on the work of the furnace was generally, though not invariably, bad. In my own experience I have seen a furnace whose bosh was too large for the work it was doing and whose work was less satisfactory than smaller furnaces had been.



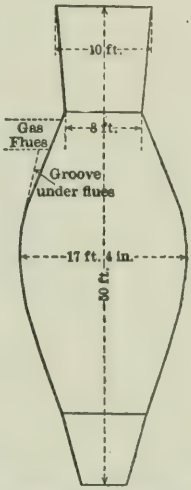
Blown-in, Jan. 7, 1869.
Blown-out, Feb. 28, 1871.
Iron per week, tons, 257.00.
Average grade of iron, 3.72.
Fuel per ton pig, tons, 1.35.
Blast-temp., 500°–650°.
Blast-pressure, pounds, 5.5–6.25.
Number of tuyeres, 7.

FIG. 22.—
Furnace No. 5.



Blown-in, Nov., 1869.
Blown-out, Apr., 1873.
Iron per week, tons, 182.86.
Average grade of iron, 4.34.
Fuel per ton pig, tons, 1.59.
Blast-temp., 650°–750°.
Blast-pressure, pounds, 4.5–5.
Number of tuyeres, 4.

FIG. 23.—
Furnace No. 2.



Blown-in, Aug. 22, 1869.
Blown-out, Feb. 6, 1871.
Iron per week, tons, 189.62.
Average grade of iron, 4.61.
Fuel per ton pig, tons, 1.48.
Blast-temp., 650°–750°.
Blast-pressure, pounds, 4.5–5.
Number of tuyeres, 5.

FIG. 24.—
Furnace No. 3.

On the other hand, many furnaces were built about 30 years ago with extremely small boshes, only one-fifth or less the height of the furnace in diameter, and some of these have been built in recent years, but except on very hard and irreducible ores which swell very little during reduction, they work with high pressure and consequent hanging and irregularity, therefore with high coke consumption, and in general very unsatisfactorily.

It would seem, therefore, that while the diameter for constant gas

velocity may not be and probably is not the correct diameter for the bosh, it is not very far from it and is certainly closer to it than some actual bosh diameters which have been used, both larger and smaller. It is evident from the discussion of hearth and stock-line diameters above that both of these must exert an influence upon the bosh diameter in the directions and for the reasons pointed out. It seems certain, therefore, that the bosh diameter must be a compromise resulting from these considerations and many others, notable among these being the height and angle of the bosh; for given these and the diameter of the hearth the diameter of the bosh obviously becomes absolutely determined —as a consequence we cannot change one of these three alone but must change at least two and this fact greatly increases the difficulty of determining the controlling conditions.

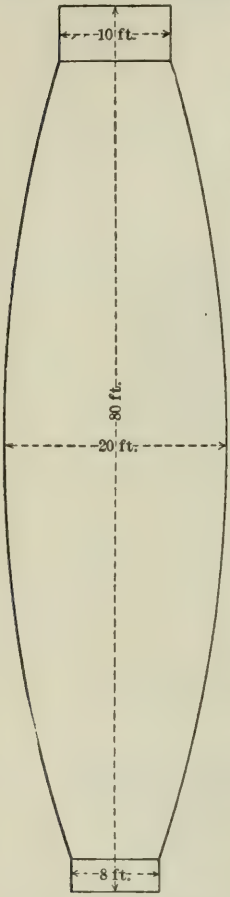


FIG. 25.—Furnace No. 2. Musconetcong Iron Works, Stanhope, N. J., 1871.

In a general way the necessity of more room for expansion for the charge in its descent and for the gas volume in its ascent through the bosh would seem to indicate a somewhat larger bosh diameter than is now customary, as none of the influences mentioned indicate any danger from a moderate step in this direction, especially with the increasing hearth diameters now being used.

Of course, in so abstruse and difficult a matter the test of time and experience is the only safe guide.

The evolution of practice from the early days of the anthracite iron industry to its decline about 30 years ago is well shown by Figs. 13 to 22 from Mr. F. Firmstone's paper.

PATHS OF DEVELOPMENT OF FURNACE LINES

About a generation ago many furnaces were built with a small hearth, a high and very steep bosh, and a top much larger than the hearth. The evolution of standard practice at the two largest furnace plants in the country using Lake ores is well shown by Figs. 29 to 42, reproduced from H. A. Brassert's paper "Modern American Blast-Furnace Practice" before the American Iron and Steel Institute in 1914.

The boshes have been lowered virtually 50 per cent., the hearth has been increased about 50 per cent., and the angle of the bosh has gone through a cycle swinging from 79° down to 72½° and now back again to

80°. The top diameters have been changed but little, as have the heights, practically all the later ones being 90 ft. These changes have taken place with an increasing rate of production, the net result of which has been to increase the tonnage per furnace to three times that of a generation ago.

With this increased output has gone necessarily an increased volume of wind. The resulting increase in pressure has increased the rapidity of combustion and reduced the amount of space necessary for that operation, so that the zone of fusion and the top of the bosh have steadily fallen. To a certain extent it is proper to say that the blast heats available have increased and that therefore there is less relative increase in volume of the gas column at the top of the bosh as compared with that at the tuyere plane and this has coincided with the increase in the hearth diameter, as it should on the theory of constant gas velocity; at the same time it must be recognized that the desire to produce a greater tonnage per furnace with the consequent necessity of burning more coke, and affording more room for this, has been the chief cause for the latter change.

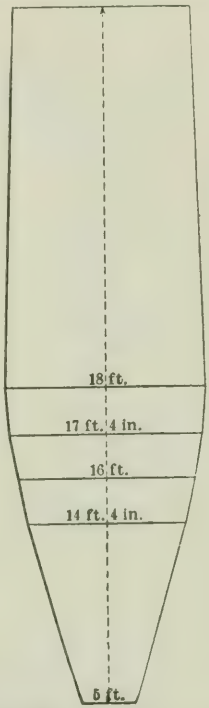


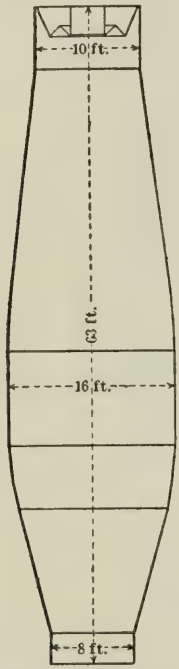
FIG. 26.—Furnace No. 1.

As to the considerations which affect the slope of the bosh, we know but little. At the beginning of the period covered by the set of profiles reproduced from Mr. Brassert's paper it was quite customary to use very small hearths and steep bosh angles in furnaces much smaller in maximum diameter in the bosh and also at the top than No. 1 of this series. For a period of years and within limits it may be correctly said that a proportional increase of both hearth and bosh diameters took place, as it properly should on the theory of constant gas velocity, and this, combined with the lowering of the bosh, had the effect of greatly reducing the bosh angle. That this effect was highly beneficial in some cases, I have seen demonstrated so unmistakably as to leave no room for doubt, but now, as above noted, the tendency is to return to bosh angles of between 77° and 80°, and with these angles it is possible to use high blast temperatures with large percentages of Mesaba ore, something it was considered impossible to do for many years, for a reason of which many furnacemen convinced themselves by trial, that furnaces using large percentages of these ores would "stick" if given more than a very moderate amount of blast heat.

The reason for this action is not definitely understood as far as known to me. Presumably it results from the fine subdivision of the ore which, when in a partly reduced condition, enables it to form a plastic

mass too early in its descent if the furnace becomes too hot, and is analogous to the tendency of all furnaces irrespective of the ore they use to stick if they become excessively hot in the hearth.

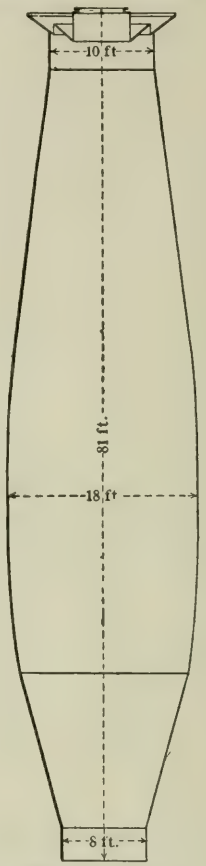
Whatever may be the cause of this tendency it is now demonstrated that it may be overcome by steepening the angle and reducing the height of the bosh, presumably so as to furnish smaller resistance



Blown-in, Aug. 19, 1877.
Blown-out, Oct. 30, 1880.
Iron per week, tons, 304.2.
Average grade of iron, 3.13.
Fuel per ton pig, tons, 1.15.
Blast-temp , 800°–850°.
Blast-pressure, pounds, 6.5–7.5.
Number of tuyeres, 5.

Same profile, Langen charger
Blown-in, Mar., 1881.
Blown-out, Apr., 1884.
Iron per week, tons, 340.2.
Average grade of iron, 3.01.
Fuel per ton pig, tons, 1.21.

FIG. 27.—Furnace No. 1.
Rebuilt 1875–77.

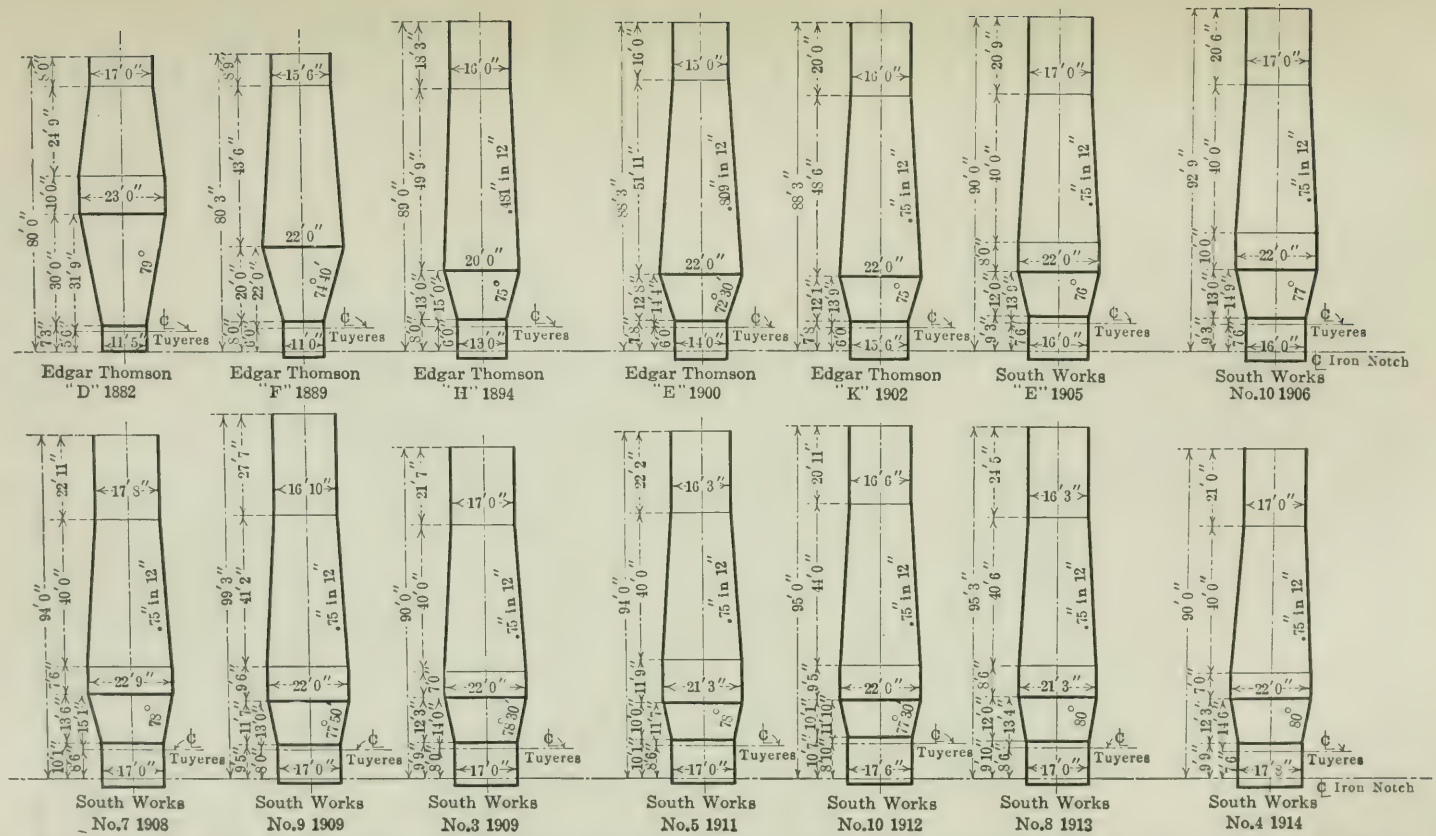


Blown-in, Aug. 5, 1882.
Blown-out, July 15, 1886.
Iron per week, tons, 412.4.
Average grade of iron, 2.75.
Fuel per ton pig, tons, 1.21
(one-eighth coke.)
Blast-temp., 800°–850°
Blast-pressure, pounds, 8–9.
Number of tuyeres, 7.

86 weeks unsized ore (1882–84):
Iron per week, tons, 349.5.
Average grade of iron, 2.53.
Fuel per ton pig, tons, 1.32.
118 weeks sized ore (1884–86):
Iron per week, tons, 458.3.
Average grade of iron, 2.88.
Fuel per ton pig, tons, 1.15.

FIG. 28.—Furnace No. 2.
Rebuilt 1881–82.

to the descent of the charge column and thereby counteract the tendency of the charge to hang from being sticky.



FIGS. 29 TO 42.—Showing the development of blast furnace lines from 1882 to the present time, as illustrated by the furnaces built at the Edgar Thomson, Carnegie Steel Company and the South Works, Illinois Steel Company.

With the change in practice worked out at the South Chicago Works of the Illinois Steel Co., described in the papers of Messrs. Brassert and Mathesius, has gone an increase in the pressure drop for penetration as mentioned earlier in this chapter. The increase is more than proportional to the hearth diameter through which it must act while the tuyeres used are very long, and it is probable that the acute jetting action which results virtually builds up the inside of the hearth and the lower portion of the bosh, owing to the effects described under the head of penetration.

Considering these two circumstances together it may be that the high penetration produces "phantom" bosh and hearth lines on which the furnace really works in operation, the bosh flatter, and the hearth diameter smaller than those provided in the construction and yet short and steep enough to prevent too great support of the stock by the bosh walls in the (upper) pasty zone, thus giving a certain amount of latitude in the working lines of the furnace, within which it may find those best suited to the conditions.

These views in regard to the South Chicago practice are intended merely to be suggestive, they must not be considered as established. It must be noted also that this change has been accompanied with an improvement in the quality of fuel used which has permitted practice which would not have been so successful with an inferior fuel. The concentration of heat with a poorer fuel is not sufficiently great in so large a hearth and a tendency would arise that might be very troublesome for the hearth to build up in the bottom. Even now it remains to be demonstrated that a sufficient concentration of heat in the hearth can be made with these furnace lines to produce foundry and other high-silicon irons, furnaces of this type having made their records on steel-making irons low in silicon, and having in some cases definitely failed to produce foundry iron satisfactorily.

Reviewing all these complex considerations, many of them obscure and difficult to understand and almost all virtually impossible to measure, it becomes evident that the mechanical principles of the blast furnace are not second in practical importance to the chemical and thermal principles and that if furnaces are to yield a satisfactory commercial result we must consider with the utmost care not alone chemical equations and heat balances which often largely take care of themselves anyway, but questions of regular and uninterrupted descent of the charge column, leading to low fuel consumption, low flue-dust loss and regular product, of low and uniform blast pressure permitting the use of small and inexpensive power plants and small consumption of furnace gas, and other purely mechanical questions.

It is a safe statement that if one-half the scientific research had been expended on these practical mechanical questions that has been spent on chemical equilibria and lopsided heat balances the science and art of furnace operation would be far ahead of where they are to-day.

PART II
OPERATION

CHAPTER VII

THE SEQUENCES OF THE CHANGES WHICH OCCUR

The three preceding chapters on the principles of the blast furnace have necessarily to some extent formed a picture of the operation, but we may now consider in more detail the progressive changes which take place within the stack, first, in the raw materials as they descend, and second, in the gas as it ascends.

THE CHANGES IN THE DESCENDING RAW MATERIALS

While the changes through which these pass shade from one into another so that the number of stages is literally infinite, yet these stages may be divided into four main zones, first, that of drying and warming; second, that of the reduction of the ore, the decarbonating of the stone, and some solution of coke; third, incipient fusion, and the early stages of slag formation; fourth, the reduction of the last remaining portions of the ore from the slag, the completion of the carbonization of the iron, its siliconization, and also its impregnation with the phosphorus and manganese to the extent these may be present.

The Warming and Drying Zone.—As to the warming and drying zone not very much need be said. In coke furnaces in good practice there is a sufficient amount of residual heat in the gases at their exit from the stock column to give them a temperature of seldom less than 300° or 400°, and ranging from this up to 1000°, as we have seen in the chapter on thermal principles. This provides an ample interval between their temperature and that of the incoming raw materials to provide for the rapid drying and warming of the latter, so that the temperature of the charge rises quite rapidly for a short distance below the stock line, and thereafter much more slowly because the temperature interval is much reduced by this rapid warming of the cold incoming stock.

The Zone of Reduction.—In passing through the second zone, the ore and fuel react with the ascending gases according to the complex laws set forth in the article on chemical principles. In a broad way oxygen is continually taken from the ore and imparted to the gas so that the content of oxygen in the latter constantly rises in its progress through this

zone, but in detail we have the complicated reactions whereby some of the CO of the gas is broken by the catalytic action of the iron ore into CO_2 and C, the latter being deposited as an impalpable dust in the interstices of the charge, thus obstructing the free passage of the gas through it and not infrequently raising the resistance in this zone and the pressure below it. This carbon dust is carried down with the charge to a zone of higher temperature in which the ore can no longer remain in equilibrium with the carbon, so that the latter takes part of the remaining oxygen from the ore, is reconverted into CO, and rises again with the rest of the gas, perhaps to go through the same reaction again.

In this zone also the carbon dioxide of the limestone is driven off by heat, the greater portion of this action probably taking place in the upper portion of the zone. This, of course, results in adding to the gas more CO_2 which entirely alters the equilibrium relation between the gas as a whole and the ore and carbon of the charge, a portion of the latter being dissolved by the gas to reduce a part of this CO_2 to CO and restore the equilibrium.

Frank C. Roberts several years ago called attention to a case where a furnace which had been using a coarse, lumpy limestone changed to a rather finely crushed stone, with the result that slips became much more pronounced. The operators finally decided that the change in the size of the limestone was the cause of the slips and upon going back to the larger stone the frequency of the slips declined to the same as before the change was made. Mr. Roberts accounted for this on the hypothesis that with the lumpy stone, because of the time required for the heat to penetrate the large lumps, decarbonization was delayed down to the point where carbon deposition was taking place freely. The result was that the CO_2 from the stone dissolved the carbon dust deposited and prevented it from obstructing the interstices in that zone, leaving a free passage for the gas. With the smaller stone, on the other hand, the CO_2 was driven off at a level above that at which the carbon deposition took place, and the latter was, therefore, not removed by this agency, with the result that a tight zone was formed with slipping as a direct consequence.

I have had no experience of the conditions described but the explanation, in addition to being very ingenious, is entirely reasonable and illustrates how difficult it is to determine in advance the effect of any given change on the operation of a furnace, for it is almost universally believed and is probably very generally true that limestone crushed down to a reasonable size is very much to be preferred to coarse, lumpy stone.

When the ores charged are in the form of lumps, or particularly if the ore be magnetite, the action of reduction is very much slower and the individual pieces of ore may descend well down toward the top of the bosh before they are disintegrated by the reducing action. If the

ores are magnetic and lumpy also both causes contribute toward a still further delay in reduction, and we are likely to have solid lumps of ore descending into the bosh and even into the hearth of the furnace, where it is certain that they are reduced by the direct action of carbon with all the loss of both heat and fuel which have been shown to inhere in that action. Such furnaces must inevitably suffer from a fuel consumption materially higher than that of a furnace working on ores inherently more reducible or better prepared. On the other hand, we have come within recent years to realize that ores may cause almost as great fuel loss by being too reducible as by being too irreducible.

THE EFFECT OF FINE ORE

With the introduction of large percentages of Mesabi ore into the burden, the universal experience was that the furnaces worked much more irregularly, with more frequent and more violent slipping and kicking, with not infrequent explosions of a violent nature which we will consider later, and that the fuel consumption was materially increased, even on furnaces working, for the time being, free from slips; so that the increased fuel could not be charged to the irregularity of the descent of the material into the hearth.

The reason for this increase in fuel does not seem to have been understood by anyone until within a year or two. In the summer of 1913 I obtained some authentic data as to the quantity of blast required to burn a pound of coke based on a vast amount of accurate and reliable investigation at one of the largest plants in the country. This amount was 51.4 cu. ft., whereas the amount required to burn a pound of the same coke, if there were no solution loss, under the same circumstances, would have been about 63 cu. ft. Obviously, then, the solution loss under these conditions was about 20 per cent. The fuel consumption was about 2200 lb. per ton.

I had recently been making some investigations based on the practice described in the paper of Mr. Arnold K. Reese before mentioned, in which the solution loss based on both engine displacement and gas analysis seemed to have been very small, while the fuel consumption for this run which was made altogether on Old-Range ores was, if not a record, at least within a few pounds of any authentic record made until very recent months, about 1700 lb. per ton. What could cause this enormous difference in the solution loss?

After making allowance for the solution loss in modern practice, the amount of fuel per pound of iron actually burned in front of the tuyeres was almost identical in the two cases, perhaps about 100 lb. higher in the modern practice, corresponding to a slight increase in the slag volume as compared with Reese's comparatively rich mixture, then the difference

accounted for by solution alone amounted to about 400 lb. per ton of iron.

The difference in the physical condition of the ore was the only notable difference in the two cases. In Reese's practice the ores were Old-Range, therefore either lumpy or plastic, and contained no fine sandy material, whereas in the case taken from modern practice the burden was some 80 per cent. Mesabi. When a layer of lumpy or plastic ore is charged upon a layer of coke it has little opportunity even after thorough drying out to run down into the interstices of the coke; the lumps, of course, cannot so run and the plastic material when dried out becomes not powdery but lumpy and is, therefore, almost equally unable to penetrate through the coke charge.

With fine, sandy ores the conditions are totally different. As soon as the ore becomes thoroughly dried a large portion of it runs almost like a liquid, especially when in a state of constant agitation caused by the gas current passing up through it, and this portion of the ore rests not only upon the top surface of the coke charge, but runs all through it and makes contact with the coke practically throughout the mass of the coke charge. It must be remembered that ferric oxide and carbon in contact at any temperature above a few hundred degrees are essentially in unstable equilibrium, and that direct action takes place between them, a part of the oxygen of the ore attacking the carbon and carrying it off as CO.

With the Old-Range ores this action could take place only along a single plane of contact, but with fine, sandy ore scattered throughout the coke charge the number of points of contact is almost infinitely increased, and obviously the solution loss must necessarily be very much higher under these circumstances than with lumpy or plastic ores.

This, then, taken with the effect of solution loss set forth in the article on thermal principles, forms the explanation of the greatly increased fuel consumption of furnaces working fine ores over those using ores of similar analysis but different physical characteristics.

There has been for many decades, and probably many centuries, a strong prejudice among furnacemen against the use of fine ores, and it is probable that this action just described is responsible for a great portion of this prejudice. Moreover, with certain kinds of fine ore the conditions may be even worse. Furnaces working on fine magnetic concentrates have had the greatest difficulty in securing regular work, irrespective of the care with which the furnace might be burdened and filled, for the reason that the fine ore, as the furnacemen expressively describe it, "runs ahead." That is to say, under the agitation of the gas current it runs almost like a liquid, not only down through one fuel charge but perhaps through several if the conditions happen to be just right, and owing to its irreducibility, and to its having reached the hearth

perhaps several hours ahead of the fuel which should have accompanied it, the furnace is unable to carry the additional load and serious trouble results.

In recent years much progress has been made in treating fine ores before charging them so as to convert them into some form of lumps. This was originally undertaken with the purpose of preventing the very fine portions from being carried out by the top gases and lost, but it has been found that in some cases a real benefit to the operation of the furnace has been brought about, and the reason for this improvement is believed to be that set forth above, that the physical structure of the ore is so changed as to prevent its running through the charge. Perhaps in some cases also, the lumps act as a blanket on top of the coke to prevent fine portions of the ore charge from finding their way down into the coke. Several of these processes reduce the ore partly to the condition of magnetite and thereby decrease its reducibility, but leave the product so porous that the gas and heat have free access to its interior portions, and so prevent its acting as do the large irreducible lumps of magnetite above described.

Throughout this zone of preliminary reduction a continual warming up of the ore takes place, partly by the physical absorption of the heat of the ascending gas current, and partly by the action of the oxygen of the ore in oxidizing the CO formed in the hearth to CO_2, a reaction which gives off more heat per unit of oxygen than is absorbed by the removal of the same amount from the ore and therefore produces a net increase in the amount of heat present.

It will be noted from the equilibrium diagram in the chapter on chemical principles that the equilibrium line for both Fe_3O_4 and FeO descends toward the right or high-temperature side of the diagram, which means that as the quantity of oxygen remaining in the ore is reduced a higher heat and higher percentage of CO in the gas is required to remove the remaining portions, and as the ore descends these are precisely the conditions into which it passes, a continually increasing temperature, and increasing concentration of CO in the gas, until at the top of the bosh practically all the carbon in the gas is in that condition.

It is probable that it is because of the long slow slope of these equilibrium lines that this second zone of the furnace requires to be the largest of any in point of size, almost as large as all the other three put together, so that time and space may be allowed for the relatively small but approximately constant reaction pressure (to coin a crude term), to do thoroughly and well its work of preparing the ore as completely as possible for the final operations which take place in the hearth and bosh.

Many other reactions and changes probably go on within this region but from the point of view of operation these are the only ones with which we need to concern ourselves.

The Zone of Preliminary Slag Formation.—This zone is one located approximately at the top of the bosh where, as we have previously seen, the materials pass through a pasty stage and finally into a fluid slag, but one by no means of the composition which subsequently is tapped from the furnace.

In a paper of Mr. F. E. Bachman before the American Iron and Steel Institute in October, 1914, occurs the following paragraph which describes in a few words better than anything I have ever seen the action which I believe takes place in this zone.

"My conception of the formation of a blast-furnace slag is that at a point approximately 25 ft. above the tuyeres the minerals which have the lowest melting point in the ore begin to melt, then the free SiO_2 combines with FeO and with the melted minerals forms a fusible slag somewhat similar to heating furnace cinder. This slag flows down over the pieces of lime and coke, and when it reaches the hotter section of the furnace, the FeO is gradually reduced to Fe and replaced by CaO or by CaO and MgO from the lumps of burned stone. In front of and immediately above the tuyeres the coke ash is set free and combined with the slag produced above, and a portion of the lime not completely fluxed often passes below the tuyeres and is absorbed in the bath of slag in the hearth."

It may be doubted whether in practice other than that described by Mr. Bachman the initial fusion of the materials takes place as high as 25 ft. above the tuyeres. It seems likely that in furnaces on Lake ores this height is more likely 15 to 20 ft., but leaving aside this detail, the fact that slags form in a broad way as described by Mr. Bachman cannot be too strongly emphasized. The furnace does not make initially a clean iron-free slag of the final composition which we tap out, but following the law of most metallurgical operations it makes first of all a slag to suit itself, that is the most fusible one which can be produced from the ingredients present.

Oxide of iron lowers the melting point of lime-silica slags by several hundred degrees, and these are, as Mr. Bachman states, of the general nature of mill cinder, although probably considerably limier than that material. We never see anything of this intermediate slag when the furnace is in normal operation, but when it is in trouble and without sufficient heat in the hearth to furnish the reducing action we obtain from it, to our sorrow, slags of various and sundry descriptions, some of them, thin, flowing almost like water at temperatures literally hundreds of degrees below the running temperature even of charcoal slags, and yet with so little reserve of heat above their melting point that the liquid surface can hardly be seen for the scull which freezes over it instantly when it strikes the air, and a hand ladle dipped into such a slag for a sample will come out with a heavy crust instantly frozen on its surface, not tough or pasty, but sharp and brittle almost like ice, and as black as pitch itself.

These slags have compositions varying over a very wide range, but the most fusible one that I have ever seen contained a large percentage of iron, something like 35 per cent. FeO. In normal operation probably there is not in the zone of initial fusion sufficient unreduced iron to form a slag of this composition, but there is enough to form one of the stiffer and more plastic and more infusible slags such as we sometimes obtain from a furnace when it is limed up, that is, when the fusion point of the slag has been raised so high by excessive lime that there is not enough heat above its running temperature to give it complete fusibility or to remove all the iron from it, it is probably such a slag as this which first forms in the upper portion of the pasty zone. All the observations which we have of the slag from furnaces in normal operation, but taken from above the tuyeres, are of this general character, tough and black, proving the presence in them of some iron still unreduced. This, for instance, is the character of the slags which drip down from above and which we see when we are changing tuyeres and coolers or the like.

It is well to note how completely this physical evidence of unreduced iron in the hearth of the furnace agrees with the deduction in the article on thermal principles that the final reduction of the iron is not accomplished until it descends into the bosh. We have here a conclusion reached upon theoretical grounds, borne out by all the objective evidence available.

In considering the matter of slag formation there are several points of much importance to be borne in mind. The first two are those mentioned in the chapter on chemical principles. First, that the formation temperature of slags is generally higher than their fusion temperature which is almost a corollary of the fact that the fusion temperature of the ingredients is far higher than that of the slags. Second, that the fineness of subdivision and intimacy of mixture of the different ingredients has a pronounced effect upon the formation temperature; as it is almost obvious that it should in view of the first condition.

In addition to these it must be noted that in coke practice a very large proportion of the total silica to be fluxed comes from the coke. In most Lake ore practice this probably amounts to about one-half, the other half coming from the gangue of the ore. Now no matter how intimately the flux and the ore may be mixed the lime must be in great excess at the top of the bosh because approximately one-half of the silica is contained in the coke and locked up securely therein so it is not all exposed to the solvent action of the slag until the coke has all been burned away, which as we know does not take place until it reaches the tuyere zone. It is obvious, therefore, that we must have a much limier and therefore more infusible slag at the top of the bosh where the temperature is relatively low than we have in front of the tuyeres where the temperature is at its maximum.

Considering the extremely stiff and pasty nature of these excessively limey slags, judged by the occasional ones which we get from the furnace, it is not a matter of surprise that the zone of incipient fusion should be a pasty zone, but rather that it is not a much pastier one, as in fact it probably would be were it not for the presence of the considerable percentages of iron oxide with its strong action in lowering the melting point.

With those classes of ores which contain an excess of lime such as the hard red ores of Alabama we have a somewhat different condition in respect to slag formation than that which exists with ores containing roughly the same amount of silica per unit of iron, but which require to be fluxed by the use of limestone additions. In the first case the lime and silica of the ore are in very intimate contact, and therefore the formation of the slag is greatly promoted, whereas when the silica is in intimate association with the iron alone and must be fluxed by separate lumps of lime derived from the limestone, the tendency is for the silica to unite with the iron in its partly reduced condition and carry it out of the furnace as a black slag, and either more time or more heat must be provided to obtain equally complete reduction in the latter case. This probably accounts for the fact that the soft red ores of Alabama, having virtually the same ratio of silica to iron as the hard ores, are much less desirable in the furnace. Either slower driving or more fuel is required in exact accordance with the above reasoning, for which I am indebted to Mr. W. L. Kluttz.

Impregnation of the Fuel with Slag.—In connection with the necessity for reasonable fluidity on the part of the slag it may be as well to call attention here to a curious fact of practice which, if it has been observed, has at least not been the subject of any published comment of which I am aware.

Several years ago seeing a pile of carefully screened slag which had been lying in the weather for some time I noticed scattered through it several pieces of material which looked like coke except that instead of being black they were rust-colored, and when picked up were found to be very heavy, perhaps twice the weight of coke. The question as to what this material might be was discussed between the manager of the plant and myself with much interest. Finally we broke open one of the lumps and found that it was coke impregnated with some other material. Mr. B. G. Klugh was chemist of the plant at the time and on being called in, he ground and polished a broken face of one of these specimens; examination immediately showed that a great percentage of the cell spaces, even in the very center of the original lumps, was impregnated with slag. Subsequent investigation at other plants showed that all the coke which came from the tapping hole and had therefore passed through the hearth, was in this condition. In some cases particles of iron as well

as slag were found in the center of the pieces of coke. It was noticeable that this slag was always milk-white, irrespective of the slag which the furnace might be making at the time.

When I first began to operate a charcoal furnace I noticed on the casting cinder little piles of coarse fibers about like white horsehair, the individual fibers 2 or 3 in. long, and not lying criscross but parallel, as if they had come done up in a neat package. I asked what caused this but obtained no satisfaction. A short time after, however, coming past soon after cast, I noticed on the surface of the cinder which was still hot, pieces of charcoal with a white appearance around their ends in various stages of very slow combustion, no flame, merely a quiet dull red glow hardly visible, by which the carbon was slowly passing away. Closer examination showed that the white appearance at the ends was due to the presence of fibers projecting from the cells, and presently it became evident that the neat little package of "horsehair" were fibers of slag cast absolutely perfect into the cells of the coal in the hearth, and exposed by the slow burning away of the charcoal as it lay on the hot slag in the open air. Analysis of this material proved it to have the same composition as the main body of the slag made at the same time.

The extreme whiteness of the slag in both these cases is an index of the completeness with which the iron oxide is reduced and removed from it, and suggests the possibility that this extraordinarily intimate contact between the slag and the fuel may be a factor of some practical importance in the final completion of the smelting operation, and certainly it is a factor which cannot exist except with a reasonably fluid condition of the slag.

The Zone of Final Operations.—This is the region of highest temperature in the furnace, extending from a short distance above, to just below, the tuyeres. In it the slag attains its final composition, the coke having all burned away and released the slag-forming ingredients which it contains, while the intense heat suffices, in a proper-working furnace, to deoxidize the last remaining portions of the iron and causes them to enter the iron bath leaving a slag which in good practice contains not to exceed 0.2 to 0.3 per cent. of iron.

In coke practice, owing to the fact that the slags used are on the lime side of the most fusible ratio of lime to silica, additions of silica cause the production of a more fusible slag, hence the release of the silica from the coke ash, and the increase in temperature, owing to the conditions in the region, both contribute to make the slag more fluid. As we have many times reiterated, the "critical" temperature of the furnace not only in the theoretical sense of that word but in the actual sense that the operation of the furnace depends upon it, is that temperature at which the slag becomes sufficiently fluid to free the remaining traces of iron, both shot and oxide, which it contains, and sufficiently mobile to cover the coke

and carry away practically all the sulphur it contains, as fast as the latter is disengaged, thus keeping all but small traces out of the iron.

We see, therefore, that the slag has only to reach this condition in its final stage, but it is absolutely essential that it be reached, if not, evil consequences will follow very rapidly. First, the sulphur is no longer sufficiently absorbed by the slag, and deleterious quantities enter the iron, lowering its value and finally reducing it to a non-merchantable commodity. Simultaneously with this begin considerable losses of iron carried off with the slag, sometimes as shot, more often in the form of ferrous oxide dissolved in it, and finally as an inextricable mixture of bad iron and bad slag which do not separate instantly with a clean line of parting like oil and water, but which, partly for physical and partly for chemical reasons, remain mixed together if not dissolved one in the other.

Following these conditions, the slag becomes too stiff to be flushed from the furnace through the ordinary opening, 1 to 2 in. in diameter, and the water-cooled monkey through which this operation is performed must be removed bodily making a hole some 6 to 10 in. in diameter through which the slag will flow unless the furnace is lime-set or in serious trouble from lack of heat. "Lime-set" was a term used principally by the furnacemen of an older generation, before the simple principles of furnace burdening were as well understood as they are now, to describe the condition to which furnaces were not infrequently brought by the addition of more and more lime to accomplish certain results in the kind of iron produced, or through a misunderstanding of some abnormal condition of the furnace and attempting to correct it with what turned out to be an overdose of lime.

The fusion temperature of slags with increasing lime content goes up with great rapidity, and after a certain point is reached the free-running temperature of the slag becomes higher than any temperature obtainable within the hearth of the ordinary blast furnace, with the result that the slag cannot be removed, and if the furnace continues to be blown this infusible slag rapidly builds up in the hearth and bosh making it more and more difficult for the blast to penetrate from the tuyeres up through the stock column until finally the hearth and bosh of the furnace are almost filled solid with this excessively limey material, which when it is exposed to air or cooled off, not infrequently breaks down much like slacked lime.

In charcoal furnaces occasionally we reach a similar condition from a cause exactly the opposite since slags containing a great excess of silica, while they are not as infusible as those containing a similar excess of lime, are extremely stringy and viscous, with the result that at the comparatively low temperatures of the charcoal furnace they may build up on its walls almost as badly as do excessively limey slags in the coke furnace. But the temperature range through which they may be made to flow, even if slowly, is wider than in the case of the limey slags, and charcoal fur-

naces are therefore not so liable to become completely "bunged up" in the expressive language of the furnaceman, from this cause as were coke furnaces a few years ago.

In the zone of final operations important changes occur in the iron itself. We have already seen that the silicon and phosphorus can be reduced only in the presence of incandescent carbon at the highest temperatures obtainable in the furnace, and when the iron is present to absorb them. The same thing is true of the manganese in a less degree. That is to say, a furnace charged with an ore of phosphorus or silicon without iron would not reduce any of those materials, and a blast furnace operated in the ordinary way charged with manganese ore without iron would reduce little or none of that element, although by material changes from regular iron furnace practice it can be made to do so. In order then that these elements may be reduced, it is necessary that the iron be present as such so that its affinity for them may assist the action of the incandescent carbon and the high temperature in reducing them from their oxides.

These actions must evidently then go on exclusively in the hearth. It is probable that a large portion of the carbonization in the iron also goes on at this point because it is quite difficult, by any other process, to make iron absorb as much carbon as the product of the blast furnace ordinarily contains. Even the electric furnace with its enormous temperature has found some difficulty in securing the conditions which would give the carbonization of iron necessary to constitute real cast iron, while other methods of melting have generally not been able to raise the carbon much, if any, above 3 per cent.

In the hearth of the furnace we have the condition that iron is subdivided into extremely small streams, trickling down over incandescent coke, in an atmosphere as reducing as it is possible to produce, and at the highest temperature of the furnace. Under these conditions the completion of the carbon absorption takes place.

As to how much carbon is absorbed in the regions above this we do not know. We do know that iron exposed to intimate contact with fine carbon over long periods of time and fairly high temperatures, absorbs 1 or 2 per cent. of carbon, and when the ore is of a nature to produce the deposition upon itself of carbon dust from the gas, we have the conditions under which carbonization may easily take place, but so far as I know no determinations have ever been made as to the extent of this action.

In addition to these, other actions go on in the hearth, and some of them we find it extremely difficult to account for. One of the most notable problems is the composition of the salamander taken from the hearth when the furnace is blown out. Salamander is a term covering literally a multitude of sins.

The salamander of the old-fashioned charcoal furnace consisted of what geologists would call "pudding stone," of charcoal and charcoal

slag of all colors and compositions, interlaced and tied together with a stringy or spongelike mass of iron.

In coke furnaces we find masses not unlike this in general characteristics except that imbedded coke is rare, and the iron portion of the structure is less sponge-like. The intimate mixture in this case is of iron, slag, graphite, and sometimes firebrick, but in the center of the coke furnace we usually find a depression well below the level of the original brick hearth of the furnace filled with iron, which, below the surface, is quite unmixed with slag. The body of solid iron varies much in size and is generally very graphitic around the edges, but frequently extremely dense and solid in the center. Sometimes this mass consists only of the frozen pool of metal last formed in the furnace which could not be removed from it because of its depth and of the absence of a sufficient blast pressure to lift it out through the tapping hole. But usually in addition to this there is another mass below it, and generally quite distinct from it, which likewise consists of solid iron, but whose composition bears apparently no relation whatever to the composition of the iron made during any portion of the blast. For instance, it is well known that the affinity of iron for phosphorus is so great that practically all the phosphorus introduced into the charge is taken into the iron, yet these salamanders often contain only a small fraction of the phosphorus contained by the iron made during the blast. The manganese is generally low, the silicon also is quite low, and I have seen the carbon which in cast iron runs practically always from 3.5 to 4.25 per cent. in one of these salamanders down to about 1.5 per cent.

This material was really a poor grade of high-carbon steel of which the crystals were distinctly bent when the broken faces were slid over one another, and of which a piece taken to the blacksmith's shop could almost, but not quite, be forged.

I am advised by John Reese that he has had a practically identical experience.

Comparing the analysis of such a material with the pig iron from which it has presumably been produced, we can only reach the conclusion that there has gone on here a slow but none the less effective oxidizing action at the bottom of the bath although cut off from access to the blast by a layer of iron or slag, or both, and at cast time when the hearth is relatively bare, covered by a mass of coke several feet in depth below the tuyeres, conditions apparently precluding any possibility of access to this region by the oxygen of the blast.

The cause of this peculiar action is not fully understood as far as known to me, but it is impossible to resist the conclusion that the oxidation must be carried on by slag not completely reduced; of the kind which we always find trickling down the walls whenever we have occasion to investigate conditions inside the furnace.

It would seem necessary to suppose that oxygen in this form is carried down into the hearth, that it is cut off from the reducing action of the coke column by the fact that the latter is in part floated on the surface of the charge as described in a previous article, and that this slag which is known to be a very active oxidizing agent satisfies its desire for oxygen at the expense of the metalloids in the plastic but not quite fluid mass of iron in the bottom of the furnace.

The mechanism by which this action is carried out I do not pretend to understand. If anyone will work it out and publish the results he will satisfy the acute scientific curiosity of a great number of his professional brethren.

THE PROGRESSIVE CHANGES IN THE ASCENDING GAS COLUMN

Turning now to the changes in the gas column, we find that these are of three separate kinds, but owing to the fact that the physical state of the gas does not change they are less sharply divided into zones than in the case of the solid and liquid materials. The three kinds of change are chemical, thermal, and physical. That is, change in composition, in temperature, and in pressure and density of the gas.

Chemical Changes.—Considering first the chemical changes, we have the blast entering, in coke practice, in a highly heated condition at the tuyeres, and in good practice distributed by their action with approximate uniformity over the tuyere zone, from which it rises through the coke column, at first being converted to CO_2, but as it rises from the tuyeres the gas is exposed to an excess of carbon precisely as in a gas-producer bed, with the result that the CO_2 quickly breaks down, the additional supply of carbon taking from the CO_2 half its oxygen and reducing the whole to CO. With the blast enters a certain amount of water vapor, and this is instantly dissociated by the incandescent fuel into hydrogen and oxygen, the latter uniting with the fuel exactly as if it entered in the form of oxygen, the hydrogen rising through the lower zones of the furnace as such, but meeting with a fortune in the upper regions which varies according to the conditions.

We have already seen that the combustion of all the oxygen of the air to CO is complete at the top of the bosh, and as it rises from this point it is progressively exposed to ore containing more and more oxygen, from which the gas progressively removes this element, converting a portion of the CO into CO_2.

It is well to reiterate here, what I have tried to make clear in earlier chapters, that the ratio of CO and CO_2 in the issuing gases does not depend upon any equilibrium diagram no matter how scientifically derived, but upon the simple arithmetical fact that each unit of ore requires for its final reduction and melting in the hearth a certain quantity of hearth

heat, for the production of which a certain definite quantity of fuel is necessary, an amount which can easily be calculated if the conditions are given. This fuel is, as we have seen, burned to CO in the hearth, the unit of ore contains a definite quantity of oxygen, and this quantity of oxygen combining with the given quantity of CO produces a mixture of CO and CO_2 of a composition depending purely upon chemical arithmetic, at least within limits far beyond those which we have ever reached. This condition is somewhat modified by the amount of solution loss of fuel which occurs, and this does depend, among other factors, upon the relative concentration of the two gases, but it cannot be too strongly emphasized that the arithmetical relation rather than the chemical equilibrium is the predominant factor in determining the ratio of the top gases.

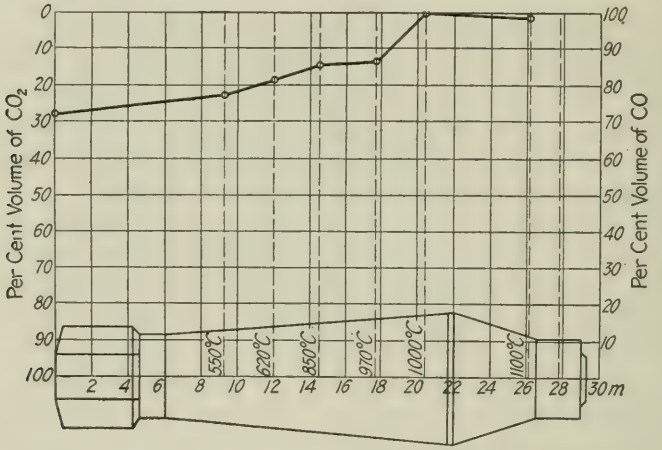


Fig. 43.—Temperature and percentage of CO_2 at different levels.

When we reach a certain point in the furnace the rather slow and orderly change of gas composition takes a sudden turn, the percentage of CO_2 increasing quite rapidly, this increase coming from the CO_2 driven off from the limestone by the heat of the furnace exactly as in a lime kiln.

Figs. 43, 44 and 45 are reproduced from *Stahl und Eisen*, vol. 31, Fig. 43 from an article by W. A. Schlesinger, Figs. 44 and 45 from one by M. Levin and H. Niedt. These are based upon experimental determinations made by sampling the gas at different heights in the furnace through holes drilled in the wall.

Fig. 44 shows quite plainly the sudden rise of CO_2, Fig. 45 does not show it, although there is an increase in the rate of rise of the curve in one region, and Fig. 43 shows an absolutely uniform rise of CO_2 after a sudden increase just above the top of the bosh. These figures are given because of the scarcity of experimental data of this kind, and because experimental

data even though they be not representative of our conditions are better than purely theoretical illustrations.

At the same time these curves are all lacking in a strongly marked feature which I found with unmistakable plainness in the course of some experimental work. This is the fact that when CO_2 is driven off from the limestone it at once attacks the carbon vigorously, and a part of it is reduced back to CO so that the concentration of CO_2 at the top of the furnace is considerably less than it is at a point somewhat lower down. This fact was determined by running a 6-in. pipe down through the center offtake of a furnace with the Longdale type of top, to a point some 8 or 10 ft. below the stock line, and taking simultaneous samples of the gas discharged through this pipe and that at the top of the furnace. Determinations were made several times, and with a result broadly the same in every case.

This, it must be admitted, is to some extent a contradiction of my statement above that the equilibrium ratio was of minor importance in determining the composition of the top gases, because obviously here we have an established equilibrium disturbed by outside conditions and automatically restoring itself. But my impression is that, as intimated above, this is a matter affecting the solution loss of the coke rather than the equilibrium between the iron ore and the gas composition. It is, moreover, probable that this condition was much more marked in these two furnaces than in many others for three reasons, that the ore was lean, and the quantity of limestone charged, and of CO_2 disengaged, therefore very large; that the top of the furnace was quite hot, and that the coke was distinctly of a soft and, therefore, readily soluble variety. There can, however, be no doubt that this tendency exists. I believe that the same result has been obtained by other observers sending pipes down from the top of the furnace, but I have no data as to these tests.

Temperature Changes.—Figs. 43, 44 and 45 each show a scale of temperatures at different elevations taken through the same observation holes as the gas analyses, but I am unable to accept the temperature given for a point just above the tuyere plane, 2012°F., as correct, because this is the hottest zone of the furnace and must be at least as hot as the issuing iron and slag which in ordinary coke practice are from 2650° to 2850°F.

This temperature has been obtained by many hundreds of direct pyrometric observations on issuing iron and slag at several blast furnaces. This is a line of work which has been too little followed, partly because of the lack, until very recent years, of pyrometers of sufficient accuracy to inspire any respect, and partly because of indifference on the part of furnacemen. It is gratifying to note that at the extensive test of titaniferous ore at Fort Henry a pyrometer expert was employed to make observations of the temperature of running iron and cinder, and it is a

matter of much personal satisfaction that the results of these accurate tests indicated a temperature of about 2800° on this experimental run using all magnetic ore (which requires more fuel and a hotter hearth than softer ores), as against the figure of 2750° obtained by me as the result of many thousands of observations with a much less accurate in-

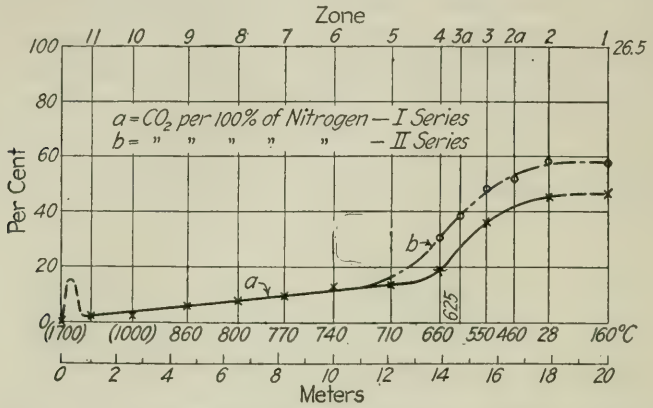


Fig. 44.—Temperature and percentage of CO_2 at different levels.

strument, a number of years ago, on a furnace working a more reducible, though leaner ore, and almost certainly running with a somewhat colder hearth.

Another reason for mistrusting the data given in Figs. 43 to 45, particularly Fig. 43, is that the drop in temperature from a point just above the

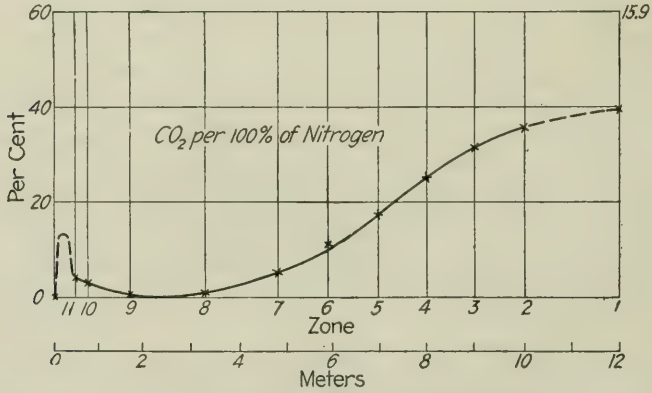


Fig. 45.—Percentage of CO_2 at different levels.

tuyeres to the top of the bosh is given as only 100°C. or 180°F., whereas all the facts of practice—above all observations on blown-out furnaces—indicate by the condition of the walls at these points that a far greater difference in temperature between them has existed. For instance, when iron-pipe cooling blocks are used, the cast iron around the wrought

pipes is frequently entirely melted away so that the pipe runs naked in the furnace, in and just above the tuyere plane, while precisely similar blocks at a plane 10 or 12 ft. above are not only perfect in shape, but frequently look when they are taken out at the end of the blast as though they had never been used.

From the top of the bosh upward we have a practically uniform drop in temperature to that at which the gas is discharged, this depending, as shown in a previous chapter, upon the thermal conditions of the operation, the total drop being roughly proportional to the iron produced per ton of fuel.

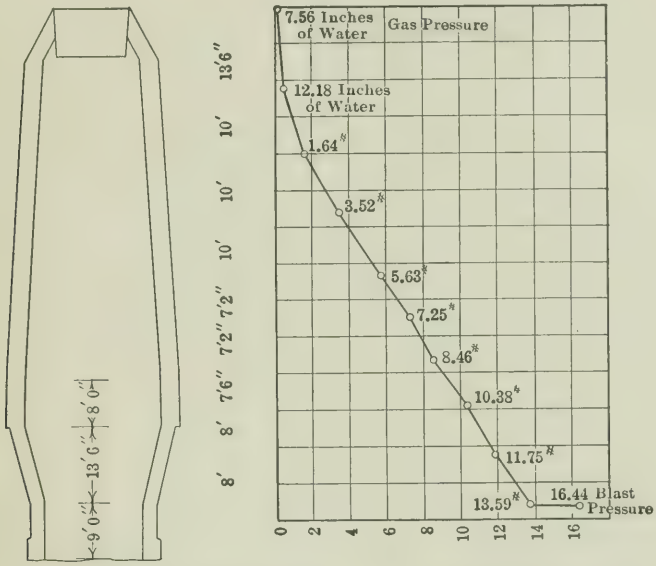


Fig. 46.—Pressure test on No. 4, furnace average of 25 readings.

Changes in the Gas Pressure.—Here fortunately all speculation can be laid aside, for owing to the kindness of Mr. Reese I am able to present a diagram, Fig. 46, giving the results of 85 sets of observations of pressure made at holes cut at different levels in one of his furnaces.

There will be seen first a quick drop from the tuyere pressure. This is the penetration drop described in a previous chapter. From this point on we have a practically straight line drop to a point quite close to the top when the rate of drop slows down, and the curve becomes convex to its base line. This is not due to any change in the law of pressure drop but merely to the fact that the top of the stock is not a level plane but a conical crater, probably 8 or 9 ft. in depth. The gas pressure begins to be relieved at the bottom of this in the center, but, of course, there is still some resistance and therefore some pressure at the circum-

ference of the furnace at any point below the top of the crater, hence the tapering off in the rate of the drop.

These observations were all made when this furnace was working regularly and properly, but Mr. Reese has also had observations made when the furnace was working irregularly, shown in Fig. 47, and these are equally instructive, if not more so. It will be seen that there are regions in which the pressure drops very rapidly indicating a decided constriction at this point followed by a rate of drop slower than the average, indicating that above the obstruction the gas had ample room to slow down and so reduce the friction drop.

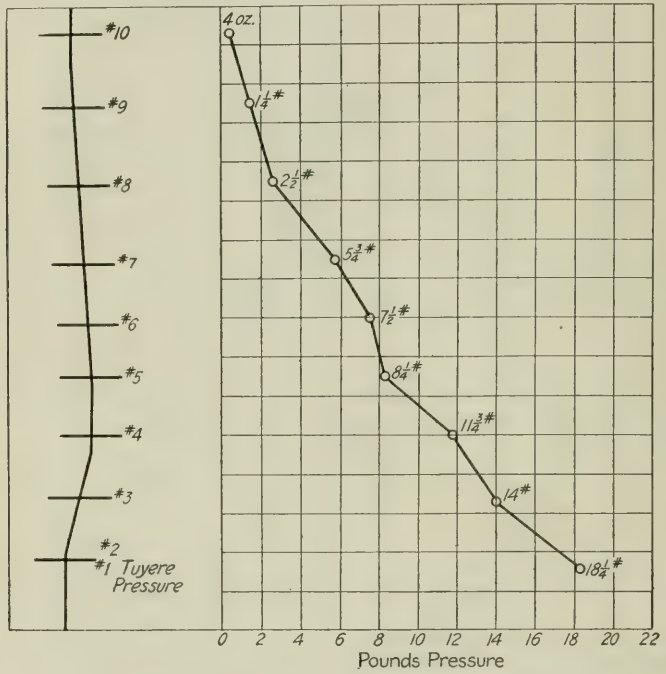


Fig. 47.—Pressure of furnace moving irregularly.

Whether the sudden pressure drop was due to abnormal changes in the charge and produced the irregular working, or whether a partly scaffolded condition produced the sudden pressure drops it is virtually impossible to say, but bearing in mind what has been said about the importance of uniform flow of gas, from the practical point of view in cutting down dust losses and the like, the very serious results which must follow from these irregular pressure conditions become obvious, and it is a matter of no surprise that the furnace working under these conditions should produce unsatisfactory results. On the other hand, the extremely smooth curve was obtained as the result of many observations on a smooth

working furnace, and its regularity (which must be a matter of surprise to those accustomed to the many minor changes which even a good-working furnace makes) indicates that a uniform and regular pressure drop is both the condition and the product of smooth and regular working.

These extremely valuable and interesting results have never before been published and I feel that Mr. Reese has placed not only me but the other members of the profession under a lasting debt of gratitude by so generously allowing their publication here.

Shape of Pressure Curve.—The rate at which the pressure drops is a matter of some interest. The shape of the curve of decreasing pressure in a pipe line given by the formula quoted in the last chapter, and established by experiment, is a parabola, the pressure falling slowly at first and more rapidly afterward, just as a horizontally thrown ball does under the influence of gravity. The same should be true of the curve of pressure drop in the furnace because in it as in the other the difference of the squares of the pressures is proportional to the resistance.

Mr. Reese's curve is almost exactly a straight line. One cannot help but wonder if a slight increase in the bosh diameter yielding a lower rate of pressure drop at first, and a proportionately somewhat more rapid one later, would not give a closer approximation to the theoretical parabola, which would correspond with a more nearly uniform velocity, and might easily result in slightly better working for reasons pointed out in the last chapter.

CHAPTER VIII

THE RAW MATERIALS

FUEL

The raw materials for the production of iron are three, the ore, the fuel, and the flux.

Flux has received all the discussion necessary in the chapter on chemical principles, so we have only to deal with fuels and ores.. The fuels used in the blast furnace are in the order of their importance as follows: Coke, charcoal, anthracite, raw coal.

COKE

This subject is so important that volumes have been written about it; to these, those in search of profound information are referred. It is only possible to give a bare outline here.

Coke is a light, very porous fuel produced by the distillation of mineral coal containing sufficient bituminous matter to cement together the whole mass at a certain temperature.

The distillation drives off nearly all the volatile matter and good coke consists almost entirely of fixed carbon and ash.

Coke is made in four ways, of which only two are metallurgically important.

Heaps, or Meillers, on The Ground.—These heaps are covered with turf and dirt to prevent the access of sufficient air for complete combustion. The limited combustion permitted generates heat enough to drive off the volatile matter from the remainder of the coal, and coke, results, but the yield of coke per ton of coal is very small, the cost is high, and the valuable by-products are of course completely wasted in this process.

This process is not in industrial use in America so far as known to me, though it is sometimes used to determine whether a given coal can be coked, and once during the last boom in the iron business it is said to have been used for a short time to secure a supply of coke for a furnace which could not get one otherwise, but the broad statement stands that the process is not in industrial use in this country. A development of this is the use of open-topped brick stalls which cut off the air from the sides of the heap. These are used considerably in China today.

Gas Retorts.—One process of supplying illuminating gas for cities consists in distilling a high volatile coal in air-tight retorts externally

heated. The coke is purely a by-product and is used in part for heating the retorts and in part for domestic and other non-metallurgical uses.

Its quality is very poor. It is soft and friable owing in part to the kind of coal from which it is made and in part to the process of manufacture; for this reason it is not used in blast furnaces; its interest comes from the fact that the gas retort was one of the progenitors of the by-product oven.

Bee-hive Ovens.—These now produce about 75 per cent. of all the coke made in this country, and are, therefore, of vast commercial importance.[1]



Fig. 48.—Battery of bee-hive ovens with larry car.

They consist of a bee-hive shaped structure of firebrick generally from 9 to 13 ft. in diameter approximately hemispherical in shape. They have a floor of firebrick, a doorway about 30 in. wide by 36 in. high, in one side, at the bottom, and a charging hole and smoke outlet combined known as the "eye" in the center of the dome. These ovens are always built in batteries and frequently in double batteries with the doors in one row on the opposite side to those in the other. The space between them is filled with dirt level with their tops and a track runs over the top of each row to carry a "larry car" which delivers the coal to them. In the case of a double battery the track may be between the rows and the larry have a spout on each side to deliver the coal to either row desired The front of a battery with the larry is well shown by Fig. 48.

[1] The percentage has decreased to about 60 per cent. as this goes to press Jan. 1918.

The track for the larry in good practice is always supported on brick pillars coming up from below the base of the ovens so as to eliminate the jar of the passage of the larry cars from the oven proper, as the life



FIG. 49.—Pulling bee-hive oven.

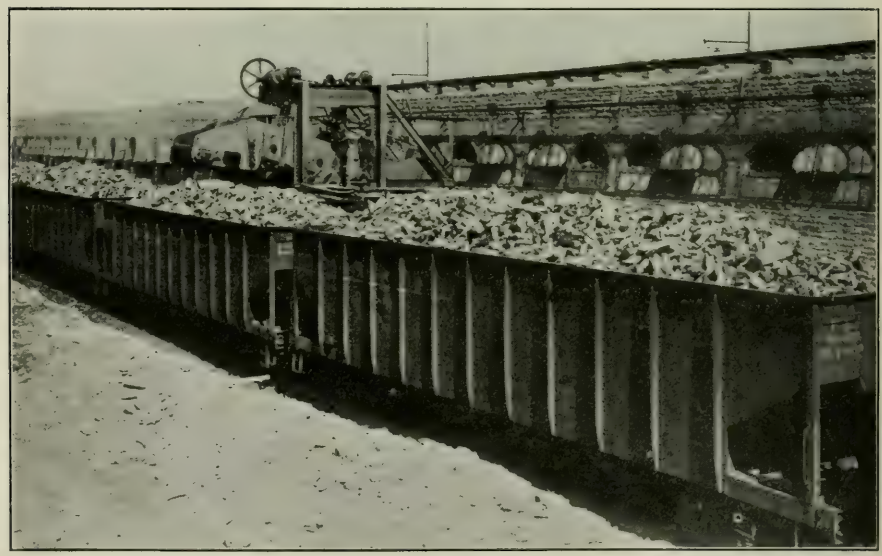


FIG. 50.—Welch oven.

of the latter is seriously curtailed when it is subjected to this continual pounding.

The Welch or rectangular oven is a modification in shape but not in principle; these ovens are in plan a long narrow rectangle with doors at

both ends and provided with an arched roof. This construction permits the charge of coke to be pushed out of them with less labor than is required for hand pulling. A battery of these with their discharging machine is shown by Fig. 50.

In starting the floor and walls of the oven are heated by maintaining a fire on the floor for several days. Then coal which will fill the oven to about 50 per cent. of its capacity is charged through the "eye" in the dome; and leveled off. The doorway has previously been built up with brick and clay almost to the spring of its arch which prevents the coal from running out. After the coal is leveled off, the rest of the door is built in the same manner, airtight except that two or three draft holes are left.

In a short time the heat of the oven begins to distil off the volatile matter which ignites and burns in the free space in the dome. This further heats up the coal and causes more volatile matter to distil off and burn in its turn. The whole mass becomes heated and fuses together in a plastic condition, its temperature being a dull red. The gas from the lower portion of the coal forces its way out through the plastic mass with the result that its structure is cellular to a high degree. Good cokes have a cell space of about 45 per cent. of their total volume.

As a result of the decreasing combustion when the gas evolution diminishes, the temperature begins to fall and the mass of coke develops vertical cracks.

The process is not finished until the volatile matter is reduced to 1 or 2 per cent. As the amount of volatile matter coming off diminishes by degrees, the supply of air through the draft holes is cut off so that, as nearly as possible, it may be only as much as is needed for the combustion of this gas, thus leaving no air free to attack the coke itself. The air supply is then shut off altogether and after a few hours a spray pipe is introduced through the top of the doorway and the surface of the coke thoroughly watered down. As little air as possible is admitted during this operation so as to prevent loss of coke by combustion. After the oven is watered down the brick door is removed and the coke pulled out with hooks, rakes and other appropriate tools on to the platform in front of the oven where the watering-down process is further carried on if any of the coke is hot enough to require it. This operation is well shown by Fig. 49.

As soon as possible after the oven is empty the brick door is reset and the oven charged again. This time the heat of the floor and walls of the oven is sufficient to ignite the coal in a short time without any preliminary firing. The process is then carried on continuously, charging and drawing as rapidly as possible, because after the oven gets too cold it will not ignite the incoming charge of coal, or if the charge becomes

ignited more of it has to be burned to waste to make up the heat lost by the oven by radiation while standing idle.

The work of drawing is laborious and very hot. For this reason oven pullers are among the most difficult of labor forces to keep in regular supply in an industrial organization. On account of the severity of the labor it is not customary to draw ovens on Sunday and this, with the necessity for having an oven charged immediately after drawing, necessitates two periods of burning. These are commonly 48 and 72 hr. This is regulated in large part by the size of the charge and in part by the supply of air admitted for combustion. The yield of coke in percentage of the coal charge is larger in good practice with 72-hr. coke than with 48 hr., but the yield of coke per oven per day is considerably smaller with 72-hr. than with 48-hr. coke.

The coke made in the two periods differs to some extent in its physical characteristics. Forty-eight-hour coke is considered harder and therefore more desirable for foundry purposes.

The operation of coke ovens on this plan is so simple that it can be done by almost anyone, but in order to get the best results much skill and careful oversight are required. It is not impossible by first class management alone to increase the normal 55 per cent. yield of coke from a given coal to 65 per cent. The matter of drafting is particularly important and a large percentage of the coke in the front of the oven may be burned up by improper draft.

It is considered by some coke-oven authorities very objectionable for all the air to be admitted at the relatively low elevation of the top of the doorway and all in one place because, owing to the slowness of mixing of the air with the volatile matter, as the latter distils, the air has an opportunity to attack the coke.

Owing to these considerations ovens have been built with an annular passage around the dome above the level of the doorway, this passage communicating with the oven proper by narrow radial slits in the brickwork around the circumference of the oven and communicating with the outside air through a draft door. There is little doubt that better results can be secured with this construction if proper attention be paid to it, but the annular passage is likely to become filled with dirt and the narrow ports stopped up. These are difficult to clean out and when this is neglected the oven is no better than the plain oven which costs rather less. With first-class supervision the annular air passage is probably a valuable feature, but where the operation of the ovens is left to careless and untrained men its benefit is short-lived.

The volatile matter which distils off from the coal contains a considerable quantity of tar and during the operation this breaks up at the surface of the mass of coke, presumably owing to the intensity of the radiation in that region, depositing fixed carbon of a beautiful silver-like luster on

the face of the coke. If the watering-down is done without admission of much air, this will be cooled below its ignition point before air reaches it and the coke when drawn from the oven will have the silver luster by which its quality has been so widely judged in the past and is even yet to a considerable extent.

By-product Ovens.—Even with the best practice there is considerable loss of fixed carbon in coking in bee-hive ovens. Moreover the coal contains valuable by-products, especially tar, ammonia, benzol, and toluol, which cannot be recovered with this oven in ordinary practice.

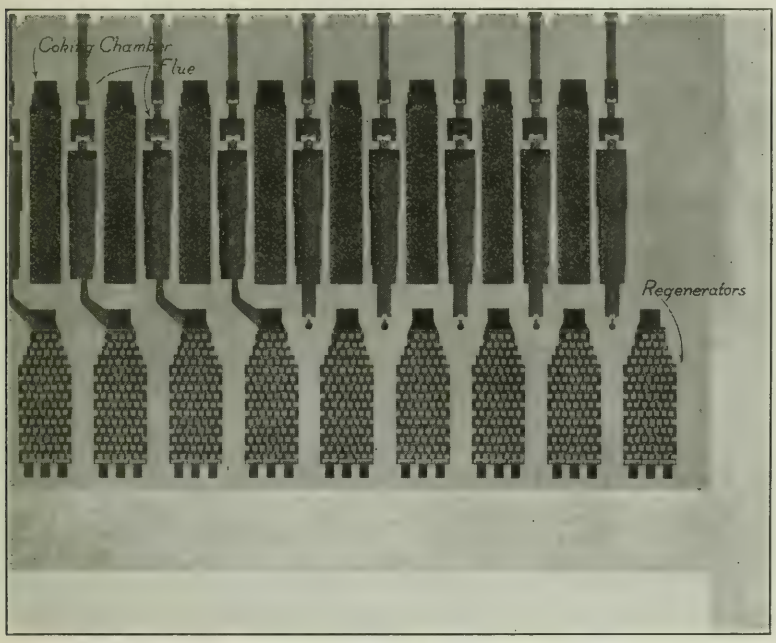


FIG. 51.—Koppers oven. Transverse section of ovens, heating chambers and regenerators.

Also, the heat value of the volatile matter is much in excess of that required for the coking operation. This is plainly indicated by the considerable flame rising from the "eye" of every oven in operation.

In the distillation of coal in gas retorts and its coking in coke ovens we have exactly the same fundamental operation carried on for two different purposes and for two different products. In the case of the retort the gas is the desired product, the ammonia and tar are recovered from it and sold. The coke is of little value.

In the bee-hive oven, on the other hand, the gas is distilled off from the coal much as in the retort, but the gas itself is thrown away or burned up, as are its valuable contents of by-product, the coke itself being the only product.

It was natural that in the course of industrial development attempts should be made to consolidate these two processes and to make simultaneously coke for metallurgical purposes and gas useful for heating and lighting, with the recovery of tar and ammonia. Such attempts began in Europe more than 50 years ago and owing to the greater cost of coal, with the lower cost of technical supervision and labor, the ovens resulting from these attempts have almost completely supplanted the bee-hive oven there. In America the opposite conditions prevailing, bee-hive coke still constitutes three-fourths of the total output, but the by-product oven is making rapid strides and it is only a question of time when it will have displaced the bee-hive oven as completely as it has done in Europe.

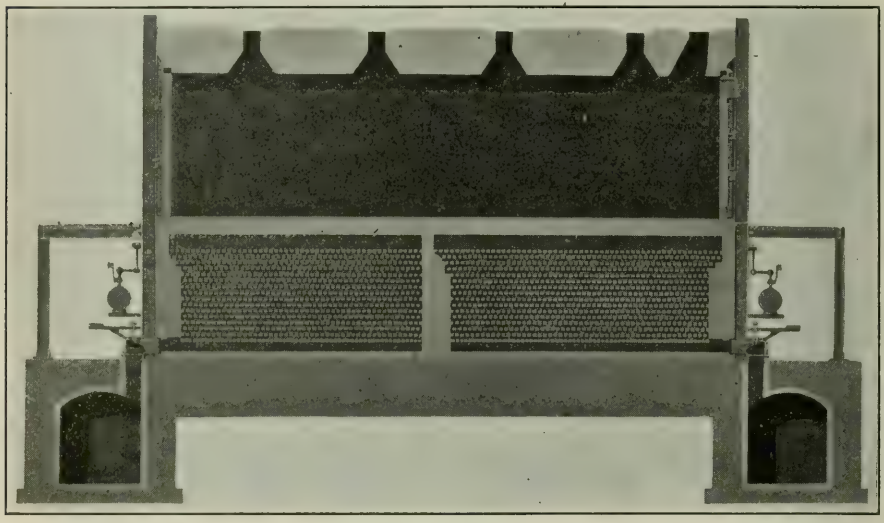


FIG. 52.—Koppers oven. Longitudinal section through coking chamber and regenerators showing air and gas flues at ends.

Since this was written late in 1913, the occurrence of the great war and the consequent shortage of chemicals which are produced from coke oven by-products, has accelerated the rate of building by-product ovens to an almost incredible extent, and the extinction of the bee-hive oven which appeared to be a matter of 20 years or more when this was written, may now be not much over 5 (January, 1917).

In its essentials the modern *by-product* or *retort oven* consists of a firebrick chamber about 18 in. wide, 9 to 11 ft. high and 35 to 40 ft. long, with flues on each side in which gas and air are burned. The ends are closed by metal doors lined with brick set against metal frames built into the brickwork of the oven. Instead of one opening for charging in the top there are three or more, and instead of the laborious operation of drawing by hand the finished charge is pushed out of the oven by a mechanically

actuated ram carrying on the front end a sort of rectangular piston of the same general shape as the oven, but somewhat smaller. This is so powerful that it forces the whole mass of coke out at the opposite end of the oven. There it is caught in a suitable grating or rack, and quenched with a heavy shower of water as quickly as possible. But no matter how quickly this may be done it has had access to the air and enough combustion results to destroy the silver luster characteristic of good bee-hive coke. This makes the coke look black and lusterless. For this reason furnacemen in the past have frequently been prejudiced against it and in fact it was a matter of years before the builders of by-product ovens were able to produce coke of metallurgical quality equal to the best bee-hive. But that point has now undoubtedly been reached.

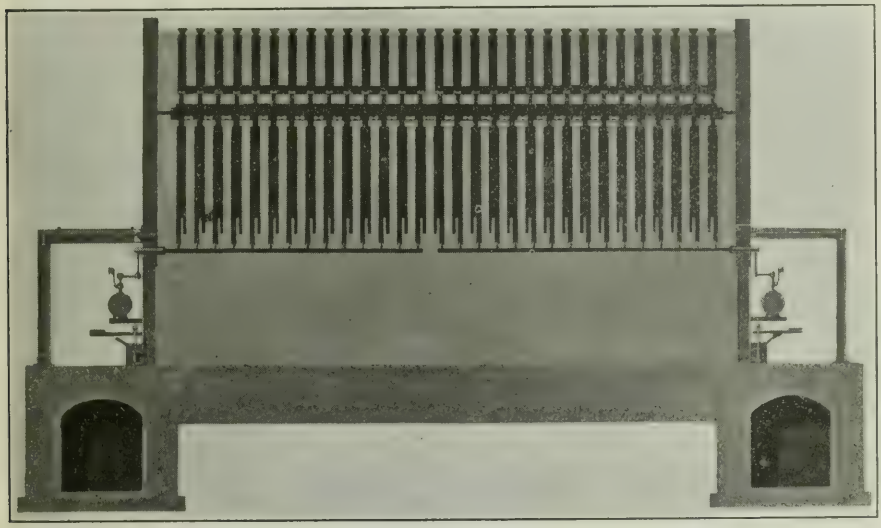


FIG. 53.—Koppers oven. Longitudinal section through heating chambers and regenerator wall.

By-product ovens are built in long batteries parallel to one another and separated only by the air and gas flues on each side. The modified "larry" for delivering the coal to them runs overhead as in the bee-hive oven, but in handling the gas a vast difference exists. No air whatever is admitted to the ovens, the greatest pains being taken to preserve them absolutely air-tight. The gas is taken off through pipes which deliver to a common gas main, and all the gas is sent to a central purification plant where the tar and ammonia are removed and a portion of the gas is then returned to supply the heat needed for the coking process. The rest of the gas is available for either city lighting or industrial purposes.

In order to maintain the high temperature necessary to force the heat for coking through the firebrick walls of the ovens regenerators are com-

monly used to preheat the air for combustion and where regenerators are not used recuperators are substituted for them. The results obtained with these latter are not so economical of gas as those obtainable with the regenerators and the best practice tends more and more strongly to the use of the regenerator oven.

These regenerators are commonly built as the substructure of the oven itself. Sometimes each oven has its own separate regenerator, and in other cases the regenerators are common to a whole battery of ovens.

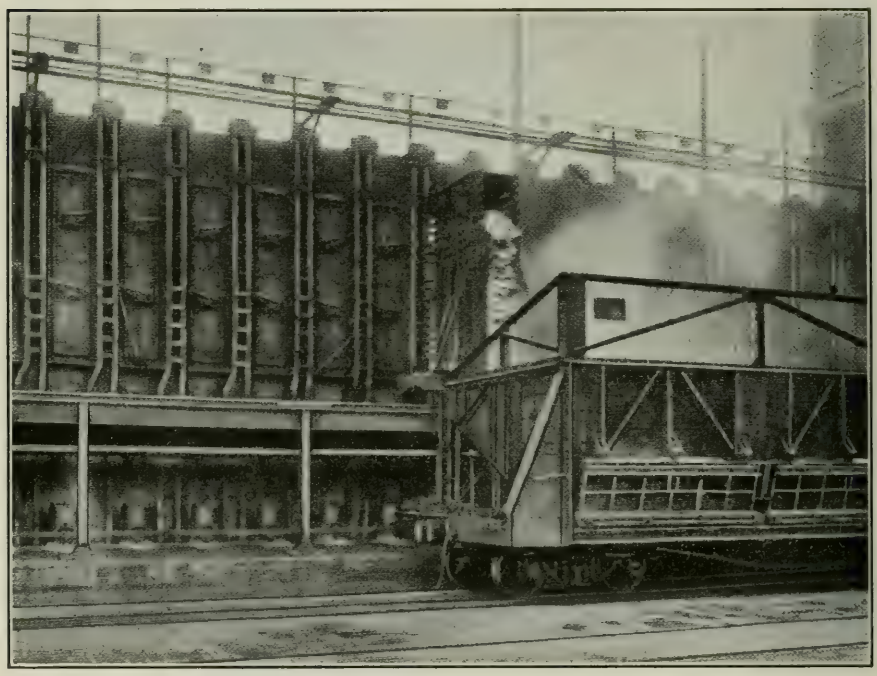


Fig. 54.—Koppers ovens. Coke side and quenching car.

The first two types of ovens to achieve commercial success in America were the Semet-Solvay and the Otto-Hoffman. The former design uses horizontal flues, the latter vertical. In more recent years the Koppers oven or ovens of which it is the prototype have taken the lead over the other two. These have vertical flues like the Otto-Hoffman oven of an earlier date, which they have largely replaced. Through the courtesy of the Koppers company, I reproduce here some of their drawings and photographs, Figs. 51 to 57, which show the construction and general appearance of their ovens very clearly. The ovens of the other builders differ in important details, the effort made in all cases being to secure control of the heating in the different sections of the oven.

The yield of coke with the by-product oven is always higher than

with the bee-hive. In fact the quantity of fixed carbon in the coke is greater in good practice than the fixed carbon in the original coal.

This apparent paradox comes from the fact that during the coking operation the tar and volatile matter of the coal are broken up by heat as described for the bee-hive oven, but to a greater extent due to the much higher temperature, while unlike the bee-hive the by-product oven does not permit the combustion of any appreciable fraction of the coke produced. The consequence is that the fixed carbon of the coal is augmented by the fixed carbon resulting from the breaking up of the bituminous matter without any loss through combustion.

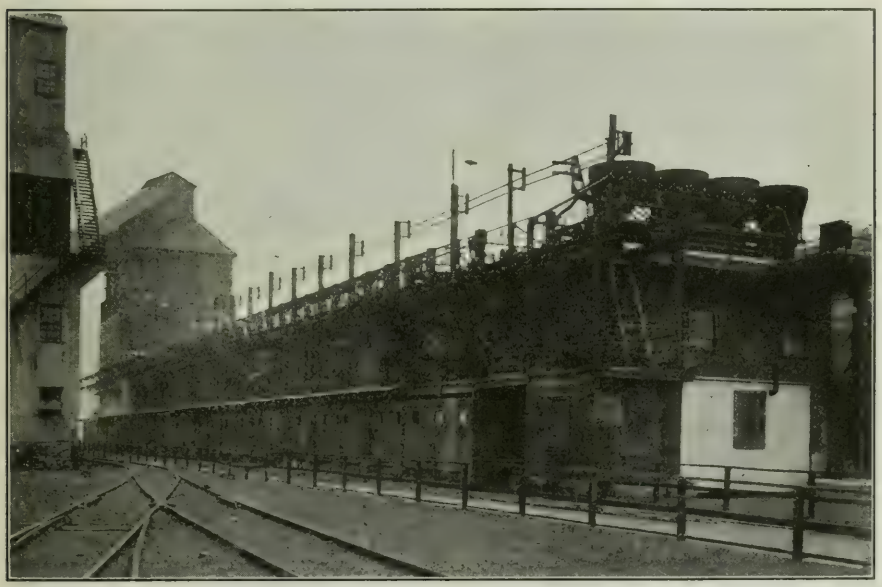


FIG. 55.—Battery of Koppers ovens.

A wider range of coals can be successfully coked in the by-product oven than in the bee-hive, though, on the other hand, some coals that can be successfully coked in the bee-hive oven swell to such a vast extent during the distillation of their volatile matter that it is impossible to push them from the by-product oven. These, however, are few in number.

Much attention has been paid to the best percentage of volatile matter for coking purposes in by-product ovens and its line of commercial development has been very different from that of the bee-hive oven. The latter has very generally been built as close to the mouth of the coal mine as possible with the object of avoiding transportation charges on the volatile portions of the coal to the point of consumption, and, as the yield from such ovens is relatively small, this is an important consideration.

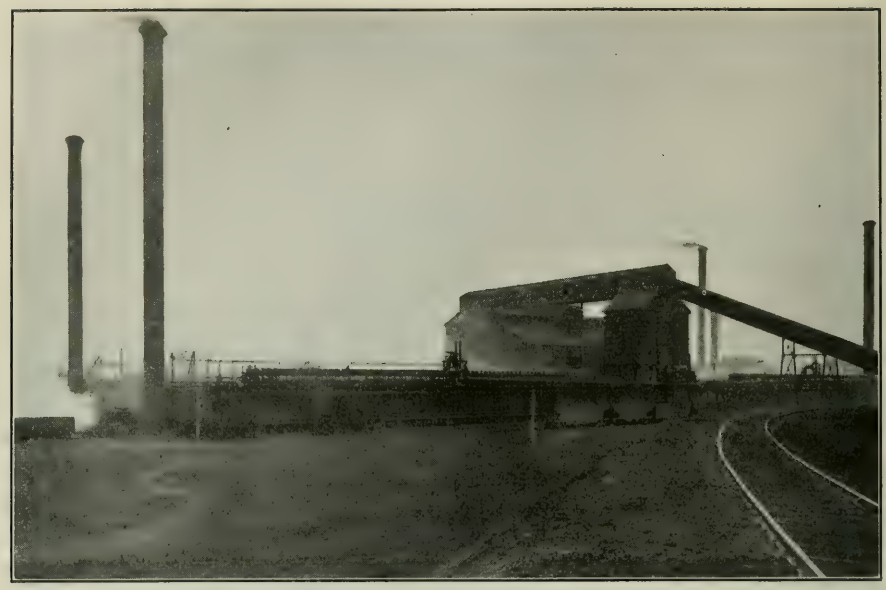


FIG. 56.—Battery of Koppers ovens from a distance.



FIG. 57.—Koppers ovens showing coke wharf in foreground.

With the by-product oven, on the other hand, the yield of coke is very much larger, so the loss in freight is less and moreover the gas is of great value, as above mentioned. In addition to this the by-product oven will do its best work on coal of a certain content of volatile matter approximately 25 per cent. This is naturally not always found in nature, as the volatile matter in coking coal covers a wide range. It is only from 18 to 20 per cent. in the excellent coals of the New River and Pocahontas field and as high as 40 per cent. in some other coals. The coal of the Connelsville district contains from 27 to 30 per cent.

In order to secure the advantage of coal the nearest possible to the exact composition desired, recourse is often had to mixtures of different varieties of coals. Mixtures of two are common and mixtures of three or more are sometimes used. Such mixtures enable the best results to be obtained in yield and quality of coke, in quantity of gas and reduction of coking time.

The advantage of making mixtures operates in the same direction as the value of the gas and the yield of coke in making it very desirable to place the ovens at the point of consumption of the coke rather than at the mouth of the mine. These considerations are so powerful that by-product ovens are almost always so located.

COKE AS FURNACE FUEL

Coke has many of the most desirable characteristics for a blast-furnace fuel. Well-made coke from good coals is always in large lumps, thereby supplying one of the fundamental requirements of a blast-furnace fuel. It has sufficient strength to resist breaking during the necessary handling which it undergoes while it is being charged, and during its descent through the furnace. It has a highly cellular structure which exposes the largest possible amount of surface per unit of weight. Consequently a very large amount of coke may be burned in a given area per unit of time, one of the necessities for rapid operation and high output of furnace.

The tarry constituents in the volatile matter of the original coal are completely destroyed by the coking operation, and there is, therefore, no tar to fill up the interstices in the charges and cut off the passage of the gases of combustion.

The worst objection to coke as a furnace fuel is its sulphur content. This varies from 0.4 per cent. in the very best coke up 2 per cent. or more in inferior cokes. But when this limit is much exceeded the fuel ceases to be suitable for the blast-furnace no matter how desirable it may be in other respects. In ordinary good cokes the sulphur varies from 0.8 to 1.5 per cent.

The second objection is its content of ash derived from the original coal; this varies from about 6 per cent. in extraordinarily pure cokes to

18 or 20 per cent. in poorer ones. Ordinary furnace fuels range in ash from 8 to 12 per cent.

Phosphorus is ordinarily low, generally under 0.05 per cent., but its amount is important because it all goes into the iron and 0.03 per cent. is the maximum amount allowed in some special grades of iron. As some phosphorus is always present in the ore and some in the flux the amount in the coke is of great importance in such cases.

The sulphur can be removed in the blast furnace to a very large extent by proper use of fluxes, but the melting of the slag resulting from the use of these fluxes requires more coke and therefore increases the cost of iron made from high-sulphur fuel. Similarly the ash which generally consists in large part of silica has to be fluxed and this is objectionable for the same reason.

It is, of course, obvious that the more ash the less fixed carbon and the fixed carbon is the only useful component of the coke. This ranges from 80 to 95 per cent., but good furnace cokes ordinarily contain from 85 to 90 per cent. of fixed carbon.

One of the most important characteristics of coke is its resistance to solution. If the coke be "soft," an excessive proportion of it is dissolved by the CO_2 in the ascending current of gas and never reaches the hearth. This causes the disastrous loss of both hearth and shaft heat described in "Thermal Principles."

It is very probable that the stress laid on physical strength in the past has been excessive. Very ordinary coke withstands crushing stresses of several hundred pounds per square inch without difficulty, while we have seen in "Mechanical Principles" that the pressure of the stock column never exceeds 35 or 40 lb. per square inch.

It is almost certain in my mind that ordinarily good coke never crushes in the furnace in spite of the abundance of discussions we have of the "coke crushing under the burden."

It seems to me much more probable that as coke becomes stronger and therefore harder, its resistance to solution rises. Solution is almost certainly higher with high pressures than with low and therefore soft cokes dissolve worse in large furnaces using heavy pressures. Hard coke resists this tendency much better and is therefore better for such furnaces, but the reason for its superiority is not its physical strength but its resistance to solution.

The clearest and most rational discussion that I know of coke in relation to the blast furnace was delivered by H. A. Brassert of South Chicago before a private meeting of furnacemen in 1914, and which through his kindness I am permitted to quote in full below. Mr. Brassert has probably had the best opportunity of any man in the United States to work out the complex relation between the manufacture and characteristics of coke and its behavior in the blast furnace, because

some of the most important developments of by-product coke ovens were made at plants which supplied some of the furnaces under his management with coke and a vast amount of experimental work was done in which Mr. Brassert had a highly important part.

NOTES ON BLAST-FURNACE COKE WITH PARTICULAR REFERENCE TO COMBUSTIBILITY

By Hermann A. Brassert

In the paper on "Modern American Blast-Furnace Practice" which I read before the American Iron and Steel Institute last May, I drew attention to certain physical properties of coke which vitally affect the furnace practice, and therefore concern alike the coke producer and the blast-furnace man.

Fifteen or 20 years ago, when most of the American furnaces smelting Lake ores were using the standard grades of Connellsville, the coke was easily the most stable of all the elements entering the blast furnace. The only variables that were noticeable were the ash and dust contents, and these were kept well within bounds. In those days there was therefore not much opportunity to study the influence of different kinds of coke on the blast-furnace process. Later, however, the coke field expanded, and coals from adjoining and distant fields were coked, some of the latter differing considerably in coking qualities. A great demand for the coke also led to shortening the coking period, and it was soon found that a variation of the coking time altered the product. It was then that we began to realize that variations in the physical qualities of the coke seriously influence the blast-furnace practice. This has been brought out still more clearly since we began to manufacture coke in by-product ovens, from widely varying coal mixtures and under many different operating conditions.

It stands to reason that the coke is a more potent factor in affecting the blast-furnace process than the other elements entering therein. Ore and stone together usually represent but one-half of the bulk of the coke charge in the furnace burden; the density of the stock column is therefore much more influenced by variations of the coke size than by those of ore and stone. Where Lake ores are used, the ores are very uniform and maintain the same reducibility year in and year out. Variations in analysis are also generally kept well under control. Even where magnetites are used, the same mixture is adhered to and violent changes from the proven burden are carefully avoided. The limestone, too, has been improved in regard to its physical and chemical uniformity. Each plant ordinarily uses a certain kind of stone of constant refractoriness.

The coke, on the other hand, still subject to the same variations in analysis which occur in ores and limestone, and which influence the basicity of the slag, is further liable to fluctuations in carbon content, and besides, to physical variations of such a nature as will completely change its combustion qualities and directly affect the heat balance of the furnace.

Since we rely upon the coke to obtain the necessary heat to carry through the entire process of reducing and melting the ores, if there is any variation in its carbon content or combustion properties, the whole process becomes upset. The usual changes in the ore burden cannot influence the furnace in such a crucial way;

and only a complete change from hematites, for instance, to magnetites could so radically affect the working of the furnace.

As indicated above, the value of the coke in relation to the heat reactions in the furnace is determined not only by its carbon content, but even more so by its combustibility. This in turn is governed by its size, the physical and chemical composition of the carbonaceous substance forming the cell walls, and the interior and surface structure of the coke pieces. These properties are in turn influenced by the chemical and physical properties of the coals used for coking, the density of the cake of coal in the oven, by the coking time, temperature and heat regulation of the ovens, and last, but not least, by the method of quenching, screening and handling of the finished coke.

From a chemical standpoint, coke must be considered as a combination of amorphous and graphitic carbon, intimately mixed with some mineral matter or ash, and containing a small and varying per cent. of volatile. Although for other purposes the inflammability of coke is of importance, what principally concerns the blast furnace is the rate of progression of the combustion, which depends not so much upon the chemical analysis as on the physical qualities of the coke. It is this rate of progression that we term combustibility, which is the speed at which the carbon molecules in the coke combine with oxygen under given conditions. In general, what the blast furnace requires is a coke which will burn rapidly and with intensity at the tuyeres, yet which has a sufficiently strong structure and hard surface to resist abrasion and solution by CO_2 in the upper part of the stack.

When the coke is not sufficiently combustible, the combustion at the tuyeres takes place slowly and consequently extends too high in the furnace, being carried up into regions where the reduction of the ores by the gases has not been finished; thus the ratio of "direct" reduction by carbon to "indirect" reduction by the gases is increased, and large heat losses and high top temperatures[1] are the result. Owing to the slower combustion, the charges do not shrink rapidly enough in the restricted area of the hearth and bosh to permit a fast movement of the furnace charges, and the blast pressures increase, augmenting the air losses through leakage and retarding the action in the furnace. With the lower temperatures in the hearth, the burden is not properly melted and clogs the melting zone, again slowing up the furnace movement. With Mesaba ores, periods of "hanging" are liable to follow, which further disturb the equilibrium of the process. In order to accelerate the combustion when such slow-burning coke is used, it is often necessary to blow more wind and carry high pressures, and if possible, higher blast temperatures.

On the other hand, coke of good combustibility burns rapidly at the tuyeres; each oxygen molecule finds its carbon molecule in or near the tuyere zone, and an intense hearth temperature results, the heat of combustion being concentrated in a comparatively small area. The temperature diminishes rapidly toward the top of the furnace as the ascending gases meet the descending heavy ore charges. Low top temperatures and a maximum ratio of "indirect" to "direct" reduction is the result, and the process becomes highly economical.

However, coke which burns rapidly is also more liable to be attacked by CO_2,

[1] Mr. Brassert is as we have seen in error regarding the effect of solution loss on top temperature.—J. E. J., Jr.

and too large a portion of it may be consumed by the gases in the upper part of the furnace. This robs the hearth of just that much coke and increases the volume of top gases without benefiting the melting process. Unless the ore burden is reduced, the hearth temperature falls below the point where the proper reactions of the hearth can take place, and off-grade iron is the result.

For blast-furnace use, therefore, a coke must be produced which will burn rapidly at the tuyeres and yet not be too vulnerable to the gases. A coke with a well-developed cell structure that is porous and of light weight, but with hard cell walls and surfaces, will give the best results. Such a coke will offer more carbon surface, per unit of weight, to the oxygen of the blast than a denser, heavier coke, and since the rate at which carbon molecules are burnt to CO determines the rate of production of heat as well as of the molten products, it is evident that the lighter, more combustible coke has the greater furnace value. The foundryman, on the other hand, for cupola practice demands a dense, heavy coke which favors the combustion to CO_2 by offering less carbon surface to the wind.

The quality of the coke which the furnaceman desires varies somewhat according to the size of his furnace and his operating conditions. The smaller the furnace, and the lighter the blast pressures, the more combustible a coke he must have, and he can also use a more porous, softer coke, since his coke is exposed to less abrasion. With a large furnace, and higher blast volumes and pressures, on the other hand, a less combustible coke can be made to burn faster; and on account of the coke being more subjected to breakage and abrasion, and thereby more susceptible to solution in CO_2, large furnaces demand a coke of stronger structure and harder surface. When making grades of iron necessitating an extension of the melting zone further up in the furnace and higher stack temperatures, the zone where the coke is attacked by CO_2 is lengthened, and soft, very combustible cokes are therefore not desirable when running on foundry iron. Furthermore, the concentration of heat in a narrow zone at the tuyeres, with a fast-burning coke, militates against the reduction of silicon, which has to be accomplished by solid carbon at high temperatures, and requires time. The quality of the ores and the method of furnace operation also should be considered in the choice of coke. Easily reduced ores and fast driving demand a fast-burning coke; refractory ores and slow driving, a slow-burning coke.

As stated before, the combustibility of the coke is affected by different properties, such as its size, the physical and chemical condition of the cell-wall substance and the interior and surface cell structure of the coke pieces. Not one of these qualities by itself is a true indicator of the furnace value of the coke. For instance, a coke of good porosity might be less combustible than a denser coke, if the cell walls themselves were more refractory; and it is a well-known fact that by decreasing the size of the pieces, the coke mass can be made to burn much faster, for the reason that the total surface exposed to the blast is very much increased. Again there is a difference as far as the size is concerned, whether the coke was rendered small in the oven or outside of the oven by breakage, as I will explain later.

The kind of coal used exerts the biggest influence of all. It is a very difficult matter to make combustible coke out of a coal which tends the other way, and always the easiest and most effective means of changing the combustibility of the coke is to substitute more suitable coals in the mixture.

There exists no fixed rule governing the quality of coke resulting from different coals. A great many coals of widely varying nature have the ability to cake or fuse upon being heated to a certain temperature. With the fusion a decomposition of the chemical compounds forming the coal takes place under evolution of volatile gases, leaving a solid residue consisting of carbon and ash. Many coals possess this "coking" property, and through all the various degrees, from mere sintering to being capable of complete fusion. Some coals expand more, some less, others not at all, during this process of distillation, depending on their fluidity, as well as their fusibility, that is, whether the coal becomes liquid or only plastic, and whether it changes from the solid to the liquid state rapidly or slowly. Coals which are difficult to fuse and do not go beyond their plastic state, do not release the gases as readily as those which fuse quickly and become very liquid. The gases, therefore, inflate the pores and the cake of coal becomes much swollen before the pores burst and release the gases. In case the fusing coal mass remains more viscous the walls of the cavities are heavy and do not collapse after the gases are expelled; if, however, it becomes more fluid, the gas bubbles quickly explode, the cake does not rise appreciably, and collapses readily after the evolution of gases has stopped. These conditions are in part responsible for the fact that with most coals a lower coking temperature tends to increase the size of the pores, whereas a high temperature, through more completely liquefying the coal charge, allows the gases to escape more easily, leaving smaller cavities and a denser coke. In the bee-hive oven, where the coal is allowed free play to rise, an expanding coal will produce a more open cell structure than in a by-product oven where the coal is confined.

This property of expanding, although having its share in forming the original cells, does not determine the final cell structure, since the pores created during the distillation process are again filled more or less with deposited carbon. While there is no fixed relation between the quality of expanding and the percentage of volatile matter in coals, still the latter and its composition influence the coke structure to a large extent. Coals which are either very high or very low in hydrogen and oxygen do not fuse at all, whereas the good coking coals are found in between or with a volatile content of from 16 to 40 per cent. Among these the higher-volatile coals produce the more porous, faster-burning coke. As a rule these are geologically younger, and it is generally correct to state that the more recent coal deposits produce the lighter, more combustible coke. There are, however, exceptions to these rules, because other matters influence the coking quality of coals, as for instance, the thickness and the composition of the overlying strata of rocks protecting the coal against outside influences and subjecting it to different pressures and temperatures.

A varying ash content, as well as the chemical composition of the ash, has an effect on the hardness and the combustibility of the coke. Coals which are chemically and geologically alike can still differ in coking, due to the nature of their carbonaceous and volatile matter, and their peculiar action under destructive distillation. We do not know but what the carbon in different coals may have a different molecular structure. Coals of equal analysis are influenced differently by weathering. The study of coking qualities of coals is a very intricate one and deals with a subject containing many unknown quantities. Even with known coking qualities of individual coals, the results from percentages in a mixture can-

not be exactly predetermined. As a matter of fact, the question of suitable coal mixtures to produce a coke of certain quality is one that can only be solved by a large amount of experimentation under actual operating conditions.

We do know, however, that the by-product oven has made an immense amount of coals available for coking which previously were considered non-coking coals. That is in part due to the mechanical effect of having the cake of coal confined between the two oven walls in the by-product ovens, whereas in the bee-hive oven the coal lies loosely, allowing the cell structure to become fully developed through free expansion. The Pocahontas coal, for instance, which is an expanding coal, when coked in bee-hive ovens makes a soft coke of very open cell structure and of rather too rapid a combustibility, whereas in the by-product oven, it produces a hard, dense, slow-burning coke. Poor coking coals, which in the bee-hive oven cannot be made to bond, assume a fairly strong structure in the by-product oven. By compressing the cake of coal before charging it into the oven, non-coking coals can be made into suitable blast-furnace coke. The oven operator has many means at his command to alter and improve his product. Coarser or finer grinding, wetting of the coal, dimensioning of the ovens, method of applying the heat, all have their influence on the coke structure.

In order to better understand the causes in oven operation influencing the structure and combustibility of by-product coke, let us contemplate in a general way what goes on in the oven after the raw coal has been charged. The heat accumulated in the oven walls by burning gas in the combustion flues is conducted from the walls into the coal, heating first the layer next to the oven wall. The zone of heating and distillation progresses from the wall towards the center of the oven in two lateral planes, parallel to the oven walls, which finally meet at the center of the oven. Along these advancing planes the mass of coal has become plastic, and the volatiles distil out, escaping toward the oven walls through the lines of fracture formed by the shrinkage in the coke mass.

It is these shrinkage lines that determine the contour of the coke pieces. On the cauliflower ends next to the wall where the temperature is the highest, the gases decompose and deposit carbon or graphite, closing the cells, and forming a hard, dense surface. The same deposition takes place along the shrinkage lines, and a more or less denser surface structure forms around every coke piece except of the soft end next to the oven center, which, being coked last, retains its cells as originally developed during the distillation. The longer the coking is carried on, and the higher the local temperature is allowed to rise, the more cells are filled with carbon deposit and the farther in the denser surface structure reaches. When the temperatures are very high and the nature of the distilling products favor the formation of graphite a silvery coating of graphite may cover and completely seal the coke surface. Such a coating is called a skin, and quite generally occurs with bee-hive coke made from Connelsville and Klondike coals. While a thick layer of dense structure greatly retards the combustibility, the silvery skin, probably on account of its thinness, seems to have no deleterious effect on the speed of combustion at the tuyeres. Yet it evidently protects the coke against solution by CO_2, the same as the denser surface layer on by-product coke.

It will now be readily understood why the breaking of the coke, after it leaves the oven, increases the combustibility far more than producing a smaller coke in the oven. The former exposes the soft interior cell structure, whereas the latter

merely increases the outer surface exposed to the blast, but this surface is dense and less combustible.

When the volatile has all been driven off there is naturally a rapid increase of temperature, as no more heat is used up in the process of distillation, but more is continually being added from the oven walls. By prolonging the coking period beyond the proper time, in other words, by over-coking the charge of coal, the coke continues to shrink, it breaks up into smaller brittle pieces, the cells shrivel up, and the thickness of the denser surface structure is increased; in short, the coke is rendered less combustible. On the other hand, by under-coking, the surface remains more porous, and the average porosity of the coke also remains greater; the cell walls are thinner, thus weakening the coke and making it more friable. Over-coking occurs with a short as well as with a long coking period. In fact, over-coking is more liable to be a serious factor with a short coking time since the same number of minutes of prolonging the period has a greater relative influence.

By coking the same coal mixture at a higher temperature, which means on a shorter coking time, the evolution of gas becomes more rapid, the lines of fracture multiply, and a smaller coke is produced with harder surfaces and more brittle. On the other hand, by decreasing the temperature and increasing the coking time, the cell structure becomes more fully developed and there is less carbon deposition, and the coke pieces then become softer and larger.

Since both temperature and coking time have an influence on size, cell structure, and surface hardness of the coke, and since different coals behave differently under the same treatment, it is most important for the coke-oven operator to determine for his particular coal mixture by careful experimentation which coking time and temperature produce the most suitable coke for the blast furnace.

As the speed of coking varies with the temperature, it is most important to carry the oven walls at a uniform temperature all over. To quote from my paper on "Modern American Blast-Furnace Practice," read before the American Iron and Steel Institute in May, 1914:

> "The proper remedy is the manufacture of a coke with suitable and uniform combustibility. This is achieved, not only by using the proper coal mixture and coking time, but primarily by careful heat distribution in the oven, avoiding over-coking part of the coal charge, which destroys the combustibility; and under-coking of other parts, which makes a product too soft and vulnerable to CO_2. The coking must be finished simultaneously at all parts of the cake of coal, which at that moment must be pushed and quenched without delay."

Of considerable influence on the quality of the resulting coke, from a blast-furnace standpoint, is the method employed in quenching. When the coke is quenched with a comparatively small stream of water requiring a long period of time, the pores fill with water gradually and the coke becomes soaked to the core, the cells retaining a quantity of water. Such coke is poorly suited for use in the blast furnace. To quench correctly, a large amount of water must be applied over a short period of time, so that the heat retained in the center of the coke pieces is sufficient to drive out the water remaining near the surface. The ideal method would appear to be dipping the cake of coke into water and quickly withdrawing it. To obtain the desired result by spraying is not an easy matter, on account of the different thicknesses of the layer of coke on the ordinary quenching car or on the bench.

Improper quenching results in irregular and high moisture contents of the coke and seems to do a great amount of damage in the furnace. The exact action that takes place has never been definitely ascertained. Whether the coke itself undergoes a change, or whether the moisture leads to unfavorable reactions in the furnace, is still a disputed question. It has been suggested that the heat which remains in the center of the coke and drives the moisture out leaves the cells in a more open condition, rendering the coke more combustible. But I believe that the cell structure as formed in the oven cannot be altered in quenching. It is possible that some chemical change takes place on the cell-wall surfaces through the dissociation of water in the interior of the coke pieces, and that this differs when sufficient heat remains in the center, compared to when the entire cell mass is soaked through and completely chilled. The appearance of properly quenched coke compared to that of improperly quenched coke seems to corroborate the theory of some chemical reaction having taken place during the process of quenching.

I believe, however, that the main reason for the different action in the furnace of properly against improperly quenched coke is to be found in the reactions of the moisture in the furnace itself. We know from our laboratory experience that it is very difficult to thoroughly penetrate a piece of coke with water. That the hot coke is able to take up high percentages of water in the short quenching period is easily explained by the fact that in cooling down the gases contract, thus sucking the water into the innermost cells. It is equally difficult to expel every molecule of water from coke, and over-quenched coke charged into the furnace must retain its moisture until the coke gets into fairly hot zones. When this moisture is driven out of the interior of the coke pieces, it is heated to a point where in the presence of so much red-hot carbon it is instantly dissociated. That this takes place we know from the increased hydrogen in the gases when using over-quenched coke. The nascent oxygen, just liberated, eagerly combines with carbon to CO or CO_2, depending on the local temperature, and increases the volume of top gases. This may explain why with improper quenching the top gases of the furnace look rich and abundant, indicating a hot furnace, while the furnace actually works with a cold hearth and makes off-grade iron. Undoubtedly the sudden liberation of these gases from the coke cells is accompanied by more or less breaking of the coke pieces, which thereby become more vulnerable to CO_2. The reaction of CO_2 on carbon, being endothermic, tends to lower the top temperature, but increases the volume of gases. But the carbon thus consumed is lost to the hearth, and the furnace shows a heavier coke consumption.

The fact that wetting the coke in the skip has no influence on the action of the coke in the furnace is no argument against this theory, for the reason that water applied to the surface of cold coke does not penetrate the cells and therefore has no chance to descend far enough into the furnace to be dissociated, but is driven off near the top as steam, without injuring the coke.

Next to proper quenching, the method of screening and handling the coke enhances its value for blast furnace use. The size of the coke should be within certain limits, determined by experience for each kind of coke and for the existing furnace conditions. Having established the best size, it should be kept uniform. The combustibility of coke is greatly altered by a change in size, and uniform blast-furnace results cannot be expected with coke varying from day to day in size.

The deleterious effects of coke fines in the furnace are too well known to be dwelt upon here. After the coke is screened it should be protected as much as possible against further breakage on its way to the furnace top.

The greatest difficulty which confronts the producer as well as the user of coke, is the lack, not only of a thorough knowledge and understanding of the kind of coke needed to best suit existing furnace conditions, but of practical coke tests which might reveal those physical qualities of the coke which are vital to the furnace practice. It has been said that such tests are not needed because the furnace itself tells the tale. This is not always the case; for instance, a furnace which has been running on a "limey" slag and has become built up on the walls, causing high pressure, will not do justice to the best of cokes. In fact, the appearance at the tuyeres might indicate that a slow-burning coke was used, whereas the fault would lay entirely with the condition of the furnace.

When judging the combustibility of the coke by its appearance at the tuyeres and the working of the furnace, and in order to secure reliable information, it is essential that the coke to be tested is tried out on a clean, normally working furnace. Such tests must be conducted over sufficient periods of time so that any irregularities, such as are bound to occur, will be minimized and averaged. To secure data on the value of coke by furnace tests is at best a tedious and expensive task, and it would, indeed, be of the greatest assistance if a practical laboratory test were devised which would correctly determine the combustibility of coke.

Any effort along these lines should be encouraged as being perhaps instrumental in solving some of the most important and perplexing problems concerning the manufacture as well as the economical use of by-product coke today.

CHARCOAL

It is an interesting fact that the development of the manufacture of charcoal has been along a similar line to that of coke, there being three principal methods: pits or meillers, bee-hive-shaped ovens (ordinarily called kilns when used for charcoal), and retorts. There is no equivalent in the case of wood for the process in which distillation is performed for gas only and the resulting charcoal practically disregarded, as in the case of coal.

Charcoal is in general made from cord-wood, trunks and limbs of trees cut 4 ft. long, and in good practice when more than 10 in. in diameter, split down to a size equivalent to an 8-in. stick. There are two general classes of woods recognized in charcoal manufacture known as "hard" and "soft." The principal hard woods are hickory, hard maple, beech, yellow birch and several varieties of oak, while the soft woods embrace principally the resinous woods, very commonly the yellow pine and allied species.

The production of soft-wood charcoal is smaller and less important than that of hard-wood charcoal and the value of the coal produced therefrom is less for furnace purposes, it being lighter and softer.

Pits.—In the production of charcoal by this method a space about 30 ft. in diameter is leveled off on the ground and on this wood is stacked up on end in the form of a truncated cone two lengths, or 8 ft. high, leaving a chimney through the center. The entire structure is then covered with earth and leaves and fired at the bottom of the chimney. A supply of air is admitted insufficient for complete combustion. The volatile matter is distilled off and burns, supplying the heat to keep the operation going. This continues for a week or 10 days, when the wood is all charred and the process completed except the cooling off of the charcoal by standing covered.

There is, of course, some loss of charcoal through excessive air supply and as a result the yield of charcoal per cord of wood in this process is poor, nor is there any recovery of by-products. As a consequence of these disadvantages this process has gone out of use almost completely.

Kilns.—These constitute the next step in the development of charcoal production. They are built of red brick because only low temperatures are needed for the charring of wood and are very much larger than coke ovens, about 30 ft. in diameter at the bottom tapering to about 24 ft. at a height of 18 to 20 ft., the whole covered with a flat dome rising about 6 ft. further. They are provided with three rows of draft holes at regular intervals, one immediately at the bottom, one about 3 ft. higher, and the third about 3 ft. above the second. An opening about 5 ft. square, through one side of the dome, is provided through which they are charged, and a door about 5 ft. wide and 6 ft. high at the bottom through which the charcoal is removed, also an opening at the bottom on one side which communicates through a short chimney with a smoke main. They are also provided with a small hole about 1 ft. in diameter in the center of the dome.

These kilns are filled with wood to the top, the wood being piled as uniformly and smoothly as possible with a stack up through the center. Fire is started at the base of the stack and the large top and side openings are then closed with steel plate doors and luted air-tight. The fire is permitted to burn very slowly for a few hours with natural draft through the hole in the top of the dome. This opening is then closed and the kiln is connected with the smoke main, on which suction is maintained by a system of fans. The draft is carefully regulated, the bottom row of holes being used first and the higher ones later in the operation. At the end of about 10 days most of the volatile matter is distilled off, then the kiln is disconnected from the main, the draft holes are sealed up air-tight and the kiln is allowed to stand for a period of 10 to 20 days in order to cool the charcoal well below the ignition point.

Charcoal is extremely inflammable. It ignites spontaneously even at atmospheric temperature under certain conditions, presumably on

account of its very great power of absorbing gases; the action would seem to be not unlike that of spongy platinum in igniting hydrogen.

The situation is further complicated by the fact that the use of water to extinguish fires in this fuel is highly objectionable. Charcoal absorbs vast quantities of water which appear not to be driven off except at a very high temperature so that the charcoal seems to descend almost to the hearth of the furnace still containing water and the effect of such water is exactly the same as if introduced at the tuyeres. On these accounts charcoal must be cooled with great thoroughness before exposure to the air.

After the coal has been properly cooled the door and charging hole are opened and the buggies which are to deliver the charcoal to the furnace are taken into the kiln and there loaded.

The shrinkage during the charring operation is very great, about 50 per cent., so that while the kilns are entirely filled with wood they are only about half full of charcoal when opened.

The smoke drawn off through the mains by the fans as above described is subjected to cooling and scrubbing whereby its volatile constituents are removed and recovered, but in a very dilute condition because of the great quantity of water vapor in the smoke which comes from the water of the wood, because even thoroughly seasoned wood contains about 50 per cent. water. Of the other 50 per cent. about one-half is charcoal and one-half volatile matter. Unseasoned wood contains much more water than this.

The valuable by-products in the case of wood are methyl alcohol, acetic acid, and wood tar. The latter is not so valuable industrially as coal tar and for that reason is commonly used only as a fuel to aid in the distillation process. The wood alcohol is first obtained in the form of a 2.5 per cent. solution. This is rectified by distillation up to 95 per cent. or more. It is perfectly possible to make it chemically pure by proper distillation and a little chemical treatment.

The acetic acid cannot be recovered by distillation because its boiling point is too close to that of water and the two substances dissolve one another thoroughly in all proportions. The acetic acid is therefore recovered by neutralizing it with a mineral base, commonly lime, which forms a soluble but non-volatile acetate. This is recovered by evaporation of the water.

The Retort Charcoal Process.—This process is very similar to the by-product coking process, but on account of the lower temperature the retort is built of steel instead of firebrick. It consists of a steel chamber, roughly, 6 ft. wide by 8 ft. high and 50 ft. long, surrounded with a brick setting and provided with a firebox under each end. A stack is provided to draw the products of combustion from the fireboxes around the retort. These retorts are charged with 8 cords of wood on four-wheel trucks

carrying bodies built of steel slats. The retort is closed at both ends by air-tight steel doors and is provided with an outlet for the volatile products of distillation.

After charging, the doors at both ends are closed and fires built in the fireboxes. The gas outlet is connected to a water-cooled condenser and all the volatile products are condensed therein. The non-condensible gases are highly combustible and are led back under the retort to assist in supplying the heat it requires. In about 20 to 24 hr. the process is complete, the doors are opened, the trucks containing the charcoal are withdrawn and immediately replaced by others containing a fresh charge of wood. The doors are then closed again and the process repeated.

The trucks containing the charcoal are drawn as rapidly as possible into the coolers which are steel chambers exactly like the retorts in general shape and size, but more lightly constructed and set out of doors so as to get the maximum cooling effect. There are two of these to each retort set in line with it and separated from it and from each other by a short open space. The charcoal is put first into the nearest one and there allowed to cool for 24 hr., and at the next drawing of the retort it is moved into the second one, the fresh charge being put into the first cooler.

On account of the rapidity with which charcoal burns on exposure to the air, the transfers, particularly the one from the retort to the first cooler, when the charcoal is very hot, are made as quickly as possible and the air-tight doors of the coolers are immediately closed so that no air can reach the charcoal. Even with these precautions and with an additional cooling of 24 hr. in open air, fires by spontaneous combustion of the coal are not infrequent.

This process gives much better yields of by-products than the kiln process. The latter in good practice yields 4 to 5 gal. of refined methyl alcohol and 85 to 100 lb. of acetate of lime per cord of wood.[1] The retort process yields in good practice 8 to 10 gal. of refined alcohol and 170 to 220 lb. of acetate of lime.

The reason that this great superiority in the yield of valuable by-products has not forced the introduction of the retort more rapidly is that it suffers under two disadvantages. First, the cost of plant per cord of wood carbonized is about three times that of the kiln plant and for large capacity it runs into such a heavy expenditure as to put these plants out of the reach of any but relatively large and wealthy corporations. Moreover, the high interest charges, and especially the amortization charge caused by the relatively short life of these plants makes their financial returns very much poorer than their technical returns. In other words, a large portion of the profit realized from the greater yield of by-products is consumed in paying interest and amortization charges on the very high capital expenditure involved. Second, the maintenance charges of the retorts and plant generally are very heavy, the bottoms are liable to be

[1] Recent developments have increased these yields to about 7 gallons of alcohol and 125 lbs. of acetate which greatly reduces the advantage of the retort process (Dec., 1917).

burned out by a few hours careless firing and the retort as a whole may be warped so as to be worthless without heavy repairs, unless it is managed with great skill.

Those who have installed and managed retort plants with skill and intelligent care think that they constitute the only method of wood distillation worthy of consideration, while those who have operated them carelessly and ignorantly declare with equal positiveness that from a commercial point of view they are inferior to kilns, in spite of the much lower yields of the latter, which are undoubtedly very much easier to manage.

The yield of charcoal in the two cases is not very different, about 50 bu. (of 20 lb. to the bushel) per cord of wood.

It is probable, however, that this statement is not quite fair to the retort because it can and does drive off the volatile products more thoroughly than the kiln can do without waste of coal by combustion, so that while the weight of charcoal is about the same in two cases the fixed carbon in the retort coal is higher than that of the kiln coal.

This is partly compensated in the opinion of some operators by the fact that the retort coal is more brittle and therefore breaks up worse in the furnace than the kiln coal. Such personal experience as I have had tends to contradict this view as I have found that better fuel economy was obtained with retort than with kiln coal.

In a large-scale charcoal operation the difficulty of obtaining an adequate and steady supply of cord wood is very great. The yield of cord wood per acre of timber land is from 5 to 10 cords when only the material unsuitable for saw timber is taken and 40 or 50 cords per acre when all the timber is taken. The former condition is the more common and for this reason areas of several square miles must be cut over every year to supply a large charcoal operation. This makes many transportation difficulties.

In the earlier days of the industry small batteries of kilns were built close to the timber supply and the charcoal was shipped from these to the furnace, no attempt being made to recover the by-products. When commercial conditions forced the abandonment of this wasteful procedure the small batteries of kilns in the woods were abandoned and one large central battery was built, preferably at the furnace, because the labor of handling the finished charcoal and its consequent breakage were reduced to a minimum, and, what is equally important, the waste gases of the furnace became available to supply steam for the great amount of distillation involved in the recovery of the by-products.

In those cases in which retorts are installed the same considerations hold and such plants are located at sites where timber may be shipped to them by rail from a large territory. Very frequently these also are located at the furnaces which consume their coal, but not necessarily, because, owing to the greater profit on their by-products they can sell

their coal more cheaply than can the kiln plants and can, therefore, deliver it over considerable distances in competition with kilns.

Methyl alcohol is worth at the plant from 25 cts. to about 40 cts. per gallon, depending on the location and the perfection of the rectification.

Acetate of lime is worth from 2 to 2¾ cts. per pound at the plant, depending upon the state of the market.[1]

The cost of recovery with properly designed plants is low and therefore the income received from these by-products has a very important commercial bearing on charcoal production. In fact, the charcoal is the real by-product at many of these plants and the furnace is built simply as the most convenient means to consume this fuel.

CHARCOAL AS A FURNACE FUEL

Charcoal is almost an ideal furnace fuel. It is nearly free from sulphur, having only a few hundredths of 1 per cent. as against approximately 1 per cent. in coke and about 1 per cent. of ash against about 10 per cent. for coke. Moreover, this ash consists very largely of lime and alkalis, so that it supplies a part of the flux required for the gangue of the ore instead of being largely silica and requiring to be fluxed with additional bases as is the case with coke.

Charcoal has a highly porous structure and can therefore be burned at a rapid rate per square foot of hearth area. This fuel, however, is subject to one drawback. It has not quite the physical strength of coke and would perhaps be unable to stand the conditions existing in a large furnace. On the other hand, owing to the difficulties of wood supply above mentioned, charcoal furnaces are always small as compared with coke furnaces, and therefore the necessity of its having to withstand the pressures customary with large furnaces does not arise.

Charcoal has one bad characteristic not widely appreciated. In spite of its low ash (about 1 per cent.) its percentage in fixed carbon is very low, only about 69 per cent., or less in kiln coal. The remainder, about 30 per cent., is volatile matter which is not driven off at any heat which it is permissible to use in charcoal distillation. This volatile matter is about one-half hydrogen and of the remainder a large portion consists of gases of high reducing power, methane and CO among the number.

Because of its valuable characteristics, the fuel consumed per ton of iron is less with charcoal than with coke.

ANTHRACITE COAL

Anthracite coal has about the same chemical analysis as good coke for the reason that it is simply bituminous coal whose volatile matter

[1] These are the prices in normal times; during the great war prices two or three times as high have prevailed.

has been distilled off under conditions of heat and pressure arising from the geological movements of the earth's crust. The pressure has closed up the cells as they were formed and anthracite instead of being cellular like coke is in fact the most close-grained of any variety of coal. It occurs in quantities of commercial importance only in a small district in eastern Pennsylvania in the United States, though small deposits are known elsewhere, and deposits of much importance occur in Wales.

The following analyses are averages of actual shipments of blast-furnace anthracite which were obtained through the kindness of Robert C. Lea, Esq., of Philadelphia.

	Steamboat		
Vol. matter	4.120	5.100	4.470
Fixed carbon	84.280	84.680	83.570
Ash	11.600	10.220	11.960
Sulphur	1.220	0.610	0.620
Phosphorous	0.034	0.027	0.027

Owing to its abundance and cheapness in the early days of the industrial development of the United States it was the principal fuel used in the blast furnace until about 1860, when the development of the coking process began to furnish a rival fuel. As the magnetite mines of New Jersey and the limonite mines of eastern Pennsylvania are in close proximity to the anthracite coal fields, a great iron industry was developed based upon these materials.

But the increasing use of anthracite as a domestic fuel enhanced its value, while the development of the blast furnace proved coke to be the better fuel of the two for its purpose. The anthracite iron industry, therefore, declined, and there are only a few small furnaces using this fuel exclusively, though in the eastern Pennsylvania district, where it is cheaper than good coke, a certain amount of it continues to be used in admixture with coke to lower the cost of the fuel charge.

ANTHRACITE AS A FURNACE FUEL

Anthracite has three disadvantages as a blast-furnace fuel when compared with coke.

First, it is entirely lacking in cellular structure and is accordingly of much greater density, so that the ratio of surface exposed per unit of weight is only a small fraction of what it is in the case of coke and only a proportionately small amount can be burned per square foot of hearth area. This means that the output of a given furnace is necessarily much smaller when supplied with anthracite fuel than with coke.

Second, it has a tendency to spall or decrepitate under the action of heat. As a consequence of this spalling action the interstices through the fuel which form the principal passageway for the gases are greatly obstructed and the pressure required to drive the gases through the furnace is much increased. Moreover, this spalling seems to produce a tendency to scaffold the furnace, which will be further discussed in a later chapter.

Third, the much greater density of the fuel as compared with coke reduces the volume of the fuel charge very greatly. This increases the density of the charge as a whole and permits a longer time for the passage of the ore through a furnace of given size. But, for the reason already mentioned above this advantage is useless in increasing the output. On the other hand, the increased density of the charge means increased resistance to the blast.

As a consequence of these three conditions anthracite furnaces are characterized by slow driving and small outputs, high pressure, and a strong tendency to become scaffolded and work irregularly. These are the technical conditions, which, joined with the commercial considerations above outlined, have caused the decline of anthracite as a blast-furnace fuel.

RAW COAL

Certain coals, called "bituminous" for lack of a more descriptive name, while they contain a normal amount of volatile matter, are largely free from tarry ingredients. These are known as "dry" bituminous coals. On account of their relative freedom from tarry matter these fuels fall within the fundamental requirements of a blast-furnace fuel and in the past were quite extensively used as such.

But the development of the coke blast furnace has caused a retrogression in the use of this fuel very similar to that in the case of anthracite.

In certain districts where these coals may be obtained cheaply and for the production of certain special irons they are still used in admixture with coke, but so far as known to me there are no furnaces now running in the United States on raw coal fuel exclusively.

RAW COAL AS A FURNACE FUEL

A lack of porosity and the consequent slow rate of combustion of these coals are presumably the principal reasons for the decline in the use of this fuel. Moreover, though these coals are relatively dry they are not entirely free from tarry matter, and as but a small quantity of tar is required to obstruct the passage of the gas, this also has tended to reduce the rate of driving possible with this fuel. The tendency for the furnace to scaffold and work irregularly even with a small amount of tarry matter present is pronounced. The use of these coals is, therefore, generally confined to a district in southern Ohio, where they occur and are applied

in admixture with coke to the production of ferrosilicon containing 10 to 15 per cent. of silicon.

The characteristics of these fuels have modified furnace practice, and this in turn has modified equipment and product, so that the classification of iron by the fuels used in their production is fully justified. But as will be seen from what has already been said the only units in the classification which have preserved their individuality unchanged are coke and charcoal, with which are smelted the only two varieties of iron now in common commercial use.

ORES

The ores of iron differ from those of any other metal in that they are exclusively the oxides.

Oxides of iron found in nature are three in number, ferric oxide Fe_2O_3, hydrated ferric oxide $Fe_2O_3 + H_2O$, and ferric ferrous oxide Fe_3O_4, commonly known as magnetic oxide or magnetite.

There is a fourth oxide, ferrous oxide FeO, but it does not occur in nature under ordinary conditions for the reason that when produced it instantly absorbs oxygen from the air or any other source and converts itself to ferric oxide Fe_2O_3.

It is a matter of much geological importance as affecting the origin and cause of iron ore deposits that iron in the ferrous condition is soluble in water containing carbonic acid and in dilute solutions of vegetable acids.

The only ferrous condition in which we ordinarily find iron is as the carbonate. This occurs in nature in great quantities. Its solubility in water containing carbonic acid is not so great as that of limestone, and when an iron-bearing solution meets a body of limestone the iron is deposited and the more soluble limestone removed.

It is probable that an action of this general nature has been responsible for the existence of a large percentage of those iron concentrations in nature which are commercially known as ore deposits; though in most of such cases the iron has undergone a process of subsequent oxidation which has left the iron as ferric oxide sometimes hydrated and sometimes not.

There are no deposits of carbonate of iron in the United States now being worked on a commercial scale, though in the Lake Superior region there are vast deposits of lean carbonate which may eventually, by concentration or otherwise, come into commercial use.

There are, however, very large deposits of iron carbonate on the Canadian side of Lake Superior which promise to become of much commercial importance to the iron industry of Canada. These ores are unusually high in manganese and quite high in sulphur. It is necessary to eliminate both the sulphur and the carbon dioxide, the latter because its

weight is about 30 per cent. of the total so that the freight is correspondingly reduced by its removal, and because the coke solution loss caused by the liberation of this carbon dioxide in the furnace would be ruinous.

The removal of both objectionable components is effected by roasting and the resulting product contains over 50 per cent. iron and unusually low phosphorus, about 0.01 per cent.

The gangue of the ore consists very largely of lime and magnesia, so it is more than self-fluxing, which is a great advantage, while its physical condition is excellent as it is crushed to small lumps almost free from fines, and retains that condition after roasting.

The black-band iron ores which occur in some coal fields and which were formerly successfully worked in western Pennsylvania are impure carbonates, but these are no longer in commercial use, having been superseded by richer and cheaper ores. In Europe, in England especially, there are great bodies of iron carbonate. The iron industry of the Cleveland district in England is founded on a great deposit of this material, locally known as "clay iron stone," and there are some deposits of great commercial importance on the continent of Europe.

Limonite.—Limonite is a term commonly employed in commercial usage to describe all the common hydrated oxides of iron, of which there are three, turgite, goethite, and limonite, containing different quantities of water of crystallization ranging from 5.3 to about 14.5 per cent. This is the only distinction between them, and as limonite is much the more common in nature this name is applied to all three indiscriminately. They are also known generically under the name of brown ores, that being their characteristic color and the color of the "streak" which they yield under that geological test. The chemical formula for limonite is $2Fe_2O_3 + 3H_2O$ and its content of iron when pure is therefore 59.85 per cent.

Brown-ore deposits are probably more numerous than those of any other ore. There is hardly a State in the United States which has not deposits of sufficient size to be worked where the commercial conditions are favorable, but they do not ordinarily occur in as large masses as the magnetites and hematites.

The principal districts where such ores are now commercially mined in America are in western Massachusetts and Connecticut and eastern New York, eastern and central Pennsylvania, the western portion of Virginia, the central and western portions of Tennessee, the northwestern portion of Georgia, the northern portion of Alabama and northeastern Texas where limonite bodies with great commercial possibilities have recently been developed.

There are deposits of ore of this kind in various Western States, but on account of the lack of any important iron industry on the Pacific slope no limonite orebodies are at present in operation on an important scale in that region.

There are also brown-ore bodies of importance in the Lake Superior district, but those are not generally so highly hydrated as those in eastern and southern portions of the country, and for this reason, presumably, they are commonly not spoken of as limonites, but as "brown hematites."

Limonite occurs as the immediate result of the oxidation of iron carbonate or other ferrous compound deposited by circulating water which carries the required oxygen. It may frequently be seen in the actual process of deposition at the present day, the best-known illustration being that of the "bog ores." Streams carrying much vegetable matter in a region of ferruginous rocks dissolve the iron from these rocks and carry it in solution as a carbonate; or in combination with vegetable acids, to a lake or marsh where it has time to absorb oxygen from the atmosphere. This oxidizes it to ferric oxide which absorbs from its surroundings the necessary water of combination to convert it into limonite. This settles to the bottom and cements itself together as a true ore deposit.

The purity of limonite varies greatly and within short distances, even in the same mine, its content of phosphorus fluctuating considerably, but not as rapidly as that of silica which may range all the way from 3 or 4 per cent. to 25 or 30 per cent. without greatly affecting the appearance or even the specific gravity of the ore under certain conditions.

This ore is ordinarily low in sulphur, probably because of its aqueous origin and for the reason that the process of oxidation which converted it from the ferrous to the ferric form simultaneously oxidized any sulphur which it may have contained and so facilitated its removal in solution. These iron ores are commonly not so low in phosphorus as many others, limonite below the Bessemer limit in phosphorus being comparatively rare. A typical analysis of southern limonite as far as so variable a material can be said to have one is iron 45 to 48 per cent., silica 10 to 22 per cent., alumina 2 to 4 per cent., manganese 0.3 to 1 per cent., phosphorus 0.2 to 0.5 per cent., sulphur trace, combined water 9 to 11 per cent.

The principal characteristic of limonite in the blast furnace is its extreme reducibility. The water of hydration begins to be driven off at quite a low temperature and is completely removed at 800° or 900°F. It is commonly believed that the driving off of this water facilitates the access of the gas to the interior of the ore and while the ore shrinks more in volume than it does in weight from dehydration, thus indicating that no porosity is developed thereby, its action in the furnace lends color to this belief, since it is the most reducible material with which the blast furnace ever has to deal. It is highly valued on this account particularly for admixture with less reducible ores, on the action of which in the furnace it seems to exercise a beneficial effect.

Hematite.—The chemical formula of this ore being Fe_2O_3 it would contain if pure 70 per cent. of iron and 30 per cent. of oxygen. The ores embraced under this designation constitute the source of more than 80

per cent. of the iron produced in America. Their origin is less obvious than that of the limonite, but it seems certain that in very many instances they were deposited originally as limonites and subsequently dehydrated by conditions of temperature and pressure resulting from some of the more important geological actions of the earth's crust.

The largest known deposits of iron ore in America and probably the greatest number of large deposits are hematites, but this name is employed to denote material covering a wide range of characteristics. As has already been mentioned, the partly dehydrated limonites of the Lake Superior region, which range from yellow to dark brown in color, are classified as hematites. The geological "streak" of true hematite is blood-red and that is its most common color. But it varies from the light yellow of the partly dehydrated limonites of Lake Superior on one hand to the blue-black ores which, still carrying the same name, have been partly converted presumably by still further heat and pressure, into magnetites. It also varies in physical structure from the "soft" ore almost without hard particles and nearly as plastic as clay itself to a dense crystalline structure so hard that a steel drill will scarcely attack it, and from a lumpy mass in which fines are almost absent to great deposits of such fineness that 75 per cent. or more will pass through a 100-mesh sieve. Its content of impurities is equally as variable, ranging from bare traces of sulphur and phosphorus to a sufficient quantity of these elements to bar its use as a furnace material.

The principal districts in which these ores are commercially mined in America are: first, the Lake Superior region; second, the Birmingham, Ala., district, and third, a district in Colorado and Wyoming which serves the plant of the Colorado Fuel and Iron Co.

The Lake Superior region is divided into five main ranges, as follows: The Marquette, the Menominee, the Gogebic, the Vermillion, the Mesaba and the Cuyuna, this being their order from east to west and approximately also the order of their chronological development.

These five ranges constitute probably the largest body of rich iron ore in the world,[1] shipments being made from them at the rate of about 60,000,000 tons in 1916 with sufficient ore in sight to maintain this rate for many years to come.

The predominating characteristics of the ores from the different ranges vary considerably. All the Marquette and Menominee ores are either lumpy or soft, seldom or never fine like sand. The ores of the Gogebic are almost wholly "soft" or clay-like. Almost all the ores of the Vermillion are extremely hard, there being virtually no soft and no fine ore. The ores of the Mesaba are almost without exception fine, like sand, seldom or never lumpy to any great extent and while sometimes clayey never so much as those of the Gogebic. The ores of the finest grain size

[1] Recent investigations show that Brazil has deposits considerably larger and of extraordinary purity, but not yet commercially developed.

commercially used anywhere come from this range. The ores of the Cuyuna embrace all three varieties to some extent, but its discovery is so recent and its development so incomplete that it is not possible to say positively what the predominating characteristic of its ores will be.

The characteristics of these ores for use in the furnace depends in great measure on their physical structure. The hard, lumpy ores are less reducible than the fine and sandy or the soft ores, but are highly valued because the looseness with which they lie in the furnace permits the passage of the furnace gas through them much more easy than do the fine or the soft ores. The soft ores are characterized by high reducibility, and on account of their plastic nature are not much subject to being blown out of the top of the furnace by the gas current. On account of presenting less surface to the action of the gas than the extremely fine ores the initial changes in their condition occur more gradually and the furnace works better in consequence. Because of these characteristics, these ores are among the most highly valued of all varieties.

The fine ores present neither the free passage for the gas offered by the hard lump ores nor resistance to being blown out of the furnace like the soft ores, while the vast quantity of surface which they expose to the action of the furnace gas causes the initial reactions to take place in them with great velocity, thus further increasing their fineness and so rendering them still more likely to be blown from the furnace. Moreover, they tend to cause excessive solution loss by running down through the coke charge and enormously increasing the number of points of contact of ore with coke. For these reasons it was almost impossible for furnaces to work on large percentages of these ores in the early days of their use, and even with the increase in knowledge of how to handle them they are still much less desirable than coarser or more plastic ores.

Magnetite or Ferric Ferrous Oxide.—The chemical formula of this oxide is Fe_3O_4 and its theoretical percentage of iron is therefore 72.4, higher than that of any other oxide of iron occurring in nature. Ores of this nature appear to have originated in three separate and distinct ways.

First, by a continuation of those conditions of heat and pressure which dehydrated limonite and converted it into hematite; these if carried far enough seem to have converted hematite in its turn into magnetite.

Second, this ore appears to have originated in many cases as a segregation from a mass of molten igneous rock; an igneous origin is attributed to some of the largest known bodies of magnetite.

Third, it is chemically possible to deposit magnetite from an aqueous solution of certain iron salts and it is possible that this may have been the origin of some ore deposits of this kind.[1]

[1] The great contact methamorphic deposits of China and of our Pacific coast have originated by the deposition of magnetite from iron-bearing solutions arising from the igneous mass; generally the iron has replaced the more soluble limestone at its contact with the igneous mass.

This ore when approximately pure is distinguished by its intense black color and high specific gravity, about 5.2, also by its strong attraction for the magnetic needle. This is so great that the compass cannot be used for ordinary surveying in districts where there are considerable deposits of this ore. On the other hand, the deviation of the needle from its proper bearing, determined by the solar compass, indicates the presence of bodies of magnetite under the ground, though these are not necessarily of commercial importance on the strength of such indications. In prospecting work a special compass is used for this purpose to some extent.

Its magnetic condition gives this ore an important advantage over other ores since this makes it relatively easy to concentrate by magnetic separation from its gangue, so that deposits of magnetite can be worked and rendered commercially available when lower in iron than can be permitted with non-magnetic ores. In addition to the relatively harmless gangue, elements are frequently removed in the concentration which would exercise a deleterious influence on the quality of the iron if it remained in the ore. This is particularly true of magnetites containing phosphorus. Lean ores high in phosphorus in their crude condition can in some cases be concentrated to Bessemer ores of exceptional purity. The process of magnetic concentration has been more highly developed in the Lake Champlain district in New York than anywhere else in the United States.

In its action in the furnace this ore differs greatly from limonite and hematite. It is generally much more dense than either of these and resists the reducing influence of the furnace gases, even at temperatures at which the other ores are almost completely reduced. For this reason a large portion of its oxygen can only be removed from this ore with solid incandescent carbon in the lower regions of the furnace. These conditions require that more time be given for the reduction of this ore than is necessary with the other varieties and in consequence the output of a furnace on a burden of this ore is smaller and its fuel consumption higher than those of a furnace using a hematite of similar composition and physical characteristics.

Treated Ores.—In addition to these natural ores of iron there are various iron-bearing materials which owing to their mechanical condition, or their chemical composition, are not suitable for charging into the furnace in the condition in which they occur. These may be natural ores of abnormal composition or condition, or they may be the by-products of another industry.

Ores in many districts occur in conjunction with foreign materials which can be removed from them by simple means, thus often rendering suitable for furnace use a material which it would be impossible to consider using in its native condition. Perhaps the most notable instance of this is the brown ores or limonites which, in a great if not preponderating proportion of mines, occur admixed with heavy clay and sand to an

extent that renders the native material entirely unfit for the furnace, but by a simple process of washing with water, by means of vigorous agitation, the foreign material may be removed and a very desirable ore produced. Of all the limonite ores in the United States it is probable that 90 per cent. are so washed before they are used. In other cases these ores, and sometimes others, are admixed with pieces of barren rock, but so intimately that while in the larger sizes separation can be effected by hand picking, in the smaller sizes it is necessary to use jigging, and various jigs have been developed which are extremely successful for this purpose. Probably the largest washing and jigging apparatus in the world is that at Coleraine on the Western Mesaba field where some 25,000 tons of material a day are handled, which are entirely unfit for blast-furnace use as received, but from which some 15,000 tons of excellent ore are recovered.

Magnetic ores are often, if not generally, mixed with barren rock, and this being non-magnetic the ore can quite easily be removed from it by magnetic separation. In order to make this feasible the material must be crushed to a degree of fineness which depends upon the intimacy of mixture between the rock and ore. The ores of Lake Champlain are particularly well adapted to this treatment, the individual mineral particles are quite large in the case of both the rock and the gangue, and being distinctly crystalline the minerals tend to separate at the crystal faces. This favorable condition combined with the enterprise of the owners has resulted in the development of magnetic separation at these mines on a large and very successful scale. In other mines such as that at Cornwall, Pa., the intimacy of the mixture is much greater and much finer crushing is required, while at the Moose Mountain mine in Canada the crystals are so small and so intimately mixed that the ore has to be ground almost as fine as flour before a satisfactory separation can be secured. This fine grinding brings the ore into the same condition as other fine iron-bearing materials of which there are two principal classes, flue dust produced by carrying over mechanically the fine particles of the charge by the gas current, and pyrites cinder, commonly known as "blue billy," the residuum which is obtained from finely ground pyrites used for the manufacture of sulphuric acid. This latter material like the fine concentrates of the Cornwall mine contains from 1 to 2 per cent. of sulphur; this with its fineness makes it an undesirable ore burden from the operating point of view because it is liable to a very heavy loss of the ore itself by blowing over; because it causes high solution loss, and therefore relatively high fuel consumption as already described, and because it has a tendency to travel ahead in the furnace, build up on the bosh walls, and then slide off in masses of sufficient size to put the furnace almost out of business, while the sulphur necessitates a limey slag and therefore still further raises the fuel consumption. For all these reasons then

these ores must receive another treatment. Fine ones may be agglomerated or stuck together by processes not involving the use of heat, but for sulphurous ores some sort of roasting is absolutely necessary to get rid of the sulphur, and this operation can be carried on at a sufficiently high temperature to frit the ore, and stick the particles together in a plastic condition.

For the purpose of binding together fine ore without roasting various processes have been proposed and used. Ore has been mixed with cement, the setting of which stuck it together in lumps which could be charged back into the furnace. Clay has been used for the same purpose, but most of these cold processes depend upon the production of briquettes by pressure in combination with the use of a binder of some description.

In the "Scoria" process ground hydrated furnace slag is used, and after the briquettes are formed under heavy pressure they are baked with high-pressure steam for several hours in a steel retort so that a further hydration takes place and the slag sets, acting as a binder.

The Schumacher process makes use of the fact discovered by Dr. Schumacher in Germany that certain substances have a catalytic action on flue dust which causes it to set and harden somewhat like cement. Magnesium chloride and ferric sulphate are two of the substances successfully used for catalyzers. The quantity used, and its cost, are not sufficient to cause a heavy charge against the product, while the quantity of sulphur introduced with the ferric sulphate is not sufficient in amount to affect the use of briquettes in the furnace in ordinary proportion. More recently it has been found that the fine dust separated from furnace gases by the Halberger-Beth system also had this catalytic power, and briquettes are being made with this material to contribute the cementing property, but not, as far as known to me, in this country.

All these briquettes are liable to disintegration if exposed to the weather, and if they are to be stored must be put under cover, otherwise they will decrepitate to a detrimental extent in a comparatively short time. A further fact to be considered in connection with them is this: they consist of the original particles of dust bonded together perhaps quite firmly, but still separate particles, with bonds capable of dissolution. The decomposing tendency of furnace gas on iron-bearing materials has been many times set forth. How far then will these briquettes progress down in the furnace before they are decomposed by the action of the furnace gas itself, and so returned to that objectionable condition of fineness which is one of the most important reasons for agglomerating them in the first place?

If this action takes place well above the top of the bosh we may have the high solution loss which it should be the principal function of agglomerating to prevent. Some effort has been expended by the advocates of these systems to prove the reducibility of their product, but if it be

true, as I have shown in an earlier chapter, that a furnace may suffer as severely by too great reducibility of the ore as by too great irreducibility, the results of their efforts are not convincing. They may in fact be proving the very condition which would be worst for their product.

Turning now to the processes of agglomerating by heat we have four which in the order of their development are the rotary kiln, like a cement kiln, usually fired with powdered coal, the up-blast converter pot of the Huntington-Heberlein type and the down-draft pot or pallet, and the tunnel furnace of the Gröndal type in which briquettes formed under pressure are burnt to strong and durable condition.

The fuel required for the first is about 15 or 20 per cent. of the weight of the material agglomerated, when the latter is carbon-free material such as fine ore or blue billy, but a less percentage in the case of flue dust. The up-draft converter or pot is an apparatus not unlike a Bessemer converter with a grate in the bottom through which a strong current of air is forced by a positive pressure blower. A fire is built on the grate and this is covered over, when well started, with flue dust or ore (though this process has been used principally for flue dust), taking care so to place the material as to stop up the holes in the bed, and produce as nearly as possible a uniform blast over the whole surface. A little coal is thrown in from time to time with the charge, the air continuing to force its way from the bottom upward through the porous material formed. Only enough coal is charged to bring the material to a sticky condition so that the individual particles are partly fused together, and the blast blows holes through the mass while soft, making it spongy. When the pot is full it is tipped like a converter and the resulting "chunk" of sinter of many hundred pounds weight is broken up partly by its drop onto a grating and partly by hand sledging.

In the down-draft apparatus a grate is provided at the bottom, but as the products are drawn down through the bed and reach the grate in their hottest condition it has generally been found necessary to cover the grate over with some harmless substance which protects it from the severity of the hot gas to some extent.

There are two down-draft processes, the Dwight-Lloyd and the Greenawalt. In the first an intimate mixture of the material to be sintered with as much fine coal or coke as may be necessary for the operation is spread upon the grate in a uniform and homogeneous layer. The top surface is ignited by a flame which plays upon it for a short time, and the down draft through the mass pulls the plane of combustion gradually down to the bottom of the mixture, stopping on top of the inert material on the grate, this material being generally limestone spalls, which are not only harmless but are needed in the charge any way, and whose partial calcination is that much advantage to the furnace.

The difference between the Greenawalt and the Dwight-Lloyd proc-

esses is briefly that the former is a batch or charge process, one definite quantity being handled at each operation, whereas in the Dwight-Lloyd system the operation is continuous, the apparatus being in substance no more than a chain grate arranged for down draft. Both types of apparatus have their champions, and each claims advantages over the other, but they are very similar in principle and in product, so that eventually that one will probably win which can show the lowest operating cost. Both these types of apparatus produce a very desirable product. It is even more spongy than that of the up-blast pot while owing to the uniformity and better preparation of the charge before combustion begins a much larger percentage of properly sintered material is produced. The exposure of all the particles to the blast is excellent, and in consequence the desulphurization is good. Monthly records have been made in which blue billy ranging from 1 to 4 or 5 per cent. in sulphur was reduced in the sinter to a very uniform figure of about 0.1 per cent.

The great advantage of the down draft over the up draft for sintering is that with the up draft the surface particles are in a constant state of agitation, than which nothing could be more unfavorable to sintering them together without producing an unduly pasty or liquid condition. In the down-draft apparatus, on the other hand, the surface layer, as well as all the other layers below it, are held to place by the passage of the blast through them. The agitation of the charge during sintering is, therefore, entirely eliminated and a larger percentage of the charge can be sintered as above stated.

This material has two great advantages for blast-furnace purposes. It is lumpy and irregular to the last degree; therefore, it is impossible for it to penetrate through the coke bed in the way that fine ore does. The particles have lost their separate identity and been merged into a homogeneous mass, and while the mass is black and, therefore, partly magnetic, it is claimed by those who have investigated that it does not consist in the main of magnetite with the irreducibility characteristic of that material.

Owing, on the other hand, to its physical and chemical composition this material does not suffer from the excessive reducibility of fine ores as above described. At the same time it is so porous and permeable to the gas that by the time it reaches the hearth of the furnace it is sufficiently deoxidized not to require extra fuel in the hearth for that purpose. Authentic figures are available which seem to indicate that an admixture of 15 to 25 per cent. of this material in the furnace burden actually exercises a beneficial effect on the fuel consumption and the output.

As compared with the product of the rotary kiln this material has several advantages. If the material under treatment is to be desulphurized the greatest care is necessary with the rotary kiln not to heat the material above the softening point until the desulphurization is com-

plete, as otherwise the small particles are stuck together into balls by the rolling of the kiln and seal up a sulphurous mass inside which no amount of roasting will desulphurize. The conditions are made more difficult by the fact that the melting temperature of the sulphides is very far below that of the oxides. Even if the material be thoroughly desulphurized in the kiln, as it undoubtedly can be, the agglomeration takes place by the rolling action of the kiln in bringing the pasty particles together, like the rolling of a snowball down a hillside, and this process necessarily tends to hammer out, or seal up, all pores which might accidentally form in the material, which is, therefore, dense and round, as compared with the porous, rough, irregular condition of the sinter produced by the passage of the blast through it. The consequence is that material produced in the kiln when used in mixture with softer and more reducible ores exercises a distinctly unfavorable influence on the working of the furnace necessitating slower driving and higher fuel consumption. This is a matter concerning which I have had definite and positive experience.

In addition to these materials there are others, by-products of other phases of the iron industry itself, notably an iron-silicate slag produced in the manufacture of puddled iron, heating furnace cinder, the scale from ingots or blooms charged into reheating furnaces for the purpose of bringing them to the rolling temperature, and mill scale, the black magnetic oxide of iron which forms on the red-hot material being rolled, and cracks off at its passage through the rolling mill. The latter is almost a pure oxide of iron which is quite free from silica, but on account of being magnetic oxide is somewhat irreducible in spite of its rather finely subdivided condition.

The first two, as stated, are fused silicates of iron, the scale in the second case fluxing itself with materials dissolved from the brick of the furnace. These materials are produced by true fusion, and complete chemical union of the iron with the silica. Ferrous silicate is in itself a very irreducible compound, probably the most irreducible with which we have to deal, while owing to its being produced in the completely molten condition, and in the absence of any passage of blast through it the material is exceedingly dense and impenetrable to the gas, thus increasing its irreducibility. These facts were well shown by some remarkable transparent slides like geologists' rock sections prepared by Mr. G. B. Klugh, and shown at the October meeting of the Iron and Steel Institute in Chicago in 1913. From the magnified image of the section thrown on the screen the differences in the materials were clearly apparent, and the reason for the superiority of sintered material over fused silicates became very evident.

The Use of the Different Ores in the Furnace.—The varying characteristics of these different ores, natural and artificial, affects their use in the blast furnace materially. The variations are so numerous

that it is impossible to deal at length with all of them, but we may touch upon some of the more important. Perhaps the most important is the difference between the magnetite and hematite, of which the former contains materially less oxygen in proportion to the iron and, therefore, contributes a smaller quantity of oxygen for the oxidation of the gases in the shaft, thus cutting down the heat development in the shaft materially. On the other hand, this ore retains its oxygen more strongly than does hematite and probably carries a larger proportion of its total oxygen into the hearth, so increasing the requirements of hearth heat for its final reduction and also increasing the solution loss of coke simultaneously. The result of these two actions undoubtedly causes magnetite ores to require more fuel and a longer time in the furnace for smelting, thereby increasing both the fuel cost and fixed charges for the iron so produced, and these causes have militated against the popularity of this ore in spite of the fact that it is frequently quite rich, either naturally or by magnetic concentration.

Another factor of great importance is the size of the individual ore particles. If these are lumpy so that they cannot roll down through the coke charge solution loss is diminished, while the smaller surface presented to the gas in the zone in which decomposition of CO takes place probably reduces the extent of that catalytic action, and thereby diminishes the deposition of carbon dust with the evils which it causes by obstructing the interstices of the charge and so causing high pressure and consequent slipping in this zone.

If the ore be too lumpy, that is, if the individual lumps be too large, particularly with a dense ore, their exposure to the action of the gas is insufficient and either the ore is not properly reduced when it reaches the hearth, or else more time is required for that operation. If great variations in the size of the ore occur, some being charged quite fine and others as large lumps, then the lumps are reduced much more slowly than the fines and are likely to descend unreduced into the hearth causing raw slag and other bad operating conditions.

Plenty of cases are known in which the failure to break large lumps by tke stock-house men charged with that duty has caused furnaces to work very badly, and ore should never be charged in that condition.

The evils of excessively fine ore, on the other hand, have already been pointed out. Its tendency to run ahead through the charge, its excessive catalytic action on the gas, and above all the excessive solution of coke which it causes, render fine ores inherently less desirable than ores of the same analysis in a better physical condition.

It is also a matter of great importance that ores of different physical condition act very differently on the bell. The lumpy ores slide freely and with high velocity, the plastic ores, or fine ores containing alumina, slide very slowly and even build up on the bell. The consequence is

they are delivered into the furnace at a much slower speed, and their position relative to the coke charge and the walls of the furnace is very different, so that a change from an ore of small lumps to one of coarse lumps in one direction, or of plastic fines in the other, all being of the same composition, would work considerable and probably serious changes in the operation of the furnace.

CHAPTER IX

SLAGS

This subject has received an enormous amount of study at the hands both of practical men and scientists, but particularly the latter. Much experimental work has been done upon the subject, but in my opinion by far the larger part of this has been entirely wasted because the kind of information needed has not been appreciated.

The purpose of the slag is twofold: First, to remove in a convenient form the impurities of the charge which come from all three of its components, the ore, the fuel, and the flux, and render them fusible so that they may be removed from the furnace at the lowest possible temperature, since, as I have many times reiterated, this is the critical temperature of the furnace, and as was shown in the section on thermal principles this is the point about which everything else revolves. Second, the slag must remove the sulphur which is always present in mineral fuel, and sometimes in the ore, so as to prevent its entering the iron. In a narrow sense this is only a subdivision of the broader subject of removing the impurities of the charge, but in practice and in the habits of thought which grow up from the operation of the furnace, these two functions are separate and distinct, and we may well consider them so.

Let me make clear here what I think has too often been not clearly stated in dealing with this subject.

Our knowledge of it is 99 per cent. empirical. It is true that good furnacemen calculate the slag they desire to produce with some care, but they do it *not* according to any scientific law, or on the basis of any chemical formula, but simply to produce a slag which they know from experience will produce the desired result to the best advantage. In some departments of metallurgy it may be necessary to figure the oxygen ratio of slags, that is to say, whether they are bisilicates, monosilicates, or sesquisilicates, but in the blast furnace we not only may, we must, ignore all these considerations if we desire successful results. This is an extreme case of that general law that in the furnace we deal not with a chemistry of definite proportions but with an infinitely varying balance between two or more, generally many, contending forces, and we would be unable to detect in the plotted curve of our results, if we could make one, the slightest sign of a cusp indicating a critical point, or sudden change in the characteristics of the slag. If we know that an increase of 2 per cent. in the silica in the slag will make a certain change in its character then

we may be perfectly sure that the next variation of 2 per cent. will produce a change in the same direction, and of approximately the same amount.

The sketch diagram, Fig. 58, gives approximately the free-running temperatures of slags having alumina virtually constant at 12 to 15 per cent. with silica ranging from 33 to 60 per cent. This is not intended to be accurate, for unfortunately I have not the data to make it so, but represents the results of much observation and many hundred pyrometer readings on actual slags throughout the range mentioned.

In charcoal practice we have ordinarily no sulphur to consider. That contained in the fuel is very slight, probably well under a tenth of 1 per

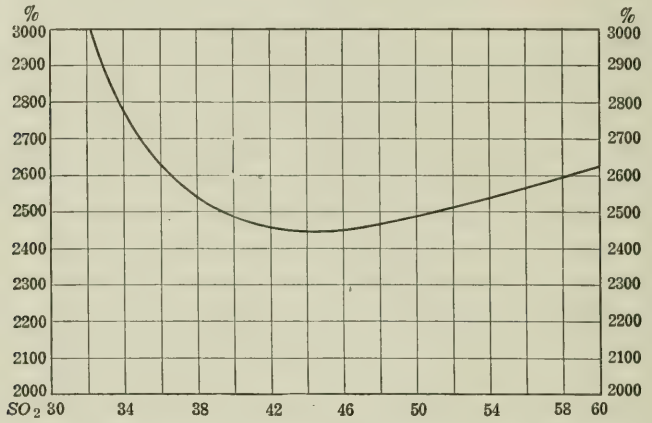


Fig. 58.—Tentative curve of free-running temperature of actual slags based on observations and pyrometer readings in practice.

cent., and since the great advantage of charcoal as a fuel is its freedom from sulphur, and since it is possible to obtain ores and fluxes quite free from that impurity, such furnaces are commonly operated only with such materials, and under ordinary circumstances should never be operated in any other way.

In this case then we have to consider only the production of a slag with the lowest possible melting point to permit its removal from the furnace, so as to have the lowest critical temperature, and as we have already seen, this is the reason that charcoal furnaces are able to run not only with a smaller weight of fuel per ton of iron, but with a fuel containing only about three-fourths as much fixed carbon as is contained in coke. In charcoal furnace then we are free to use virtually any slag which will accomplish our purpose best, or briefly, that which is the most fusible in the sense of having not the lowest melting but the lowest free-running temperature, and I have used slags which ran all the way from below 40 per cent. silica up to almost 60 per cent. in that element.

No refined means of measuring the fluidity of these slags was at hand, but observations were made with a pyrometer, and by eye, and as a result of long experience it was found that both of these extreme slags were less fusible than a slag ranging from 46 to 49 per cent. silica, as indicated by Fig. 61. Accordingly in running for low-silicon iron a slag of the latter kind was used, but when high-silicon iron was desired a more siliceous slag was used, both because its hold on the silica was weaker, and therefore the latter could be more easily reduced and thrown into the iron, and because its free-running temperature was higher and therefore gave the somewhat higher temperature necessary to force the desired silicon into the iron. By both these means, therefore, we facilitated the introduction of the silicon into the iron with the least excess of fuel over that required for low silicon.

Turning now to coke-furnace slags we have an altogether different condition. The sulphur in the fuel varies from about 0.3 per cent. or lower in very exceptional cases up to 1.5 per cent. or 2 per cent. in some cases, and in abnormally bad cases even higher than this, even up to 3 per cent. On the basis of a ton of coke to make a ton of iron this means in the average case that sulphur is present in the charge, to the extent of about 1 per cent. of the iron, and to obtain a merchantable product we must eliminate this at least down to 0.05 per cent., leaving the sulphur in the iron 0.05 per cent. or under, therefore 95 per cent. of the sulphur must be eliminated. To accomplish this we have two principal means both of which are accomplished simultaneously by one change in the burden. We must increase the bases, generally the lime, in the charge, over what we use in charcoal practice.

The lime divides itself between the silica and the sulphur according to some law which has never been worked out, but in general the more basic the slag the more ready it is to satisfy itself with sulphur, and increasing its basicity has the effect also of increasing its fusion temperature; and this, by increasing the reducing action of the furnace, exerts a more powerful action on the lime to reduce it to calcium sulphide, and thereby further increases its activity for desulphurization.

But here we work under very different conditions from those which prevail in charcoal practice, because we come now to the fact that the change in fusibility of the slag toward the two ends of the range mentioned is very different, due to the fact that some slags are "short" and lacking in viscosity, like water or mercury or light oils, whereas others have a long viscous range like molasses or tar. They begin to soften and are no longer solid at temperatures far below those at which they can in any proper sense be called liquid and become liquid far below the temperature at which they become free-running.

The limey slags in a general way belong in the former class, whereas the siliceous slags belong in the latter class. To illustrate this: if a

limey slag be poured from a hand ladle it falls in little round pellets, almost like shot, which are individual drops when they strike the ground and when still red hot, whereas a siliceous slag under the same conditions does not produce pellets but long strings, or if a little puddle of it be poured this will remain connected with the ladle by a string, and even when it is apparently almost cold this string can be drawn out like glass to great lengths.

This is probably one of the most important facts of furnace operation. For as has been so often reiterated, the important point is the free-running temperature of the slag, and with a limey slag this is only a few degrees from its softening point to the point where it runs freely, whereas with a siliceous slag on the other hand this range is 200° or 300°. Although some work has been done along this line, exact data in regard to iron blast-furnace slags on this basis have never been published, but Professor Fulton of the Case School of Applied Science published before the American Institute of Mining Engineers in 1912, a paper on "Copper Blast-Furnace Slags," in which this point was well brought out, and from which Figs. 59 and 60 are reproduced. It will be clearly seen that the range between the free-running temperature shown by the upper line and the softening temperature shown by the lower one varies enormously. It is this fact which has done so much to minimize the value of investigations by scientists on this subject.

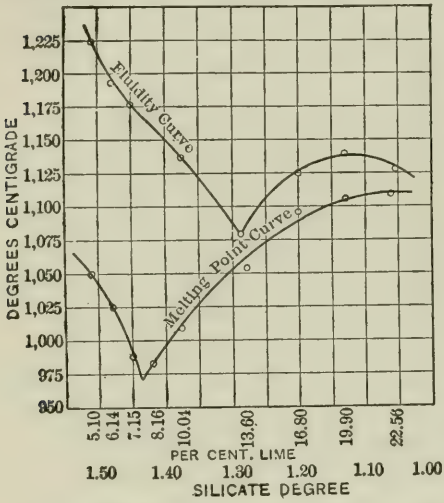


FIG. 59.—Melting-point curve—fluidity curve.

It is comparatively easy by making slag-forming materials into cones and observing the temperature at which the tip of the cone begins to deform to determine their softening point, but it is exceedingly difficult to determine their free-running temperature. The suggestion of W. McA. Johnson to do this by timing the discharge of a given weight of slag at different temperatures through a standard-size hole in the bottom of the crucible containing it, is the best of which I have knowledge. I have suggested as a method of standardizing the orifice that the free-running temperature of an actual slag be taken at the furnace, and then that size of the orifice determined by experiment through which a given quantity of this slag at this temperature would run in a given time. The temperature at which any other slag would run through the same orifice

in the same time would be its free-running temperature. It seems lamentable that with the facilities for doing this work possessed by modern colleges and universities, nothing has ever been done along this line, although it would go further than anything else to solve the practical problems of blast furnace operation (see Appendix to this chapter).

The difference between coke and charcoal practice consists not only in the fact that the critical temperature in the latter is lower, but also in the fact of almost equal importance that in charcoal slags we are free to choose the flat range along the bottom of the curve of Fig. 58, and a variation either way does not affect the operation of the furnace very materially. But to secure the desulphurization required with low-silicon coke irons a ratio of lime to silica of about $1\frac{1}{2} : 1$ is necessary which is

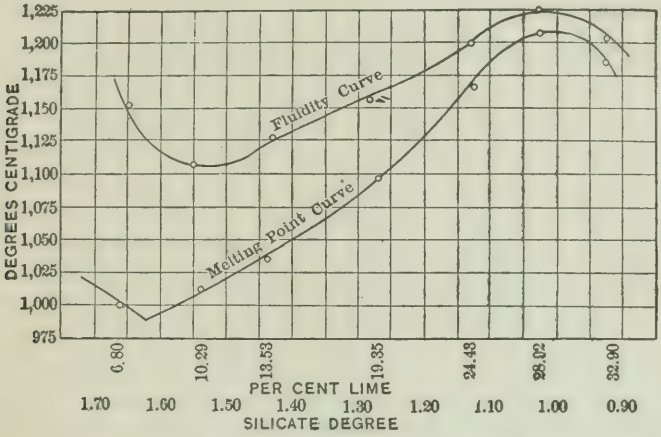


Fig. 60.—Melting-point curve—fluidity curve for copper slags.

reached at approximately 34 per cent. silica. It will be seen that this is on a decidedly steep portion of the curve; the result is that a slight change in the ratio of the lime to the silica has a great influence.

If the silica rise to 37 per cent., the ratio of lime to silica is only 1.35 : 1 and we are likely to have insufficient desulphurization, which in plain language means high sulphur or generally an unmerchantable product, while if the silica fall to 32 per cent., the critical temperature rises on the basis of this sketch-diagram about 250°F., with a very serious effect on the operation of the furnace because we have not only the increased critical temperature and the consequent rapid diminution of hearth heat as shown by the chart (Fig. 3), in the chapter on thermal principles, but we have a decided increase in the amount of slag to be melted.

If the silica be reduced from 34 to 32 per cent. by increasing the lime, this involves an increase of 6 per cent. in the total volume of the slag, and the increased hearth heat required for this, added to the diminution

of hearth heat produced per pound of fuel by the increase in the critical temperature quickly uses up any reserve of heat the furnace may have. Failing sufficient hearth heat, the slag is no longer heated to its free-running temperature so becomes stiff and inactive; the iron is unable to free itself from the slag and heavy losses of iron occur, while on account of its lack of fluidity the slag is unable to desulphurize the iron, in which therefore the sulphur rises not infrequently to several times the permissible limits and the iron thereby becomes entirely unmerchantable. If this condition endures for more than a short time without obtaining relief from additional fuel or additional blast heat the slag is likely to become so stiff that it can no longer be withdrawn from the furnace and the interruption to operation which results may last from 12 hr. to many days.

Before this chain of events was thoroughly understood, and especially before it was realized that if the percentage of lime exceeded a certain amount, the desulphurization became worse and not better, because the stiffness of the slag more than outweighed its greater basicity, furnaces were frequently "lime-set," that is, reached the point where the slag became nearly or quite infusible, and freezing up around the walls of the furnace prevented the iron from being withdrawn on one hand, and the ingress of the blast on the other. Stopping the supply of blast resulted in stopping the combustion of the coke and the generation of heat; this, of course, quickly exaggerated a condition already very serious and the furnace became entirely frozen up. In more than one case where the furnace was watered down preliminary to shoveling out, the quantity of lime in the hearth under these conditions was so great that it burst the structure. Many such cases have occurred in quite recent years and even down to the present time furnaces not infrequently come perilously close at least to the early stages of this condition.

It is necessary to remember here also the results of the investigations of Mr. James Bell mentioned in Chapter I, which tend very strongly to show that with a slag only moderately basic, a considerable portion of the total sulphur is eliminated by volatilization, while an excessively basic slag, to a great extent prevents this action, and by carrying down a greater quantity of sulphur into the hearth, defeats the very end it is designed to acccomplish.

A partial confirmation of this result is to be found in the well-established fact of practice that a small increase in blast-temperature is much more effective in promoting desulphurization than a considerable increase in limestone.

On the other hand, those who while making basic iron have chased higher sulphur with increasing lime know to their sorrow how hard it is to catch and how easily they defeat their own ends, and that they may put the furnace temporarily out of business by going too far in that direction.

It will be seen, therefore, that a coke furnace must be driven along a narrow path like that on the side of a mountain. If we deviate from the course on the upper side our progress is stopped and damage may result. If we go too far the other way we plunge to destruction at a rapid rate.

The elements with which we have so far dealt are particularly the lime and silica, the latter being the principal impurity, as well as the most acid in its action, which we have to flux out, and the former the base by which this acid is both neutralized and fluxed. The sulphur, as pointed out in the article on chemical principles, is present as calcium sulphide, a neutral substance, and not to be regarded either as an acid or a base. We have, however, other ingredients to consider, of which by far the most important in quantity and effect is alumina.

Magnesia and Alumina.—The effect of alumina has been a matter of vigorous dispute. Many furnacemen have been accustomed to consider it as an acid, and adding it to the silica, to consider the two jointly as "total acids." A few, on the other hand, have claimed that alumina, being the oxide of a metal, was necessarily a base, and as such have added some portion of it to the lime and magnesia.

Considering these opposite contentions, I began to believe a good many years ago that it was neither one, but acted only as a neutral addition, affecting the physical condition of the slag, but not affecting its basicity or acidity to any important degree. This view was set forth by me in a paper before the American Institute of Mining Engineers in 1912, part of which is quoted as follows:

"We may as well dismiss the obscuration which comes from the introduction of oxygen ratios and other abstruse theoretical considerations, and admit frankly that experiment on the furnace itself is the only safe foundation for practice or for a useful theory.

"I am moved to lay stress on this point, because in years past I was greatly puzzled and befogged by some of the older school of furnacemen, who emphasized the mysterious nature and difficulty of making slag calculations, the fact being that, given the materials to be used and the slag to be produced, the college student who could not be taught in a day to make the calculations would have a poor chance of ultimate usefulness. The omission or concealment of the fact that the slag to be produced was known only by experiment and experience with the furnace itself caused my mystification, and I therefore emphasize it here.

"The object to be sought may be briefly stated as follows:

"Given the materials to be used and the kind of iron to be made, to ascertain the slag which will produce the results with the least cost for coke and for flux and will permit the greatest output. The three desiderata come in the order given.

"We may in this discussion omit consideration of charcoal practice because the slag question is of minimum importance in that field, and the field itself is of minimum importance in the iron industry. (This was written before I had ever been engaged in the charcoal iron industry.)

"Coming then to normal coke practice, and remembering that generally the

lowest fuel consumption is obtained with the lowest critical temperature, the object desired may be stated more definitely as the production of the most fusible slag that will give the necessary desulphurization of the iron. This statement is, perhaps, subject to certain limitations from the fact that there are circumstances in which it is necessary to raise the critical temperature in order to enable the iron to absorb a large quantity of silicon.

"The desulphurization effect of the slag is proportional, not only to its basicity, but also to its fluidity in an almost equal degree, so that while increased lime *per se* has a desulphurizing influence, this is to an increasing extent neutralized, and finally reversed completely, by its decreased physical activity.

"This is well shown in basic practice, in which the highest sulphur iron is made, not with deficient lime, but with an excess (due to a change in ore or the like) so great that the heat available is unable to bring the resulting very refractory slag to the free-running condition necessary for proper desulphurization.

"In further illustration of the point, there are two distinct methods of making this kind of iron. The first consists in running on a very calcareous slag, with which the silicon in the iron is kept down by the basicity of the slag in spite of the high temperature necessary to keep the latter fluid. The second consists in maintaining a slag of only moderate basicity and much lower fusion temperature, and keeping down the silicon by carrying a heavy ore burden, which, of course, can easily be done with the lower critical temperature.

"Furnaces running on the first plan always require more coke for basic than for foundry iron, while those running on the second plan use less than for foundry iron.

"It seems to me practically certain, therefore, that there is a considerable range of lime content in the slag for given conditions, in which the desulphurization of the iron is not appreciably affected, while the coke consumption necessarily rises with the increase in the fusion temperature consequent on the higher lime ratio, as well as the increased slag volume.

"In all theoretical slag calculations the quantity of magnesia is multiplied by 1.4 to put it on the same basis as the lime, which, from the point of view of the oxygen ratio and molecular weights, is perfectly correct. Practically, however, this does not work out. Furnacemen using a limestone with a variable content of magnesia have told me that careful observation had failed to show any difference whatever on the furnace, whether the magnesia was high or low, and I have seen a furnace using half calcite and half dolomite, the calcite being relatively impure and the dolomite very pure, put onto all dolomite, which should have made the slag excessively basic, on the basis of molecular weight, but which, as a matter of fact, showed no observable change.

"The truth seems to be that magnesia is less active chemically than lime in about the same proportion that its molecular weight is less.

"Sir Lowthian Bell's opinion that magnesia was so inert as to be useless for the removal of sulphur in the blast furnace is well known, but this opinion is no more borne out by practice than that giving it a greater value than lime, the truth appearing to be that for furnace purposes, in all ordinary proportions, one is about as effective as the other.

"It is very necessary, however, to recognize that the addition of a certain amount of magnesia has a marked effect in lowering the fusion temperature of the

slag, and is therefore of great use where calcareous slags are required, particularly in the manufacture of basic iron.

"For practical purposes lime and magnesia may be considered as being of equal value, and hereafter in this paper "lime" will be used to mean the sum of lime and magnesia.

"The Effect of Alumina.—The foregoing portion of this paper contains nothing essentially new, and is intended as an introduction to the remaining portion, the substance of which seems to have been unknown to most of the furnacemen with whom I have discussed the subject.

"The effect of alumina has been the subject of much discussion; some regard it as an acid, others as a base, while a few declare it can be made to act as a base or an acid almost at will.

"It has seemed to me that under such circumstances the probability was that its action was neither acid nor basic, but was perfectly neutral, simply a diluent affecting the viscosity of the slag to some extent, but, with a given ratio of lime to silica, not affecting its chemical nature at all.[1]

"For several years the range of alumina in slag of which I had knowledge was so limited that I could not prove this contention, but in 1909 a furnaceman gave me complete information of a remarkable series of experiments he had carried out, in which the alumina in the slag had been as high as 39.5 per cent. with silica as low as 21 per cent. on individual flushes, and averaging for an entire day SiO_2, 24.7; Al_2O_3, 36.0 per cent.

"The iron made was good Bessemer iron, about 2 per cent. of silicon, with sulphur about 0.023 per cent.

"It is unfortunate that the experimental run was on Bessemer instead of basic iron. The records of other days, which show basic iron made, are not so complete, but they indicate only a small difference in the slag, that shown, of course, being an increase in lime.

"The coke consumption of this slag was not materially different from what it was in standard practice; the slags were free-flowing, and did not have a noticeably higher fusion temperature than ordinary.

"With this let us compare standard Lake-ore slag on basic iron running about Al_2O_3, 13.5; SiO_2, 33 per cent., and Virginia slag on the same iron, Al_2O_3, 6.5; SiO_2, 36 per cent.

"Here, then, we have three cases, in all of which the coke is of about the same sulphur content, the desulphurization of the iron is the same, the coke consumption does not differ more than would be accounted for by the different kinds of ore. The only difference of importance is the silicon in the iron, which is not

[1] This conception of a given constituent affecting the physical but not the chemical properties of slag, in which two kinds of properties are so closely interwoven, is difficult at first sight, but I have illustrated it for myself as follows: If we had an ordinary acid, such as hydrochloric acid, in one beaker, and a solution of caustic alkali in another, we could mix the two in any proportions and each addition of one or the other would result in a corresponding change in the acidity or basicity of the resultant solution, but if we added a considerable quantity of molasses, we would alter its viscosity and its "free-running temperature," without affecting its chemical properties in any way. The illustration is a homely one, but in my opinion the case is precisely parallel to that of slags.

sufficient to require a very great change in the slag composition. We will refer to this condition later.

"The amount of lime in these slags can be determined by subtraction, but it is necessary to remember that there is a small quantity of neutral material, CaS, FeO, MnO, etc., which may be taken at 3.5 per cent. in all cases as a close approximation to good practice. Following this procedure, the results shown in the first four columns of Table XI are obtained.

TABLE XI.—COMPOSITION OF SLAGS

	1	2	3	4	5 Ratio	6 Ratio	7 Ratio
	Al_2O_3 per cent.	SiO_2 per cent.	CaO by difference, per cent.	Neutral substances, per cent.	$\frac{CaO \div}{Al_2O_3 + SiO_2}$	$\frac{CaO + Al_2O_3 \div}{SiO_2}$	$\frac{CaO \div}{SiO_2}$
Virginia practice	6.5	36.0	54.0	3.5	1.27	1.68	1.50
Lake-ore practice	13.5	33.0	50.0	3.5	1.08	1.92	1.51
Special experiment	36.0	24.7	36.8	3.5	0.59	2.90	1.44

"Columns 5 and 6 present the ratios of lime to silica + alumina, and lime + alumina to silica. These ratios change from 1.27 to 0.59 in the first case and from 1.68 to 2.90 in the second case.

"No one can hope to show any relations between these ratios that can bear in any intelligible way on the variation of the alumina content.

"Column 7, however, shows the ratio of the lime to the silica, which is virtually a constant throughout. The result in the experiment is the lowest, and corresponds to the higher silicon in the iron.

"If the lime were increased in this latter case about 5 per cent. of its own weight, this slag would then have identically the same ratio as the others, and would be just about as much "limier" as would permit the production of basic iron by the addition of a little more burden.

"It may be claimed in opposition that the analyses chosen as representative of Virginia and Lake-ore practice have been taken with the object of showing the result desired rather than representing the typical slags. For the Virginia practice this certainly is not true, and if there be any error in the slag analysis for Lake ore, I do not know how to better it. Certainly no correction that could be made would fail to leave the lime-silica ratio infinitely nearer a constant than either of the others.

"It may be well to reiterate here that such a comparison is useful only in the case of furnaces on a comparable basis on other respects; that is to say, working for the same degree of desulphurization and the same silicon and using materials of about the same sulphur content.

"The question of the slag volume also enters here, and the question whether a given slag volume is as efficacious in the removal of sulphur when the alumina is high as when it is low. We know that if the slag exceeds a certain content of sulphur in ordinary practice, the desulphurization of iron will be incomplete, and if the alumina be simply a diluent, the effectiveness of the slag might be diminished in proportion as the percentage of the alumina rose.

"In spite of this theoretical consideration, the sulphur in the slags in the high-alumina experiments mentioned ran about 1.75 per cent. with perfectly satisfactory desulphurization, while the relative slag volume was little, if any, higher with alumina approaching 40 per cent. than with normal alumina.

"The decreasing grade of the ores available must result in the increasing use of many ores higher in alumina than those of present practice. If the laws governing its action are not known bad results are bound to follow.

"A furnaceman recently told me of a case in which the alumina had been regarded as an acid, and the slag had been calculated to give the same ratio of lime of silica + alumina as in standard practice, with the result that the furnace had been badly "bunged up" with lime.

"In conclusion, it seems worth while to point out that the increased viscosity accompanying high alumina may be of benefit in making foundry iron.

"That iron will not take up much silicon except at a relatively high temperature is well known, and as its melting temperature is relatively low, its tendency is to run down out of the region in which it can absorb silicon into the crucible.

"The fusion temperature of slag is much higher than that of iron, and being more viscous, it acts as a retardent on the iron and delays its descent so that it can acquire the necessary temperature.

"A too-fusible slag does not perform this function properly, and I have personally seen a case in which no reasonable reduction of burden would raise the silicon to ordinary foundry limits, but in which this was easily done by increasing the lime considerably beyond that necessary for desulphurization, in spite of the desiliconizing influence of the more basic slag. For the same reason it is more difficult to make foundry iron when enough magnesia is present to increase the fluidity of the slag, and a limestone as free as possible from magnesia should be used for making foundry iron for that reason.

"Now if alumina increases the viscosity of the slag without the accompanying desiliconizing influence of the limier slags of the same free-running temperature, then the introduction of the silicon into the iron should be facilitated by high alumina."

This paper was written in 1909 though published only in 1912. In the interval since all my experience has gone to confirm the opinions expressed therein, both as to the general effect of alumina and as to the entire possibility of using this element as a means of raising the free-running temperature of the slag without increasing its basicity, for the manufacture of high-silicon irons.

In very recent years a vast amount of work has been done under the auspices of the Carnegie Institution by G. A. Rankin, A. L. Day and E. S. Sheppard upon the melting points of the ternary system CaO — Al_2O_3 — SiO_2. Through the courtesy of Mr. Rankin I have obtained a copy of his paper bearing that title published in the *American Journal of Science*, vol. xxxix, which gives the results of these investigations. These are plotted on the triaxial diagram, and from the plot an actual model was constructed, photographs of which, reproduced from Mr. Rankin's paper, are shown at Figs. 61, 62 and 63.

Before discussing these results it may be well to call attention to the characteristics of the triangular diagram. They are based upon the fact that in an equilateral triangle the sum of the perpendicular distances of any interior point from the three sides is a constant, irrespective of the location of the point, and therefore the composition of any substance made up of three components may be graphically represented by the position of a point whose distances from the respective sides are represented

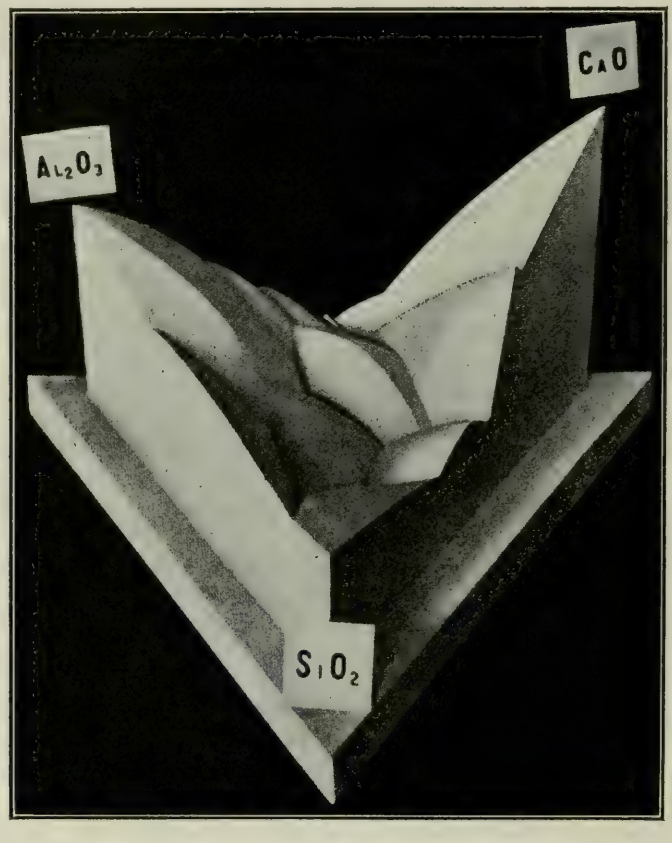


FIG. 61.—Photograph of solid model of concentration-temperature diagram of ternary system; showing relation of binary systems CaO—SiO_2 and Al_2O_3—SiO_2 to the ternary system.

by the percentages of the corresponding components. Each angle of the triangle represents one component unmixed with anything else. Any point on one side represents a compound consisting solely of the two materials represented by the two ends of that side without any of the third component, and the percentage of this third component increases in proportion to the perpendicular distance from this line. This explanation, with a little study of the diagrams, will give a clear understanding of the principle involved.

This enables us to plot the proportions of the three fundamental variables on one plane, and therefore to plot any independent function of all these upon ordinates normal to that plane (vertical). The surface passing through the tops of these ordinates furnishes a graphic representation of the variation of the independent variable with changes in the composition of the material under consideration.

The diagram in three dimensions was first used, as far as my information goes, by Professor R. H. Thurston in the middle seventies to portray

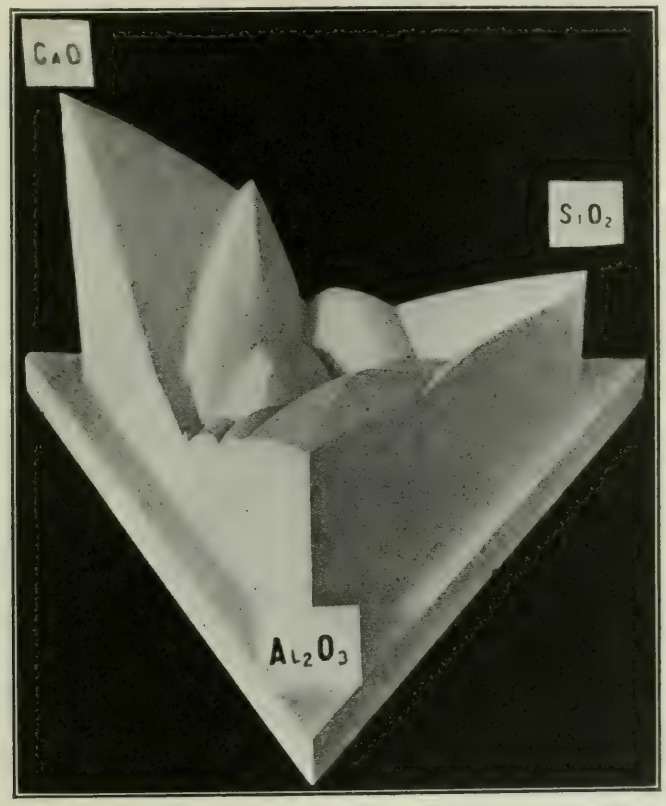


FIG. 62.—Photograph of solid model showing relation of binary systems $CaO—Al_2O_3$ and $Al_2O_3—SiO_2$ to the ternary system.

the results of an extensive investigation of the properties of the copper, zinc and tin alloys.

This form of model has been used more or less for slag diagrams and slag calculations for a number of years. Various references to it may be found in technical literature, notably in the *Transactions* of the American Institute of Mining Engineers.

A study of the photographs of Rankin's melting-point model shows, first of all, what may perhaps properly be called a general law of nature,

that the admixture with a given substance of a small amount of another substance always results in lowering the melting point, since a study of the different views of the model shows that in every case it slopes from the angles of the triangle down, and from the sides, in practically every case, it slopes downward toward the center, thus forming a sort of rough crater with high walls along the sides and much higher peaks at the apices of the triangle. The different ridges and valleys in the diagram are caused by the occurrence of different definite chemical compounds. These are indicated by Fig. 64.

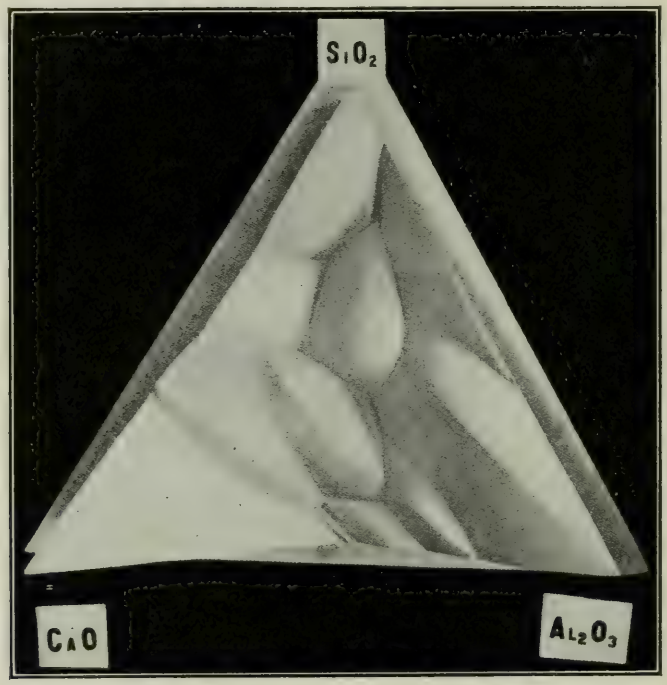


FIG. 63.—Photograph of solid model taken from above, showing relation of various fields.

This investigation is one of the most elaborate ever made, and is distinguished from most others, whose results were useless, by the fact that great pains were taken to secure not softening points, but complete liquefaction or melting in every case.

This diagram while interesting from the furnaceman's point of view is difficult to use because the range of alumina commonly and preferably used in furnace practice is only from 5 to 15 per cent., which confines us to quite a narrow belt parallel to the CaO—SiO_2 side, and within this belt we are further limited to the ratios of lime to silica which we are permitted to employ, especially in coke furnaces.

In order to make the result of this vast scientific work applicable to blast-furnace purposes at least in some degree, I obtained through the great kindness of Mr. Rankin three curves representing sections of the model along the planes of 5, 10 and 15 per cent. alumina. These curves have all been plotted on one diagram, Fig. 65, so as to make them comparative. The silica is taken as the independent variable, the alumina is constant on any one curve, and the lime may be obtained by subtracting the sum of the silica and alumina at any point from 100. The curves terminate at different points because obviously in the one representing 15 per cent. alumina the silica must be limited to 85 per cent., while in the one representing 5 per cent. alumina the silica can go to 95 per cent. Hence the right-hand limits of the diagram are not coterminous.

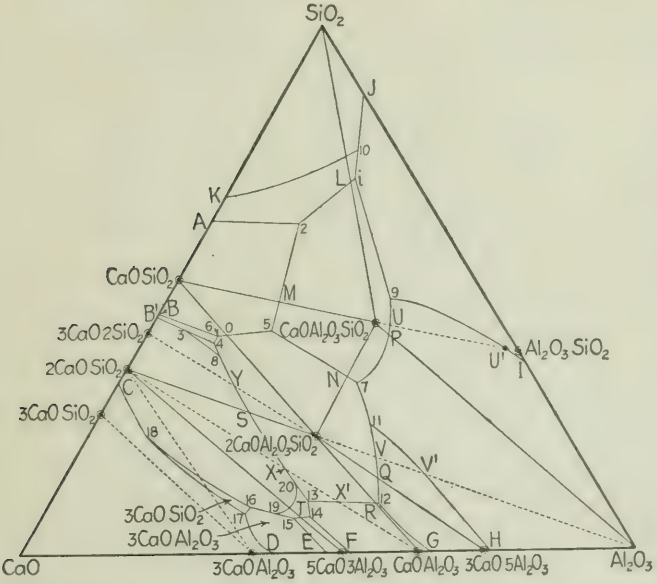


FIG. 64.—Diagram of the ternary system, showing the various binary systems within ternary system.

It will be seen that the diagram contains two sets of lines; the lower one is made up of short sections of vertical and horizontal straight lines, which show that the softening temperatures of the different compounds remain constant over quite wide ranges and then change by sudden jumps, while the changes in the temperature of complete fusion take place along continuous curves, although these latter contain three prominent cusps.

I have added to this diagram a reproduction on the same scale of the curve shown in Fig. 58, which gives, as already described, my judgment of the free-running temperatures of different slags containing about 15 per cent. alumina with different percentages of silica, this curve being drawn

as a result of observation and experience, with some pyrometer readings, covering a great many years, but on purely commercial slags always containing other ingredients besides the three represented in the diagram; notable among these are magnesia, calcium sulphide, manganese and iron.

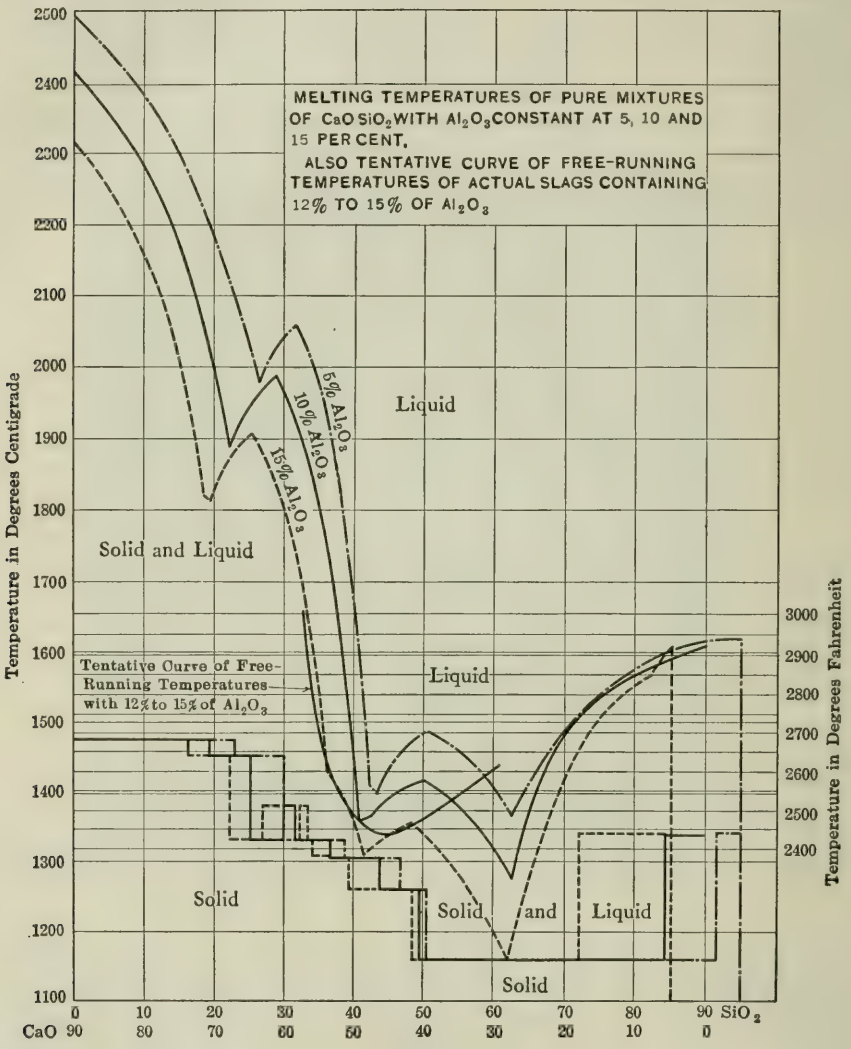


FIG. 65.

Considering that my curve was laid down simply in accordance with my experience, and entirely without reference to the correct scientifically derived curve of Mr. Rankin, its agreement with the curve for 15 per cent. Al_2O_3 is in my judgment quite remarkable. The fact that it lies in part below the Rankin curve, although it represents free-running temperatures

while the Rankin curves give melting temperatures, may be explained either by my being in error or, as I prefer to believe, by the presence of the other ingredients mentioned above, magnesia, calcium sulphide, etc., etc., which lower the melting point.

Assuming the reasonable correctness of my curve for free-running temperatures, the tremendous variation in the range between these and melting temperatures is well shown.

It will be noted that the low point corresponding on all the curves to about 62 per cent. silica is not reflected in my rough curve. I do not think that I ever ran a furnace on a slag containing more than 56 to 57 per cent. silica in charcoal practice, but I have run on one containing that amount. I have heard of others who have run furnaces on even leaner slags, containing up to 63 per cent. silica, but I have never heard that they noticed particular fusibility in that region. On the contrary, my own experience and that of others with whom I have talked concerning this little-known subject has been that these slags tended to make a hotter iron than one lower in silica. This is, in my judgment, for the reason that the increase in viscosity due to the higher silica more than compensates for the lower melting point.

I have noticed, however, in charcoal practice that slags of 49 to 51 per cent. silica, with about 12 per cent. alumina, were distinctly less desirable than slags of somewhat lower silica, which may very well correspond to the high point occurring on all three melting-point curves at or very close to 49 per cent. silica. As a result of this fact, I usually preferred to burden the furnace to produce a slag of 46 to 48 per cent. silica.

As a result of general observation I should say that the slags from 50 per cent. silica up were fusible at a lower temperature than those below that point, but as this fusibility was not of a kind which could be translated into free-running temperature it was not a matter of much moment; in fact, the free-running temperature of the slag in charcoal practice, especially with wet, rich ore, is immaterial, since we have seen that the limitation to fuel economy comes not from a deficiency of hearth heat but from a deficiency of shaft heat. This fact was reflected by the circumstance that we could change the lime-silica ratio of the slag over a very wide range without particularly affecting the fuel economy of the furnace. But the free-running temperature of the slag was of importance because it was quite generally believed that better iron could be made with more fusible slags. The belief, though rather vague and shadowy, was entirely justified by knowledge which we subsequently obtained as to the conditions controlling the quality of charcoal iron, all of which will be explained later.

The range between the scientifically determined melting-point curves and my approximate curve based on experience, which begins to increase at 50 per cent. silica, corresponds precisely to the varying range between

melting points and free-running points shown by Professor Fulton's curves. It will be noted that leaving out the two downward cusps due to the formation of definite compounds with a low melting point at 41 per cent. and 62 per cent. silica, the general course of my rough curve follows in a general way the scientifically determined melting-point curves; that is to say, the left-hand limb of the curve is very steep, the bottom section approximately horizontal, it then rises again on the right, but much more slowly and to a much smaller height, within any practical limits, than the left-hand limb.

In similar wise it will be noted that each increase of alumina, from 5 to 10 and from 10 to 15 per cent., corresponds to a distinct lowering of the fusion point throughout the entire practical range of furnace slags, but this again does not correspond to the facts of practice, and I think for the same reason, the increase in viscosity contributed by the alumina raises the free-running temperature of the slag above its melting temperature by an increased range equal to or greater than the reduction in melting temperature due to the presence of the alumina. This is partly contradicted by one experience of which I have heard. In that case the furnaceman considered that his alumina was too low for good work, and when it fell to about 10 per cent. it was deliberately raised by the addition of a more aluminous mixture. This, however, was on an old and badly worn furnace, and on a new furnace with good lines the same tendency did not manifest itself. The furnaceman concerned, who gave me this information, did not seem to feel very positive that he had either proved or disproved anything very positively in regard to this. On the other hand, I have had some experience which leads me to believe that low alumina is really beneficial, even though that fact may contradict the results shown by Mr. Rankin's diagram, for the reason that he determined melting points, whereas the blast furnace is concerned only with free-running temperatures.

Mr. Gilbert Rigg of the New Jersey Zinc Co. has done an immense amount of research work on slags, and has very generously discussed some of his results and conclusions with me.

His work has tended strongly to confirm my conclusions as to the marked difference in range between melting and free-running temperatures with different slags, and the decided effect of this difference in altering the physical action of the slag.

Mr. Rigg has suggested that when the slag is relatively acid, alumina acts as a base and partly masks the effect of the acidity, but when the slag is relatively basic the alumina tends to combine with magnesia and forms a magnesium silicate known as spinel, which is exceedingly infusible and by its presence very markedly stiffens the slag.

Moreover, Mr. Rigg states that magnesia and alumina when brought into intimate contact far below the fusion temperature of either or of

the resulting compound form a spinel. Such an action can have only the most serious result in the slag finally formed, and is probably responsible for the bad repute as a flux in which magnesia was held by some furnacemen, especially those of an earlier generation. There was a very general opinion at one time that the formation of spinel led to the building up of the hearth and all the bad consequences of that action. It is quite likely that this did occur in some cases, but I have no definite knowledge of the circumstances, and it does not seem to constitute a serious danger in modern practice. The subject of spinel, like the whole subject of slag, is one concerning which but little is known, or if known the knowledge is not generally available.

Gas in Slag.—All slag seems to contain a large quantity of gas, not in the form of bubbles, for these are often entirely absent, but presumably dissolved or, as we say to conceal our ignorance of the real conditions, "occluded." This gas may be seen passing off from the slag in large volumes as it runs from the furnace, but is most conspicuous when a ladle of molten slag is quickly dumped; a great cloud of gas is evolved from the running surface of the slag and ceases as soon as the slag ceases to flow, usually in a few seconds. This occurs when the slag is dumped on the dry, clean surface of the slag last dumped, and so cannot be caused by the presence of any foreign matter.

It is worthy of note that the gas evolved partakes of the nature of the top gas being produced at the time. If the furnace is working hot and well, the top gas is white and heavy, so also is the gas evolved from the slag; when the furnace is working "raw" or cold, the top gas is thin and clear, and the gas from the slag is the same, and apparently present in much smaller quantity.

No satisfactory reason for these changes in the top gas has ever been given so far as known to me, but the relation of cause and effect between the maintenance of the critical temperature of the slag and the proper work of the furnace, on one hand, and between the proper working of the furnace and the nature of the gas, on the other, is so close that one is led to suspect that the fume which gives the gas its thick white appearance is a product of a slag at its proper temperature, and that the gas evolved from the slag is simply a portion of the hearth gas dissolved in the slag. That this gas is combustible is clearly shown by its often burning when a small jet of it comes out through a crack in the pot, though the gas evolved at the time of dumping does not burn.

No considerable investigation of the nature and cause of this gas has ever been made so far as I know, but Mr. Rigg has suggested a very interesting possible result of its presence, which is that the presence of this gas may have a decided effect on the fluidity of the slag. Certainly it is true in a general way that the most fluid slag evolves the most gas.

Mr. Rigg has reinforced this suggestion by citing the case of certain

finely divided solids which, when heated, act exactly like liquids as long as they contain any "occluded" gas, but become simply hot granular solids when this gas is all driven off.

As an illustration and confirmation of the broad principles of the nature of slags above set forth there may be cited the following case which came within my experience:

About 1894, when the basic open-hearth furnace began its period of rapid development in this country, a sudden demand sprang up for what has since come to be universally known as basic iron; that is, iron suitable for this process. On account of the severity of the chemical specifications a small premium was offered over the price of mill iron, whose place it took, and the times being exceedingly hard, most furnaces selling iron below the cost of production, the incentive to earn the premium and make this iron was very great.

It is, I believe, generally admitted that the Longdale furnaces were the first to make this iron in such a way that a very large percentage of the total output came within the chemical specifications of silicon under 1 per cent., sulphur under 0.05 per cent. Other furnaces which made it in those early times ran the best they could under the conditions tending to make the desired product, picked out the suitable irons, and either sold the other at a reduction in price or remelted it.

At Longdale it was at first attempted to make this iron with the use of straight calcite or limestone as a flux, but the destruction of the furnace walls by the extremely basic and infusible slags so produced was very rapid and made the operation difficult and unsatisfactory. Steps were then taken to secure a supply of dolomite containing almost the theoretical percentage of lime and magnesia, and this was substituted for half the limestone in the charge. The result was almost instantaneous. The trouble with the eating away of the furnace walls ceased, and it became possible to run the furnaces regularly and continuously on iron of the specifications given, and it is probable that no furnaces ever exceeded the records of those furnaces in the percentage of good basic iron produced for many years thereafter. It is a matter worthy of remark that one furnace ran for a whole 6 months without making a single "off-cast." The reason for the success of these furnaces in making this iron was for many years a matter of speculation among iron and steel people. A part of it was undoubtedly due to the fact that not having high-blast heat available, nothing beyond 850°F., they ran on the high-burden low-temperature basis, and having iron pipe stoves, at an extremely regular blast temperature.

A further factor in addition to the above, all of which has been the subject of previous comment, is the fact (so far as I know never noted in this connection before) that these furnaces ran on an ore very low in alumina and quite high in silica, so that the alumina in the slag was

only about 7 per cent. Owing to the low viscosity of the slag, this tends to produce an iron considerably lower in temperature than the slag, the retardent action of the latter being reduced to a minimum. This fact I confirmed by pyrometric observations made many hundreds of times.

These furnaces, therefore, had for the making of this iron these advantages: the correct principle of manufacture, high burden and low lime, the correct or approximately correct proportion of lime or magnesia in the slag to give the lowest fusion point, very low alumina content to produce a "short," non-viscous slag, and so avoided superheating the iron.

The Loss of Iron in the Slag.—The slag losses of iron are of two kinds: First, iron chemically contained by the slag as a low oxide; second, fine shots of metallic iron mechanically suspended in the slag, and so small that their difference in specific gravity is not sufficient to make them settle out in the time available for that operation. This loss is considerably greater than is usually appreciated. It is probably safe to say that no furnaceman has ever taken up the subject either to investigate the matter or to recover the iron who has not been surprised at its amount.

A few years ago when operating a charcoal furnace from which the slag was crushed and used as road material, I found that between 0.1 and 0.2 per cent. of the weight of the iron was recovered in pieces picked out from the streets. A magnetic separator was installed in the expectation of being able to recover this amount by passing the crushed slag over it before shipment. To my great surprise we recovered three times the amount expected. This being a charcoal furnace the volume of slag was exceedingly small, about 400 or 500 lb. per ton of iron, or about half the slag volume in coke practice. Assuming that the coke slag contained as large a percentage of its own weight as the charcoal we should reasonably expect to recover almost 1 per cent. of the total iron made by a coke furnace if we could treat this slag the same way. (Since the above was written I find that this percentage is actually being recovered at some coke furnaces.)

At plants where special efforts have been made to settle the slag before disposing of it very respectable tonnages of iron per month are recovered almost without expense. Mr. Reese has probably carried this work further than anyone else, and has recovered iron in this way amounting to hundreds of dollars a month per furnace. Where the slag is handled in hot pots a visit to the slag dump will almost always reveal a vast number of stringers of iron which had evidently settled to the bottom of the ladle during its journey to the dump, and run out underneath the cinder when the ladle was emptied. This is a matter which will undoubtedly receive increasing attention as time goes on.

As regards the iron chemically contained in the cinder the conditions are very different; this is commercially quite impossible of recovery.

The amount varies with the kind of iron produced and the furnace practice—it is in a general way proportional to the color of the slag.

A white slag probably contains 0.1 per cent. of iron or under, while one which contains 1 per cent. of iron is dark brown or black. The black slags made when a furnace is in trouble contain much more than this. When a furnace is simply cold and making high sulphur iron, but still operating regularly, the percentage is likely to go up to 5 or 7, but when the furnace is in serious trouble, and the cinder too cold to be tapped in the regular way, it runs even higher than this in iron.

As a general thing conditions around the plant at such times are not conducive to scientific investigations of the slag, and not many have been made as far as my knowledge goes. But once or twice when a charcoal furnace under my management was in one of its periodical "messes" it produced a rather remarkable slag, and analysis of this showed about 25 per cent. of iron, and as I recollect it about equal amounts of lime and silica. This slag was almost as fluid as water in spite of an exceedingly low temperature. No determination of the latter was made, but basing the estimate on its appearance as compared with that of many slags whose temperature was determined, I should think that it did not exceed 1800°F. This slag was very interesting from another point of view. In spite of its fluidity it was evidently immediately at the temperature of solidification, because while the stream of slag flowed rapidly on account of its fluidity it was instantly covered with a frozen crust as it came out of the furnace, the whole surface of the runner being covered solidly over with this dead-black crust, and a good-sized hand ladle of the material, no matter how quickly it was dipped, was covered solidly with this black crust the instant it was dipped, though beneath it was full of this thin fluid slag at a red heat.

This, of course, does not bear on the question of the loss of iron in the slag in normal practice, since such conditions are about as far from normal as they can go without having the furnace absolutely frozen up. It is of interest, however, as showing that as the temperature drops the percentage of iron passing into the slag increases. In fact, all furnacemen who have brought a furnace through a serious "sickness" know that there are certain phases of furnace conditions in which the iron and slag do not separate, or only after a considerable interval of time, coming out of the furnace as a more or less homogeneous solution of one in the other.

In all matters concerning slags, and especially in trying to correlate with the results of practice scientific data based on the use of chemically pure ingredients, we must remember two vital facts: First, the oft-reiterated difference between melting temperature and free-running temperature; second, the important, and at times overwhelming, influence exerted by small quantities of foreign substances upon admixtures of chemically pure materials. All such substances as were mentioned

earlier—magnesia, calcium sulphide, oxides of manganese and iron, as well as the alkalies arising from the ash of the coke or occurring in the ore—have a marked tendency to produce silicates of lower melting temperature than those of lime and alumina, and we do not know what effect even small percentages of these materials may produce upon the melting point and free-running temperature of the actual furnace slags which always contain more or less of them.

At the present time it does not seem likely that we shall know anything about this until a great quantity of water has run under the bridges.

While this volume was undergoing final revision a paper on the "Viscosity of Blast-Furnace Slags" was published by Mr. A. L. Feild before the American Institute of Mining Engineers. The results obtainable by Mr. Feild's method of determining slag viscosity promise to increase our knowledge of this subject enormously. I regard the matter as so important that I reproduce here Mr. Feild's paper with some discussion of my own indicating what I believe to be the best course of investigation.

THE VISCOSITY OF BLAST-FURNACE SLAG[1]

By Alexander L. Feild,[2] a. b., m. s., Pittsburgh, Pa.

Introduction.—The Bureau of Mines is investigating the problem of slag viscosity, its variation with the temperature and with the composition of the slag, and its effect upon the distribution of the sulphur between molten iron and slag, as introductory to a series of contributions to the theory of the metallurgical processes. The method of measurement, viscosity apparatus, furnace and other accessories mentioned in this paper have been described fully in a Bureau of Mines report.[3]

The Literature on Slag Viscosity.—The viscosity of blast-furnace slag had not been measured previous to the investigation described in this report. A number of investigators have determined the "fusibility," or softening temperature, of slags by means of the cone method or other deformation method, but these methods supply only limited information regarding the temperature-viscosity relations of the slag in question. Any deformation method that may be employed indicates only the temperature at which the slag attains a more or less definite viscosity, the magnitude of the value obtained depending on the method used. For details of the various methods used by different investigators, see the Bureau of Mines paper already referred to. An isolated measurement by Doelter on a single mixture at 1300°C. represents the highest temperature reached in the various viscosity investigations previous to those described in this report, in which results have been referred to absolute units. Arbitrary deformation tests have of course been made at much higher temperatures.

[1] Published by permission of the Director of the Bureau of Mines.

[2] Assistant Metallurgist, U. S. Bureau of Mines.

[3] A. L. Feild: A Method for Measuring the Viscosity of Blast-Furnace Slag at High Temperatures, *Bureau of Mines Technical Paper* 157, 1916, 29 pp.

In these investigations the author has used a modification of the method originated by Margules[1] in 1881. In this method the liquid is confined between two concentric cylinders. The outer cylinder is rotated at a constant speed and the torque exerted upon the inner cylinder is measured. The method is applicable to liquids of a wide range of viscosity, and has been used, with modifications, by Gurney[2] in the accurate measurement of the viscosity of water. The principle of the method is used in the Stormer and Clark viscosimeters, and in those of Carmichael and Grosvenor, and of Kottmann.

The principle of the method employed by the author is therefore not a new one. The torsion method, however, had not hitherto been employed at all for measurements of viscosity at temperatures higher than are generally used in testing oils, etc., *i. e.*, about 250°C. Quite paradoxically it appears to be the only method of measurement which is possible experimentally over a large range of temperature and of viscosity, and for this reason may be called a quite universal method. In applying the method to temperatures as high as 1600°C., which is about 400°C. higher than the property of viscosity had been hitherto measured by means of any method, certain modifications in the construction of the apparatus were necessary and which alone made possible the attainment of a relatively great accuracy under the rather severe experimental conditions. These modifications consisted in the use of Acheson graphite in the construction of all parts of the apparatus subjected to high temperatures, and in the use of a system of damping the suspended system so as to give to it the stability and aperiodicity characteristic of the familiar damped D'Arsonval galvanometer.

The present modification of the method of Margules has been applied without difficulty to measurements on slags over a range of viscosity from 200 to 3000 (H_2O at 20°C. = 1). It is certain, however, that the method is applicable over a much wider range of viscosity than this.[3]

For a full discussion of the theory of the method the reader is referred to *Bureau of Mines Technical Paper* 157, pp. 7–10. It is sufficient here to say that the viscosity of the substance under examination is proportional to the torsion couple exerted on the inner concentric cylinder and inversely proportional to the speed of rotation in revolutions per second; while, conversely, the torsion couple is proportional to the viscosity and to the speed of rotation. With cylinders of fixed dimensions, therefore, and with the inner cylinder suspended by means of a calibrated steel ribbon, the viscosity of the slag melt is directly proportional to the product of the time of rotation of the outer cylinder and the deflection produced by means of the confined slag melt upon the inner cylinder.

The Application of Viscosity Data to Metallurgical Operations.—Before taking up the description of the viscosity apparatus, furnace, and accessories, and tabulation of the experimental results obtained, it is advisable to consider

[1] MAX. MARGULES: Über die Bestimmung des Reibungs—und Gleitungscoefficienten aus ebenen Benegungun einer Flussigkeit, *Sitzsungsberichte, Kaiserliche Akademie Wissenschaften* (*Vienna*) vol. 83, pt. 2, p. 588 (1881).

[2] L. E. GURNEY: The Viscosity of Water at Very Low Rates of Shear, *Physical Review*, vol. 26, pp. 98–120 (1908).

[3] See *Metallurgical and Chemical Engineering*, vol. 15, p. 541 (Nov. 1, 1916), where the application of the method to very viscous substances is discussed, with experimental data on a sample of asphalt over a range of viscosity from 80 to 4000.

briefly the application of accurate viscosity determinations on metallurgical slags to manufacturing processes, and also to related research in this field. Particular attention must be given in the present paper to a consideration of the principles of the metallurgy of iron, although in many other metallurgical operations, such as the smelting of copper for instance, a knowledge of the temperature-viscosity relations of different types of slag is of great importance.

Apart from the question of mining cost and freightage, the value of an iron ore sufficiently rich in iron to be considered marketable is largely dependent upon whether it can be made to yield economically a slag of desirable viscosity and desulphurizing power. A casual glance at the slag analyses in Table 1 shows at once the comparatively wide range of slag composition that has been found practicable by different manufacturers. In each case the particular slag composition was undoubtedly determined in a large measure by the composition of the ore mixture and fuel which it was deemed expedient to use, and also by the grade of iron produced. However, it is entirely probable that in certain cases the slag composition was not the optimum one from the standpoint of economy and excellence of product. It is one of the purposes of these investigations to determine what are the optimum conditions.

In spite of the lack of scientific research on the physical and chemical properties of slags at high temperatures, it is quite well understood what functions the slag must perform in the blast furnace. In the first place, it must be sufficiently fluid to flow from the cinder notch at the temperature which exists in the hearth. In the case of charcoal practice where desulphurization is a minor item, the viscosity of the slag at flush is a primary consideration. If, for instance, it is found that a siliceous charcoal slag possesses a viscosity of 800 at the temperature of the hearth, the question arises whether a limey slag would perform its functions properly if it possessed an equal viscosity. The limey slag may be prevented from performing these functions for one or both of the following reasons. In the first place, the limey slag with a viscosity of 800 might have an extremely high rate of change of viscosity with temperature, *i.e.*, this particular point on the temperature-viscosity curve might occur at a temperature where the slag underwent rapid softening or hardening with small changes of temperature. In the second place, it might not be at a sufficiently high temperature properly to desulphurize the pig iron.

The Desulphurization Process and Its Relation to Slag Viscosity.—The greater portion of the sulphur enters the furnace in the coke, in which it is present as ferrous sulphide to the extent of from 0.5 to 1.4 per cent. sulphur. The total quantity of sulphur is for practical purposes entirely distributed between the molten iron and slag.[1] It may be assumed quite safely that the sulphur which is dissolved by the pig iron exists as ferrous sulphide, FeS. On the other hand, it is necessary to assume in the case of the sulphur dissolved in the slag that it exists for the most part in normal slags as calcium sulphide, CaS. In high-manganese slags, however, it is probable that a portion of the sulphur exists as manganese sulphide.

According to the well-known distribution law of Nernst,[2] when a substance

[1] The results of Mr. James Bell given earlier indicates that this is not necessarily true since a considerable portion of the sulphur may be driven off with the gas.

[2] Walter Nernst: *Theoretical Chemistry*, pp. 485–487. New York, Macmillan & Co., 1904.

is distributed between two immiscible solvents, such as molten iron and slag, the ratio of the concentrations of the given substance in the two solvents, when the condition of equilibrium is reached, is constant for any given temperature, *provided* the dissolved substance has the same molecular weight in the two solvents. Moreover, in the case of several dissolved substances each substance distributes itself as though the others were not present.

Let us consider an ideal case where manganese is entirely absent from the slag and iron. Since calcium sulphide is insoluble in molten iron, the distribution effect must be that of ferrous sulphide between molten iron and slag. The ferrous sulphide present in the slag undergoes the following reaction:

$$FeS + CaO \lesseqgtr CaS + FeO. \qquad (1)$$

Since the concentration of lime, CaO, is very large in comparison with the concentrations of the other reacting substances, it may be considered to be a constant; wherefore, it would follow, from the general law in chemical equilibrium,[1] that the concentration of the ferrous sulphide of the slag is proportional to the product of the concentrations of the calcium sulphide, CaS, and the ferrous oxide, FeO.

Assuming ferrous sulphide to be distributed according to Nernst's distribution law, the concentration of the ferrous sulphide, and, therefore, of the sulphur, in the pig iron would be proportional to the product of the calcium sulphide and ferrous oxide concentrations in the slag layer, provided no other side reactions occurred.

However, there is a side reaction which must inevitably occur since ferrous oxide is not stable at high temperatures in the presence of carbon. This reaction is as follows:

$$FeO + C \lesseqgtr CO + Fe. \qquad (2)$$

On combining equations (1) and (2), the net effect is seen to be:

$$FeS + CaO + C \lesseqgtr CO + Fe + CaS. \qquad (3)$$

Equation (3) is the usual one given by most authorities to illustrate the course of the desulphurization process.

In the course of the chemical reaction represented by equation (3) it is necessary that FeS diffuse from the iron into the slag and also that the CaS, which is a product of the reaction, diffuse with sufficient rapidity to prevent the reversible reaction from coming to a standstill prematurely. For this reason the desulphurization reaction is conditioned largely so far as its speed is concerned by the viscosity of the slag, and resolves itself into a reaction confined to a great extent to the boundary plane between molten iron and slag. This boundary plane exists around the molten iron globules previous to their fall to the bottom of the hearth and between the contiguous layers of iron and slag in the hearth. To what extent desulphurization is completed previous to and during the fall of the iron globules though the slag layer is not known.

If it is true that during the smelting process equilibrium is reached under normal conditions in the case of the partition of sulphur between iron and slag, then the desulphurizing power of any given slag is independent of the viscosity of the slag, as such. In such a case the distribution of the sulphur would be a function only of the composition of the iron and slag and of the temperature of the hearth.

[1] Nernst: *op. cit.*, pp. 434–435.

However, if equilibrium is not reached under normal conditions, there cannot be in the strict sense of the word a distribution of sulphur, since the laws of distribution refer only to equilibrium conditions. In this case, the amount of sulphur absorbed by the slag depends on the speed of the reaction of desulphurization, which, as has been noted above, is conditioned by the viscosity of the slag, as well as by the temperature and composition of molten iron and slag.

With the help of the temperature-viscosity data of a number of different slags, obtained by means of the method which is described in this report, the Bureau of Mines is undertaking research investigations to determine the following facts: (1) By determining the speed of sulphide absorption by different slags at such temperatures as to possess identical viscosities, to deduce the effect due simply to differences of temperature and composition; (2) by determining the speed of sulphide absorption by the same slag at different temperatures, to deduce the effect due to changes in viscosity and temperature; (3) and by determining the speed of sulphide absorption by different slags at the same temperature, to deduce the effect due to changes in slag composition and in viscosity. Also, in each case, the final conditions of equilibrium are to be determined.

This work when completed should give a clear insight into the mechanism of the desulphurization process, and should be a test of the validity of the theory of Turner[1] and of Schafer,[2] that the silicate of the slag acts as a comparatively inert solvent for the spinels (aluminates) which alone are capable of reacting with the sulphide sulphur in the pig iron. According to this theory a slag low in alumina should possess a relatively weak desulphurizing power; and there should exist a lower limit of alumina content below which a slag could not be made to act satisfactorily in the blast furnace.[3]

The Relation Between the Composition of Blast-Furnace Slags and their Softening Temperatures Determined by the Cone Test.—Formerly in the absence of a method of viscosity measurement at the extreme temperatures of the blast-furnace hearth, it was customary for investigators to obtain an idea of the softening temperature or deformation temperature of slags by means of the familiar cone tests, in which test pieces similar to Seger cones are made from the slag and the temperature noted at which these test pieces bend over, melt to a ball, or otherwise show signs of incipient fusion.

In the ceramic industries and also in determinations of the fusibility of coal ash, cone tests furnish valuable information, since in these cases the important point in view is to determine the minimum temperature at which deformation or softening occurs. If, for instance, a firebrick softens appreciably at 1600°C., it is not a matter of technical interest to know how this brick would behave at 1800°C., nor would a cone test give any information in regard to this question.

Mellor[4] has defined the softening temperature concisely, as follows: "The

[1] *Journal of the Society of Chemical Industry*, 1905, p. 1142; *Stahl und Eisen*, vol. 26, No. 1, p. 172 (1906); *Metallurgie*, p. 164 (1906).

[2] *Ferrum*, vol. 5, p. 129 (Feb. 8, 1913).

[3] We have seen that such facts as we have, point to the reverse conclusion. —J. E. J., Jr.

[4] J. W. Mellor, A. Latimer, and A. D. Holdcroft: The Softening Temperatures of Lead-Silica Glasses, *Transactions of the English Ceramic Society*, vol. 9, pp. 126–149.

softening temperature measures the temperature at which the inward surface pressure of the substance becomes greater than those intra-molecular forces which hinder the molecules taking up a position of stable equilibrium-minimum surface area."

It is undoubtedly true that silicate mixtures at temperatures at or near their softening point possess a surface tension of considerable magnitude, as may be shown by the rounding off at the end of a glass rod when held in the flame of a Bunsen burner. What is observed actually is the resultant effect of decrease of viscosity and action of surface forces upon the softened body.

There are given in Table XII the softening temperatures and analyses of 18 commercial slags. These determinations were made in a platinum-wire resistance furnace in an atmosphere of air, temperatures being measured by a platinum-rhodium thermocouple. The sulphur content of the slag is accordingly entirely converted to the sulphate by the oxygen of the atmosphere, and possibly a portion was volatilized. The measurements cannot, therefore, be considered as representing entirely the conditions within the blast furnace with its atmosphere of carbon monoxide and nitrogen. The slags are arranged in the table in the order of increasing refractoriness.

TABLE XII.—SOFTENING TEMPERATURES OF SLAGS BY THE CONE TEST

Slag lab. No.	SiO_2	Al_2O_3	Percentage of		CaS	MnO	Softening temperature, °C.
			CaO	MgO			
22,967	48	8	32	5	2.0	0.1	1,244–1,254
22,965	38	10	40	4	3.1	1.2	1,262–1,264
22,964	38	9	43	2	2.4	0.2	1,263–1,266
22,968	44	9	40	2	2.7	0.2	1,279–1,279
22,960	37	11	25	20	3.5	2.2	1,297–1,300
22,958	34	27	27	6	4.9	0.3	1,342–1,342
22,953	36	12	41	6	3.1	0.7	1,331–1,346
22,956	35	11	42	7	3.6	0.5	1,352–1,357
22,963	34	14	41	6	3.4	0.6	1,343–1,360
22,969	34	12	43	6	3.2	0.5	1,358–1,364
22,961	34	15	38	10	2.9	0.3	1,365–1,368
22,955	32	16	44	1	4.4	0.1	1,356–1,390
22,952	32	12	45	6	3.4	0.5	1,383–1,391
22,957	31	15	36	10	5.5	0.2	1,388–1,398
22,954	18	35	31	10	4.1	0.3	1,410–1,410
22,966	33	11	44	4	5.9	0.5	1,425–1,441
22,962	32	15	48	2	3.5	0.2	1,403–1,443

While it is impossible to draw any definite conclusions as to the variation of the softening temperature with the composition from these measurements, it is at once evident that, in so far as the effect of silica is concerned, low softening temperatures are in general associated with high silica content in the slag. In regard to the effect of lime or of alumina the data in the table yield nothing conclusive.

As is well known, the softening of a silicate mixture such as blast-furnace slag depends upon the amount of eutectic which is formed during incipient fusion and

upon the viscosity of this eutectic. It is obvious that, given a sufficient amount of this eutectic to overcome the rigidity imparted to the test piece by the unfused portion, deformation will occur even though the eutectic possesses an extremely high viscosity. This softening may require time on account of the high viscosity of the eutectic mixture, but in cone tests sufficient time is usually furnished for this slow deformation.

Reference to the work of Rankin and Wright[1] at the Geophysical Laboratory on the system lime-alumina-silica, shows that the minimum ternary eutectic of this system is composed of CaO, 23.25 per cent., Al_2O_3, 14.75 per cent., and SiO_2, 62 per cent., which melts at a temperature of 1170°C. Further examination shows that in all cases low-melting binary or ternary eutectics in the system lime-alumina-silica correspond to a higher silica content than is usually found in blast-furnace slags. Therefore, in all blast-furnace slags which possess more than the usual amount of silica there is formed on incipient fusion a large amount of a low melting eutectic, which when it attains a sufficiently low viscosity, causes the test piece to soften and deform visibly.

It follows that high-silica slags, which are known to be more viscous at furnace temperatures than more basic slags, possess quite paradoxically a very low softening temperature. One might attempt to explain the high viscosity of siliceous slags in practice by claiming that such slags produce a low hearth temperature, and that the high viscosity is due to the low temperature of the slag. Whether this be true or not, the measurements which have been made in these investigations show conclusively that at all practicable hearth temperatures a siliceous slag is much more viscous than a normal slag at the same temperature.

If, therefore, one should assume that the slags given in Table 1 required the same amount of superheating above the softening temperatures there given, 200°C., for instance, no importance could be attached to subsequent deductions, because actual measurements of viscosity and temperature show that during a range of 200° of superheating certain slags attain a fluidity three times as great as others.

Emphasis should be placed upon the distinction between the physical melting point and the softening temperature of silicate mixtures, which latter is often loosely referred to as the "melting point." The former refers to a temperature which is perfectly definite in the case of the majority of silicate mixtures, viz., the temperature at which the *last* crystalline phase disappears upon slowly raising the temperature of the melt. Only in the case of silica[2] itself and certain alkaline feldspars[3] does the physical melting point appear to be a rather uncertain point. The softening temperature may differ enormously from the physical melting temperature, nor can deductions be made simply on the basis of melting-point determinations as to the relative positions of the softening and melting points, with

[1] G. A. Rankin and C. E. Wright: Ternary System: $CaO - Al_2O_3 - SiO_2$, *American Journal of Science*, ser. 4, vol. 39, pp. 1–79 (1915).

[2] C. N. Fenner: The Stability Relations of the Silica Minerals, *American Journal of Science*, ser. 4, vol. 36, pp. 331–384 (1912).

[3] A. L. Day and E. T. Allen: The Isomorphism and Thermal Properties of the Feldspars, with optical study by J. P. Iddings, *Publication* No. 31, *Carnegie Institute of Washington*, 1905.

respect to each other. For complete information in regard to the melting points and stability relations of the silicates the reader is referred to the monumental work[1] of Day, Shepherd, Rankin, Wright, Merwin, and Sosman at the Geophysical Laboratory.

Slag Temperatures Measured at the Blast Furnace.—In the course of the investigations described in the present paper a number of attempts were made by the author, with the coöperation of Dr. J. K. Clement, physicist of the Bureau of Mines, to determine slag temperatures by means of a Holborn-Kurlbaum optical pyrometer. The conclusion reached in the course of these observations was that, due to the impossibility of obtaining a clean surface on the outflowing slag and of obtaining a slag which was entirely free from fumes, such measurements, at the best, were liable to a very large error. Accordingly a special type of platinum platinum-rhodium thermocouple was constructed, the inner mechanism of the couple being protected by a sheath of Acheson graphite where subjected to the action of the molten slag.

For the sake of comparison, a number of simultaneous measurements of temperature by means of the optical pyrometer and thermocouple were made at furnaces Nos. 2 and 3 of a large Pittsburgh steel company. For purposes of illustration a few of these results are given in Table XIII.

Table XIII.—Temperatures of Slag at Flush by Means of Holborn-Kurlbaum Optical Pyrometer and Platinum-Rhodium Thermocouple

Date	Flush	Temperature	
		H. K. pyrometer	Thermocouple
Furnace No. 2:		°C.	°C.
Jan. 24, 1916.....	2d, a.m.	1,487	1,470
.....	3d, a.m.	1,487	1,572
Furnace No. 3:			
Jan. 24, 1916.....	1st, a.m.	1,465	1,525

Further measurements were made with the thermocouple alone. Some of these measurements are given in Table XIV.

[1] A. L. Day and E. S. Shepherd: The Lime-silica Series of Minerals, with optical study of F. E. Wright, *American Journal of Science*, ser. 4, vol. 22, pp. 265–392 (1906).

E. S. Shepherd and G. A. Rankin: The Binary Systems of Alumina with Silica, Lime and Magnesia, with optical study by F. E. Wright, *American Journal of Science*, ser. 4, vol. 28, pp. 293: 333 (1909). Preliminary Report on the Ternary System $CaO - Al_2O_3 - SiO_2$; a Study of the Constitution of Portland Cement Clinker, with optical study by F. E. Wright, *Journal of Industrial and Engineering Chemistry*, vol. 3, pp. 221–227 (1911).

G. A. Rankin and F. E. Wright: Ternary System $CaO - Al_2O_3 - SiO_2$, *American Journal of Science*, ser. 4, vol. 39, pp. 1–79 (1915).

G. A. Rankin and H. E. Merwin: The Ternary System $CaO - Al_2O_3 - MgO$. *Journal of the American Chemical Society*, vol. 38, pp. 568–588 (1916).

R. B. Sosman: The Common Refractory Oxides, *Journal of Industrial and Engineering Chemistry*, vol. 8, pp. 985–990 (1916).

TABLE XIV.—TEMPERATURE OF SLAG BY MEANS OF A PLATINUM PLATINUM-RHODIUM THERMOCOUPLE

Date	Furnace No.	Temperature, °C.	Date	Furnace No.	Temperature, °C.
Jan. 25, 1916.....	2	1,515	Jan. 25, 1916	2	1,415
.....	3	1,485	.....	2	1,490
.....	3	1,502	.....	2	1,538
.....	3	1,440	.....	3	1,475

The average temperature at flush by means of the thermocouple was, on the basis of the data given in Tables XII and XIII, equal to 1500°C. for furnace No. 2, and 1485°C. for furnace No. 3, with a variation in temperature at flush during the day of 108°C. (the 1415° reading is omitted since its correctness is questionable) in the former case, and of 85°C. in the second case. Both furnaces appeared to be working perfectly normally, so far as could be judged from the behavior of the slag at flush.

Table XV gives the analysis of the slag from both furnaces on the day upon which the temperature readings were taken.

TABLE XV

	Furnace No. 2, per cent.	Furnace No. 3, per cent.
SiO_2.....	35.18	37.60
Al_2O_3.....	12.08	12.46
CaO.....	43.73	40.80
MgO.....	4.23	3.66
CaS.....	4.21	3.65
MnO.....	0.39	0.55
	99.82	98.72

An examination of what Johnson calls the curve of free-running temperature[1] shows a decided minimum at a silica content of approximately 44 per cent., this minimum free-running temperature corresponding to 2450°F. or 1339°C.

The results of the present investigations demonstrate conclusively that, for alumina content approximating 12 per cent., the slags of minimum free-running temperature correspond with a certain degree of approximation to a silica content of 36 per cent., rather than 44 per cent.

It is of interest to note that such a silica content (36 per cent.) corresponds to average blast-furnace practice using coke as fuel.

Of course, in charcoal practice using high-silica slags, it is possible to work with a more viscous slag than is the case in coke practice. However, in constructing such a curve as given by Johnson, the term "free-running temperature" necessarily refers to a temperature corresponding to a definite and constant viscosity.

The Temperature-viscosity Relations of Graded Series of Synthetic Slags.—The only satisfactory method of studying the temperature-viscosity relations of

[1] See Fig. 58.

blast-furnace slags and the effect of the different constituents on the viscosity is the determination of such relations for a graded series of synthetic slags in which one constituent is gradually replaced by another. Such investigations are now in progress in these laboratories.

To illustrate the experimental results which are being obtained, there is shown in Fig. 66 the temperature-viscosity relations of a synthetic slag containing 48 per cent. lime (curve A) and of a synthetic slag of the same composition except

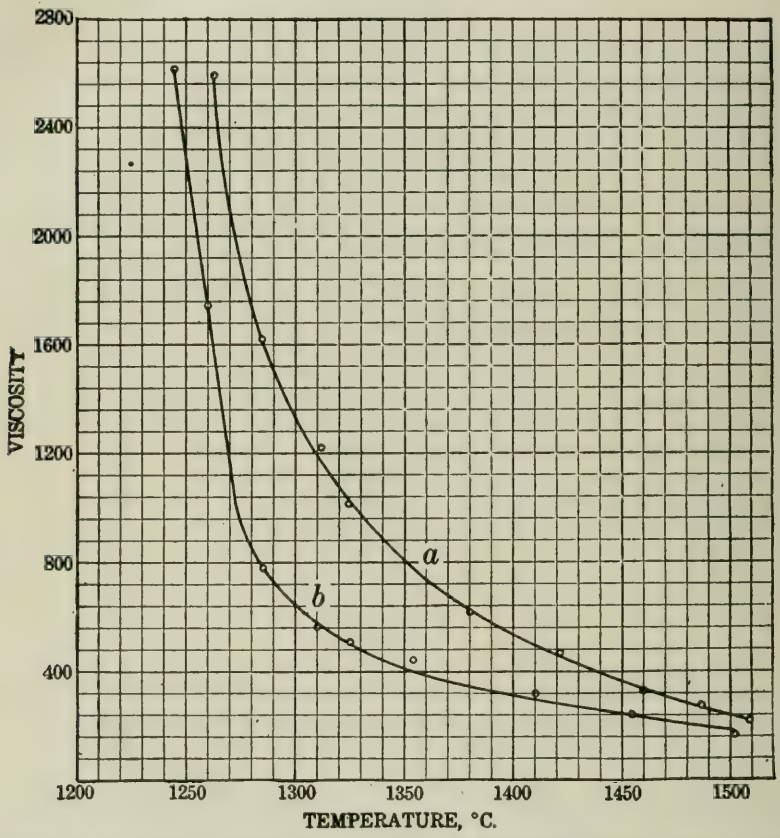


FIG. 66.—*a*, Temperature viscosity curve of synthetic slag containing 48 per cent. CaO. *b*, Same slag in which 20 per cent. CaO has been replaced by 20 per cent. MgO.

that 20 per cent. of the lime has been replaced by an equal percentage by weight of magnesia.

Description of Furnace and Accessories.—The electric furnace used in the experiments of the author is of the granular carbon, resistance type, and is similar as regards the arrangement of resistor and supporting refractories to the one described by Jeffries.[1] The arrangement of the furnace and accessories are shown in Fig. 67. This is also described fully in *Technical Paper* No. 157 of the Bureau of Mines.

[1] ZAY JEFFRIES: Notes on the Gran-Annular Electrical Furnace, *Metallurgical and Chemical Engineering*, vol. 12, pp. 154–157 (March, 1914).

Rotating Device.—A ¾-in. steel shaft, by means of which the cylindrical crucible containing the slag is rotated, projects up into the furnace through a stuffing box placed centrally in the base of the sheet-iron shell. The lower end of the shaft is supported on a bearing fixed to the tripod. The steel shaft extends only a short distance beyond the bottom of the furnace shell, and is bored for the reception of a slightly smaller supporting rod of Acheson graphite. This supporting rod is threaded at its upper end for the reception of the graphite slag

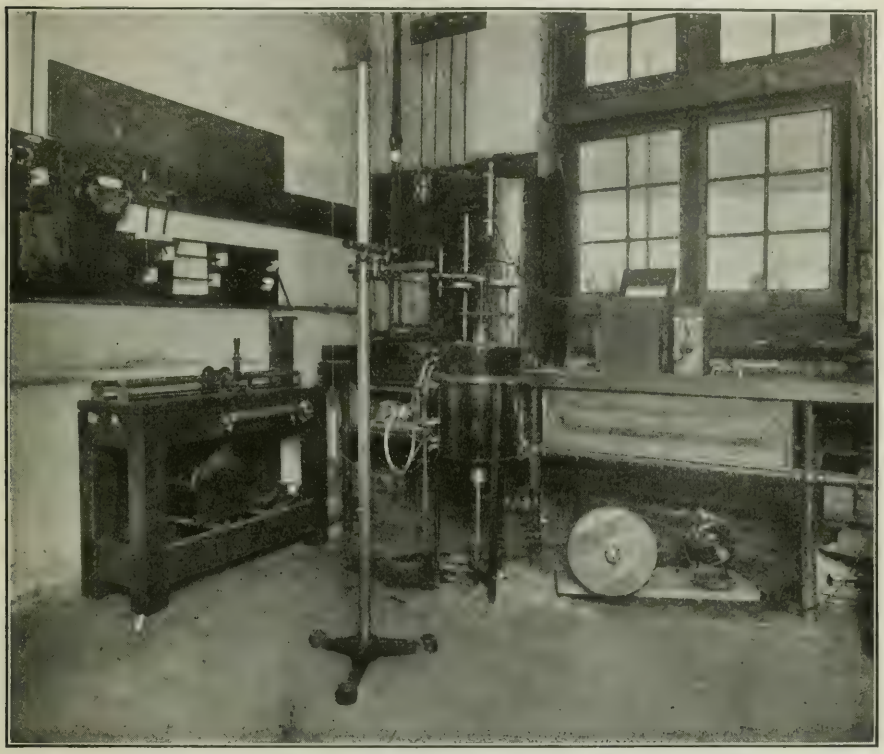


FIG. 67.—Apparatus for measuring viscosity of blast-furnace slags.

crucible (Fig. 68), the graphite rod being tapered at its upper end to a diameter of ⅜-in. in order to eliminate, as far as possible, conduction of heat from the crucible. The crucible possesses an inside diameter of ¾ in. and an inside depth of 3 in., with a thickness of wall of ¼ in. The bottom of the crucible is ½ in. thick, so that the rod may be firmly threaded into it. The supporting rod fits snugly into the hole in the axis of the steel shaft to a depth of 2½ in., and its length between the top of the steel shaft and the bottom of the crucible is about 6 in. In the earlier experiments with the method it was thought necessary to introduce a Marquardt porcelain rod between the crucible and steel shaft to prevent excessive heat conduction. By using a graphite rod tapered down to a diameter of only ⅜ in., no excessive heat conduction has been noted; and this also eliminates the undesirable experimental features of using a brittle porcelain part in the supporting system.

Source of Heat.—The heating current is supplied by a transformer equipped with an adjustable panel which gives voltages ranging from 40 to 100 volts in steps of 2 volts. The maximum power input amounts to slightly over 5 kva. and the maximum current to 110 amp.

Furnace Atmosphere.—The normal atmosphere of the furnace is a mixture of carbon monoxide and nitrogen, corresponding to that in the hearth of the blast furnace.

Viscosity Apparatus.—Acheson graphite seems to be the only refractory available for such use as that of high-temperature viscosity measurements on blast-furnace slag. This possesses the advantages of having a very low coefficient of expansion, a relatively great mechanical strength at high temperatures, desirable working properties, and shows inappreciable alteration on being kept

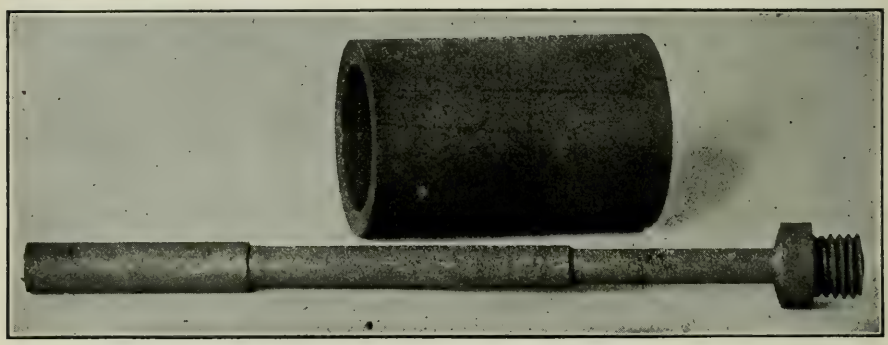


FIG. 68.—Graphite crucible and supporting rod.

for long periods at high temperatures. The action of the molten slag on the viscosity spindle immersed in it is so small that the radius of the spindle decreases only approximately 0.005 cm. during a viscosity determination. The action of the slag is perfectly uniform over the surface of the spindle, so that the same spindle may be used repeatedly, due allowance being made for the slight change in its radius.

The construction of the viscosity spindle and connecting rod is shown in Fig. 69. The large cylindrical part, *a*, at the base of the spindle (on the left of the figure) dips into the molten slag, while the upper part is threaded into the base of the connecting rod (shown in the right of the figure). This connecting rod is also made of graphite, except for the steel cap at its upper end, *d*, by means of which the connecting rod is in turn attached to the upper part of the suspended system shown in Fig. 70.

The distance from the surface of the slag to the bottom of the steel suspension (*r*, Fig. 70) is approximately 21 in. Such a system would not in itself be at all stable under the conditions of measurement. It was therefore necessary to place a weight of about 200 grams between the suspension ribbon and the spindle at a point just outside the furnace shell and about 4½ in. below the suspension. This weight gives stability to the system, decreases the effect of vibrations upon the mirror, and holds the spindle in its position in the slag mass. Moreover, in order to further increase the inertia of the system about its longitudinal axis and to

render the system aperiodic and practically non-susceptible to disturbing influences of short duration, the 200-gram weight (see *w*, Fig. 70) is furnished with two diametrically opposite vanes (*v* and *v'*) which dip into cups filled with a viscous fluid, such as castor oil, at a distance of about 4 in. from the axis of the system.

The mirror deflection is measured in the usual way by means of a telescope and scale.

The entire suspension system is fixed to a rod that projects horizontally from an apparatus support, firmly fixed to a heavy table and provided with a milli-

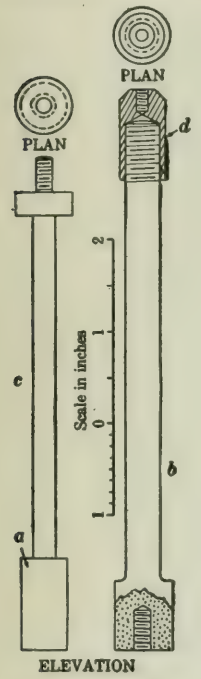


Fig. 69.

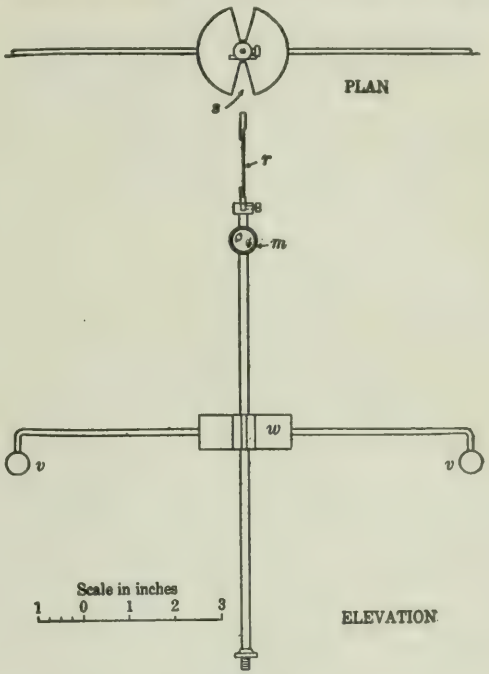


Fig. 70.

Fig. 69.—Viscosity spindle and connecting rod. Left view, viscosity spindle—*a*, graphite spindle; *c*, spindle shaft. Right view, connecting rod—*b*, graphite rod; *d*, steel connecting collar.

Fig. 70.—Upper part of suspension system. *m*, Mirror; *r*, steel suspension ribbon; *s*, open sector, *w*, weight; *v*,*v*, vanes.

meter scale for precise vertical adjustment of the apparatus. The furnace itself is first adjusted so that the steel shaft is in a vertical position, which insures the alignment of the crucible also. The point to which the suspension system is fixed is then aligned by means of a plumb bob with the axis of the shaft and crucible. In this manner the viscosity spindle is suspended centrally within the crucible.

The fluctuation of the scale reading rarely amounts to more than 1 per cent. of the scale reading. It is probable that the mirror reading which is a measure of the viscosity of the slag is more precise than the reading of temperature in certain cases, although not so accurate.

The Measurement of Temperature.—The temperature of the slag was measured by means of an optical pyrometer of the Holborn-Kurlbaum type. The pyrometer is sighted directly upon the surface of the rotating slag through an open sector in the 200-gram weight (see Fig. 70.)

As a check on the black-body conditions of the furnace used in the viscosity measurements, a sample of artificial diopside, $CaO.MgO.2SiO_2$, was prepared, and its temperature-viscosity relations determined in the same manner as adopted in the case of slags. This compound has a physical melting point at 1392°C. and is converted, coincidently with its melting, from a crystalline substance to a fairly fluid liquid.

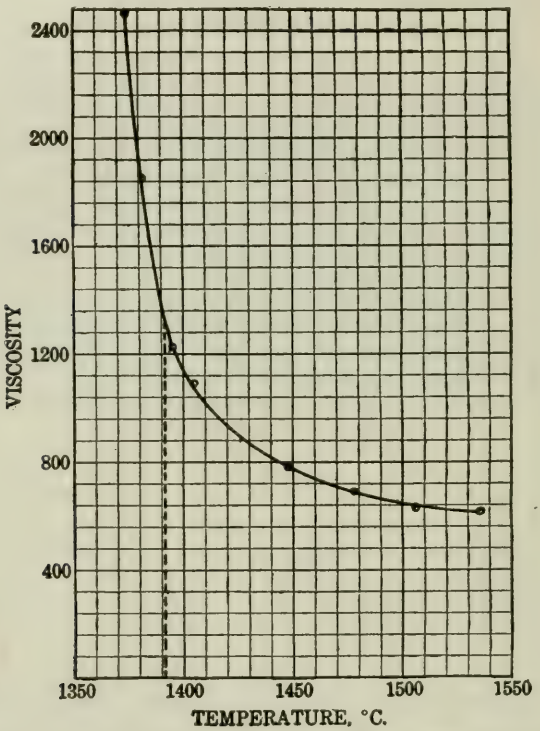


FIG. 71.—Temperature-viscosity curve of an artificial diopside.

The results of these measurements are given in Fig. 71. The viscosity curve bends quite sharply upward in the neighborhood of the theoretical melting point, the observed difference of about 20°C. being probably due to the fact that the artificial diopside did not have exactly the theoretically correct composition. Analysis of the artificial diopside gave the following composition: CaO, 25.98 per cent.; MgO, 19.48 per cent.; SiO_2, 55.08 per cent. The correct composition is: CaO, 25.84 per cent.; MgO, 18.58 per cent., SiO_2, 55.58 per cent.

Operation and Manipulation of Apparatus.—The method of using the apparatus is as follows: 175 grams of slag is placed in the graphite crucible. This quantity of slag, when ground to 100 mesh, approximately fills the crucible. Although the height of the crucible internally is 3 in. the slag after having been

melted and cooled forms a cylinder only about 1⅝ in. in length. The crucible, containing the slag, is properly placed, and the upper removable part of the furnace is fixed in position. The crucible is then rotated and the furnace is heated at such a rate that at the end of about 1½ hr. the slag reaches a temperature of 1200°C. The rate of heating is then decreased in order that the large mass of slag may acquire the temperature of the heating tube and diminish the lag effect. When the slag has become sufficiently fluid, as determined by several tentative lowerings of the viscosity spindle, the suspension system is carefully lowered until the viscosity spindle rests on the bottom of the crucible. During this operation the rotation of the crucible is stopped in order to avoid the possibility of breaking the spindle while it is being introduced into the viscous slag. The spindle is then raised exactly 0.5 cm. above the bottom of the crucible, the adjustment being made by means of the scale in the apparatus support.

After the suspension system has been lowered and the depth of the viscosity spindle adjusted, the temperature of the slag is slowly raised at a rate of 2° to 5°C. per minute, the temperature and scale deflection being noted at approximately regular intervals. When the highest temperature desired, usually 1500° to 1600°C., is reached, the heating current is so adjusted that the furnace cools at approximately the same rate that it was heated. Readings of deflection and temperature are taken, until the maximum deflection (corresponding to a viscosity of 2000 to 3000) is reached. The spindle is then raised out of the slag before the latter becomes hard enough to prevent withdrawal.

Calibration of the Viscosity Apparatus.—For the method of calibration used, the reader is referred to *Technical Paper* 157, p. 18. Measurements are referred to the viscosity of water at 20°C. as unity. In order to convert to c.g.s. units, these values should be divided by 100.

Results of Viscosity Measurements.—The results of viscosity measurements on eight different commercial slag samples (Lab. Nos. 22,954, 22,962, 22,958,

TABLE XVI.—THE VISCOSITY OF TYPICAL BLAST-FURNACE SLAGS AT VARIOUS TEMPERATURES

[H_2O at 20°C. = 1]

Temperature, °C.	Viscosity of slag, lab. No.							
	22,954	22,962	22,958	22,963	24,016	23,663	22,960	22,968
1,275	.....	.....	.....	1,400	2,600			
1,300	.....	.....	1,700	1,000	1,500	.....	1,900	
1,325	.....	.....	1,060	820	1,080	2,000	1,100	3,000
1,350	2,600	.....	800	680	800	740	840	1,800
1,375	1,150	.....	640	540	620	560	640	1,220
1,400	750	3,000	510	460	500	480	510	1,000
1,425	540	580	420	400	420	410	440	820
1,450	410	480	350	350	350	360	380	680
1,475	320	415	300	310	290	300	320	580
1,500	230	380	260	280	250	250	280	480
1,525	160	340	225	250	230	200	240	400
1,550	.....	290	.....	220	205	.....	.....	340
1,575	.....	.....	.....	.....	.....	.....	.....	310

22,963, 24,016, 23,663, 22,960, and 22,968) are given in Table XVI for the temperature range 1275° to 1575°C. The composition of the slags is shown by the results of chemical analyses given in Table XVII.

TABLE XVII.—RESULTS OF ANALYSES OF THE EIGHT SLAGS

Lab. No.	Composition of slag												Total
	SiO_2	Al_2O_3	Fe_2O_3	FeO	Fe	TiO_2	CaO	MgO	MnO	CaS	Alkalies	Moisture	
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
22,954	18.30	35.30	0.00	0.47	0.05	0.58	31.24	9.69	0.35	4.07	0.50	0.02	100.57
22,962	31.54	14.79	0.00	0.07	0.22	0.29	47.65	1.80	0.21	3.56	....	0.10	100.23
22,958	33.67	26.62	0.00	0.28	0.51	0.28	26.67	6.43	0.33	4.86	....	0.12	99.77
22,963	34.27	13.78	0.00	0.07	0.28	0.56	41.30	6.39	0.55	3.35	....	0.04	100.59
24,016	35.76	a13.36	....	....	....	....	42.11	3.94	0.49	3.70	....	....	99.36
23,663	36.04	a12.10	....	....	....	....	42.04	4.03	0.35	3.92	....	....	98.48
22,960	37.18	11.46	0.00	0.31	0.11	0.52	25.33	19.58	2.21	3.51	....	0.04	100.25
22,968	43.56	9.48	0.00	0.21	0.38	0.19	40.18	2.08	0.21	2.75	0.50	0.05	99.59

a Includes Fe and FeO_2 as FeO_3 not correct.

Temperature-viscosity curves were plotted, as shown in Figs. 72 to 75 for slags Nos. 22,954, 22,958, 23,663, and 22,968. The curves closely approximate in form

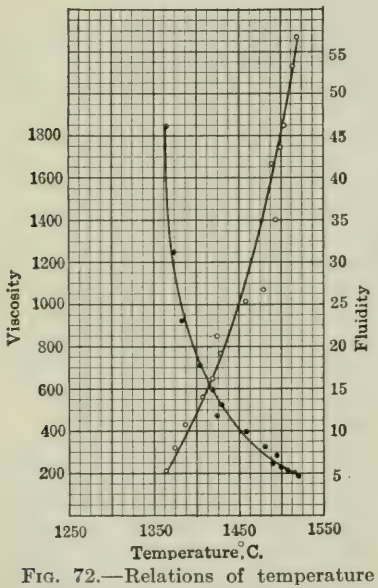


FIG. 72.—Relations of temperature to fluidity and viscosity shown in experiments with slag No. 22,954.

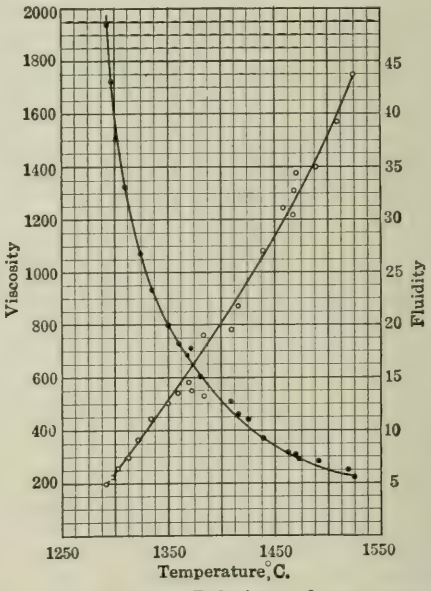


FIG. 73.—Relations of temperature to fluidity and viscosity shown in experiments with slag No. 22,958.

a rectangular hyperbola. These figures contain all the experimentally determined points obtained in the heating and cooling of the sample, so that a smooth curve drawn through all the points must represent very closely the ideal conditions desired, the deviations tending to neutralize one another.

The temperature-fluidity curves are also given in Figs. 72 to 75 for the four slags mentioned above. The values are calculated by means of the familiar relation, Fluidity = 1/Viscosity. As was to have been expected from the general shape of the viscosity curves, the curves representing fluidity at various temperatures approximate in form a straight line. The actual experimental data obtained in

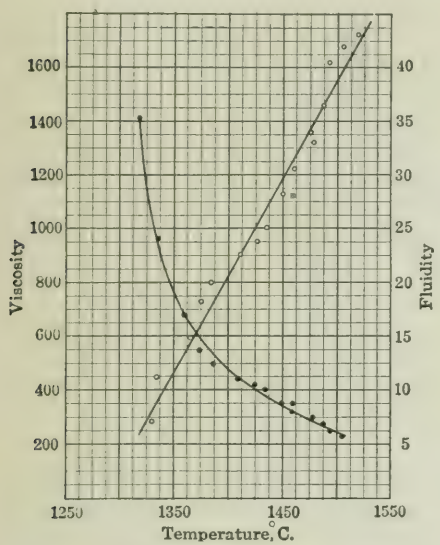


FIG. 74.—Relations fo temperature to fluidity and viscosity shown in experiments with slag No. 23,663.

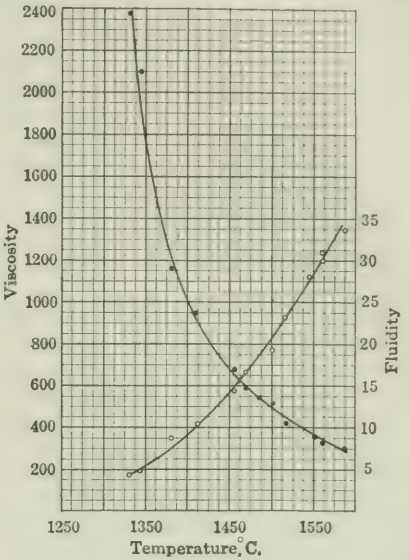


FIG. 75.—Relations of temperature to fluidity and viscosity shown in experiments with slag No 22,968.

the case of slag No. 22,958 are given in Table XVIII, which contains results obtained with rising and falling temperatures.

TABLE XVIII.—COMPARISON OF VISCOSITY VALUES OBTAINED WITH RISING AND FALLING TEMPERATURES

[Results obtained in experiments with slag designated Lab. No. 22,958]

Rising temperature		Falling temperature [a]			
Temperature, °C.	Viscosity	Temperature, °C.	Viscosity	Temperature, °C.	Viscosity
1,382	605	1,292	1,940	1,382	611
1,410	513	1,297	1,707	1,387	524
1,415	460	1,302	1,505	1,425	446
1,425	442	1,312	1,319	1,440	375
		1,322	1,074	1,466	323
1,463	320	1,337	922	1,470	304
		1,350	805	1,488	285
1,473	291	1,359	728	1,525	228
1,510	255	1,368	689		

[a] Results are given in reverse order, for easy comparison with results under "Rising Temperature."

Duplicate determinations on separate samples of the same slag gave results which agreed well within the known errors of measurement. In Table XIX are given the results of duplicate determinations on slag No. 23,663. The deflections observed with falling temperature are given for both slags, these deflections being proportional to the viscosity of the melt.

TABLE XIX.—DUPLICATE MEASUREMENTS ON SLAG NO. 23,663.

Original		Duplicate	
Temperature, °C.	Deflection	Temperature, °C.	Deflection
1,510	26		
1,487	31	1,487	32
1,477	34	1,472	34
1,460	38		
1,450	39	1,450	40
1,435	40	1,440	40
1,425	42	1,430	43
1,410	44	1,410	45
1,387	48	1,387	48
1,337	90	1,347	82

General Appearance of Slag Melts.—When cold the slag was easily removed from the graphite crucible by pressing on the bottom of the melt through the hole into which the graphite crucible support is threaded. The slag on cooling shrinks away from the graphite crucible wall sufficiently to prevent objectionable binding and sticking. The melt as taken from the crucible is cylindrical with an upper surface which is almost flat, as the viscosity at the moment when the spindle was withdrawn was not great enough to prevent the slag from flowing into the space previously occupied by the graphite spindle.



FIG. 76.—Fragments of slag melts after cooling, showing general shape and structure.

Fig. 76 shows photographs of six fragments of slag melts after removal from the crucible. Samples Nos. 1 and 3 (reading from left to right) are the upper and lower portions of the same melt (slag No. 22,968). Sample No. 2 is a fragment of melt from slag No. 22,954, while sample No. 4, containing the lower end of a viscosity spindle embedded in it, is a fragment from a duplicate determination on the same slag. In this case the spindle was not removed soon enough, and in attempting to do so the shaft was broken off at the surface of the melt. Sample

No. 5 is a fragment of the artificial diopside melt used in calibrating the black-body conditions of the furnace, as described hitherto. The crystalline structure of this melt is easily seen from the photograph. Sample No. 6 (on extreme right of photograph) is a fragment of a synthetic slag melt which does not differ greatly in composition from that of gehlenite, $2CaO.Al_2O_3.SiO_2$. The network of large crystals seen in the photograph of this melt are presumably crystals of gehlenite.

Samples 1 to 4 also show the presence of numerous smaller crystals easily visible with the naked eye.

However, the crystalline structure of the cooled slag was not studied systematically in connection with the experiments reported.

The separation of metallic iron, owing to the strongly reducing atmosphere of the furnace and the duration and intimacy of contact between molten slag and the furnace atmosphere, was frequently observed. These metallic globules were found mostly on or near the surface of the cooled melt; some were 2 to 3 mm. in diameter. Their formation was only noted in the case of slags abnormally high in iron.

Discussion of Experimental Measurements.—The measurements described above give for the first time an accurate idea of the actual magnitude of the viscosity of blast-furnace slags in units which are capable of a physical interpretation, as well as of the rate of change of viscosity of different slags with temperature over a wide range of temperature and viscosity.

If an average slag temperature of 1500°C. is assumed, an examination of the data given in Table 5 discloses the fact that the viscosity of the normal blast-furnace slag as it flows from the cinder notch approximates 250 (H_2O at 20°C. = 1). This represents a viscosity less than that of castor oil at room temperature but greater than that of olive oil.

The viscosity of the eight slags, considered in Table XVII, at a temperature of 1500°C. varied from 230 to 480. A synthetic slag upon which measurements have been recently made showed a viscosity of 770 at 1500°C., this slag containing 48 per cent. silica; while reference to Fig. 71 shows that at this temperature the artificial diopside containing 55 per cent. silica had a viscosity of 640. The effect of silica in such amounts upon the viscosity of silicates at temperatures above their melting points is thus clearly demonstrated, the increase in viscosity over that of normal slags being marked even in the case of diopside which contains no alumina and a high percentage of magnesia.

It would seem that even such high percentages of alumina as are present in the slag designated Lab. No. 22,954, although causing a high initial softening temperature, do not have a very noticeable effect in increasing the viscosity of the melt at high temperatures. This peculiar property of alumina, which may be a quite general characteristic, is probably associated in some manner with the uncertainty of its action within the furnace.

Comparison of Viscosity Measurements with Cone Tests.—It was thought a matter of interest to compare the results of viscosity measurements with cone tests made with corresponding slags. The cone tests were made, as has been previously described, under conditions which converted the sulphide content of the slag to the state of the sulphate. For this reason the comparison is not a strict one. In Table XX are given in relative order the softening temperatures of six slags and their viscosities at 1400°, 1450°, and 1500°.

TABLE XX

Slag lab. No.	Softening temperature, °C.	Viscosity at		
		1,400°	1,450°	1,500°
22,968	1,279–1,279	1,000	680	480
22,960	1,297–1,300	510	380	280
22,958	1,342–1,342	510	350	260
22,963	1,343–1,360	460	350	280
22,954	1,410–1,410	750	410	230
22,962	1,403–1,443	3,000	480	380

Acknowledgments.—In concluding this account of the investigations carried out by the author, acknowledgment is made of the active interest and help of F. H. Willcox, metallurgical engineer, at whose suggestion and under whose general supervision the work was undertaken. F. G. Cottrell, chief metallurgist, and D. A. Lyon, metallurgist, have given helpful coöperation. The slag analyses were made by F. D. Osgood, junior chemist.

Summary.—There has been described a modification of the torsion method of Margules which is applicable to the measurement of the viscosity of blast-furnace slag at high temperatures—the upper limit of temperature of 1600°C. being imposed by the furnace refractories and not by inherent limitations in the viscosity apparatus.

2. Viscosity values are given for eight typical commercial slags, two synthetic slags, and an artificial diopside.

3. The temperature-viscosity curve generally approximates in form that of the rectangular hyperbola, whereas the temperature-fluidity curve approaches a straight line.

4. The average viscosity at 1500°C. of eight commercial slags was found to be 301 (H_2O at 20°C. = 1).

5. A refractory slag—that is, a slag possessing a high initial softening temperature—is not necessarily more viscous at high temperatures than a more fusible slag.

6. The theory of the method has been discussed, and the literature on slag viscosity and high-temperature viscosity measurements has been reviewed.

7. The application of viscosity data to metallurgical operations has been briefly discussed, as well as the blast-furnace desulphurization process and its relation to slag viscosity.

8. The differences between softening temperature determined by a deformation test, the physical melting point of slags, and the viscosity of slags have been emphasized.

9. The nature of the free-running temperature of slags and the measurement of slag temperature at the furnace have been discussed.

Discussion by J. E. JOHNSON, JR.—I have read with much interest Mr. Feild's paper describing his method of testing the viscosity of slags. This is a subject which is intimately associated with the economical and successful operation of blast furnaces, and while it has received attention in the past, very few of the

investigations made have been of any value whatever because they determined softening points instead of free-running temperatures, and as I have more than once pointed out, the interval between these two may vary from 50° or less to 200° or more, and as a variation of 200° in the free-running temperature means the difference between economical and wasteful furnace operation, it is obvious that softening points are of little practical value.

Mr. Feild has apparently realized this and he has developed a method for determining the viscosity at any desired temperature, which examination indicates to be entirely practicable. The concordant results obtained confirm this conclusion.

It is not a simple matter to develop an apparatus which is reasonably free from experimental errors and which can be operated at temperatures approaching 3000°F. for considerable periods of time, and I think that Mr. Feild is entitled to congratulation on the success of his efforts.

When it comes to the practical results obtained, however, I am afraid that the practical man will not obtain the benefit he hopes from such tests until they have covered a much wider range, and particularly until they are referred to an accepted standard.

For instance, if we assume that in Lake-ore practice a normal slag is silica 33.5 per cent., alumina 13.5 per cent. and lime and magnesia 50 per cent., we shall not miss average conditions by any great amout. Furnacemen know how a slag like this will act, what coke consumption it requires with a given percentage of ore, etc. The real use of viscosity determinations is to establish the physical nature of such a slag as this under definite conditions and use it as a datum from which to measure the viscosity of other slags.

For this purpose, I would suggest that slag temperatures be determined at a furnace running on a typical slag of this general order. My personal preference as to the method of taking it would be to use on the slag as it runs over the slag dam an optical pyrometer of approved type. A few days spent in visiting normal working furnaces and making such temperature determinations would serve to establish fairly definite limits within which the temperatures of the slag vary, for they *do* vary within the length of a single cast. Now if one of these actual slags were subjected to test by Mr. Feild's process, within this temperature range, we should know the viscosity under what might be called a standard temperature condition. What we then need to know is *not* the change in viscosity at the *same* temperature which is brought about by a variation in the slag composition, but the variation in *temperature* to obtain the same viscosity. This temperature is what I have called for a good many years the critical temperature of the blast furnace. Upon it the whole thermal operation of the furnace depends.

With variations in the viscosity, on the other hand, we are not much concerned because we do not care to have the cinder thinner than a certain standard for a given purpose, while if it is thicker or stiffer than is required to meet the physical condition of flowing out through the cinder notch, the furnace will not operate and we are not interested in measuring this unusual viscosity but in avoiding it. For the latter purpose the only means available is to increase the temperature, which means increasing the fuel consumption in much greater degree.

There is only a small range of viscosity for each slag through which temperatures need be determined. This will reduce the number of determinations required and facilitate the obtaining of information which would be of great practical value to furnacemen. Collateral determinations of the effect of calcium sulphide up to, say, 3 per cent., should be made for a few slags of different composition to see whether this component has any effect on free-running temperature.

To boil the whole matter down, therefore, if viscosity determinations are to be useful to the furnacemen, they should be:

First, based on the physical characteristics of a definite slag

Second, plotted with composition and viscosity as the independent variables, and temperature as the dependent one.

CHAPTER X

THE PRINCIPLES OF BURDENING

Burdening is the technical name for regulating the different materials used in the charge and the proportions of each to bring about, first, the successful operation of the furnace; second, the production of the kind of iron desired.

The quality of the iron depends principally upon its content of six elements—silicon, sulphur, phosphorus, manganese, carbon and oxygen, these being given approximately in the order of their importance as affecting the general character of the product. Some of these elements come from one portion of the charge and some from others.

We must, therefore, consider the burdening of the furnace from two points of view, first that of the raw materials charged, which determines the quantities of foreign substances entering the furnace; second, from the point of view of the iron to be made. The content of the iron in these foreign substances varies very widely, according to the purpose for which it is intended. The different varieties of iron and their contents in the different metalloids will be discussed later in the section on "Products." We will, therefore, consider here only the methods of controlling the quantities of the different elements mentioned above which enter the iron.

SILICON CONTROL

To produce the desired silicon percentages we have two principal means which may be used singly or in combination. These factors are in the order of their importance: First, temperature; and, second, slag composition.

Since the temperature of reduction of silicon is far higher than that of iron and since the affinity of the latter for silicon diminishes as the percentage of the silicon in the iron increases, the temperature necessary to secure increasing percentages of silicon rises steadily as the silicon rises above 1 per cent. (Below that point, in coke practice, other factors come in.) Therefore, as we desire to raise the silicon we must first of all generate more hearth heat; so unless we can increase the blast-temperature we must use more fuel.

Second, we must control the silicon entering the iron to a very large extent by the character of the slag which we use. With a given temperature the limier slag will have the stronger affinity for the silica as such, and will, therefore, carry off a larger percentage of it in its un-

reduced condition, while if the temperature remains the same, as the lime in the slag is lowered the equilibrium between the iron and the slag is shifted toward the iron and more silica is reduced to silicon and passes into the iron.

It will be noted that it is definitely specified that the temperature be the same, and this is a very important stipulation because generally in coke practice the temperature of the slag rises with its content of lime, and, as I have before explained, it is the temperature of the slag which controls that of the iron, the slag being less fusible and acting as a retardant in the bosh, down through which the iron must pass on its way into the hearth. Therefore, the more infusible the slag the higher the temperature of the iron, the stronger the reducing action of the coke on the silica, and the higher must be the silicon in the iron to reach equilibrium with the silica in the slag.

This action is so important that it is sometimes impossible to obtain the required amount of silicon in the iron without increasing the lime far beyond what is necessary for desulphurization in order to raise the slag and through it the iron to the required temperature. In other words, there are actual conditions under which increasing the lime *increases* the silicon in the iron, the temperature effect of the increase more than offsetting its chemical effect.

In the chapter on slag it was shown that alumina had a decided effect in raising the free-running temperature of the slag without causing any increase in the basicity of the slag. The addition of alumina, therefore, gives us the higher iron temperature desired without increasing the affinity of the slag for the silica and so withdrawing it from the iron. For this reason the possibility of the use of alumina in considerable quantities in foundry iron slags was suggested in the paper quoted therein, and I have since come across statements in literature on the subject and from furnace operators confirming the correctness of this conclusion. My own experience does not cover the point exactly. The model showing the melting temperatures of lime, silica and alumina mixtures shows that the curve representing the effect of alumina alone is by no means a smooth and regular one, and it is, therefore, to be expected that a given increase of alumina would have different effects in different portions of its range.

THE EFFECT OF MAGNESIA IN THE SLAG

The fundamental slag is composed of silica, lime, alumina. The effect of an addition of magnesia follows the universal law that an addition to the number of bases lowers the fusion point of the whole. Magnesia is probably not more active, weight for weight, than lime, although on the basis of its atomic weight, or the molecular weight of its oxide, 40 against 56 for lime, it should be 1.4 times more active. It does, how-

ever, have the effect of thinning the slag very materially and this is of enormous value, particularly in the manufacture of low-silicon irons; in exactly the opposite way from that in which alumina is probably of value for the manufacture of high-silicon iron. It lowers the melting point without altering the basicity of the slag.

This is of particular importance in the manufacture of iron for the basic process, whether Bessemer or open-hearth, in both of which silicon is objectionable because the silica resulting from its oxidation attacks the basic (lime or magnesia) lining of the vessel and rapidly eats it away.

In coke practice it is not difficult to keep the silicon in the iron down to about 1 per cent., simply by adding more burden and thus keeping the hearth temperature too low to permit more silicon than this to enter the iron, while the furnace still remains hot enough to obtain good desulphurization. Below this point, however, difficulties begin to appear, because if the hearth temperature be kept down for the production of a lower silicon than this, with the same kind of slag, the point having been reached at which the slag is approximately saturated with sulphur for the given conditions, the surplus begins to pass into the ion. We must, therefore, take some step to prevent this action. The obvious one is to increase the lime in the slag, but this has the effect of increasing its temperature simultaneously, which in turn requires additional fuel, and these two factors are the very ones required to raise the silicon, whereas what we are trying to do is to lower it.

We must, therefore, find some method of increasing the basicity of the slag without increasing its temperature. This method, and practically the only one available for the purpose in ordinary practice, is to substitute magnesia for a portion of the lime. The famous experiments of the Swedish investigator, Akerman, while not directly applicable because he determined the softening point rather than the free-running temperature of the slags, indicated that the most fusible slag was to be found with about 2 parts of lime to 1 of magnesia, and while the data of furnace operation are seldom or never accurate enough to determine points like this with mathematical accuracy, such data as we have seem to bear out the correctness of this ratio for practice.

CONTROL OF SULPHUR

This is the element which indirectly produces most of the difficulties in the operation of the blast furnace. Charcoal furnaces have the vast advantage of a fuel almost free from sulphur, and unless this element be introduced with the ore or flux (which should never be done in charcoal practice because it vitiates the advantage of the fuel) there is so little of the element present that even a relatively very acid slag takes out nearly all of it.

In coke practice the conditions are very different; there is always sulphur in considerable amount in the fuel. There are exceptional cokes containing 0.5 per cent. or even less of this element, and considerable quantities containing from 0.5 to 1 per cent., but a large and increasing percentage of all the coke now used in the district served by Lake ores runs from 1 to 1.4 per cent. in sulphur, and in some other districts the sulphur may even go higher than this. In a rough way about 1 lb. of coke is required to make a pound of iron, and as the sulphur limit on practically all iron is under 0.06 per cent. it is evident that at least fifteen-sixteenths of the total sulphur charge must be removed by the slag, generally more than this.

There are two routes by which the sulphur can leave the furnace without contaminating the iron. It can be volatilized and passed off with the top gases or it can be fixed and carried out by the slag. In general it probably follows both routes to some extent, but the greater portion always goes out in the slag.

Very little is known as to the amount of sulphur which can be driven off with the top gases; the subject has been very generally neglected; the investigations of Mr. James Bell described in the chapter on chemical principles being the only ones known to me.

The principal condition for bringing about this end he has found to be that, as previously described, the slag shall be as acid as the conditions permit; as the slag becomes more basic more and more of the sulphur is fixed by it and prevented from volatilizing. From the point of fuel economy there is absolutely no doubt of the desirability of keeping the sulphur out of the hearth altogether rather than permitting it to enter and then eliminating it.

That the sulphur has no ill effect on the gas for use under boilers and in stoves can be stated positively, for the total amount present in that gas with the maximum degree of volatilization (35 per cent.) is but a small fraction of that in the products of combustion of many coals in successful use under boilers. The presence of sulphur does not seem to injure the gas even for gas engines, as the plant mentioned is equipped with these and no trouble from corrosion has arisen after several years' use.

For keeping out of the iron the sulphur which reaches the hearth we have available, as described in the chapter on chemical principles of the blast furnace, five possible methods: increasing the lime content of the slag, increasing its volume, increasing its temperature, increasing its fluidity, and increasing its manganese content above those required in the absence of sulphur. Some of these methods assist one another, while others are in direct conflict. The best result must be obtained by a proper balance among all, for the determination of which there is no mathematical equation; in this, as in other departments of furnace operation, there is no substitute for horse sense.

By increasing the lime, leaving out for the present all question of temperature, we obviously provide additional free base, and we can see that if the slag were in a comparative state of equilibrium before, both the bases and the silica being reasonably well satisfied, it is obvious that this additional base will hunt some other acid in order to satisfy itself, and the only one available is the sulphur in the coke. Of course, as a matter of fact, the addition of lime simply alters the ratio of the lime to the silica, and so modifies the slag, but this alters the equilibrium, and if we conceive that the amounts of sulphur passing into the iron and into the slag were in equilibrium before, it is obvious that this equilibrium has shifted toward the slag, and that more thereafter must pass into the latter.

Increasing the volume of the slag diminishes the concentration of the sulphur in it, and similarly alters the equilibrium of the slag in regard to this element. Or, to put the matter in a still simpler way, if a given amount of slag absorbs and carries off a given amount of sulphur under certain conditions, then an increased volume of slag will dispose of a proportionally increased quantity of sulphur under the same conditions. Of course, the effect of the addition of lime is to increase the slag volume and we obtain the benefit of a slight increase in volume whenever we increase the lime, but this is generally less than 5 per cent. Where an excessive amount of sulphur must be eliminated, it is sometimes necessary deliberately to add to the burden slag-forming materials, in general silica, and the necessary lime to flux them, so as to make a substantial increase in slag volume.

Here again we have to meet a condition for which theory indicates qualitatively but not quantitatively the method to be followed. By adding lime we increase the free base, increase the slag volume, and increase the fusion temperature of the slag, all of which have a very strongly desulphurizing effect. But the more limey slag brings more sulphur into the hearth to be eliminated, while the effect of increasing the temperature of the slag is to increase the critical temperature of the furnace and thereby materially increase its fuel consumption, which again increases the sulphur to be eliminated. If, on the other hand, we add to the burden silica and sufficient lime only to keep the ratio of the two the same as before we must make in general a much larger addition to the slag volume to accomplish the desired desulphurization, but we do not increase the critical temperature; we do, however, increase the requirements for hearth heat to melt the additional slag. Both of these methods of increasing the removal of sulphur, therefore, have the result of increasing the fuel consumption.

I do not believe it is possible to figure out in advance which one of these is the most economical, or whether the combination of the two is more economical than either. The latter is probably true, but the final

decision can be correctly made only on the basis of experiment on the furnace itself.

We have seen that the first three methods of increasing desulphurization work together—that is, that an addition of lime meets all three conditions to some extent. But we have the fourth method, that of increasing the fluidity of the slag; and this is extremely important. I have already described how certain slags so limey as to "slack" when cold, if the hose was turned on them, fail utterly to give satisfactory desulphurization, partly because they raise the critical temperature so high that but little hearth heat is left above it, but very largely also because the slags are too stiff and pasty to mingle intimately with the coke, and so catch the sulphur as it is evolved by the combustion of the latter.

It is evident then that this need for fluidity sets a definite limit which we may not pass in adding lime for the utilization of our first three methods. On the other hand, we have no commercial method whereby we can increase the fluidity of the slag without diminishing its liminess, except the substitution of magnesia for part of the lime, as already described, and the addition of manganese within narrow limits. So for commercial work we must be satisfied to secure a compromise between fluidity, high temperature, and basicity. In cases of serious trouble the addition of fluorspar might doubtless be beneficial because its effect in lowering the free-running temperature of slags is extremely marked, but this is a subject which may be better discussed in a later chapter, it being impossible for commercial reasons to use fluorspar in normal operation.

Manganese has a much higher affinity for sulphur than has iron and manganese sulphide formed is dissolved in the slag instead of the iron as the iron sulphide is. It is probable also that the presence of manganese oxide renders the slag more fluid just as oxide of iron does, hence the addition of manganese to the charge is beneficial to both the sulphur-carrying powers of the slag, basicity and fluidity, whereas lime is beneficial to one and highly detrimental to the other. It is, of course, out of the question to add manganese oxide to the charge as a flux, but a wide latitude of manganese contents is often to be found in ores of the same cost, and in such cases it is distinctly helpful to add manganese to the charge up to the limit set by the amount desired in the iron.

For economical desulphurization then we must have a reasonable volume of fluid slag, not too limey and preferably carrying some manganese. If the quantity of sulphur to be eliminated exceeds the sulphur-carrying capacity under these conditions, we must then go to increasing lime and increasing slag temperature or increasing slag volume or both, but in any event economy must be sacrificed.

We have then two methods whereby iron low in sulphur and also low in silicon can be produced. First: we can increase the lime, increase the

blast-temperature if possible, and increase the coke enough to offset the rapid rise of the critical temperature resulting from the more infusible slag. The hearth heat decreases in spite of the increased blast-temperature and increased coke because the critical temperature increases faster than the coke ratio. All of this tends to make the iron physically hotter but chemically colder, that is to say, to lower the silica, and this result is of course greatly assisted by the hot excessively basic slag produced with its huge affinity for silicon. The result of making low-silicon iron by this means is to increase the fuel consumption. That is to say, it requires more coke and considerably more limestone to make an iron with 0.75 than it does to make one with 1.50 silicon, because, as stated above, the critical temperature rises rapidly, with the consequences pointed out in the chapters on thermal principles.

On the other hand, we can work on the plan of making the slag just as fluid as possible, consistent with desulphurization, and then pile on burden, that is, additional ore, until the hearth heat per unit of iron is so reduced that the silicon cannot rise above the limit desired.

The result of this method of operation is to reduce the fuel consumption, so that working on this basis it requires less fuel to make an iron of 0.75 silicon than it does to make one of 1.50, but it requires more careful furnace work and involves running on a smaller margin of safety.

When it comes to making irons high in silicon, beyond 3 per cent., we have no recourse but to increase the fuel ratio so that the hearth heat per unit of iron being high, a surplus is left, a part of which expends itself in reducing more silica. Of course, the surplus is not large because the increase in hearth heat with increasing fuel is not really very rapid. The additional fuel is largely spent in keeping pace with the rise in the critical temperature necessary for greater siliconization.

It is quite probable that above a certain point, probably 4 or 5 per cent. silicon, the critical temperature ceases to be the free-running temperature of the slag and becomes simply the temperature of the iron at which it will absorb the required percentage of silicon. Here, then, we are at the disadvantage of no longer having the cinder to act as a retardant and assist in the work of heating the iron to the desired temperature by delaying its descent, and the efficiency with which we utilize the heat produced in these furnaces is therefore decidedly lower than any furnace on the ordinary range of silicon. It is because we are without this retardant action that the hearths of furnaces on high-silicon iron are made smaller than those for steel-making and other moderate-silicon irons. In order to obtain the heating of the iron desired we must give it a more intense and intimate contact with the hot gases as they arise from the hearth and this can obviously be done by narrowing the hearth and the base of bosh, in which this action takes place.

Above 15 per cent. silicon the temperature necessary becomes so high

that there is little or no hearth heat to be obtained above this point and it becomes commercially impracticable to make higher silicons even by considerable further increases in the coke ratio.

In the range from 1 to 3 per cent. silicon, we change the product of the furnace from one silicon content to another by changing the burden and leave the slag ratio almost unchanged.

MANGANESE CONTROL

Our control of manganese is not as complete as it is of some of the other elements. It is practically impossible to throw much more than about 70 per cent. of the total into the iron except perhaps at low percentages, under 2 or 3 per cent.; when, owing to the high solution power of the iron, a somewhat greater percentage of the total manganese charged may, under favorable circumstances, enter the iron. On the other hand, we cannot in practice secure its complete elimination, because with the furnace in proper working condition a certain percentage of the total amount charged always enters the iron in spite of our best efforts. With a furnace working cold, on a thin scouring cinder, making white iron, practically all the manganese is carried off, but as it is impracticable to operate a furnace this way commercially, this fact is of no real value in manganese control. It is safe to say that the lower limit of the manganese entering the iron in ordinary good practice is about one-third of the amount charged, and that in a general way the ordinary range of manganese content in the iron comprises from one-third to two-thirds of the amount charged.

Manganese is very much more active chemically than iron and therefore has a much greater tendency to act as a base, forming manganese silicate, and passing out in the slag. Its temperature of reduction, and also its heat of reduction, are considerably higher than that of iron, therefore in order to throw the maximum percentage into the iron the furnace must be very hot and the silica must be as completely satisfied as possible. Both these results are accomplished by making a very limey slag, the lime is a stronger base than the manganese and therefore when present in excess has a strong tendency to prevent the manganese from obtaining any silica with which to combine, though this action is not absolutely complete. On the other hand, as we have already seen, the effect of calcareous slags is to raise the temperature of the furnace, provided of course sufficient fuel be charged to supply the quantity of hearth heat required above this high temperature. In order to throw the manganese into the iron therefore we must use a light burden and a very limey slag. This tends to prevent the loss of manganese in the slag and to reduce it to the metallic condition, but the high heat here brings in a bad effect when high percentages of manganese are present, as the

manganese vaporizes and for some reason does not recondense in the upper regions of the furnace, but passes out with the gas as a dense yellow fume. Furnaces working on ferromanganese can be recognized by their smoke for miles.

When it is desired to lower the manganese in the iron the opposite procedure must be followed. Lime in the slag is reduced to the lowest possible limits consistent with desulphurization so as to make a thin fluid slag, to keep down the hearth temperature, and to leave some silica relatively free so that it can combine with the manganese oxide and slag it off.

We have here those conditions of gradually shifting equilibrium of which I have so often had occasion to speak. The iron itself has an affinity for manganese on one side, while the slag, especially a siliceous slag, has an affinity for it on the other. High temperature shifts this equilibrium toward the iron side, but no conditions at our command enable us to reach either end of the scale. The affinity of the iron for the manganese never completely triumphs over that of the slag so as to absorb it all into the iron, while on the other hand it never falls so low that all the manganese can pass into the cinder under normal working conditions.

We have, however, a further means of controlling manganese to some extent. I have spoken of the action of a scouring slag, and we can to a certain extent produce such a condition in a normal working furnace by charging a certain amount of material which has a tendency to produce a scouring slag, such a material for instance as mill cinder. It is well known that metallic manganese will reduce iron from slag, the oxide of manganese produced by the reduction replacing the iron oxide in the slag. The effect of thus producing a scouring slag is to supply a certain amount of unreduced iron on which the manganese in the iron can work as it passes through the slag into the hearth, and by this action the manganese is lowered materially. By the use of this expedient in charcoal practice I have been able to produce iron to low manganese specifications that could not be made from the ores available, even with the most acid cinder we could use, without the addition of mill cinder.

PHOSPHORUS CONTROL

This is extremely simple in one way because we know that when the furnace is operating properly 100 per cent. of the phosphorus charged will enter the iron. As explained in the chapter on chemical principles a very scouring slag, such as made by a furnace completely deranged, carries off as much as 10 per cent. or even more of the total phosphorus charged, but while this is a matter of some scientific interest it has no bearing whatever on the question of burdening the furnace for commercial purposes.

In order, therefore, to produce an iron containing a given amount of phosphorus we must provide a charge which contains just that amount. This sounds simple enough, but when the phosphorus limits desired are very low it becomes a matter of great difficulty to secure raw materials so free from that element that the iron will not contain more than the amount specified. In the case of specially low-phosphorus or extra Bessemer iron described later, with specifications of 0.035 per cent., and under, this difficulty becomes extreme. For instance, if 2 tons of ore, 1 ton of coke, and ½ ton of limestone be required per ton of iron, and each of these materials contains 0.01 per cent. of phosphorus, the resulting product will contain the maximum permissible amount of phosphorus, 0.035 per cent. Such raw materials are extremely rare and in consequence iron of this kind commands a premium of several dollars per ton over iron exactly similar in other respects but a trifle higher in phosphorus.

The same condition holds good in regard to the Bessemer specification, but of course in a much less degree, because both on the theory of probability and as an actual fact the supply of a material of a given degree of purity increases very rapidly as the purity required diminishes, so that many thousand times as much ore are available for making iron of 0.09 phosphorus as are available for making it of 0.035.

On the other hand, the amount even within this wider limit is a relatively small proportion of the total amount of iron ore in the world, and therefore Bessemer iron commands a premium of from $1 to $2 per ton and Bessemer ore suitable for making it commands a corresponding premium, which, however, is diminishing as the use of Bessemer steel decreases.

The same conditions are true in regard to supplies of coke, but not to the same extent. Cokes contain as a general thing only small percentages of phosphorus, and while some premium is paid for cokes extraordinarily low in this element, it is small in comparison with the premium on low-phosphorus ores.

Turning now to the other end of the scale, there are produced great tonnages of iron in which the phosphorus must not be below certain limits, in ordinary foundry irons about 0.5 per cent.; for the production of this in a district of low-phosphorus ores, high-phosphorus material sometimes commands a premium. Extra high-phosphorus ores are often hauled hundreds of miles for admixture with those of lower phosphorus when foundry or other high-phosphorus iron is desired, and in very many cases the phosphorus which the steel maker has been at such pains to eliminate from one iron to convert it into steel is charged back into the furnace in the form of open-hearth slag so as to increase the phosphorus in another iron. In some cases even phosphate rock is used to give the desired phosphorus, and one resourceful furnaceman in the Northwest, running a charcoal furnace on rather low-phosphorus ores, when he received an

order for high phosphorus iron produced it by collecting the beef bones from the surrounding lumber camps and charging them as flux.

For certain purposes steel must contain more phosphorus than is left in it by the basic open-hearth process and such steel is rephosphorized by the use of ferrophosphorus, a special product made at only one blast furnace in this country. The phosphorus in this material ranges from about 17 to 18 per cent., the raw materials being iron ore and phosphate rock, with silica as flux for the excess lime of the phosphate.

CONTROL OF CARBON

We know very little of the general subject of the carbon contents of the different kinds of iron and the obvious corollary is that we know very little in detail about methods for its control, but in a general way we do know that a large quantity of carbon in the hearth and high hearth temperature contribute to high carbon, and the opposite conditions to low carbon.

I shall later point out that an excess of hearth heat, which of course in itself tends to produce higher hearth temperature than would otherwise occur, tends to high carbonization, and a cold-working furnace hearth on the other hand tends to lower carbon. In a subsequent chapter I shall describe a certain variety of charcoal irons, known as "spotted irons," whose undesirable characteristics come from high carbon, and it was believed in the charcoal business before the cause of the iron's peculiarities was known, that this iron is produced by too small a slag volume and a limey slag. The small slag volume tends to leave an excess of hearth heat, and the limey slag tends to a high temperature, while the deficiency of heat in the shaft of these furnaces results in a comparatively large quantity of fuel in the hearth. Hence these conditions all make for high temperature, an excess of hearth heat, and a large quantity of carbon in the hearth. These are the three principal factors tending to high carbonization. This shows that there is close agreement between a rather vague belief developed, almost as tradition, through long years of practice, and the fundamental principles set forth.

On the other hand, charcoal furnaces which work with low blast temperature, very fusible slags, and quite large slag volume, sometimes produce irons very low in carbon, down to 3.4 or the like, and this also is in agreement with the principles above laid down.

In coke irons the possibilities of variations in the conditions are less, and the limits within which carbon varies are correspondingly narrower, but I have been advised by Mr. John S. Kennedy, who has paid much attention to this subject, that by using a rather irreducible ore with a limey slag, and comparatively high fuel, he was able to maintain the carbon above 4 per cent. even with silicon up to 3 per cent., although that

percentage of the latter element is ordinarily high enough to cause some reduction in the carbon. This is in line, in a general way, with the principle set forth above and with charcoal practice. On the same basis one would expect a coke furnace running with a moderate volume of fusible slag, and on a comparatively fusible ore, to produce irons low in carbon, and while I have no exact data on this subject I believe it to be a fact that the irons made in Virginia on low-alumina fusible slags, and approximately under the conditions outlined, are lower in carbon than any other coke irons made in this country.

OXYGEN CONTROL

Definite knowledge of the quantity of oxygen in cast iron dates back only to 1913, and the views set forth on its effects in a later chapter are by no means universally accepted, but their correctness has been demonstrated by a vast mass of facts, and they are accepted by some of the highest authorities, so that they will be considered as established for our present purpose.

Owing to the necessity of treating the subject of oxygen as a whole on account of its novelty, most of the data we have concerning oxygen control are included in the subsequent section on products, but a condensed presentation of the facts from the operating point of view is desirable here. The three principal factors in controlling oxygen are temperature, manganese, and the kind of ore used. The fact that oxygen could be present in cast iron, with its high content of carbon and generally with a considerable content of silicon and manganese, was not admitted until recently, because it was believed that these elements, any or all of them, would unite with the oxygen and carry it off instantly as an oxide. As a matter of fact this is not necessarily true. If the temperature of the bath be kept low, considerable quantities of oxygen—from 0.05 up to 0.1 per cent.—can remain in the iron, but as the temperature rises the affinity of the oxygen for the elements mentioned rises very rapidly, so that more and more of it is removed as an oxide, and when we reach 2800° or 2900° only traces can remain in the bath.

This is another of those cases of continuously shifting equilibrium so often mentioned, and of the other law apparently almost as general in its application that iron has a much greater affinity for small quantities of all the elements we have discussed that it has for large ones, or perhaps we might say that the reactions which chemistry leads us to expect go on much more slowly as they approach completion and practical equilibrium is reached before they are complete.

This difficulty of removing the final traces of oxygen may in this sense be considered as merely the final manifestation of the increasing difficulty of deoxidation as that process becomes more complete, as described in the

chapters on chemical and thermal principles. We must not ignore, either, the increasing dilution of the oxygen in the bath as it becomes more completely removed.

Next in importance to temperature come the quantities of silicon and manganese present in the bath, carbon being much less important and subject only to minor variations in percentage present so that its effect is approximately constant, whereas the others are subject to variations all the way from fractions of a per cent. to several per cent. Manganese is very much more active than silicon in deoxidizing. An iron with 1 per cent. Si and 0.5 per cent. Mn can probably retain twice as much oxygen as one of 0.5 per cent. Si and 1 per cent. Mn; in fact, it is probable that only a trace of oxygen can remain with more than 1 per cent. Mn, whereas appreciable quantities can be retained with 2 per cent. or more Si, when the manganese is low.

The third factor in the control of oxygen is the character of ore used. Our experience in regard to this is not yet extensive enough to enable us to attach different values to the different ores as regards their oxygen-retaining power in any quantitative way, even the crudest, but there are certain unmistakable qualitative indications which should not be ignored.

I once had charge of a charcoal furnace which was normally operated on a plastic, soft hematite from the Gogebic Range. We decided to try a fine granular limonite from the Mesabi to see whether its greater reducibility would affect the quality of the iron.

Test bars were being taken from every cast and ranged fairly well together for the same grade of iron on the normal ore mixture.

As soon as a burden containing about 25 per cent. of the Mesabi reached the hearth the strength of the iron dropped about 10 per cent. and continued to decrease as the percentage of Mesabi ores increased. The result was so marked and so contrary to the results for which some of our officials hoped that we repeated the whole experiment, with absolutely identical results.

We had not at that time begun oxygen determinations, so I have no absolute analysis to offer to prove that the oxygen dropped with the more reducible ore, but there is no doubt whatever that it did.

On the other hand, certain irons made wholly or in part from magnetite ore, with coke as fuel, have some of the strength, close grain, and chilling power of charcoal irons, especially if made on a "raw" slag.[1] It is undoubtedly on account of the oxygen which remains in these irons from the irreducible ore that they possess these characteristics. This has been proven by direct analysis in at least one case.

One plant running under these conditions has always produced iron

[1] "Raw" slag is generally the product of a slightly deranged furnace containing enough unreduced iron to darken it and give it a scouring tendency. A furnace may, however, be normally operated on a slag with some tendency in this direction.

of a high reputation for strength, and it has recently been extensively advertised as containing vanadium, to which its qualities are ascribed. Vanadium has undoubtedly been found in the iron in very small amounts, but its presence there is purely a coincidence. There is sufficient oxygen in the iron to impart a slight increase in strength as compared with ordinary coke iron, and this oxygen is undoubtedly due to the burden of magnetic ore.

General experience taken in conjunction with these concrete cases enables us to say that other things being equal the most reducible ore produces the iron with the lowest oxygen content. If, therefore, we desire an iron low in oxygen, as is desirable for some purposes, we must run the furnace hot and limy on an ore as high in manganese as the other conditions will permit, and the ore must be of the most reducible kind. On the other hand, if we desire an iron high in oxygen, we must use an ore low in manganese and run on as thin and fusible a slag as will suffice for desulphurization. We should also use at least some fairly irreducible ore, magnetite, mill cinder, or the like.

These are general principles which apply alike to charcoal furnaces and to coke furnaces, but on account of the high temperature of coke iron brought about by the refractory slag on which it is made, the maximum quantity of oxygen which can be retained is smaller and the variations of much less importance than in charcoal iron, in which the minimum amount is as small as in coke iron, but the maximum several times as large. We shall see later that the low temperature at which the charcoal furnace *can* run (though it is often not so operated) on account of its fusible slag, is the reason for the great superiority of its product for some purposes.

We shall see in a subsequent article that we can control oxygen by treatment of the iron after it leaves the furnace better than by any method of operating the furnace. In other words, by operating the furnace to the best advantage and then giving the iron a further treatment external to the furnace we can achieve results impossible by either method above. By proper treatment of suitable iron we can impart oxygen in greater quantities and under more complete control than can be produced even from a charcoal furnace, while for the limited class of work for which extra soft iron is desired we can produce it by superheating iron of proper composition in the electric furnace. The increase in temperature promotes those reactions which remove oxygen and sulphur and is also necessary for the formation of large flakes of graphite.

THE EFFECT OF SLAG TEMPERATURE ON FRACTURE

In the production of foundry iron arises a feature not covered by the analysis in the ordinary sense. This is the fracture of the iron. It is only about 20 years since all the iron used in foundry work was graded

and selected entirely on the fracture and appearance of the pigs, and this custom prevails to some extent even yet. For some foundry purposes it is necessary that the iron be very "soft," which means that when it is melted with a large proportion of scrap iron, broken castings, and the like, it must be able to prevent the mixture from becoming too hard. The general belief of the trade was that iron having a large, coarse crystallization with very shiny crystals, was soft iron, while that with fine, close grains was likely to be hard. For this reason foundry irons were very generally desired to be of the open-grained variety, and, in fact, irons not up to the standard in openness of grain were given a lower grade and brought a distinctly lower price in the market, a condition which prevails to-day to some extent.

It is therefore important that the iron shall not only have the silicon content desired for a given grade, but that it shall "grain out;" that is, have the openness of fracture which it is the custom of the trade to associate with that grade. We shall later see that sulphur is often responsible for closing up the grain of the iron, and it is undoubtedly on account of the rise of sulphur in the colder irons that a close grain is ordinarily associated with a poor iron. But even though the desulphurization be satisfactory, there are cases in which irons refuse to grade out in a way to correspond with their analysis. This is due, as we have seen and have occasion to emphasize in a later chapter, to the fact that the iron is made at too low a temperature to remove all its oxygen, and in such cases it is necessary to add lime so as to raise the fusion point of the slag, if the fracture of the product be kept up to match its quality; even though this has a desiliconizing influence on the iron which must be met by additional fuel.

This effect can be obtained in a much greater degree by electrical superheating after the iron leaves the furnace in cases in which the commercial conditions warrant the expense.

OTHER OCCASIONAL ELEMENTS IN THE CHARGE

In addition to the elements already mentioned there are several others which occur in some raw materials, generally the ore, in greater or less amounts. I have heard of cases in which barium occurred as a base, and when it does, allowance must be made for its fluxing action, which can probably be done tentatively on the basis of its being equivalent, weight for weight, to lime.

Barium sulphate is an occasional ingredient in ores, and is likely to cause trouble by increasing the sulphur from an unexpected quarter. Sulphur from this source simply adds to the total amount to be fluxed.

Titanium.—There are also in some ores several other metals associated with the iron of which it is necessary to take account. The commonest of these is titanium, which has already been mentioned as an

exceedingly common ingredient of many magnetic ores. This element has had a very bad reputation among furnacemen, and many ores have been kept out of the market for years by their titanium content.

The extensive experiments conducted by the McIntyre Iron Co., and reported to the American Iron and Steel Institute by Mr. Bachman, have already been mentioned. Mr. Bachman states in his paper that the experimental slags made up were calculated on the basis that the TiO_2 was the equivalent in acidity to three-fourths of its weight of silica. He states that there is some reason to believe that the titanium is even less acid than this. Mr. Bachman's calculations were on the basis of considering alumina as an acid, and as this is at variance with the practice which I have recommended, of considering alumina as neutral, allowance must be made for this fact in considering his conclusions. Slags containing as much as 22.5 per cent. of titanic oxide were produced experimentally, and these seemed to have a fluidity almost as high as the corresponding slags without titanium. In practice on the furnace, however, it was not found possible to operate with slags as high as this on account of the tendency of the titanium compounds to build up in the hearth. There was, however, no trouble as far as shown by the several weeks of experiment in operating successfully on a slag containing several per cent. of titanic oxide, and there seems to be no longer any reasonable doubt that it is quite possible to operate furnaces successfully on ores containing amounts of titanium which at one time were firmly believed to be prohibitive. Just what the commercial limits are can be determined in each case only by experience, not simply on test runs but on long runs in regular practice, and will depend not only on technical considerations, but on purely commercial ones, on the relative cost of titaniferous and non-titaniferous ores, their relative fuel requirements, outputs and the like.

It seems proper to note here the pioneer work done by A. J. Rossi, who more than 20 years ago became convinced that titaniferous ores could be worked successfully, and built a small blast furnace some 20 ft. high, on which he carried out a number of tests on these ores, and first demonstrated on an important scale that the ores could be used, and that the slag produced was fluid and could be handled without difficulty if calculated on the basis of titanic oxide as an acid (see *Transactions* of the American Institute of Mining Engineers, vol. xxi, page 832).

As noted earlier a part of the titanium passes into the iron. The quantity obtained in the McIntyre tests ranged around a half of 1 per cent., being roughly constant with quite wide variations in the amount of titanium in the charge, indicating that this is approximately the saturation point of this element under ordinary conditions of temperature in the hearth, etc.

Chromium.—This element is unlike titanium in that most of it passes into the iron and but little into the slag. I am advised by Professor

J. W. Richards that the heat of formation of chromic oxide is probably about half that of silicon, so it is very much less than that of titanium. This, of course, facilitates its reduction and passage into the iron. This action is probably greatly assisted by the fact that chromium seems to form a very definite compound with iron and carbon, a double carbide of iron and chromium. This probably means that the iron or iron and carbon together have a more powerful solvent effect on the chromium than they have on titanium, which does not seem to have so definite an action, having a very much smaller effect on the character of the iron. Not much information is available as to the percentage of total chromium in the charge which passes into the iron and into the slag under different conditions. This is probably in part because merchant furnaces cannot use chromiferous ores except in small quantities, and have not therefore developed any information as to the possibilities of slagging it off, etc., the reason being the very marked effect of chromium on the iron, 1 per cent. making it quite hard, and 2 per cent. making it entirely unfit for foundry purposes except as a small percentage of the mixture, and rendering the iron fit, therefore, only for steel works' purposes.

In small percentages nearly all the chromium seems to pass into the iron, but as the percentage rises more and more passes into slag, so that it is said to be impossible to produce in the blast furnace ferrochrome containing over 35 per cent. Cr.

Nickel.—Nickel, like chromium, occurs very generally in laterite ores which are the breaking-down products of serpentine rock. Nickel is more reducible than iron, having a very low affinity for oxygen, and therefore all the nickel present passes into the iron, and like phosphorus it can only be controlled by controlling the amount in the charge. Nickel enjoys, however, the unique distinction of being the only element that is beneficial alike in iron and in steel, and there is never any reluctance to having it in the product, except perhaps reluctance to waste so valuable a commodity as nickel on a relatively low-grade product like cast iron, the value of the former being forty to fifty times greater per unit of weight than that of the latter.

Copper.—Copper, like nickel, is more reducible than iron, and all that is present in the charge passes into the iron, alloying with it. The effect of this element on the product is generally considered undesirable, and therefore efforts are usually made to keep it out of the charge as much as possible. Some irons of good quality, however, contain as much as 1 per cent. on the average, and more on occasion, while tests made by introducing as much as 2 per cent. into crucible remelts have shown no effect whatever on the quality of the iron, so that this element has probably been condemned in the past, unjustly, at least to some extent.

Vanadium.—Vanadium is a metal very difficult to reduce when

smelted alone, resembling titanium in this respect, but like the latter considerable fractions of 1 per cent. pass into the iron if it is present in the charge. Vanadium is so very valuable that a content of a very few per cent. of vanadium makes an ore more valuable for that than for iron, so that as far as known no experiments have ever been made as to the action of a considerable percentage of this element in the blast-furnace charge. Little or nothing is known concerning its control.

Other elements, such as tungsten, tellurium and others, are undoubtedly sometimes present in ores of iron in small quantities, but the occasions are so rare and the quantities so small that nothing is known concerning their action.

It may be well to call attention to the fact that in some of the earlier works on metallurgy analyses are given showing considerable percentages of aluminium, calcium, and magnesium in the iron. It is safe to say that these results were due to errors of analysis, since these appear to be three elements which are not dissolved in cast iron to any extent whatever. Presumably the temperature of the furnace hearth and the affinity of the molten metal for them are jointly too small to throw any of them into the bath.

BURDENING WITHOUT CHEMISTRY

In the early days before chemistry was in universal use in the iron business the burdening of the furnace was done on a practical rather than a chemical basis, and even now it is so done at some isolated plants. The furnaceman learns from the general appearance of his slag the kind which suits his conditions, and with which his furnace works the best. He learns from both the appearance of the slag and that of the iron to judge of the different grades of iron he produces, and whether, when he varies from the kind desired the furnace is too hot or too cold. He accordingly increases or decreases the burden by an amount depending upon his judgment of what is required. Similarly, if the slag is too lean he adds lime according to judgment, and if it is too limy he removes it on the same basis.

This sounds rather crude at the present day, but much excellent furnace work, both as to regularity and fuel economy, was done on this basis, and it would be very much more correct to say that this was the foundation of furnace burdening and chemical control the superstructure, than to say the reverse. Even with advance knowledge of the composition of the coke, limestone, and ore, the factor of judgment can never be omitted or forgotten. Accidental variations arise, the coke is of poorer quality and dissolves more rapidly in the furnace, leaving less for the hearth, or the character of the coal changes in the mine and the coke becomes higher in ash or in sulphur, without notice, or a great mass of many million tons of ore on the Ranges, whose normal analysis is

known to 0.1 per cent., contains an unknown variation from the normal at a certain point, and when in the progress of mining, steam shovels cut into this, an ore is shipped different from that expected. These variations are largely eliminated in the mines of the Lake Superior region by careful analysis, sampling and sorting of cars at terminals before making up into cargoes, but in spite of this, very considerable variations of the ore from the stated analysis occasionally arise. If nothing else happens an ore of one kind runs down from its own pile onto and over a pile of totally different kind, and is taken to the furnace for the latter.

In all these cases the furnacemen must use the factor of judgment. The general characteristics of the slag can be quite accurately told by its fracture, especially if a sample of the cinder be poured hot into a small chill mold, since the sudden cooling tends to make the outside of the sample vitreous while the center is stony, and the depth of this vitreous layer in conjunction with other features of its appearance tells the furnaceman whether he is producing the slag that he needs or not. And if one had to choose between such tests of the actual slag, or an advance knowledge of the composition of the raw materials, it would undoubtedly be better and make for more successful operation to take the slag tests and let the analysis go, but the best operation can be obtained only by having both.

It is very desirable not to wait until the furnace has already made a "swing" that will take its product beyond the permitted limits, but to feel this swing coming and by taking quick action prevent it or break its force. This can be done by experienced men by methods which it would be difficult to put into words.

There is another factor in the burdening of the furnace, and in this chemistry has nothing whatever to do. This lies in the fact that the time required to bring through changes of one kind varies considerably from the time for changes of another kind, and the times required will vary within themselves according to the general conditions.

It seems an absurd statement, but a furnace really acts as if it had a reserve of heat, a sort of reservoir, upon which it can draw at need, so that when a bad condition arises for 3 or 4 hr., unless it is very serious the furnace is not thrown off its equilibrium, but if the same condition be kept up for half a day or longer the reservoir of heat appears to be exhausted and the furnace then becomes cold.

The same conditions apply to an even greater extent in the case of changes in the limestone burden than they do in changes of ore burden. If a sudden change be made in the character of the burden, for instance, if a more siliceous ore be used, or less limestone be charged, it will be found that this change does not come through in the same period that is expected to show any change of ore burden. Generally it takes almost twice as long. On the other hand, if the furnace is running too lean and

more limestone be added to the burden the effect of this will not appear for some time after the charge on which the change is made has come through. The furnace acts as though there were a thickness of lime or limy slag on the bosh walls which reaches an equilibrium with the conditions prevailing in the hearth and bosh, that is with the kind of slag that the furnace is making at the time.

I assume that when the equilibrium between the coating on the walls and slag is altered the wall coating tries to make up for the deficiency. If the slag becomes more siliceous the wall coating, being limier, gives up lime enough to bring it back to equilibrium. On the other hand, if the slag be made more limey the walls build up their limey coating again before the extra lime is permitted to reach the hearth. It is impossible to say if this is literally true, but certainly the furnace works as if it were, and in recent years I have always been accustomed to making a change of lime twice as great for the first 12 or 24 hr. as seemed to be needed. This provides the excess, whether positive or negative, required by the walls, and brings through the change of lime desired at the proper time instead of many hours later.

CHAPTER XI

THE CALCULATION OF THE BURDEN

Having set forth in the last chapter the principles which control the variations of the various elements in the iron, and in the previous one the principles on which our slags must be based, we are now able to proceed to the details of calculating the burdens for a given case. This is a matter of which a great mystery has often been made, but in reality when the very simple principles are understood, it is nothing more complicated than a sum in arithmetic.

It seems worth while here to go back once more and say that our knowledge of slags is a purely empirical knowledge. The scientist cannot sit down in his study and work out from the ultimate laws of chemistry, no matter how well he may know them, the slag which must be used or will give the best results in a given case. We know only as a result of countless thousands of trials and analyses, by our predecessors and ourselves, that certain ratios of fluxes to materials to be fluxed give the best results. These results I believe to be as set forth in the last chapter, that the alumina chemically is a matter of indifference, and that the ability of a slag to do the necessary desulphurization remains the same while the ratio of lime to silica remains the same, through a wide range of variations in the alumina, at the same time not forgetting that alumina exerts a powerful influence, particularly within a certain range, on the viscosity and the melting point of the slag, and therefore has a profound effect on the thermal equilibrium of the furnace.

We can go further and say that the ratio of lime to silica is itself almost a constant one for best results, varying from about 1.3 lime to 1 silica for foundry irons, to 1.5 lime to 1 silica on basic irons, Bessemer lying between these two with a ratio of about 1.4 : 1.

Given these facts, and leaving out of consideration for the moment the phosphorus question, the calculation of a burden for given ores becomes very simple. We have only to calculate the amount of silica brought in with the charge and to be carried out as slag, and then determine the amount of limestone which will give us the necessary ratio of lime to silica in the slag for the kind of iron we desire to make.

There are, however, some precautions to be taken here. First of all, of course, is the fact that silica and alumina are brought in not only by the ore, but also, to some extent, by the fuel and the limestone, and that the amounts brought in by these must be taken care of exactly the same as that

brought in by the ore. On the other hand, a fact of much importance in rich ores is that the silicon in the iron comes from the silica of the charge, and that, therefore, the quantity of silica to be fluxed is correspondingly reduced Take for instance the case of a charcoal furnace with a 60 per cent. ore carrying 5 per cent. silica, and disregard for our present purpose the small amount of silica in the limestone and fuel. Counting 0.95 units of Fe for a unit of pig iron we should have silica present equal to 8 per cent. of the weight of the iron, provided the iron produced were silicon-free, but if the iron contained 3 per cent. silicon corresponding to 6½ per cent. silica we should only have left to pass out into the slag 1½ per cent. of silica instead of our original 8 per cent. The case taken is intentionally an extreme one, so as to drive home the fact that the apparently insignificant percentage of silicon in the iron requires careful consideration in burdening the furnace.

There are various means of simplifying burden calculations. The limestone practically always contains some silica, ordinarily from 1 to 6 per cent. or 7 per cent.; it is generally under 5 per cent. though I have known limestone containing 10 per cent. silica to be used. Obviously, then, whenever we increase the limestone we increase the silica also, and this requires a further increase of stone. This would mean several corrections if we did not adopt some means to avoid this trouble; the proper one is to figure the efficiency of the flux and base the quantity required on this. From the percentage of lime which it contains we deduct the amount necessary to flux the silica which it contains at the ratio desired for the given slag. For instance, if we have a certain stone containing 2 per cent. silica, 2 per cent. iron and alumina, 52 per cent. CaO + MgO. the balance being CO_2, which is driven off as the stone descends through the furnace, and if we desire a slag with a lime-silica ratio of 1.5 : 1, we deduct from the lime present 1.5 × 2 per cent. = 3 per cent., leaving lime available for other silica 49 per cent., which is commonly called the "efficiency of the stone;" that is to say, every 100 lb. of *stone* contains 49 lb. of *lime* available for fluxing the silica of the ore and coke.

The Moisture in the Ore

It is customary practice to give the analysis of iron ore on the basis of its weight when dried at 212°F., and this is quite right and proper since there are variables enough with which to contend without our being uncertain as to the weight of moisture in the sample, but in figuring burdens for the furnace we do not have ores so dried, and it is very necessary to have moisture determinations made on samples of several pounds weight, so as to know the actual weights of the different materials the furnace is receiving for each thousand pounds of natural (undried) material charged.

The actual analysis of the ore must be calculated back from its dry weight and its actual moisture contents, and the analysis so determined must be used in burden calculations. This is a matter of much importance, because the average moisture of the Lake Superior ores is probably nearly 11 per cent., and, of course, it would distort our calculations past all recognition if due allowance were not made for this fact.

In addition to this many ores contain what is known as combined water, or water of crystallization, which is not driven off until temperatures several hundred degrees above the boiling point are reached. This water is, however, given in the chemical analysis where it properly belongs, and is not as likely to cause confusion as is the free moisture of the ore.

Flue-dust Loss

We have here a factor varying widely with the practice, and one for which it is difficult and fortunately unnecessary in most cases to make allowance in advance. A decidedly appreciable percentage of the ore in furnaces using 30 per cent. or more Mesabi is blown out the top of the furnace with the top gases. Some of it is recovered in the dust catcher, some in the gas washer, if there be one, and some goes out the stacks with the burnt gases leaving the stoves and boilers.

Mr. John N. Reese has made some very accurate determinations on this subject, and he has told me that he finds about 3 per cent. of the total iron charged disappears in one way or another, a figure which other furnacemen confirm.

Part of this goes out as the impalpable dust remaining in the combustion gases even after washing, and a part of it is lost in the slag, as described in the chapter on slag.

The Yield of Iron Obtained From the Ore

In spite of the losses of the iron chemically combined in the slag which in normal practice probably vary between 0.2 and 0.6, the loss of iron in the slag in the metallic condition, and the loss of ore dust in the top gases, a furnace running under reasonably good conditions always produces more pig iron than the weight of the metallic iron charged, for the reason that pig iron contains seldom more than 95 per cent. Fe, and generally less than that, there being generally about 4 per cent. of carbon and seldom much less than 1 per cent. of silicon, with generally from 0.5 to 1 per cent. of manganese, and from 0.1 up to 1 per cent. of phosphorus.

THE CALCULATION IN DETAIL

The general practice in burdening furnaces is to adopt a constant charge of coke, and to keep this invariable, changing the ratio of coke to ore when necessary by altering the weight of the ore. This system has three advantages: First, a constant weight implies a constant volume and

allows the weight of the coke charge to be checked against this volume, which is very desirable, because coke is capable of absorbing a large quantity of moisture, and if charged by weight alone when wet the charge of dry coke would be much too light. Second, there is one size of coke charge suited to the furnace, and while small variations in this are of no importance, it is desirable to have the charge constant at the most advantageous size. Third, the weight of coke being constant, and its analysis presumably so, it is a simple matter to figure out the slag-forming materials in the coke and calculate the quantity of stone necessary to take care of these once for all. This, under these circumstances, becomes a constant quantity, and we do not have to complicate burden calculations by taking into account the slag-forming ingredients of the coke every time the burden is changed, but merely calculate the stone necessary for the ore, and add to this the constant quantity required by the coke.

When the ore contains no gangue but silica and alumina, the calculation of the burden is very simple. We have only to add together the weights of silica in the different ores constituting the charge and figure the weight of limestone necessary to flux these. At the same time it is very desirable to keep track of the alumina, and after determining the amount of silica and lime-plus-magnesia to add in the total alumina, including that from the coke, and see what percentage of total slag it constitutes. If we have no choice of ores we can, of course, make no substitution to correct excessive alumina, but it is desirable to know in advance its approximate amount, because if it lies in the range which gives high viscosity and increased free-running temperature, as pointed out in the article on slags, we must expect that this will have a corresponding effect on the burden which the furnace can carry.

In one such case pure silica and lime were added to the charge to dilute the alumina, but it is doubtful if this ever pays on account of the great increase in slag volume necessary to secure any material dilution.

Where several ores are available with varying contents of silica and alumina, proportions of each can usually be chosen which will give the most desirable slag, or at least which will give a slag lying outside the comparative danger zone of high viscosity.

In calculating slags practically it is very necessary to remember that the sulphur must pass out of the furnace in the form of calcium sulphide, and if these calculations were as delicate as some would have us believe it would be necessary to add lime to supply the calcium for this purpose. But as a matter of fact the calcium sulphide in coke slags in ordinary practice does not vary very greatly except with very lean ores when its amount is smaller. In ordinary practice the sulphur carried by the slag varies from about 1.25 to 1.75 sulphur, and the calcium sulphide accordingly from about 2.75 to about 3.75 per cent.

A condition often arises which complicates slag calculations to some extent. That is that an ore may contain lime or magnesia or both. In this event we have two sources of base, one from the ore, one from the stone charged as flux. Obviously the lime required to be supplied by the flux must be reduced by the amount contained in the ore, but it is by no means a simple subtraction from the quantity of the flux because the lime as reported in the ore is pure lime and has an efficiency of 100 per cent., whereas the limestone is an impure carbonate of lime with an efficiency of generally less than 50 per cent.

Probably the easiest way to take care of this is, after obtaining the total weights of silica and of lime and magnesia in the ore charge, to deduct from the silica the amount which will be fluxed by the lime present at the desired ratio of lime to silica, and then determine limestone needed to flux the balance as before described.

Examples of Slag Calculations

In order to illustrate these principles let us run through one or two illustrations. Let us assume a coke of the following analysis:

	Per cent.
SiO_2	5.000
Al_2O_3	3.000
Fe_2O_3	1.400
(Fe =	1.000
Volatile	1.750
Sulphur	0.850
Fixed carbon	86.000
Phosphorus	0.027
Moisture	1.973
	100.000

The limestone we will take as above:

$CaO+MgO$	52
SiO_2	2
$Al_2O_3+Fe_2O_3$	2
CO_2	44
	100

Note.—Pure calcite contains 56 per cent. CaO, but pure magnesite only 47.6 on account of the smaller atomic weight of Mg. True dolomite (CaO, MgO) $2CO_2$, contains 52 per cent.

The analysis we have taken represents a somewhat magnesian stone, but not a dolomite. If it were a calcite the CaO would be $(100 - 2 - 2) \times {}^{56}/_{100} = 53.8$, but if it were a dolomite the CaO + MgO would be $(100 - 2 - 2) \times {}^{52}/_{100} = 49.9$. This is a point always worthy of attention.

Let us now suppose that we have available an ore which we will call A which analyzes in the natural (moist) state:

ORE A

Fe	49.850
Phosphorus	0.072
SiO_2	6.290
Al_2O_3	3.520
CaO and MgO	.....

Let us assume first that we are to make basic iron and that the burden of ore will be 2.2 times the coke.

Let us assume that the furnace is a small one, and the charge of coke 9000 lb., which will never vary, so we can calculate the stone for the coke at once and be done with it.

The coke will contain 450 lb. SiO_2, 270 lb. Al_2O_3, and also 90 lb. of Fe which will go into the iron.

We will assume that the best ratio of lime to silica is 1.5, then the efficiency of the stone being 49 per cent., each unit of silica will require $1.5 \div 49 = 3.06$ units of stone, and the 450 lb. of silica in the coke ash will require 1375 lb. stone.

The ore burden on the basis assumed, 2.2 : 1, will be 19,800 lb., which will contain 9875 lb. of iron, 1245 lb. SiO_2, 696 lb. Al_2O_3.

The loss of Fe is about 3 per cent., but the carbon, silicon, manganese, etc., make up more than 5 per cent. of the pig iron produced, so the yield of iron is about $97 \div 95 = 102$ per cent. of the Fe.

The iron of the coke ash, 90 lb., added to that in the ore makes 9965 lb. and 102 per cent. of this is 10,160 lb. Assume the silicon in the iron to be 0.75 per cent. or 76 lb., then the SiO_2 to yield this becomes $76 \times {}^{60}\!/_{28} = 163$ lb., which obviously does not require to be fluxed, so we deduct it from that in the ore 1245, which leaves 1082 lb. to be fluxed.

This requires, as above, $1082 \times 3.06 = 3320$ lb. of stone which, added to that for the coke as above (1375 lb.), gives a total stone charge of 4695 lb.

Now let us see what sort of a slag we shall have. Let us for present purposes ignore the impurities in the stone and the sulphur in the coke, assuming the stone to contain only 49 per cent. of CaO + MgO. We shall have:

				Pounds	Per cent.
SiO_2	From coke	450			
	From ore less that required for iron	1,082	Total.....	1,532	31.9
Al_2O_3	From coke	270			
	From ore	696	Total.....	966	20.1
CaO+MgO $4,695 \times 0.49$				2,300	48.0
				4,798	100.0

It will be seen that this slag contains a highly objectionable amount of alumina, which would make a tough, stringy slag, causing the furnace to work very "stiff," and probably not to settle regularly, while the super-

heating effect would tend to put silicon into the iron, the very thing we are trying not to do; in other words, we should consider this an undesirable ore for making any iron except high silicon, and would reject it for all other purposes, except as a portion of the mixture, on account of the high ratio of alumina to silica. The same ore applied to making foundry iron of, say, 2.5 per cent. Si, would work out about as follows:

Assume the burden ratio in this case to be 2.0 instead of 2.2 on account of the greater coke requirements of foundry iron, and assume the lime-silica ratio to be 1.3 instead of 1.5, because with the higher heat in the hearth less lime will suffice for desulphurization. The ore will contain: Fe. 8970 lb.; SiO_2, 1132 lb.; Al_2O_3, 634.

The yield in this case on account of the higher Si of the iron, will be about 103.5 per cent.

The total Fe is 8970 + 90 = 9060 lb. and the pig iron is 9400 lb. The Si is to be 2.5 per cent. of this or 235 lb., and the corresponding SiO_2 is 503 lb.

Deducting this from the total SiO_2 in the ore (1132 lb.), we have left to be fluxed 629 lb., which requires at the new ratio 629 × 1.3 ÷ 0.49 = 1675 lb. of stone. This added to the stone for the coke which now becomes (450 × 1.3 ÷ 49 lb. = 1200 lb.) gives the total stone, 2875 lb.

The slag on the same basis as before now becomes:

				Pounds	Per cent.
SiO_2	From coke	450			
	From ore less that required for iron	629	Total.....	1,079	31.8
Al_2O_3	From coke	270			
	From ore	634	Total.....	904	26.6
CaO+Mg	2,875×0.49.....			1,410	41.6
				3,393	100.0

I have never run a furnace on such a slag, and the information available concerning such slags is very scanty. Most furnacemen would object very decidedly to running on such a slag, and probably with good reason. One set of furnaces of which I had knowledge ran very unsatisfactorily even on foundry iron on slags, ranging from around 23 to 27 per cent. Al_2O_3, but I have no knowledge of the lime-silica ratio they used; if the management was attempting to maintain a constant ratio of lime plus magnesia to silica plus alumina, as described in the paper before quoted, the cause of the trouble was not really the alumina but the lime.

The very general preference is always to keep the alumina under 18 per cent., and for steel-making irons not above 12 to 14 per cent. It must be recognized that furnaces are being successfully run on slags of 24 to 38 per cent. Al_2O_3, but it is done not because the slag is desirable metallurgically, but because the cost of the ore which gives such slags is low enough to compensate commercially for the disadvantages of some-

what smaller production and somewhat greater coke consumption than would result from ores lower in alumina.

Having purposely chosen in the first case an ore which would give an undesirable slag, let us now take more normal one, which we will call B, which analyzes as follows:

ORE B

Fe	49.590
Phosphorus	0.050
SiO_2	8.700
Al_2O_3	1.910
CaO+MgO	.....

First let us take the case of basic iron and assume a burden of 2.2 or 19,800 lb. as before, then the coke charge being the same as before, we have 19,800 × 49.59 = 9840 lb. Fe; adding 90 lb. from the coke we have 9930 lb. A yield of 102 per cent. gives 10,100 lb. pig iron. The silicon in this at 0.75 per cent. is 76 lb. and the corresponding SiO_2 is 163 lb.

The silica of the ore is 19,800 × 8.7 per cent. = 1720 lb.; deducting 163 lb., the silica to be fluxed is 1557 lb. The limestone for this at 1.5 to 1 and 49 per cent. efficiency is 4770 lb., to which is added 1375 for the coke, making 6145 lb. stone. Then the slag formed is as follows:

				Pounds	Per cent.
SiO_2	From coke	450			
	From ore less required for iron	1,557	Total.....	2,007	35.4
Al_2O_3	From coke	270			
	From ore	378	Total.....	648	11.4
CaO+MgO 6,145×49				3,010	53.2
				5,665	....

This is an excellent slag on which to make basic iron, and yet there is a certain feature of this case which compares unfavorably with the former.

The slag volume is one-sixth larger than in the former case, which means, other things being equal, a larger fuel consumption, but the free-running temperature of the low-alumina slag is enough lower to offset the greater slag volume twice over *for basic iron.* When foundry iron is to be made the higher alumina is probably an advantage as the lower slag volume certainly is.

These two ores, A and B, each contain almost exactly the same SiO_2 + Al_2O_3, 9.81 for the former as against 10.61 for the latter, but still there is a proportionally much greater volume of slag in the latter case; this serves to bring out an important point: Of two ores containing the same sum of SiO_2 + Al_2O_3, the ore which contains the most silica will always produce the greatest slag volume, for the silica requires to be fluxed with

considerably more than its own weight of *lime* (not stone), while on the system recommended here no flux is added for the alumina.

Let us now see how ore B works out for foundry purposes.

Assume the burden 2.0 or 18,000 lb., the Si in the iron as 2.5 per cent. and the yield 103.5 per cent. as before.

The total Fe is 8930 + 90 = 9020. The iron is 9350 lb., the Si is 2.5 per cent. of this, or 234 lb., and the corresponding SiO_2 502 lb. The SiO_2 of the ore is 18,000 × 0.087 = 1565; deducting 502 leaves 1063 lb. to be fluxed, requiring with a lime-silica ratio of 1.3 and the same stone as before, 2820 lb. stone. The slag in this case becomes:

				Pounds	Per cent.
SiO_2	From coke	450			
	From ore less Required for iron	1,063	Total.....	1,513	37.0
Al_2O_3	From coke	270			
	From ore	344	Total.....	614	14.9
CaO + Mg (2,820+1,200) × 0.49.....				1,970	48.1
				4,097	100.0

This would be an excellent slag for foundry iron, though the alumina might well be raised a little, which, of course, could readily be done by using a certain proportion of A.

Most burdens are made up of several components, and in that case while the principle is the same we have more items to handle.

To show these more clearly, the results of a burden of one-third of ore A and two-thirds of ore B are shown in Table XXI, whose arrangement brings the separate components from whatever source into one column, so that the total amount of each to be disposed of may easily be found by addition.

This shows the phosphorus and sulphur as well as the slag-forming components. The charge contains about 15 lb. of phosphorus, all of which passes into the 10,020 lb. of iron, making the percentage in the latter 0.15. The extreme limit for Bessemer rail steel is 0.1 in the steel, so the iron is limited to about 0.09 per cent. Iron with phosphorus 0.15 per cent. would be classified as "malleable" by its phosphorus content, although much basic iron now made is as low as this.

These figures are not strictly correct, because while we have included all the impurities in the limestone which are, of course, present in the slag, we have not made allowance for the manganese and traces of iron in the slag. Most of the sulphur in the charge must be carried off in the slag as CaS. Let us see how much lime is required for this. Suppose the iron to contain 0.03 S, then this will take care of 3 lb. of the 86 lb., and let us suppose that 15 per cent. are volatilized, disposing of 13 lb. more, and leaving 70 lb. to be fluxed.

The Ca required for this is $70 \times {}^{40}/_{32} = 87.5$ lb., and the CaO corresponding is $87.5 \times {}^{56}/_{40} = 122.5$ lb.

This is 4 per cent. of the total lime charged, and so reduces our lime-silica ratio by 4 per cent., or to 1.46 : 1.

This is within the limits of accuracy of our knowledge of the best ratio and is a small matter. If an exact ratio be desired the stone required for the sulphur can be figured once for all and added to the stone for the coke ash, but a slight change in the heat of the furnace, throwing more or less silicon into the iron, will make more difference in the actual basicity of the slag than all the sulphur does. For instance, a change of 0.25 per cent. in the silicon in the iron makes a change of 25 lb. of Si and 54 lb. of SiO_2, which would call for a change of 81 lb. of lime, but such changes are of daily occurrence, almost from cast to cast, and yet no furnaceman thinks of correcting his limestone burden to suit.

These simple examples illustrate the principles of figuring burdens of which so marvelous a mystery has often been made by those who wished to emphasize the importance of their own knowledge.

In general several ores or iron-bearing materials are used, but the principle of figuring the burden is the same for a dozen as for one.

TABLE XXI

Material	Component											
	Fe		SiO_2		Al_2O_3		CaO + MgO		P		Sulphur	
	Per cent.	Lb.	Per cent.	Lb.	Per cent.	Lb.	Per cent.	Lb.	Per cent.	Lb.	Per cent.	Lb.
Coke..... 9,000	1.00	90	5.00	450	3.00	270	..	.....	0.027	2.3	0.850	76.5
Ore A..... 6,600	49.85	3,290	6.29	415	3.52	233	..	.....	0.072	4.8	0.067	4.4
B.....13,200	49.59	6,740	8.70	1,174	1.91	252	..	.....	0.050	6.6	0.010	1.4
C												
Stone..... 6,086	.....	.....	2.00	122	....	122	52	2,983				
		10,020		2,161		877		2,983		15.1		86.1
		SiO_2	for Si	165								
			net SiO_2	1,996								

Iron produced basic $1.02 \times 10{,}020 = 10{,}220$.

Si in iron at 0.75 per cent. = 76.8; SiO_2 for this Si = $76.8 \times 60/28 = 165$ lb.

Total SiO_2 2161; deduct 165; balance 1996 SiO_2 to be fluxed.

Stone to flux this at 49 per cent. efficiency of stone and 1.5 CaO + MgO per unit of SiO_2 = 3.06 units of stone per unit of SiO_2.

Correct slag volume	Pounds	Per cent.
SiO_2 2,154 − 165 =	1,996	33.6
Al_2O_3	877	14 7
CaO + MgO	2,983	50.5
Sulphur with allowance for volatilization, etc.	70	1.2
	5,912	100.0

These chemical considerations are only one of the elements in making up a burden. The physical condition of the ore, whether "lump," "fine," or "soft" (plastic), whether hematite or magnetite, whether excessively fine or only like coarse sand, and above all price, these are all questions which must be considered with the same care as the chemical composition of the ores. As a general thing it is a problem of fitting together the physical properties of the ores available in such a way as to give the charge the most desirable physical character for the least cost, then adjusting the proportions of the different components so that the ratio of silica and alumina will be within certain wide limits, and finally calculating the amount of stone required to give the ratio of CaO to SiO_2 needed for the kind of iron to be made. It is obvious from the statement of the problem that there is need for some cutting and trying of different combinations, a little simple arithmetic, and much common sense and judgment.

Of course, if Bessemer or special low-phosphorus iron is to be made, the increased selling price warrants a larger expenditure for ore, and in that case the necessity for keeping the phosphorus below the desired limit is paramount, and other considerations are subordinated in that.

In that case the phosphorus contents of the coke and the stone must be carefully watched, since ores bring a premium in proportion to the smallness of their phosphorus content, and the higher the coke and stone in this element the more expensive the ore which must be used to keep the total within the desired limit.

Let us now hastily run through a case in which one of the ores is more than self-fluxing; that is, where the major impurity to be slagged is lime instead of silica. Let us assume a coke charge of 12,000 lb. of the following analysis:

SiO_2	7 per cent.
Al_2O_3	2 per cent.
Fe	1 per cent.
S	1 per cent.

We have available ore C containing:

Fe	33.0
CaO	17.0
SiO_2	8.0
Al_2O_3	2.0
CO_2 with CaO	13.5

and ore D containing:

Fe	47.0
CaO	....
SiO_2	16.0
Al_2O_3	4.0
Combined H_2O	10.0

The burden will consist of three-fourths C and one-fourth D with an average Fe content of 36.5 per cent.

The fuel we know will be about 2750 lb. per ton of 2240 lb. Then 12,000 lb. coke will produce 9800 lb. of iron nearly, and assuming foundry iron with a yield of 102 per cent. (the yield is lower than before on account of the much larger slag volume and the correspondingly large losses of iron in slag), this will correspond to 9500 lb. of Fe, and at 36.5 ore percentage this will give an ore burden of 26,000 lb., 19,500 of C and 6500 of D.

The silica in the coke is 840 lb. The lime-silica ratio being 1.3, the silica of ore C will use $1.3 \times 8 = 10.4$ per cent. of its lime, leaving $(17 - 10.4) = 6.6$ per cent. free for other purposes, or 1250 lb. of *lime*.

The silica of ore D is 1040; this added to that from the coke, 840, makes 1880 lb.

Assuming 2.5 per cent. Si in the iron, 244 lb. of silicon per charge are required, or 525 lb. of silica. Deducting this from the unfluxed silica above, 1880 lb., we have left 1355 lb., which requires 1760 lb. of lime. Deducting from this the 1250 lb. of free lime from ore C, we have left 510 lb. of lime to be supplied by limestone. At 48 per cent. efficiency this will require 1060 lb. of stone.

Neglecting the impurities in the stone and the sulphur in the coke we obtain the following slag:

				Pounds	Per cent.
SiO_2	From coke	840	less 525		
	From C	1,560			
	From D	1,040		2,915	38.2
Al_2O_3	From coke	240			
	From C	390			
	From D	260		890	11.6
CaO	From C	3,320			
	From stone	510		3,830	50.2
				7,635	100.0

These conditions are similar to those in the Birmingham district, but the ores there contain more silica and alumina than in the case taken, so that the slag volume there is larger and the alumina somewhat higher than in the above illustration. But the example shows clearly the method of calculating a burden for a calcareous ore.

Of course, in such a case by lowering the proportion of D the change may be made exactly self-fluxing so as not to require the use of any lime. This has often been done in that district.

Here we have a good illustration of what slag calculations *cannot* do; D represents a brown ore and C a hematite; it is found in practice that an admixture of brown ore lowers fuel consumption to a material extent, and it is always used when available, but there is nothing whatever in the slag calculation to show this.

From the above examples it will be seen that the calculation of a furnace burden is by no means the complicated operation that some pretend to believe. It is no more than an old-fashioned sum in addition, subtraction and multiplication. We have only to remember the simple rule that everything which goes into the furnace must come out, and it must come out in one of four ways: as gas, as flue dust, as an ingredient of the iron, or as slag.

The foregoing chapters have shown clearly enough those elements of the charge which come out as gas, the composition of the iron tells us approximately what will come out with the metal, the balance must appear mainly in the slag, and that balance must be so proportioned as to make a free-running slag with a sufficiently high ratio of lime to silica to take care of the sulphur and yet permit the degree of siliconization desired.

In all the above it will be noted that little has been said as to the ratio of the ore burden to the fuel. We may as well confess now that this depends upon judgment much more than upon calculation, and the burden must in general be adjusted to what the furnace is willing to carry rather than to the preconceived ideas of anyone as to what it should carry. However, certain approximations are desirable, and in the light of the calculations of the chapter on thermal principles are possible.

If the conditions are normal, that is, if the slag contains only the ordinary ingredients in proportions within the ordinary range of practice, roughly speaking, silica, alumina, lime, and magnesia, if the alumina be below 17 per cent. and the sulphur not much in excess of 1.5 per cent., we can assume that we shall have a critical temperature of 2750°. If the conditions are different from these, if there are other elements to be fluxed, if the sulphur is excessive, or, on other hand, is much below normal, it is not possible to say quantitatively in advance what the effect on the free-running temperature of the slag will be, and we are, therefore, left in ignorance of the most important datum of the whole subject, the critical temperature of the furnace, and can, therefore, make no trustworthy calculations.

Assuming, however, that the critical temperature is normal we can say—that the fuel consumption with a slag volume of ½ ton per ton of iron will vary from about 1700 lb. in the best practice to 2100 or 2200 lb. in accordance with the fineness of the ore, the temperature and dryness of the blast, and, above all, with the goodness or badness of the filling. Each additional 100 lb. of slag per ton of iron will require about 35 lb. of coke up to 3000 or 3500 lb., and probably beyond that point, but that is about the limit of slag that it is commercially possible to melt in present practice, though undoubtedly with the exhaustion of our richer ores this limit will rise by slow degrees from year to year.

From these figures of fuel consumption we may easily work back through the percentage of iron in the ore and the percentage of Fe in the

pig iron, to the quantity of ore which will constitute the burden which the coke may be expected to carry in the given case.

Any such calculation, however, is an estimate and nothing more. It may be used to obtain an approximate fuel cost under untried conditions or to check up an actual fuel consumption to see if it is out of the way, but in the day-to-day burdening of the furnace the only knowledge of any real value as to the burden the furnace can carry is supplied by the performance of the furnace itself, after all the conditions have been made right.

CHAPTER XII

THE DISTRIBUTION OF THE CHARGE COLUMN AND OF THE ASCENDING GAS COLUMN

Granting that the foregoing chapters have given a fair idea of the many actions which go on inside the furnace, and the fundamental laws by which they are limited and controlled, with methods for calculating the burden required for each given case, it might be thought that the problems concerning the operation of the furnace were all solved. It would be nearer true to say that their solution was just begun.

The question on which the practical operation of the furnace depends more than any other is the distribution of the raw materials in the top of the furnace. The question of distribution of the gas in the different zones of the furnace, while far less important, is a matter of great moment, the two being obviously interdependent to some extent.

We have discussed the first of these questions at some length in the chapter[1] on filling the blast furnace, and the second in the chapter on mechanical principles. It may be as well to confess frankly at the beginning that it is far easier to handle these two questions from those points of view than it is from the complex one of operation.

As I have emphasized several times before, the prime desideratum is that each particle of the burden shall have a uniform exposure to gas and to heat in its journey down through the shaft and bosh into the hearth. The question is how to secure this condition.

DISTRIBUTION AND CONTROL OF THE GAS COLUMN

Leaving for the present the more difficult question of distributing the stock let us consider that of controlling the gas flow. This may be considered from two points of view: first, that of conditions in the lower part of the furnace within the range in which penetration is effective; second, the upper regions of the furnace, roughly speaking, the shaft.

The Distribution of the Blast in the Hearth and Bosh.—In the first region we have two factors of control. One is the penetration itself, the other the density or openness of the charge column in its different portions from the center outward. Reference to Figs. 7, 8 and 9 in the chapter on mechanical principles shows that the effect of improper penetration, whether too great or too small, is gradually smoothed out

[1] See "Blast Furnace Construction in America," Chapter II, "Filling the Furnace."

by time and flow until at a certain distance from the tuyeres the distribution of the gas is no different with bad penetration from what it is when good. Obviously the distance in which this equalizing action occurs is important. The experimental difficulties in making determinations of this point would be vast, not to say insurmountable; we have therefore to guide us only our knowledge of furnace operation.

I have often heard of attempts by varying the penetration to control the action of the gas at levels far above the top of the bosh, but as far as my own observation goes I have reached the conclusion that that region is about the limit of the height within which changes in the action of the furnace may be produced by changes in penetration. We do know, however, that they can be produced up to this level because we know that we can regulate the tendency of the furnace to build or to scour on the bosh, even quite close to the top of the latter by altering the size and length of the tuyeres, and if a scaffold forms on the bosh we know that we can generally remove it by proper alteration of the penetration. On the other hand, I have known of at least one case where a scaffold was formed on the lower part of the bosh by excessive penetration, driving the gas column to the center of the furnace and allowing the bosh walls to remain so inactive that slag and other materials built on them so as almost to shut off the passage of the gas altogether.

It is important to notice in this connection that an action which is started by the gas itself may develop in such a way as to increase that action. Thus, if the gas is passing too much to the center and a scaffold begins to build on the walls just above the tuyeres its tendency is to throw the gas still more strongly to the center and thereby favor still further building on the walls, this condition continuing until the furnace can no longer operate, as in the case mentioned.

On the other hand, I have already mentioned the case of a furnace with very deficient penetration in which the charge column built up like a cone in the center of the hearth and filled the latter up until there was nothing left except a narrow ring around the outside. In that case the formation of a "dead-man" in the center of the furnace naturally tended to throw the blast back more strongly against the walls and so to cut them away more actively, with the result that the lining of the hearth on this furnace was almost totally destroyed after a comparatively short campaign, and breakouts in consequence were numerous.

It is perhaps too broad a statement to say that improper penetration always brings about conditions which tend to increase the very tendencies that produced them, and so continually get worse, but we may safely say that this is the result in many cases, and for this reason, as well as on its own account, correct penetration is of the utmost importance.

Irregular Penetration.—In all that has gone hitherto we have assumed that the penetration was alike at all the tuyeres. But this is unfor-

tunately not true, and differences in the quantity of wind blown into the tuyeres in different sectors of the furnace have been responsible for some very unsatisfactory furnace work whose cause was to the last degree obscure and hard to find. In ordinary practice the hot-blast main strikes the annular bustle pipe around the furnace on a truly radial line, and in that case if there is a reasonable length of straight main next the bustle pipe the blast naturally divides itself evenly around the two sides of the latter, and we have symmetry of distribution on each side of this principal diameter, but in regard to the diameter at right angles to it this is not the case. The velocity of the blast in the hot-blast main is exceedingly high, and the surface friction being quite large the drop in pressure per unit of length is far greater than in most air piping, so that the pressure on the side next the inlet is on the average appreciably higher than that on the opposite side, and the pressure at the first two or three tuyeres next the inlet is considerably higher than those in the same semicircle but further from the inlet.

This condition in itself is bad and the remedy appears at first sight to be simple. We need only to increase the diameter of the bustle pipe until the pressure is virtually the same all around it. But to this there are two objections. First, the bustle pipe is enormously large and heavy even as now constructed for high velocities and would of course be correspondingly worse for lower ones. Second, the remedy under conditions which have prevailed at all plants until recently, and at most even yet, would be of short-lived benefit because the dust picked up out of the stoves by the blast is carried through the gas main and into the bustle pipe. Near the inlet the velocity is high enough to keep it moving, and instead of settling it is carried out the tuyeres, but in the portions of the circle more remote from the entrance the velocity having become proportionately diminished, the dirt soon settles and gradually builds up in the pipe, reducing its area down to that at which the velocity is sufficient to prevent more dust from settling.

In some cases the conditions are even worse than this. The hot blast main is brought into the bustle pipe not on a radial line but eccentrically. This makes a sort of back-water of the region just back of the inlet (see Fig. 77) because the blast owing to its high velocity cannot turn the sharp corner so as to supply this region properly and therefore its blast supply is deficient. This, of course, greatly exaggerates the conditions described for the symmetrical arrangement, the region immediately in front of the inlet receives a decided over-supply of blast, and the region behind it a correspondingly deficient one.

At least one case is on record in which certain furnaces having the hot main about 3 ft. off the center of the bustle pipe (not enough to be noticeable without close observation) ran fairly well on foundry iron

but very unsatisfactorily on basic iron. It seemed impossible to keep the sulphur low enough when the silicon was within the proper limits. Finally, the trouble was traced to the asymmetrical arrangement of the hot main and the tuyeres just in front of the inlet were changed to a smaller size so as to prevent the higher pressure of the blast in this portion of the bustle pipe from driving an excess of wind through these tuyeres. This cured the trouble absolutely and the furnace thereafter gave entirely satisfactory results on basic iron.

Since the realization of the conditions brought about by this case much more attention has been paid to this subject and now in some cases

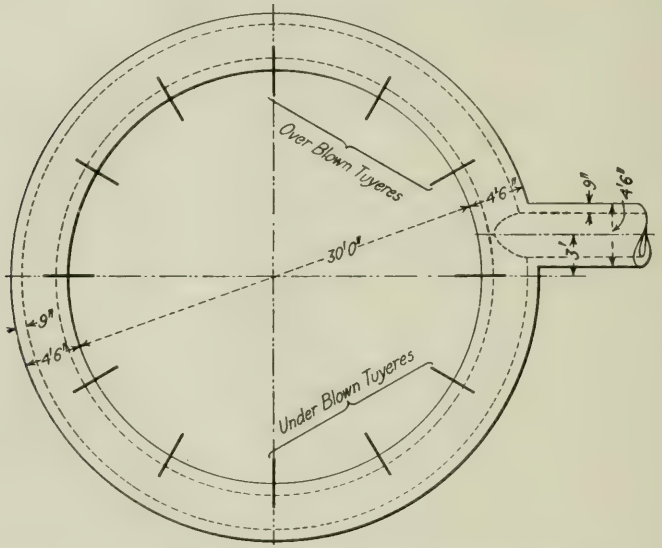


Fig. 77.—Effect of hot main entering bustle pipe unsymmetrically.

it is the practice to use smaller tuyeres next to the inlet even on furnaces with symmetrical bustle pipe, and this practice is probably well founded. It would seem legitimate also to increase the tuyeres on the far side to a corresponding extent, but this is commonly not done.

Just what is the mechanism by which the action of the furnace is upset under these conditions we do not know. Two or three theories could be advanced, some of which would be exactly opposite to others. But we do know that the prime condition for proper furnace work is absolute and complete uniformity of conditions on all sides of the furnace, and that such a condition as this, fundamentally violating that requirement, must produce bad results.

I incline to the belief that the action in such a case is somewhat as follows: We know to a certainty that if the furnace as a whole be blown to its proper capacity, the region receiving the excess of air must be over-

blown. This means that the stock is allowed less time than it should have for complete reduction and this in turn probably means a scouring slag which leads to high sulphur. The more rapid rate of driving in this sector leads to a more rapid descent of the charge in that region, and owing to the greater mobility of the lumpy portion this means that the lumps tend to be drawn toward this zone of the furnace. It is as though the layers of charge which should normally be horizontal were tilted down on this side so that the lumps tend to travel this way. These require more time for their complete reduction than do the fines, therefore tend to exaggerate the raw condition of the iron produced in this sector, and being more open and permeable to the gas they tend to increase the velocity of the gas in this sector and therefore to exaggerate the conditions which originally started the irregularity.

In other words, we have here again a case in which the tendency probably is for the results of a certain condition to react on the causes of that condition so as to make it worse, the evil being thus self-intensifying. It will be seen therefore that it is not only important to have the areas of all the tuyeres correct to give the proper penetration but it is important to have the total area so distributed among the different tuyeres as to compel an equal quantity of blast to enter the furnace in each sector.

Effect of Stock Distribution on Gas Flow in Bosh.—Turning now to the second factor in the control of the gas column in the lower portion of the furnace we have to consider the varying density of the charge column. This is a subject concerning which we know but little. I shall presently describe a case in which a dense impervious core was produced by the filling, and this undoubtedly descended into the bosh. But rodding tests at the tuyeres did not show any conclusive evidence of deficient penetration at that level, and rather drastic variations of tuyere diameters to try the effect of increasing penetration upon the dense core did not yield any results of value. This seems curious; it would be foolish to try to give a reason for so obscure and complex a phenomenon, but it may be suggested that the dense core in that portion of the charge in the shaft being made up almost entirely of ore and flux, as we know it to have been constituted, was melted by the expenditure of much extra coke somewhere up in the bosh and ran down into the hearth. This then would leave the coke free to fill the space vacated and would produce the condition of comparatively uniform penetration which we found.

Claims have often been made as to the effect on the bosh walls of changes in the filling, that they built up with certain kinds of filling and scoured off with others, etc. I have never had any experience in which I could identify these conditions myself, but they may exist. My own feeling is that penetration is the predominating factor in gas distribution up to the top of the bosh, and above that level stock distribution is the controlling, almost the sole factor.

Effect of Stock Distribution on Gas Flow in the Shaft.—In the chapter on filling the furnace we have seen the necessity for distribution symmetrically about two or more equally spaced axes, and this symmetry must not be only quantitative but qualitative. It is not sufficient to have the same total amount of material in each sector of the furnace, we must have equal quantities of *each* of the raw materials in the charge, and further than this we must have as far as possible equal quantities of each *size* of the different kinds of raw materials.

I have endeavored to emphasize this so strongly in the chapter mentioned that perhaps no additional stress need be laid upon this point here. But these requirements alone are not enough, the distribution of the different sizes of materials in the proper position radially is as important as is a symmetrical distribution circumferentially.

The Effect of the Size of the Bell.—The effect of the wall in increasing the voids in the material adjacent to it was also pointed out in the chapter on filling, and we know from the considerations there given that at least a considerable portion of the fine material should be placed against the walls by the charging operation. In regard to the quantitative effect of the further factors which control in this important and complicated matter we have no information whatever. We know that a bell large in proportion to the stock line will distribute most of the fine material against the walls, and we have already seen that this is desirable up to a certain point, but if the bell be made too large the effect on furnace work is not to improve it further, but to make it distinctly worse. We do not know precisely why this is. We may well imagine, however, that the placing of too great a proportion of the fine material immediately adjacent to the wall cuts off the currents of gas to so great an extent that that portion of the charge is not kept active, and this leads as we know by experience to building on the walls, consequently to formation of incipient scaffolds, and all the evils which they bring in their train.

Of course, if we make the bell too small then the fine material is deposited too close to the center of the furnace, the lumpy and more open portions of the charge roll to the walls, by which their natural voids are increased, as we have seen in a previous article, almost 100 per cent., and the result can only be that the gas rushes violently up the sides of the furnace, leaving a column of more or less dead material up the center which is deprived of its proper proportion of the reducing action of the gas and so descends into the hearth in a raw condition, while on the other hand the extreme rapidity of action produced next the walls by the excessive gas currents makes the lumpy portion of the charge travel too fast, which has two bad effects. First, the outer portion of the column descending more rapidly than the inner tends to increase what might be called the reversed-crater action next the walls with the result of drawing a still greater proportion of the lumpy material to that region, and so increasing the objectionable action which gives rise to these conditions.

Second, the lumpier portions of the charge need more time for their complete reduction than do the finer ones, hence the larger lumps, in spite of the excess gas to which they are exposed, tend to reach the hearth improperly reduced because not allowed sufficient time for complete reduction.

It becomes plain, therefore, that there is a satisfactory explanation for the fact, which we know so well by experience, that to do good work the stock distribution must not only be symmetrical, but the size of the bell must be such as to put the proper proportions of fine and coarse material in their proper radial positions.

Difficulties of Experiments on Models.—It might be thought that it would be simple to determine experimentally what size of bell and other top arrangements would give these desired conditions, and such attempts have been made on scales of varying sizes dozens of times. While useful, these are open to two objections.

First, it is very difficult to duplicate in an experimental way either full size or on reduced scale the actual conditions which prevail at the top of the furnace. To begin with we have no means of causing the regular and uniform settling of the charges as we deposit them in our experimental apparatus, and if we do not produce uniform settling we cause a cratering action in one or another portion of the top surface which is likely to distort or destroy the correctness of the results obtained with subsequent charges. There are, of course, many other operating and practical difficulties in the way of such experiments, not the least of which, if they be full size, is the expense.

Second, granting that we can determine correctly with an experimental apparatus the results that will be obtained with any given design, how are we to select the one which will produce the best results on the furnace?

On one occasion the general superintendent of a certain plant declared to a visiting furnaceman his intention of constructing a full-size model of his furnace top and experimenting on it with all kinds of distribution, and then at the end of the experiments selecting the one which he liked best. The visiting furnaceman asked how he knew that the furnace would like best the system that he liked best. No answer was forthcoming, and from the nature of the case it is almost obvious that none could be. The laws affecting symmetry of stock distribution, etc., we understand quite well; they are fundamental. But having that foundation, there remains a great superstructure of details to be built, for the design of which we have not, and seem likely never to have, any simple or inductive method; nothing but the slow and tedious process of trial and error, varying one detail at a time, keeping all other conditions constant, is sufficient for the solution of so difficult a problem.

Add to this the almost infinite difficulty of keeping all the other conditions constant under such complex conditions, and it becomes easier to understand why we have as yet so little knowledge even of the em-

pirical kind to guide us in these matters. General experience is sufficient to give us a fair working start and reasonably good results. Anything beyond that must be obtained by each individual furnaceman to suit his own conditions.

The Effect of Sizing on Mixed Material.—This is a subject to which too little attention has been paid. Its importance was first pointed out, so far as known to me, in a paper by Mr. Frank Firmstone before the American Institute of Mining Engineers.

The reasoning is very simple. If we take a quantity of spheres, all of the same size, we can quite easily figure the percentage of voids between them, as has already been done in an earlier chapter, and this is a perfectly definite mathematical proportion. But if we started off with, say, 3-in. spheres, we could insert into the larger interstices of these smaller spheres, say 1 in. in diameter, and into the interstices then remaining still smaller ones, say ¼ in., and into the interstices still remaining smaller ones, say 1/16 in., and so on down. The size to which we should descend in the individual case is controlled by the size of the raw materials with which we have to deal. We have then a mass made up of heterogeneous spheres with all the interstices filled with the smallest size of spheres we have available. Suppose now that we put the whole mass over screens which separate it into the original uniform sizes? Each of these sizes would contain, of course, the fixed mathematical proportion of voids above given, no matter how small the spheres might be, and the gross volume of the sized material would be far larger than the volume of the mixed mass of heterogeneous spheres, in which obviously the percentage of voids would be only a small fraction of what it was in each of the sized varieties.

What is accurately and mathematically true of spheres is true in a general way of irregular material, particularly if that irregular material be of a uniform kind, and have, therefore, an approximately similar shape, irrespective of its size, as is roughly the case with the different kinds of raw material, so that for any considerable mass of a given irregular material the same general laws hold as for the mass of spheres.

Remembering now that one of our fundamental laws for proper operation of the furnace is that each portion of the charge column must be exposed to the same quantity of gas, and considering the enormous effect of permeability on the passage of the gas currents, the practical effect of this general law becomes obvious. If we wish to make the charge column more permeable in any given portion we must have recourse to sizing of some kind, and if we desire to make the charge column as a whole more permeable sizing of all the fine portions of the raw materials is our only recourse.

Working along this line I made some experiments several years ago whose results are indicative of the great effect which may be produced in

this way. We made a heavy wooden box containing 1 cu. yd., and filled this with the car-run of hard ore of the Birmingham district, crushed to go through a 3-in. ring. We then cut this cubic yard of ore into three sizes, over one screen, and over and through another. The first attempt gave portions of very different sizes. On the second attempt we used screens of $\frac{7}{8}$-in. and $\frac{5}{32}$-in. mesh, and these two screens cut the whole mass into three almost equal portions.

The specific gravity of the solid ore was determined in the laboratory, and from the weight of the original cubic yard we could easily determine what its volume unbroken would have been. The difference between this and the cubic yard gave its voids in the mixed condition. After screening, the volume of each of the three portions was determined by putting it back in the cubic-yard box, leveling its top carefully, and measuring the depth. (This is very important, because if the volume of the portions be determined in a smaller box, the wall effect, that is, the increase in the voids next to the walls, for the reason already pointed out, is so great that the results are entirely distorted and worthless.)

By adding together the volume of the sized portions we obtained the volume of the original cubic yard in its sized condition, and deducting from this its calculated volume in the solid condition we obtained the total voids in the sized ore. This was increased 45 per cent. over the voids in the original mixed ore. The detailed results are shown in Table XXII.

TABLE XXII.—DATA OF SCREENING TEST ON BIRMINGHAM HARD ORE

Specific gravity (laboratory)	3.45
Coarse through 3-in. ring, Over $\frac{7}{8}$-in. mesh (made from No. 9 B & S wire, 1 in. center to center).	
Middlings, Under $\frac{7}{8}$-in. mesh over $\frac{5}{32}$-in. mesh (No. 5 B & S wire $\frac{1}{4}$ in. center to center).	
Fines	Under $\frac{5}{32}$-in. mesh
Weight of 1 cu. yd., actual measure of crushed unscreened ore,	3,852.5 lb.
Weight of 1 cu. yd., solid ore (from specific gravity)	5,805.0 lb.
Volume of 3,852.5 lb. ore if solid	17.92 cu. ft.
Voids in 1 cu. yd., mixed crushed ore	9.08
	27.00
Voids in per cent. of total volume of mixed ore	33.70

AFTER SCREENING

	Coarse	Middling	Fines	Total
Weight in per cent. of total	33.00	32.90	34.10	100.00
Weight in pounds	1,271.50	1,267.00	1,314.00	3,852.50
Cubic feet of solid ore	5.91	5.90	6.11	17.92
Measured volume of crushed screened ore, cubic feet	10.25	10.92	9.92	31.09
Voids in crushed screened ore, cu. ft.				13.17
Per cent. of voids	42.40	46.00	38.40	42.40

Volume of voids per *given weight* of ore, 13.17 cu. ft. in screened ore as against 9.08 cu. ft in unscreened, or an increase of 45 per cent.

This last is evidently the important consideration for practical purposes.

The effect of such an increase in the percentage of voids on the permeability of the charge could not fail to be very marked. Unfortunately, we were unable to carry out any experiments on the use of such sized ore on the furnace itself, though the conditions under which it operated gave every reason to hope for substantial benefits.

It may be thought that the true percentage of voids in the fines is not affected any more than it would be if we took a mass of fines and placed in it a series of lumps out of contact with one another, in which case obviously the quantity of voids in the whole mass would remain to all intents and purposes the same as it was before. This view is not altogether correct because it will be seen that the percentage of voids in the mixed ore was 33.7, while that in the fines alone was 38.4. A highly important practical consideration enters here, however. It is obvious that we have greatly increased the voids in the coarse ore, making them materially greater than those in the fines, although those are substantially increased. The operations of heating and reduction must go on from the surface inward and must travel further to reach the center of the lumps than they do with the fines, in order that both be as well prepared, it is, therefore, vital that the lumps be given better exposure to the gas currents than the fines in order that the processes which prepare them for final treatment in the hearth may be complete by the time the lumps reach there. The fact that sizing increases the percentage of voids in the lumps more than it does in the fines is therefore a stronger argument for that practice.

In more recent years John N. Reese has made many sizing tests of Lake Superior ores entirely independent of the work done by me, and has found that precisely the same laws hold in all fine Mesabi ores as in the coarse hard ores of the South. The difficulties, however, from the practical point of view, of sizing in the case of such material as Mesabi ore are almost insuperable, and it seems unlikely that we shall ever see a practical application of these laws in the case of such exceedingly fine material.

There is, however, one practical application of these principles which I believe could be made much more frequently than it now is, and that is to abstain from mixing ores of different sizes with the idea that the coarser would loosen up the finer. The only result which this can possibly have is to cause the finer to obstruct the coarser without being benefited itself, and if ores of different degrees of fineness are to be charged in the same furnace they should be charged separately, not even in the same round, if this can possibly be avoided, because the more they are mixed the worse the results must necessarily be. There may be one case in which it is justifiable to violate this rule. When the main portion of the charge consists of a fine sandy ore, and a minor portion of the charge is of a lumpy or plastic nature, the latter portion may be charged first separately, so as to make a blanket over the top of the coke and prevent the fine ore from running down through the fuel. The loss of porosity in this case

is more than compensated by preventing contact between fine ore and fuel, but I wish to reiterate my conviction that, generally speaking, where two ores of different coarseness are to be charged the more widely separated they can be the better will be the results on the furnace. If I had two furnaces and a total ore supply made up of one-half very fine and one-half coarse, I should be very much tempted to use all the coarse in one furnace and all the fine in the other. Perhaps alternate charges of each kind would be as good, but certainly either of these would give vastly better results than mixing the fine and coarse in the same charge.

The Size of the Coke Charge.—This is a point of much importance, and in this, as in so much else that concerns the filling of the furnace, we have only empirical knowledge to guide us. Mr. E. A. Uehling pointed out several years ago that the effect of the layer of ore on the gas rising through it was an oxidizing one, while the effect of the layer of coke immediately above was a reducing one, and that as we desired the maximum of reduction by gas, it was very important not to have the fuel and ore charged in a mixture, but to keep them in separate layers, and that, moreover, the effect of the separation was greater the thicker were the individual layers. This is simply another phase of the fact which I have already attempted to emphasize, that the more points of contact of ore with coke the greater the solution loss, and the poorer the economy, and in principle this is entirely correct.

There is obviously a limit, however, since there must be a certain intimacy of mixture between the ore and the coke which is to perform the final reduction upon it in the hearth, and it is presumably this factor which sets a limit to the size of the fuel charge which we can use. That there is such a limit has been determined by the experience of many furnacemen. My own experience covers one such case whose results were unmistakable. In order to obtain more symmetrical filling at a charcoal furnace with a very small stock-line diameter, and using very large barrows, I wished to use four barrows at a charge instead of two. A first attempt was not successful because the top as it stood was not adapted to correct dumping at four points, but on a subsequent blast, having redesigned the top so as to permit absolutely symmetrical dumping at four points, I started the furnace off with a four-barrow charge. After a week or so of operation in which the fuel consumption remained far higher than it should, I became convinced that the thickness of the charge layers might have something to do with it and changed to a two-barrow charge, obtaining symmetry by alternating the dumping positions on each alternate charge. The result was immediate. The fuel consumption of the furnace at once dropped 5 or 6 per cent., and its work became more satisfactory in all respects.

From such data as are available it seems that the average thickness of the coke charge in a 22 by 90-ft. furnace is about 2 ft. and this appears to

be more or less established practice with furnaces of this size on Lake Superior ores. For furnaces of smaller size it is probable that the thickness of the fuel bed for best results remains about the same and that, therefore, the weight of the proper coke charge diminishes in proportion to the diminished area (not diameter) of the stock line.[1]

Effect of the Location of the Gas Outlet.—In the chapter on filling it has been pointed out that the old practice was to use the center out-take for the gas, thus securing perfect symmetry for the gas current from all portions of the furnace. This was succeeded for reasons of simplicity and easy construction by a single outlet on one side communicating directly with the downcomer.

Many furnacemen have felt that this construction was open to criticism because the path of the gases originating immediately under the gas outlet is shorter and therefore easier than the path of the gases on the opposite side, and in less degree the same is true for intermediate points, and they have felt that this produced a lack of symmetry in the gas current which was likely to affect adversely the working of the furnace. Many furnaces, however, ran successfully with this construction, and other furnacemen came to believe that this was a theoretical point of no practical importance.

As the rate of driving has increased, however, the effect of this difference in resistance has become more marked, and an increasing number of furnacemen have come to believe that the single gas outlet was wrong, not only in principle but in practice. Fortunately this is a subject on which we have evidence of such overwhelming weight that the matter need never again be considered open for discussion once the evidence is considered.

The brown ores of Virginia and Tennessee contain small quantities of zinc, which is vaporized by the heat of the hearth, and since zinc oxide is one of those solids which passes directly from the solid to the gaseous condition, and *vice versa*, without passing through the liquid state, this rises through the furnace with the gas until it meets the cold entering charge and the cool top walls of the furnace, when it solidifies. That portion which solidifies on the charge itself is carried back into the furnace and again sublimed, but that portion which solidifies against the walls builds there in solid form. It grows in conchoidal layers and forms a material of great strength and toughness, especially at the temperature prevailing a short distance below the stock line, where it generally deposits, some 800° or 900°F.

Mr. H. Firmstone in a paper before the American Institute of Mining Engineers in 1876 described the action of this material in the furnace at Longdale, which was equipped with the center out-take and double bell. His drawings of the shape of the zinc ring formed, found on blowing out,

[1] See "Blast Furnace Construction in America."

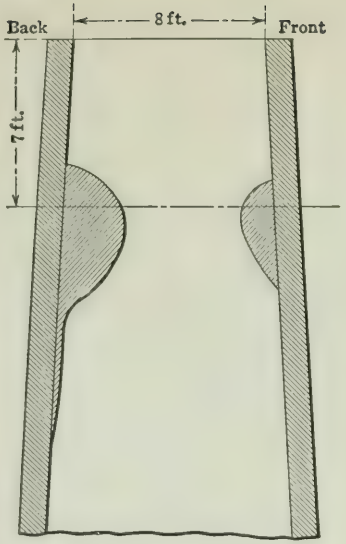
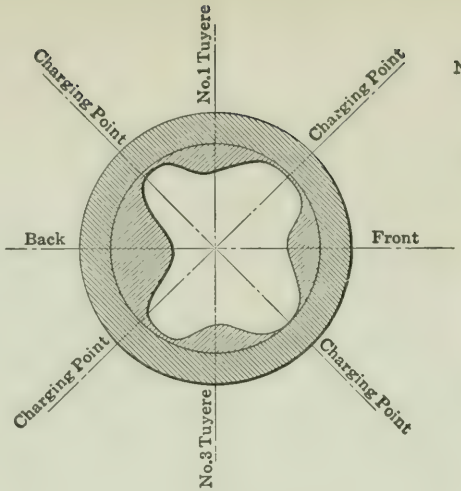


Fig. 78.—Zinc ring.
(Firmstone.)



Section 7 Feet Below Top

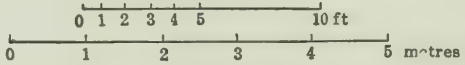


Fig. 79.—Zinc ring.
(Firmstone.)

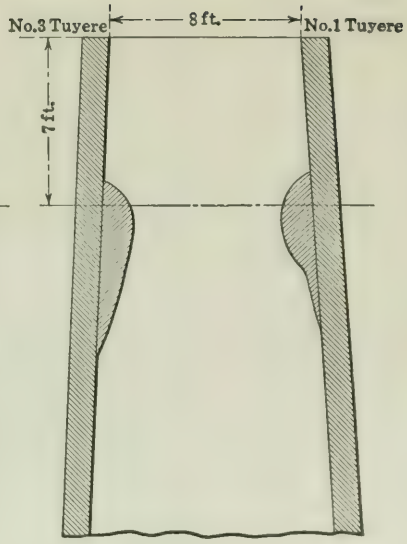


Fig. 80.—Zinc ring.
(Firmstone.)

made from very careful measurements, are reproduced in Figs. 78, 79, and 80. The approximate symmetry of the formation about two axes at right angles is obvious. The thin places in the ring are immediately under the dumping points, because most of the fines of the charge remaining at those points obstructed the gas currents, while half way between the dumping points were the coarser portions of the charge which permitted a more active gas circulation and consequently the deposit of more zinc oxide.

These results were confirmed by all the subsequent experience at these furnaces. The symmetry was not always so marked, but was in general greater in proportion as the furnace work was more regular, but any irregularity was what might be called self-intensifying, because a greater growth of zinc ring meant a greater distortion of the charge and more obstruction of the fines, which were crowded over and could not roll back under the obstructing zinc, while the coarse could and did do so, and thereby produced a more open charge condition under the obstruction and so brought a greater portion of the gas current to that section of the furnace, and thereby promoted a still greater growth of zinc formation.

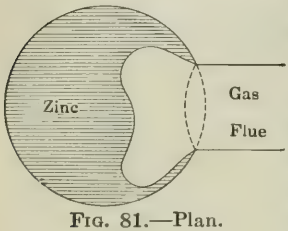


FIG. 81.—Plan.

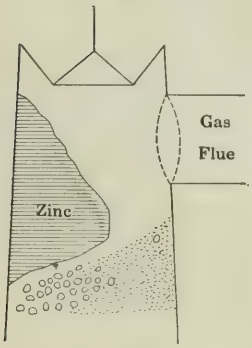


FIG. 82.

FIGS. 81 AND 82.—The effect of a single lateral gas outlet on gas flow as shown by zinc oxide deposit. (Taylor.)

This effect was so serious and the detrimental action on the regularity and fuel economy of the furnace was so great that it became the custom to shut the furnace down for about 48 hr. every 6 months and cut off the zinc ring with long steel bars, sledging them from the operating platform. Incidentally this job, including the removal and replacement of the top apparatus, was of such severity and difficulty as to make one wish at least during those periods that he had chosen another occupation.

About 20 years later W. W. Taylor described in the *Iron Trade Review* the growth of zinc "ring" in a furnace filled with a single bell and provided with a single outlet on one side, this furnace being very hard-driven for its size. Mr. Taylor's drawings of this zinc formation are reproduced in Figs. 81 and 82. It will be seen that the zinc formation started at a point exactly opposite to the downcomer opening, presumably because the smaller gas current, due to the longer path the gas on that side had to travel, permitted a greater cooling effect. The stock was forced to flow over the nose of the zinc formation toward the center of the furnace. The fines stayed where they fell in that position. The coarse

rolled back to the wall underneath the zinc formation and induced a more rapid flow of gas to that side. Greater cooling followed the more rapid downward travel of the lumpy material and more zinc followed the greater upward flow of gas. Consequently, the deposit of zinc was bound to grow here and to work its way down the furnace as the cooling effect of the coarse material descended further and further, until the lower end of the zinc formation reached down almost to the top of the bosh.

The furnace was working almost entirely on this side, and the other side was presumably almost dead. I have seen the same thing at Longdale in a less degree on several occasions. The zinc formation descended to the lowest level in the furnace underneath those points where the obstruction to the descending charge had been the greatest. Of course from this reasoning it is evident that once the zinc formation were started in this way with the single gas outlet it had no recourse but to grow increasingly worse. This, however, is not the most important lesson to be learned from this most instructive bit of furnace history; it is that the original zinc formation *would never have occurred in the way it did in the first place*, if there had not been a decided lack of symmetry in the gas current due to the longer path on the side opposite to the single gas outlet, and I believe that all experienced furnacemen will agree that the above constitutes an absolute proof that an unsymmetrical gas outlet is bound to lead to irregular distribution of the gas column relative to the charge column, and that while its effects are probably not so strongly self-intensifying as when zinc is present, nevertheless it offers possibilities of trouble, to avoid which no reasonable expense in construction should be spared.

The Effect of the Tapping Hole and Cinder Notch Location on the Gas Column.—It has been contended by some furnacemen that the drawing effect of removing the liquid contents of the furnace hearth in one direction or another toward the tapping hole or the cinder notch affected the gas distribution, and that this effect could be offset by a corresponding lack of symmetry in the location of the gas outlets, but I have never seen anything in my own experience to confirm this contention, nor have I been able to discover any reasoning which would lead to such a conclusion. The iron and slag are withdrawn from the furnace when the blast is on, and therefore when the conditions in the hearth and bosh are normal, which means when there is a state of violent activity throughout all those regions. Remembering that the (solid) coke in the bosh is so intermixed with slag and gas as to constitute the whole mass a liquid, it is difficult to see why it should not retain an approximately horizontal surface throughout all portions of these regions. Of course, the liquid concerned is to some extent viscous, and the tendency is for it to descend more rapidly in those portions where the flow lines are the shortest, and

so during such periods there might be some effect on the distribution of the gas current, but it does not seem likely that this should be very marked.

On the other hand, the erosive action of the liquid flow must not be forgotten, and it is easily conceivable that a tendency to build up on the hearth or bosh walls might be prevented by the scouring of the liquid flow in the immediate vicinity of the tapping hole and cinder notch, while in regions remote from these points, there being no such scouring action, building up to some extent might occur and so in time produce a lack of symmetry sufficient to be important. For these reasons it is probably better not to have the cinder notch and the tapping hole too close together, and if physical conditions permit, a wise arrangement is to have two cinder notches and to space these and the tapping hole at 120° apart, using the cinder notches alternately. This, however, represents an ideal condition toward which we may aspire rather than a practical construction which we can ordinarily obtain.

Effect of the Size and the Uniformity of Materials on Distribution.—This is a subject which has had too little consideration in connection with the general subject of stock distribution, and the penalties which have been paid for failure to observe it have been so numerous and so severe in many cases as to be almost fatal to the success of the plant. It seems not generally to have been recognized that it is necessary not only to place the same amount of material in each sector of the shaft, but that the size of that material is of equal importance with the amount, and it is perfectly conceivable that careful tests might show the most absolutely uniform size of heaps on the bell (or on the stock line if examination inside the furnace be made before blowing in), but at the same time the distribution might be horrible because one sector might be made up of lumps open and easily pervious to the gas while all the others were made up of fine or even plastic material.

Of course, in regard to the coke this is true only to a limited extent, since with reasonably uniform handling the coke from one operation should be of reasonably uniform size, and this is a point which can under ordinarily favorable conditions be watched, and precautions taken to prevent variations in the coke, or if they must occur to insure that at least all one kind of coke shall not go to one side of the furnace and another kind to the other side.

But with the ore, particularly in the Lake ore district, the conditions are very different. A certain percentage of Old-Range ores is generally, but not always, charged, and a much larger percentage, sometimes practically the whole charge, is made up of Mesabis. The ores from this range differ greatly from one another in fineness, some of them being of almost impalpable fineness, and others containing a noticeable proportion of lumps, but as a whole these ores are of a sandy structure; that is

to say, fine, relatively uniform and granular, while the great majority of Old-Range ores are either hard and lumpy, or else plastic, very much like ordinary clay except in color, the clay sometimes being interspersed with lumps, but the ores virtually never sandy.

It is obvious that the action of these ores in passing through the filling mechanism and through the furnace itself must be very different. The plasticity of some of them is so great that they will build up on almost any surface they touch, while others are almost as sharp and clean as crushed gravel. Some are so plastic that they will hold puddles of water for days, and, of course, when baked by the heat of the furnace tend to burn into hard, irregular lumps, while the sandy Mesabis, when dried by the heat of the furnace and agitated by the ascending gas currents, become almost as active as a liquid, and run almost as freely. The permeability of some of these ores to the gas current is obviously many times greater than that of others, while even with one kind of ore, if there be both fine and coarse produced in mining and crushing, the inevitable differentiation in size which takes place in dumping will divide a mass of this ore into two obviously different portions, one consisting of nearly all lumps, with very little fine, the other of a much greater portion of the fine with very little lumps. The difference in the permeability of these to the gas current is almost as different as if they were different kinds of ore.

If we start out, therefore, with a single kind of lump ore, the very action of dumping will produce a segregation, and we shall deliver two very different kinds of material into different portions of the furnace, of which one will probably contain two or three times as large a percentage of lumps as the other, with a correspondingly high percentage of voids, permitting free passage of the gas, while the closely packed fines in the other portion tend to obstruct the gas flow to a much greater degree. These conditions, of course, are repeated charge after charge, and in consequence we have perhaps all the lumps going down one side of the furnace, while all the fines and perhaps much more than half of all the material charged go down the other side.

This brings about a condition in the furnace which tends progressively to grow worse, because the freer travel of the gas through the coarse or open material causes all reaction on that side to be more rapid, and therefore causes the stock on that side to settle faster than on the side which receives the fines. This, of course, produces more or less of a crater in the top surface of the stock, and as the large lumps always travel the farthest, this means that the larger pieces to an increasing degree go into this crater while the fines stay around its rim. This increased segregation of the lumps causes still greater openness of the charge column at this point, and this in turn causes a still more rapid gas flow on this side with corresponding retardation on the other. The

blast furnace being an apparatus which accommodates itself marvelously to unfavorable circumstances may not show by its output or fuel consumption the severity of the treatment to which it is being subjected, or only to a minor degree, usually, however, this is not generally the case, bad filling being generally accompanied by extremely high fuel consumption and output poor in both quality and quantity. In any event, such a condition can have only one result on the duration of the furnace campaign, no matter what its results may be on coke consumption and tonnage, and in this respect the results of such filling cannot be concealed for a very long time.

The inevitable effect is to scour out the lining, not only by the predominance of the lumps, with their greater abrasive action on one side and their greater velocity, but also by the velocity of the ascending gas with its burden of abrasive dust. The lining is soon cut through, a fact which manifests itself by a hot spot on the shell within a few months or even within a few weeks of the opening of the campaign.

An excellent description and full data of such a case may be found in the paper of David Baker before the American Institute of Mining Engineers, vol. xxxv, giving the results of the first campaign of the blast furnaces at Sydney, Nova Scotia, which were skip-filled and supplied with a burden of all lump ore.

The campaigns were not a matter of years, but scarcely one of months before the segregation, due to the use of the ordinary double bell top, without any attempt at circumferential distribution, had scoured through the lining to the shell in a rather narrow vertical zone, with the resulting necessity of blowing out and relining the furnaces, at an expense of many thousands of dollars.

Where fine ores are used exclusively it is obvious that such great segregation of the ore cannot take place, there being no coarse material upon which the segregating tendencies can operate. Consequently, with fine ores, if the quantity distributed to each sector of the furnace is the same, the results are not so serious and may be fairly satisfactory, because the absence of a difference in size eliminates the necessity for one of the fundamental conditions, viz., that in each sector the same proportions of lumps and fines, as well as the sum total of material, shall be charged.

It is a matter of painful recollection to those in the industry during the period of the introduction of Mesabi ores that the furnace practice was notoriously unsatisfactory, particularly in the matter of life of linings, although at that time it was considered an achievement to use 50 per cent. of fine Mesabi, the remaining 50 per cent. being Old-Range ores, much of it of a lumpy or partly lumpy structure, whereas now 80 to 90 per cent. Mesabi is common.

It has seemed to me probable that these Old-Range ores, which were

kept on to temper the admittedly bad effects of the fine Mesabis, may have been responsible for many of the lining troubles which were so frequent during that period. It is true that fine ores in themselves are very bad for reasons which I have previously pointed out, but it is also true that if the burden is to be improved by mixing lumps with it, these lumps must be charged in such a way that an equal percentage of lumps and fines must go to every sector of the furnace. If they do not, the benefit due to the presence of the lumps, which is, I think, not nearly so much the opening up of the charge as has been believed, does not compensate for the fearfully bad effects of a segregation of lumps in one vertical segment of the furnace.

In confirmation of this it is certainly true that as the percentage of the objectionable Mesabi ores has *risen*, and that of the desirable lumpy ores has fallen, furnace practice generally has improved instead of growing worse, particularly in relation to life of linings. This is undoubtedly the product of many factors, and it may be a more or less academic question to discuss what those factors were, but I am firmly convinced that lumps not properly charged will not benefit a burden of fine ore, but will produce an additional detrimental action of their own, and I would rather run a furnace on an all fine-ore burden entirely without lumps than I would on a mixture of lumps and fines if I could not absolutely guarantee the proper distribution of the lumps.

While matters are, as just stated, much improved now from what they were 12 or 15 years ago, the question of stock distribution is still a very live one among the best-informed furnacemen, and the development of the furnace is not yet at a standstill.

More than one furnace manager has told me that after the most painstaking experiments he has found it impossible to obtain a distribution with a plain double-bell top which was good for more than one condition of weather, ore, etc. It is this conviction which has brought about the introduction of the rotating top or rotating distribution.

EXPERIENCE WITH THE REVOLVING DOUBLE-BELL TYPE OF TOP

A very unusual experience with furnace distribution a few years ago has imbued me with certain ideas in regard to stock distribution which are by no means held by all furnacemen, so that I shall give the facts on which my conclusions are based.

At the time stated I was in charge of a plant of three furnaces, all equipped with the revolving double-bell type of top, the receiving hopper under the skips being a cone almost exactly as illustrated in Fig. 83. These furnaces, which were in the South, were operated on a coke of only moderately good quality, and on an ore consisting, as mined, entirely of lumps, but containing when received a considerable quantity of fine on

account of unsatisfactory methods of crushing. Their performance was exceedingly unsatisfactory. A fair tonnage could be obtained from them only at the expense of a high fuel consumption, a high blast pressure, and an exceedingly limited life of lining. The revolving top was fitted with automatic electrical recording pens, and it was the special duty of the burden clerk to check over these records to see that the skips were dumped in the proper sequence, that the receiving hopper was rotated to the proper angle, that the bells were manipulated after the proper number of skip loads, and that in general all details of charging were correctly carried out.



Fig. 83.—Kennedy top.

Within a few weeks after blowing in these furnaces would show a hot spot on the shell some 20 or 30 ft. above the mantle, not in any one position circumferentially around the shell, showing channeling, but indifferently at any point, and spreading from that point around until the furnace shell was hot in this zone most of the way around. The last 13 or 14 months of blasts, averaging only 15 or 16 months in all, were made with a water spray on the shell to keep it cool. At the end of this period the furnace could no longer be operated safely and was blown out and relined completely.

As one of the furnaces was approaching the time set for it to be blown out for repairs its shell failed at a point some 40 ft. below the top, and a section some 8 ft. high by 12 long swung out like a barn door, letting all the material in the furnace run out down to that level. I took charge within a day or two afterward, and as there had been discussion as to the distribution in these furnaces it was decided to shovel out the stock remaining in the furnace, not from the bottom as is customary, but from the top, so that by cutting vertical faces across the stock in various directions we could obtain an accurate idea of the distribution which prevailed in actual operation, this being an opportunity which would not ordinarily arise once in a lifetime, the furnace having been in full operation up to the time of the shell failure, then immediately stopped and watered down.

The condition which this investigation revealed was astounding, and was one under which no one would have believed that a furnace could operate at all. The brick being all gone at the zone in question the furnace was about 24 ft. in diameter; the outside 4 ft. of this was taken up by a ring of coke entirely unmixed with ore and limestone, while the center was made up exclusively of ore and limestone with only an occasional piece of coke.

The assistant superintendent, Mr. W. L. Kluttz, who had been at the plant for several years under the previous administration, had maintained for some time that the furnaces were working with a core in the center, and had much valid evidence to support this view, but even he was not prepared for such a confirmation of his opinion.

It seemed obvious that the bell was too small for the stock line, that the fine material dropping from the edge fell in a heap in the center, or at best in a small ring around the center, while the coke being larger traveled further and lodged entirely against the walls. Obviously, then, the thing to do was to reduce the size of the stock line or increase the size of the bell. To make sure we did both, and careful inspection of the stock surface made by going in under the bell, when the furnace was being filled preparatory to lighting, showed practically all the fines against the walls and nothing but large lumps of coke in the center. Air could be felt drawing up through the center freely, whereas no draft could be felt against the walls.

I felt convinced that we should obtain a different result and the furnace was blown in with high hopes, but after being in operation for 6 weeks without doing any better work in output or coke consumption than on the previous blast, and finally developing a small hot spot on the shell, we became convinced that we had not solved the problem.

Mr. Kluttz then suggested that the difference between that furnace and some other furnaces in the district, which were giving much more satisfactory results under precisely similar conditions, was that our stock

distribution was in uniform rings while theirs was in heaps on the main bell, and he suggested that we so modify our top to secure this effect at least in part, which we could do without great expense.

The spout which we could put in was limited, and we were not sure that it would be long enough to secure approximately the same distribution when opposite to the skip and when directly under it, but it seemed that nothing could be worse than the present conditions, so the change was made. No change of ore, coke, burden, blast, heat, or any other factor of furnace operation was made.

At the end of the first day no change in the working of the furnace was visible. At the end of the second day the furnace came up on 8 per cent. silicon iron. It then became a matter of increasing the burden rapidly enough to bring the furnace down to normal foundry iron without danger of chilling it if the change suddenly went the other way. No such untoward event occurred, however, and at the end of 5 days from the time the change was made the furnace had gone from a daily production of 223 tons, with a coke consumption of 3300 lb., to a daily production of 285 tons and a coke consumption of 2750 lb.

The same change was made on another furnace which was supposed to be so nearly worn out as to be good for only about another month, but its work improved so greatly with the change that it was kept in for 7 or 8 months longer. As a result of this successful experiment the top of the next furnace which went out of blast was redesigned so as to convert it into the spout type of top somewhat similar to the Brown, but designed to secure the proper distribution both radially and circumferentially. This furnace ended only recently the campaign on which this modified top was installed, having run about 45 months instead of the 15 which was formerly standard practice for those furnaces, and after making a record for tonnage and coke consumption such as no furnace at that plant had ever approached.

In view of these facts it is perhaps not surprising that in my judgment distribution in heaps on the bell is to be preferred to a distribution in rings, altogether apart from the question of symmetry. Every furnace in that district fitted with the double bell type of top had given results precisely similar to ours, running with high fuel consumption, low output, high blast pressure, and short life. Other furnaces with the same type of top in other districts using very different types of ores had experiences so similar that a description of theirs might have been taken for ours. At the same time it must be admitted that in those districts where the ore is nearly all fine the contrast between ring distribution and heap distribution is much less marked in operation than it is in districts where the greater portion of the ore burden consists of lumps.

This experience agrees in a general way with experiences along a similar line at the time of the introduction of the closed-top furnace. I have

been informed by Mr. Frank Firmstone (private communication) that during the régime of the open top it had been considered good practice to spread the stock as smoothly and uniformly over the top as possible. But when the introduction of the closed top brought about the use of the filling barrow, which necessarily dumped in heaps on the bell, the furnace work instantly and very generally improved. Why this should be so has never been made clear. I have never seen any explanation of the fact, which in itself is not very widely known. The only explanation that I have been able to make even tentatively is that when the ore is all dumped uniformly in rings the percentage of voids in it is much smaller than that which occurs in the lump portion when segregation of the lumps takes place. When the ore is dumped in heaps on the bell the tendency is for the lumps to segregate to some extent not only at the bottom of the hopper, but also along the sides of the piles made by dumping, and as the sides of these piles are practically radial this causes radial lines of more open stock to descend through the furnace, and thereby open up to the action of the gas the fines which may tend to gather there, thus preventing the formation of a column of more or less "dead" stock down through the center of the furnace.

That such a column may be formed, the facts I have already cited amply prove, and that by descending more slowly in consequence of its impenetrability to the gas this column tends to perpetuate itself by affording a lodgment for the fine material of the charge, while forcing the coarse to roll to the periphery is also true, and that the effect of dumping in heaps is to cause segregation of fine and lump, and thereby cause vertical planes of greater openness at the sides of the individual heaps is also true to some extent. But whether the comparatively slight change in the penetrability of the central column so produced is sufficient to cause the vast changes in the working of the furnace which I have seen at this plant and others, cannot be considered as proven. Anyone who will advance a logical and satisfactory explanation of this action will lay the blast-furnace profession under a lasting debt of gratitude.

Since this was written, there was published before the May, 1916, meeting of the American Iron and Steel Institute an account of tests carried on at the furnaces of the Cambria Steel Co., of an invention made by their Vice-President, E. E. Slick.

Mr. Slick reached the conclusion that the columnar charge column was desirable and in order to produce it without moving mechanism of any kind, designed a saw-toothed distributor hanging below the main hopper, shown by Fig. 84. The stock sliding off the main bell strikes the teeth of this distributor; the effect is to produce depressions behind the teeth and hills between them, the lumps roll off the hills and the fines stay where they fall, so a somewhat columnar structure is produced. The results obtained with this apparatus have shown great improvements

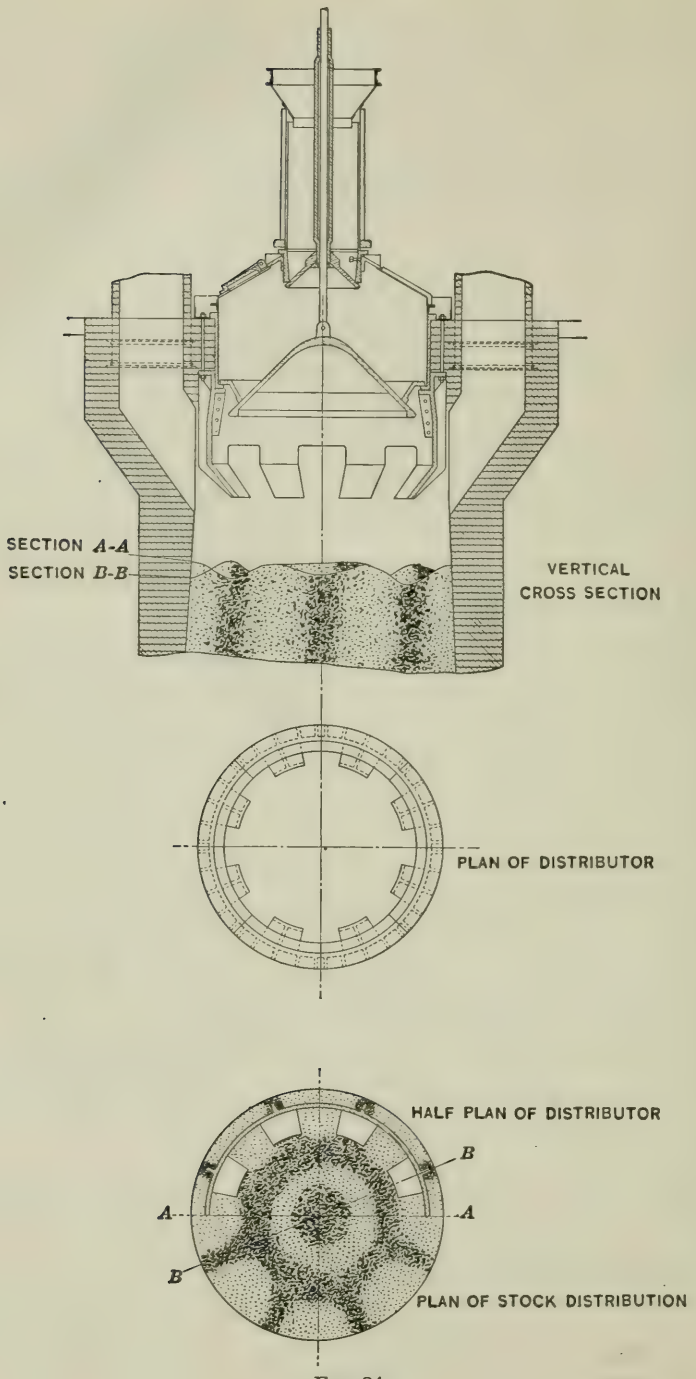

SECTION A-A
SECTION B-B
VERTICAL
CROSS SECTION
PLAN OF DISTRIBUTOR
HALF PLAN OF DISTRIBUTOR
B
A
A
B
PLAN OF STOCK DISTRIBUTION

FIG. 84.

over the former ones in regularity of working. Flue dust losses were reduced 50 per cent.

I do not like the saw-tooth distributor as well as a properly designed heap distribution on the main bell because the latter corrects irregularities in the filling and I believe makes for a greater columnar effect in the charge column. The results obtained with this distributor on a burden of excessively fine ore do, however, confirm absolutely the results of my own experience on coarse ore. These experiences definitely prove to my mind that the best furnace work cannot be done with a charge column made up of uniform annular layers, even though these be perfectly symmetrical, but that the coarse and fines must be segregated in these layers in such a way that the whole charge column shall be made up of sectors of alternately coarse and fine material. It is, of course, vital that these columnar sectors should be symmetrical with respect to two or more diameters of the shaft, spaced equiangularly.

CHAPTER XIII

THE RATE OF DRIVING THE FURNACE

One of the most important items in the control of furnace operation is the rate of driving. This is to say, how much iron we should make per day from a given furnace, which depends, other things being equal, upon the amount of coke we burn and that in turn on the amount of blast we blow per unit of time. The best rate must be determined with reference to two sets of considerations, one technical and the other commercial.

The technical ones are: first, effect upon the regularity of the settling of the charge; second, the effect upon fuel consumption; third, the effect upon the power required for blowing; fourth, the effect upon flue dust lost; fifth, effect on the life of the lining. The commercial ones are: first, the effect upon profit, since other things being equal the annual profit is proportional to the tonnage produced; second, the effect upon costs other than fuel cost, principally labor and overhead, since these costs per ton are, other things being equal, inversely proportional to the output; third, the effect upon the value of the power consumed for blowing. This distinction between technical and commercial considerations is more or less arbitrary since all these considerations are partly one and partly the other, but the distinction is permissible to facilitate the more technical treatment of the subject now, leaving commercial considerations to be discussed in a later chapter.

EFFECT ON DESCENT OF CHARGE

The effect of the rate of driving upon the regularity of the descent of the charge is placed first because it is of capital importance and affects every other item. Without regularity of descent of the charge we cannot secure the maximum monthly output, we cannot, above all, secure highest fuel economy, and, finally, without it we cannot keep our flue dust losses within any reasonable limits, when running on fine ore.

Reverting to the chapter on mechanical principles it will be seen that the resistance to the passage of the gas rises as the fourth power of the quantity of blast blown, so that from our pressure chart it can be shown that while a 22 by 90-ft. furnace, blown with 45,000 cu. ft. of wind, requires about 13 lb. blast pressure, the same furnace blown with 55,000 ft. of wind would require about 17½ lb. pressure. As pointed out in that chapter, these figures are both probably a pound or so low, but this fact only exaggerates the difference.

From the conclusions reached as to the relatively accurate balance between the weight of the charge and the forces supporting it, it will be seen that a change like this of about 35 per cent. in blast pressure might easily result in disturbing the floating equilibrium between weight and resistance, and so result in hanging the charge column or some portion of it lying about a tight zone. This would result in slipping, with all its attendant evils—reduced output, poor and irregular quality, higher fuel consumption, and all the rest—these results, of course, being in some rough degree proportional to the seriousness of the slipping caused.

EFFECT OF THE RATE OF DRIVING ON FUEL CONSUMPTION

This is a very complicated matter. In the early nineties, when outputs were on the average less than half of what they are to-day, it was supposed that the maximum rate of driving, consistent with economy, had been reached. In the interval which has elapsed since, we have seen a much more rapid rate of driving accompanied by a much higher fuel consumption, but this has been succeeded in more recent years by a marked reduction in fuel consumption, so that the best of to-day is better than that of any past time, irrespective of the rate of driving.

In order to make an adequate comparison it is necessary to have a measure of the rate of driving. This is quite generally taken as the number of pounds of coke burned per hour per square foot of hearth area, so that if a furnace with a 16-ft. hearth were burning 480 tons of coke per day, that is, 20 tons of 2000 lb., or 40,000 lb. per hour, the area of a 16-ft. circle being 200 sq. ft., the rate of combustion is 200 lb. per square foot per hour.

It is commonly considered that 250 lb. per square foot is about the maximum amount consistent with good work, and this figure is in fair agreement with most practice of to-day, though I have operated furnaces burning over 300 lb. per square foot with excellent results in fuel economy for the given conditions. On the other hand, the large-hearth furnaces with which very economical results have been reached in very recent years are only burning about 40,000 lb. of coke per hour in a 17½-ft. hearth, which is less than 200 lb. per square foot.

It has seemed to me that this basis of comparison was not altogether a correct one. I have endeavored to show in the earlier chapters that the real combustion space of the furnace was not a single plane at the tuyeres, but that combustion was going on throughout the bosh, that is, from the tuyere plane to the top of the bosh, and in order to obtain truly comparative figures we would use the coke burnt per cubic foot of this space rather than that per square foot of hearth area. On that basis the large-hearth furnaces are really as hard driven as any, for two reasons: First, while the hearth is very much larger than that of other furnaces with the

same height and bosh diameter, by this method of figuring this change affects only the smaller diameter of the frustum of an (inverted) cone whose base is the bosh diameter, so that the percentage of change in its volume produced by this increase in its smaller diameter is less than half that produced in the smaller area itself. Second, the wide-hearth furnace has been accompanied by a lowering of the top of the bosh so that its vertical height is decidedly smaller, and this reduces the volume of this zone of the furnace as much as the widening of the hearth increases it.

It is an unfortunate fact that we have no figures for coke consumption per cubic foot of bosh space, and this unit of measure can therefore only be introduced into general use after a considerable campaign to replace the older but less accurate unit.

Concerning the results of the true rate of combustion upon fuel economy we know much less than we should, but some of the factors which affect it may be pointed out. The first of these is the velocity of the combustion of coke in a blast initially air, but burning progressively to CO and nitrogen. A simple calculation shows that the blast can be but a few seconds in passing from the tuyeres to the top of the bosh. The volume of air blown into the modern furnace is about sufficient to fill it twice a minute if the furnace were empty and the air under atmospheric conditions. As a matter of fact the air is increased in volume between three and four times by heating, and this volume is reduced by the compression under which it enters the furnace, this decreasing, of course, as it rises, so that its average pressure is about one and a half times atmospheric, while its absolute temperature at the top of the bosh is six or seven times atmospheric, and the average something like four times atmospheric, hence its actual volume is nearly three times that under atmospheric conditions. This would mean that the furnace, if empty of solid and liquid matter, would be filled by gas six times per minute. But we have seen that if it were filled with uniform spheres the total voids would only be about 25 per cent. of the total. With very irregular material such as broken ore, the voids when at rest are greater than this, but with the continual settling which tends to fit them into one another, and with the deposition of carbon of almost impalpable fineness, in a considerable region of the furnace, the voids are probably no greater than they are with spheres, or 25 per cent. of the total contents of the furnace. This indicates that the actual gas volume is sufficient to fill the voids at least 24 times per minute, so that in about 2 sec. the blast which enters at the bottom of the furnace passes through it and is discharged as gas at the top.

Now taking the height from the tuyeres to the top of the bosh as one-eighth or even one-sixth of the total height of the furnace we see that less than $\frac{1}{3}$ sec. is available for the complete combustion of the oxygen of the air to CO. Such a velocity makes it impossible that combustion should

go on in the interior cells of the coke because it is impossible that the air should penetrate a solid (though porous) structure and make its exit in that time; therefore combustion must proceed only upon the surface of the coke. This is not unlimited, and as we know that an appreciable interval of time is necessary for the complete combustion of air, it becomes evident that there is a limit beyond which we cannot drive the furnace and have the combustion completed in the proper zone.

This means that for still faster driving more volume would be necessary to complete the combustion, and, therefore, that this would extend to a higher level in the furnace. All our experience in operation, and all of the chemical and thermal theories set forth in earlier chapters, tend to the conclusion that the best work can be done only by keeping the zone of fusion as low as possible. It is impossible to go over all the reasoning which leads to these conclusions here; it is a fact based primarily on experience, and one of the best proofs is that the remarkable work of the wide-hearth furnaces has been built upon and around the principle of keeping the zone fusion as low as possible, and the economy which has been obtained in furnaces in which a low bosh is one of the outstanding features, creates a strong presumption that the lowering of the zone of combustion is at least an important factor in the very economical results obtained.

When furnaces are overblown it is a quite general impression, and I believe an entirely correct one, that the upper zone of combustion rises, in accordance with the above reasoning, and this is accompanied by an increase in fuel consumption. In fact, it must be evident that if the fuel consumption be controlled by the quantity of high temperature heat obtainable, anything which tends to dissipate this limited supply of heat over a wider zone must militate against its concentration, and therefore against fuel economy.

The same reasoning which applies to combustion applies to other reactions which must go on. The reduction of the ore is essentially a task which demands time for its completion to the maximum degree possible in each zone before descending into the next, and as this is the essential condition for the maximum possible oxidation of the gases, on which, as we have seen, the total heat development depends, a sufficient allowance of time for the completest possible reduction of the ore in each zone is an indispensable condition for maximum economy. If the ore descends so rapidly as to reach the hearth without the completest possible reduction, the effect is of the same general kind, but of a much higher order. We have in such a case the conditions which led to low fuel economy with wet ore in the charcoal furnace, described in the chapters on thermal principles.

So it is with all the other reactions; the decarbonation of the limestone, the complete union of the flux with the impurities of the charge,

etc. If sufficient time be not allowed for these we shall pay for it by expending more heat than is absolutely essential in bringing about the necessary conditions.

On the other hand, there are heat losses of vast importance which are irrespective of the rate of driving. The furnace is constantly undergoing a loss by radiation and cooling water of some 15 or 20 per cent. of its heat, especially of that in the hearth; this is 15 per cent. of the total developed when the furnace is running at full speed, which is a convenient measure.

But if the furnace stops, the loss continues at the same rate per hour as long as the zones of the furnace remain at the temperature which they have in operation, so that if the furnace were to be run at 15 per cent. of its normal rate we should supply just enough heat to make up for the losses without supplying any for the production of iron; if we ran at 30 per cent. of the normal full rate we should, on this basis, lose 50 per cent. of the heat produced, and the fuel consumption would accordingly be nearly twice what it is at the normal full rate. If we drive at 45 per cent. we lose one-third on the same basis, and so on. The figures used are not intended to be exact, though they are approximate to the best of our knowledge.

This line of reasoning shows that we must not allow any more time for combustion, reduction, etc., than is necessary for those operations. We are not at liberty to increase the economy of the furnace indefinitely by slowing down to obtain more complete reactions, because the purely physical radiation and reduction losses begin to assume an increasingly menacing proportion the slower we run. Obviously, then, if we make some loss by allowing a slightly insufficient time for completest reduction, we may offset it by cutting down the radiation losses in a greater degree. If we were considering only fuel economy, our effort should be to run under the conditions which would make the sum of these two losses the minimum. But we shall see when treating of commercial considerations this is only one factor and sometimes by no means the greatest in the solution of the commercial questions involved, and therefore it would be useless to attempt a solution of the purely technical question involved on so theoretical a basis.

THE EFFECT ON POWER REQUIRED FOR BLOWING

This is a subject of the utmost importance from two points of view: first, that of the first cost of the blowing plant; second, that of the consumption of gas required to operate it. There was a time when the surplus gas was considered of no use or value, but that time is now long gone by, and it is well understood that the gas represents roughly one-half the value of the fuel, in the best and most convenient form. In

modern plants it is applied to the production of power for uses outside the blast furnace and is an asset of great value, therefore, it is desirable to use as little of it as possible for the blowing of the furnace itself, since power so spent is a necessary evil and nothing else.

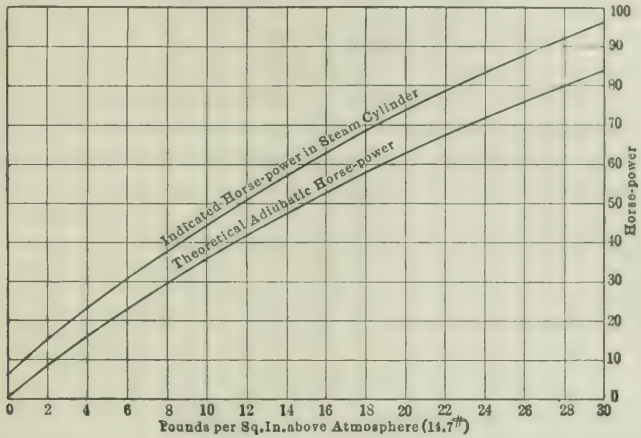


FIG. 85.—Theoretical and actual horsepower required to compress 1000 cubic feet per minute of free air (14.7 lb.) to different pressures.

The power required for the compression of a given volume of air to a given pressure varies with the type of apparatus used, whether steam engine. gas engine or turbo blower.

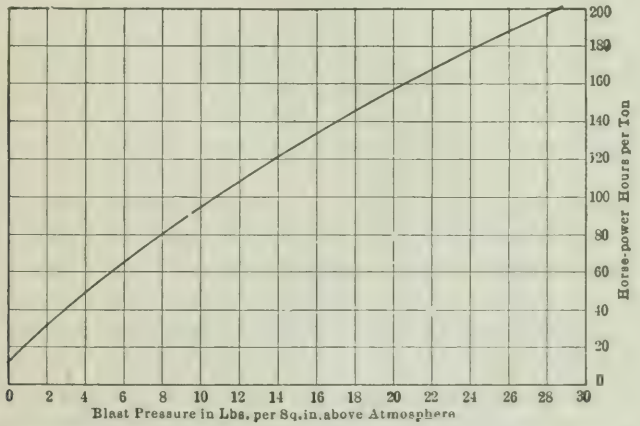


FIG. 86.—Horsepower-hours per ton of iron produced required to blow furnaces with different blast pressures.

More data are available in the case of the steam engine, and I have therefore used it for developing the facts in the following discussion. The lower curve of Fig. 85 shows the theoretical power required to compress adiabatically 1000 cu. ft. of air per minute from atmospheric pressure

(14.7 lb. abs.) to different pressures. The upper curve shows the actual indicated power required in the steam cylinders of a blowing engine to compress it to the same pressures with normal assumptions based on practice as to the efficiency of the blowing cylinders and the friction of the engine. By assuming now a figure for the amount of air to burn a pound of coke and the amount of coke consumed per ton of iron we obviously can calculate the horsepower-hours per ton of iron with different blast pressures. The curve of Fig. 86 gives these figures based on normal assumptions for Lake ore practice. But in order to obtain the information that we really need we must go a step further and find the horsepower-hours per ton required with different rates of blowing in a given furnace.

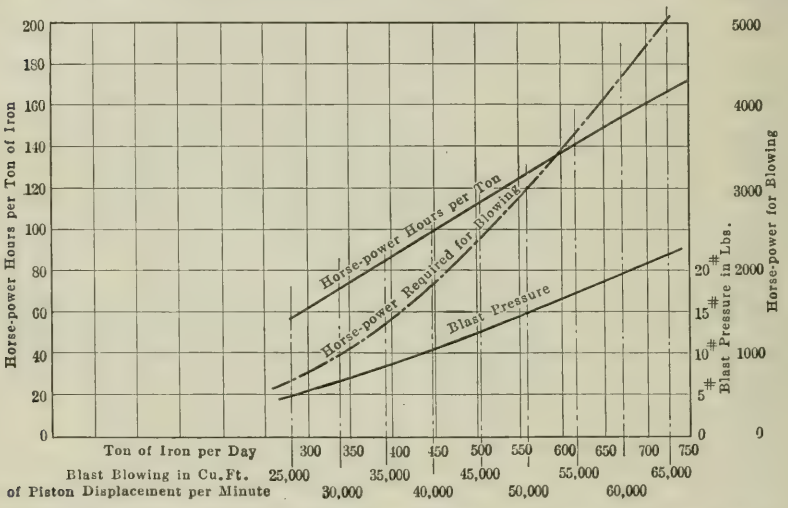


FIG. 87.—Blast pressure blowing power and horsepower-hours per ton required at different rates of production with a furnace 22.5 × 90 feet.

By assuming that the results of the blast pressure chart given in the article on mechanical principles are correct, and combining its results with those just given we may obtain a very fair idea of the horsepower-hours required per ton of iron produced at different rates of blowing. Fig. 87 gives the results of such calculations for a 22.5 by 90-ft. furnace.

It will be seen that the total horsepower required for blowing rises very rapidly, and that the horsepower per ton of product rises at a rate almost exactly proportional to the rate of driving; at 350 tons per day 75 hp.-hr. per ton are required, and at 650 tons 150 hp.-hr. This increase of 75 hp.-hr. per ton represents a real loss, even if the gas be worth nothing, for the fixed charges on the investment and the operating labor to burn it and utilize the resulting steam are important, however much or little the gas may be worth. Leaving a more extended discussion of these values to a later chapter, we may note that the sum of fixed charges and

labor is seldom less than 0.25 cent per horsepower-hour, and therefore the difference in power cost at these two rates of driving is nearly 20 cts. per ton.

It may well be reiterated that these are not absolute figures, and that they may vary considerably from the actual figures in a specific case, but that they are based throughout on assumptions in substantial agreement with facts, and it is believed they represent very well the relative power requirements under the given conditions.

Similar curves worked out for smaller furnaces show the same characteristics with so little difference, except in absolute values, that they need not be reproduced here.

The results will be shown in dealing with commercial considerations.

EFFECT ON FLUE-DUST LOSS

This is frequently the really controlling consideration as to the rate of driving in fine-ore practice.

A. N. Diehl in presenting his paper "Data Pertaining to Gas Cleaning" (*Transactions* of the American Institute of Mining Engineers, vol. 1, page 3), stated verbally as the result of careful investigation that the surface of the stock in a modern furnace was in a continual state of "teeter," particles rising and falling back continually in the gas current; under these conditions some of the finer particles must be regularly carried over by the gas, and we know they are. The lifting power of a current on an individual particle increases as the square of the velocity, hence the number of such particles which would be within the lifting power of a slightly increased gas current is very great, and as a result such an increase would quickly lead to a prohibitive flue-dust loss; in other words, the difference in rate of driving between an insignificant and a prohibitive flue-dust loss is a very small one, and the maximum permissible rate is found in this narrow range.

With the rapid progress being made in sintering flue dust it seems not impossible that our ideas on the subject of this limitation may experience a considerable change in the near future. The harmful effect of fine ore in the furnace has been explained earlier, and is coming more and more to be admitted, the uselessness if not absolute harmfulness of fine coke is well known; if we can transform these into a highly desirable furnace material without undue expense we may find that the cheapest course is to blow out of the furnace an increased percentage of the objectionable fine materials, put them into a desirable condition and change them back again.

Where lumpy or plastic materials are used the flue-dust loss is smaller in proportion to the smaller total quantity of fines present, and this is generally so small that flue dust ceases to be an important fact in the rate of driving under such conditions.

In actual practice we find by experience the rate of driving which suits the general conditions best, and that we regard as the normal which we desire to maintain.

SPONTANEOUS INCREASE OF RATE OF DRIVING

There often arise conditions under which the maintenance of the best rate of driving is no longer possible. The furnace will sometimes start off and drive at a vastly increased rate without any change in the amount of blast having been made. For many years I did not know the reason for this phenomenon. It was first pointed out to me by A. J. Boynton of Lorain, that this condition arises from the fact that the rate of coke loss by solution or, more accurately, the percentage of the coke dissolved in the upper portion of the furnace, suddenly increases from some change in conditions, perhaps the distribution of the stock or a change in the tightness of the charge, producing a corresponding change in the equilibrium of CO and CO_2, with the result that more of the latter is formed at some zone, and this then dissolves more carbon from the coke in order to restore the equilibrium.

Another cause for such change, probably the most frequent one, is increased solubility of the coke due to a difference in oven practice, coal used, structure, or the like, or to a change in the fineness of the ore or its tendency to run down through the charge.

If a furnace working on hard ore were to change from a 10 per cent. solution loss to the 22.5 per cent. solution loss which may occur with all fine ore, it would produce an increased rate in driving of about 15 per cent., and changes as great or even greater than this do at times occur.

The effect of such an automatic increase in driving is usually very objectionable for two reasons: First, it reduces proportionately the time permitted for the complete reduction of the ore; second, and much more important, it corresponds to a reduction of fuel in the hearth and a reduction of hearth heat available, exactly proportional to the increase in the rate of driving. The quantity of blast being constant, the coke to satisfy it must be constant, and therefore if each charge delivers less coke to the hearth proportionately more coke charges are consumed; that is, the rate of driving is increased.

As a result a furnace generally runs off cold in consequence of such a "spell" unless measures be taken to prevent it. The principal measures available are first, to increase the blast heat if possible so that it may make up the deficiency caused by the extra solution loss; second, to slow down the blowing engines so as to prevent the rapid driving even though the solution loss cannot be checked. If this does not result in reducing the driving to a rate proportional to the blast blown it is then necessary to reduce the burden to make up for the hearth heat lost. As a general thing a reduction in the rate of driving is usually accompanied, tempo-

rarily at least, by increased heat in the hearth due, presumably, to the more complete preparation of the stock before its entrance therein, and slowing down the blowing engines is, therefore, the proper procedure if the abnormal rate of driving be long continued.

REDUCED DRIVING CAUSED BY FURNACE BECOMING "TOO HOT"

We sometimes encounter a phenomenon the exact opposite of that last described. The furnace becomes very hot, the silicon in the iron rises, the actual temperature of the slag and iron rise visibly, and presently the furnace slows down, "won't take the wind," the blast pressure rises decidedly, the rate of driving falls off, and presently the furnace begins to hang and refuses to settle except when the blast is slacked.

We do not know absolutely the cause of this condition, but as the exact opposite is caused by a sudden increase in solution loss, it is reasonable to suppose that this is caused by a sudden diminution of solution loss bringing an excess of carbon into the hearth.

This would cause the rate of driving to be slowed down in proportion to the increase in carbon delivered to the tuyere zone per unit of time. Increased hearth heat would be developed in the same proportion, part of this would expend itself in reducing more silicon, and the rest would pass out the top of the bosh and carry the pasty zone to a greater height, thereby causing the pressure to rise, and this coöperating with the greater depth of pasty zone would cause a decided increase in the lifting action on the charge column with sticking and hanging as necessary consequences. These are so exactly the results which we see in practice under these conditions that it seems safe to assume that the cause suggested is the true one.

A further confirmation is to be found in the serious after-effect of these conditions which is only too likely to be the scaffolding of the furnace, which is what we should expect from the rise of the pasty zone due to the excess of hearth heat.

After this was written I obtained extraordinary confirmation of its correctness from a chart of pressures at different heights during a "hot stick" furnished me through the kindness of Mr. John N. Reese and his assistant, R. C. Wallace, shown at Fig. 88.

It will be seen that the pressure drop in the bosh and that in shaft are about uniform, whereas in the zone just above the top of the bosh the pressure drop is 6 lb. in 9 ft. where it should be about 1½ lb., so accounting for nearly all the excess pressure in the exact location where we should expect the abnormal sticky zone to be. It is interesting to note that this occurs in the straight section at the top of the bosh; if this were absent and the upwardly converging shaft started directly on top of the bosh it is easy to believe that the sticking would be much worse.

Granting that the cause of this action has been found, what is the remedy? Obviously it is to dissipate the excess heat before it can carry the pasty zone much above the normal level and so prevent the formation at that level of a scaffold due to the adherence of chilled pasty material to the walls when normal temperatures are restored.

This can best be done by "following up" with more blast if the power is at hand to deliver it, for the same reason that we slow down when the furnace is running away. This tends to dissipate the excess heat, or rather to give it less time for action and also to keep the charge in rapid motion and so prevent scaffolding Unfortunately, the high pressure

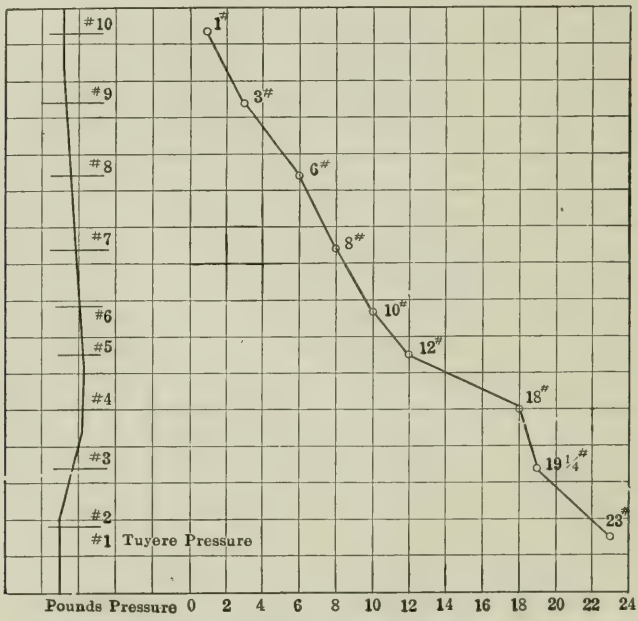


Fig. 88.—Diagram of pressure drop.

which accompanies this condition not infrequently limits the quality of wind which can be delivered at the very time we need it most.

In such a case we have no recourse but to cool the furnace off by lowering the temperature of blast to the point required to restore normal conditions. Of course, if the furnace shows a tendency to continue these conditions indefinitely the remedy is an easy and agreeable one; we simply add enough more burden to take care of the excess hearth heat and restore the normal blast-temperature, but at the beginning of such a condition a change cannot be brought through quickly enough to prevent bad consequences, so the other remedies must be applied first in any event, for they reach the seat of the trouble almost instantly whether or not they are sufficient to effect a cure.

THE EFFECT ON LIFE OF LINING

It was at one time believed that any rate of driving in excess of a very moderate figure must necessarily result in reducing the length of life of the lining and increasing almost prohibitively the expense and loss of time for relining.

We know now that this is not generally true and that where practice has been good the greatest tonnage per lining is made on steady and uniform but fairly rapid driving.

As a matter of fact, rate of driving is only one, and by no means the most important factor in the life of lining.

The really controlling feature in life of linings is stock distribution. If that be correct we shall be able to drive faster and still have the lining last many times longer than it does with poor distribution; channelling due to the concentration of the lumps on one side of the furnace has destroyed countless linings in a few weeks, but even when this is absent there are frequently conditions due to distribution which destroy a lining quickly. In the last chapter I described a case in my own experience in which a change of distribution gave a life of lining three times as long as before.

Slow driving may be almost as destructive of linings as excessive driving, for the movement of the charge becomes so slow that the whole of the furnaces is not kept in action, a portion of the charge ceases to descend and by long contact adheres to the wall and forms a scaffold; this causes irregular work and channelling which quickly cuts the lining out, or else the scaffold eventually falls off and brings a quantity of brick with it. This starts a failure of the lining and its end soon comes.

There are other conditions than wear which destroy linings; they disintegrate behind the glazed face which forms on the bricks sometimes in a comparatively short period, 1 or 2 years or even less. A lining is just as effectively destroyed by this action as if worn out, and therefore might better have been worn out so as to obtain maximum production from it.

Speaking broadly then, we may say that while the rate of driving is one factor in the life of linings, it is such a small one, with proper conditions in other respects, that we may disregard lining cost in determining the best rate of driving.

From all that has been said as to changes in the height of the pasty zone, the danger of scaffolding they cause, etc., we may see some of the reasons for one of the best established facts of practice, that first class work can only be done over a long period by determining the best rate of driving and adhering to it rigidly except when corrective measures are needed temporarily. The furnaces which have, in the long run, made the best showing technically and have made the most money for their owners are run on that principle.

CHAPTER XIV

HANDLING THE FURNACE

CASTING AND FLUSHING THE FURNACE, BLOWING IN, BLOWING OUT, AND BANKING

In earlier chapters the descent of the iron and slag into the hearth has been described. One of the important factors in operation and one not always easy to accomplish is their removal at the proper time and under strict control.

In the earlier furnaces no attempt was made to withdraw the slag separately from the iron; it simply ran out after the iron at cast. At charcoal furnaces this practice is still followed in some cases; the cinder comes out of the iron notch at casting time and at no other time.

The introduction of coke and anthracite as furnace fuels brought about much larger slag volumes, as already described. These resulted in causing the hearth to fill up much more rapidly, and when outputs had reached a point only a fraction of what they are to-day it was found that the slag rose around the tuyeres and impeded the driving of the furnace, causing increased blast resistance and covering the fuel so as to impede its combustion. This resulted in providing a separate outlet for the slag at a considerably higher level than the tapping hole for the iron, but well below the level of the tuyeres, so that by draining off the slag down to this point it would be removed from the tuyere zone and its bad effect on the operation of the furnace eliminated.

The earlier cinder notches were a sort of low doorway, a foot or two wide by 3 or 4 in. high, with a water-cooled lintel or "tymp" above it, which could only be closed with clay balls driven in with a stopping hook. This operation involved taking the blast off the furnace at each flush, because the sparks and flame blown out the opening not only made it virtually impossible for a man to work in front of it, but also blew away the clay stop as fast as it could be put in. This practice involved taking the blast off the furnace from one to four times between casts. This reduced the output, disturbed the regular action of the furnace, particularly the settling of the stock, and necessitated much work.

About 40 years ago Mr. F. W. Lürman of Germany invented the water-cooled cinder notch which is now practically in universal use. By a gradual process of evolution since that time this has now developed into a water-cooled monkey, which is exactly like a tuyere in its general outline and appearance, but much smaller. This is supported and protected

by a larger water-cooled bronze casting, known as the cinder cooler, which is practically identical except in size with the tuyere cooler. Frequently this in turn is protected by a still larger cooler extending back to the outer wall of the furnace, which may be either of the iron-pipe coil construction or a still larger bronze casting, generally the former.

The cinder notch, as it is called—that is, the monkey—is closed by an iron plug on the end of a long iron rod, which serves as a handle. This piece, called the "bot," acts as a plug and also as a chill. When blubbering or sputtering of the stream of cinder indicates that the blast is blowing out above it, and therefore that its level is down to that of the notch, the furnace "keeper" takes the bot by its long handle, puts it through the cooler and up to the base of the monkey, then gives it a quick thrust and holds it for a few seconds. The cold bot and the water-cooled walls of the monkey chill the thin skin of slag between them and instantly make a perfect joint. The bot does not project through the cinder monkey, and is virtually not exposed to the heat except on its extreme end, and even that is chilled over by the cooling action of the adjacent monkey. Consequently this bot lasts quite a long time. It is generally allowed to remain in the monkey until the time for the next flush, when it is pulled out with a ring and wedge. A sharp steel bar is inserted into the hole which it left and the scull is broken through either by poking with the bar or by a couple of blows on the head of the latter with a sledge. By having the handle of the bot bent it can be operated by a man standing, not directly in front of the cinder notch but well to one side, and consequently to some extent out of danger from flame and shots of slag. A shield can be provided where necessary, from behind which the bot can be operated without the keeper's exposing his face to injury.

It will be seen that by this method the necessity of taking the blast off the furnace at each flush is entirely eliminated, while the labor incident to opening and shutting the slag notch is reduced to an insignificant fraction of what it was by the old method. Moreover, by the use of these water-cooled apertures the slag can be allowed to run for an indefinite time without cutting out the hole, whereas under the old system the hole gradually became enlarged by the blowing of the blast through it, so if the cinder ran too long it was difficult to stop.

Coke furnaces are now flushed from two to five times before cast and virtually without any labor. In very recent months an apparatus has been introduced at the Lucy furnaces whereby the bot is controlled by a system of levers. The bot is so held that it must enter the monkey properly without being guided by hand, and consequently the keeper can shut the slag notch from any desired distance. This eliminates absolutely the danger to the operator from shots of slag, which in time gone by have caused many slight burns and occasionally the loss of an eye.

The slag cannot be all removed by flushing, because the cinder notch must be located at a safe height above the top surface of the molten iron at its highest point, so in the case of a delay of an hour or two in casting the iron will not rise high enough to come into contact with the monkey and cinder cooler, therefore there must in normal operation be an appreciable height between the top surface of the iron and the cinder notch which must be filled with slag before any can be tapped out.

The reason for keeping the cinder notch well above the iron is that while water-cooled bronze is almost absolutely safe against the cutting action of the stream of molten slag, it has only a slight resistance to the cutting power of a stream of molten iron, and, the cooler walls being very thin, if the iron does cut the bronze it immediately runs into the water-cooled cavity and a terrific explosion inevitably results.

The violence of these explosions, which is almost beyond belief by those who have not seen their effects, was well illustrated by one case which I saw: a bronze cinder cooler exploded when it was cut by iron; a piece of it was picked up within so few seconds of the explosion that it was still hot, at a distance of 300 yd. or more from the furnace, and in such a location that it could not have been thrown directly from the cinder cooler, but must have ricochetted from some other object.

To avoid such accidents it is therefore necessary to have the cinder notch set at such an elevation that iron will never in normal operation have an opportunity to run out through it. Moreover, if the cinder notch is set too close down to the surface of the molten iron the furnace will "lift" iron through the notch at flushing time, and this iron running along under the cinder will very frequently be entirely lost, constituting a very serious loss of product.

The reason why charcoal furnaces, especially those working on rich ores, sometimes run without flushing is twofold. First, the slag volume is relatively small and so does little harm; second, since it is impossible to remove all the slag through the cinder notch, the smaller the total amount the larger the proportion of it which must remain in the furnace even after flushing, so that it is sometimes not worth while to flush at all.

CASTING THE FURNACE

As the molten iron descends into the hearth its level gradually rises. I have already described the danger to which water-cooled bronze parts are exposed by the cutting action of molten iron. When the iron does not run across them, but only lies in contact with them, the danger is much less, but it is still great, and, as we have just seen, the cinder notch is located so that in proper operation the iron is withdrawn before it reaches the level of the cinder cooler. The capacity of the hearth up to a safe distance below this point is a measure of the quantity of iron which should

be allowed to gather in it, and this in conjunction with the hourly product of the furnace is the fundamental factor controlling the frequency with which the furnace must be cast. (We speak now of casting the furnace; presumably the original phrase was "casting" the iron, in the sense of throwing it or discharging it from the furnace, but the former term is in universal use among furnacemen.)

Until within quite recent years it was the almost universal custom to cast four times a day, but with the increase in outputs which came with the Duquesne Revolution the capacity of the hearths of existing furnaces was not sufficient to hold the increased output for this length of time, and furnaces were cast five, six, and even eight times a day. There is, however, a certain amount of labor involved in preparing for each cast and cleaning up after it. The iron runners have to be made ready before and generally cleaned after cast, the skimmers must be set, the iron trough grouted, and various other practical but nevertheless imperative details attended to before and after this important rite can be performed; therefore the more casts the more work, and the increased outputs were soon followed by larger hearths to give greater storage capacity for iron. Perhaps it would be at least partly correct to say that the larger hearth made the increased output possible, and after a certain point was reached this was true.

In addition to the increase in diameter the depth of the hearth below the tuyeres were increased so as further to increase its capacity, and this practice has now so far developed that H. A. Brassert has spoken of the possibility of casting only three times a day on some furnaces, and declares that even this number may be reduced.

Personally I believe that the reduction in labor by reducing the number of casts per day below four is less than the increased risk of handling the largely increased quantities of iron, because the results of accidents occurring when the furnace is full of iron are correspondingly more serious. Moreover, while modern furnaces are provided with sufficient blowing power to make their tonnage even though there be considerable quantities of cinder up around the tuyeres, it is a matter beyond all doubt that in the older practice with poorer blowing engines when the blast pressure increased as the cinder rose around the tuyeres, the driving of the furnace would always drop. The action of the slag in gathering on the coke and preventing access of the air to it can scarcely be denied, and I cannot help but feel that the more the slag rises above the tuyeres in streamers blown by the blast, as already described, the greater will be its action in covering the coke and preventing the proper action of the blast upon it in the lower regions of the bosh, and the further the top of the zone of combustion will be forced upward with consequent possibilities of derangement.

It seems to me desirable, therefore, to keep the hearth as free of slag

as possible, and this can most easily be done by keeping down the level of the iron on which the slag floats. Further, I believe that the advantages of having less than four casts do not compensate for the possible dangers and disadvantages.

It is impossible to obtain the benefits of a water-cooled aperture through which to cast the iron in the same way that we do the slag, for the reason that there is no metal which is not cut by a current of iron running at high velocity, no matter how thorough the water cooling, and as I have already explained, the results of cutting such cooling members by molten iron are likely to be catastrophes rather than accidents, involving certainly many hours of delay on the furnace, with possibly great physical damage to it, and, worst of all, almost certain serious injury or death to the workmen around the front of the furnace. We are, therefore, compelled to use refractory materials, and in common practice there is only one used for a base, fireclay, though other substances may be mixed with it. This is rammed into the tapping hole at the conclusion of each blast by a method which may be best described in advance of describing the operation of casting itself, because the two are so interdependent that to say which comes first is like answering the old riddle, "which comes first, the hen or the egg?" At the conclusion of cast we have a hole 3 to 6 in. or more in diameter, but preferably 3 or 4, leading inward and downward into the hearth of the furnace, through which the contents of the latter have just been discharged.

It would seem at first sight remarkable that the hole should lead downwardly into the furnace, since it would seem that the furnace could not drain itself properly through a hole so located, and it would not except for the pressure of the blast which, as we have seen in an earlier chapter, is equal to that of a column of iron several feet in depth, and which, therefore, lifts the iron and slag through the tapping hole, the latter acting as an inverted siphon. When the blast is taken off the remaining molten material drops back through this hole into the hearth and out of the way, so that there is no dribbling of molten iron through the tapping hole while it is being stopped.

Until a few years ago it was the universal custom to stop the tapping hole with balls of fireclay driven in by a stopping hook operated by hand labor, but as pressures and outputs rose, resulting in a greater depth of molten metal in the hearth, and a greater pressure of blast on top of it, it became increasingly difficult to drive the clay in far enough by this means to prevent this combined pressure from forcing the iron out through it, and once a trickle of this kind started it was rapidly enlarged by its own cutting action until it was soon beyond control, constituting a "breakout at the tapping hole" which, while less serious than one through the hearth jacket, was a mishap of no mean proportions, particularly if it occurred before the iron trough was grouted, the skimmer

set and the sand beds made up ready to receive the iron, these representing general practice at that time.

About 25 years ago the late Samuel Vaughan, then superintendent of blast furnaces at Johnstown, Pa., in order to overcome these disadvantages invented the "mud gun." This consists of a steam cylinder carrying in front of it a smaller cylinder much after the general style of a direct-acting steam pump, the pistons of both cylinders being connected to the same rod. The forward or mud cylinder is open at its front end, provided with a nozzle some 3 or 4 in. in diameter, the cylinder being 7″ or 8″, depending upon the size of the furnace. A hole is provided through the mud cylinder just in front of the piston when the latter is drawn back into its farthest position. This front cylinder is loaded with tempered clay, plastic but quite stiff. At the conclusion of cast this whole apparatus, which is mounted on a small jib crane hung to one of the furnace columns and connected to the steam by swing joints or hose connections, is swung around in front of the furnace, the nozzle of the mud cylinder is entered into the tapping hole, then a pair of dogs or cams on a shaft running across the two front columns take hold behind two lugs on the mud cylinder, and by the rotation of the shaft force the nozzle down hard into the tapping hole. The hand-operated valve which controls the steam supply is quickly opened and the whole charge of clay is shot into the tapping hole. After allowing it to stand for a few seconds the piston is withdrawn and clay balls fed by hand into the opening at the rear of the mud cylinder. These in turn are rammed down to place by throwing on steam and driving forward the steam piston; the mud piston acts as a combined piston and steam hammer, being used not only to push but to pound the clay down into the hole.

As at first designed the shaft which holds the gun to place was operated by man power through a lever, but a few years later Felix McCarthy of Pottstown applied to this purpose a vertical cylinder fastened to one of the furnace columns, and by simply throwing steam on this cylinder the mud gun, once in place, was held securely without the necessity of any men to hold it, the only men required being the keeper to operate the hand valve of the steam cylinder on the mud gun, and a helper to feed clay balls into the mud cylinder.

With this powerful apparatus there is virtually no limit to the amount of clay which can be forced into the front of the furnace, nor to the solidity with which it can be driven in. The danger from kicks of iron and slag due to the contact of the wet clay balls was very great in the days of hand stopping, men were frequently burned by the iron stopping-hook driving through the clay stop and striking molten iron, or by some of the other minor explosions which are almost universal coincidences of the contact of wet material of any kind with molten iron and even molten slag. This danger is entirely eliminated by the mud gun, as is the

terrific manual labor of driving clay into the front of the furnace while standing right over the top of the iron trough which is heated to a white heat by the iron and cinder passing through and remaining in it.

Moreover, this invention has done more to make it easy to cast the furnace than all the other attempts along that line put together. In the days of hand stopping the clay necessarily became more or less intermixed with iron and slag in the tapping hole, and these (particularly the iron), enmeshed in the clay, becoming cold, made exceedingly difficult drilling. Then, too, owing to lack of power to drive the clay in very far, the tapping holes were very short, only a few inches in length, like an irregular hole punched through a very thin wall, and the result of this was to permit the iron to come very close to the outside of the hole, and the resulting matted mixture of clay, iron, and slag was burned in many cases to a hardness almost beyond that of the drills. By the use of the gun two things are accomplished: First, sufficient clay to fill the tapping hole solid full is thrown into it almost instantaneously, and with such power as to sweep all liquid material before it, the clay acting almost like a solid piston flowing into the hole. This prevents the intermixture of the iron and slag with the clay, and eliminates the difficulties which arise from that condition; second, the hole is carried so much longer that it reaches well toward the center of the furnace. In the old practice the tapping hole was at the bottom of a sort of pocket in the hearth opposite the front of the furnace, and was the farthest point away from the heating influence of the tuyeres. With the use of the gun this pocket is entirely eliminated; so much clay is forced into the front of the furnace as to put the inside end of the tapping hole inside the line of the hearth proper. The consequence is that instead of having to drive or drill through a chilled convex surface of exceedingly hard material we have now only to drive through a concave surface of material almost at a white heat, and not hard because free from iron and slag, although by its thickness mechanically strong enough to resist the pressure. This being a pure refractory clay, offers more resistance to heat than it did when intermingled with fusible substances like iron and slag, and practically eliminates breakouts at the tapping hole.

In very recent years two or three apparatus have been designed whereby the mud gun can be thrown into the tapping hole by purely mechanical means operated by a steam cylinder, so that the furnaceman, standing at a distance, can turn steam on the control cylinder, throw the gun into the tapping hole, hold it there, and then turn the steam on the gun cylinder proper, throwing the clay into the tapping hole. The result is that this operation can be done even when the iron is running full force from the furnace. This was impossible in the days of hand-stopping, and exceedingly difficult and dangerous with the mud gun when the latter was swung in and locked fast by hand, though I have known cases in

which furnacemen of unusual nerve and presence of mind, seeing something about to go wrong with the disposition of the iron, such as filling all the ladles available before the conclusion of the cast, or the like, have

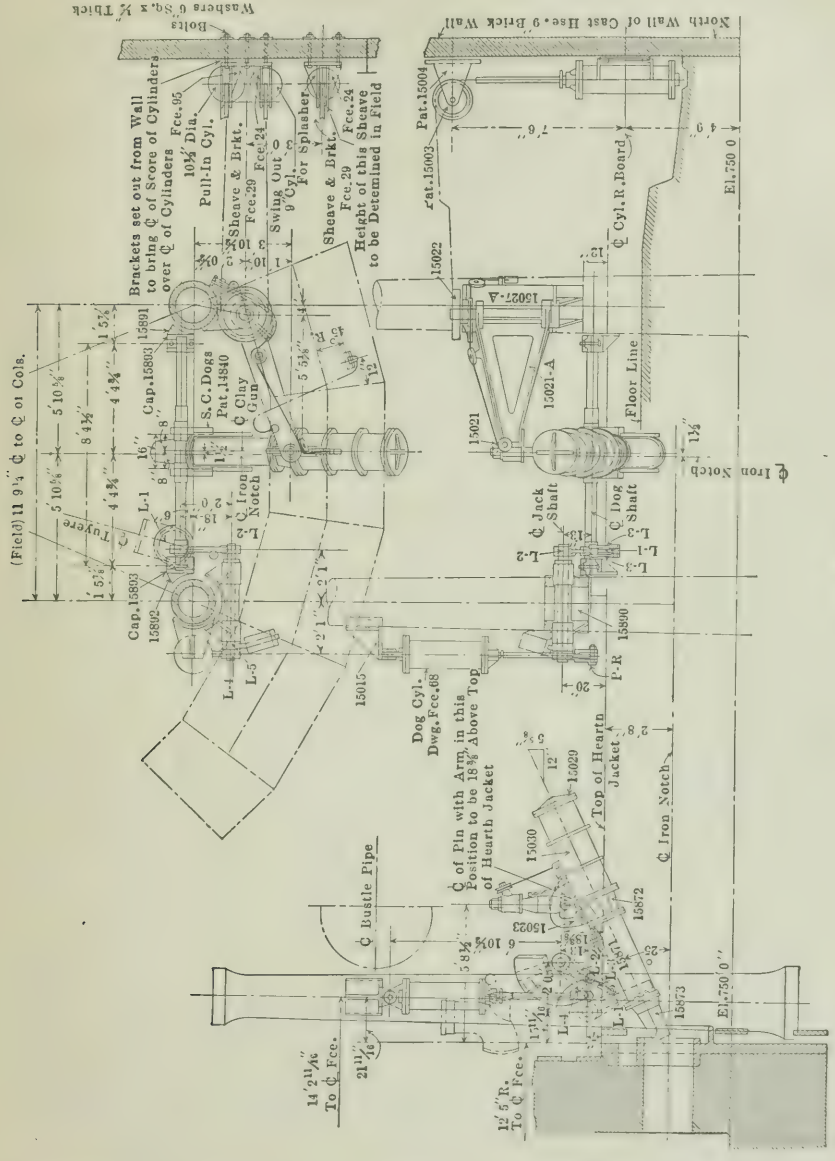


FIG. 89.

succeeded in throwing the gun into the hole and stopping it with the iron running full force. With the modern mechanically controlled apparatus this can be safely done as a regular practice. The consequence is that

the blast does not require to be taken off the furnace, with the consequent disturbance in the rate of settling of the latter, and casting instead of definitely ending each period of furnace work becomes merely an occasional incident in its steady and continuous operation.

The apparatus in use at the Edgar Thomson furnaces was designed by the Assistant Superintendent of that plant, F. H. W. Gerwig, to whose courtesy I am indebted for the drawing shown by Fig. 89.

OPENING THE TAPPING HOLE

This operation was carried on until quite recent years by drilling with hand drills. Sometimes one man held and guided a chisel bar while his helpers drove it with sledges virtually in the way that old-fashioned drilling for mining was done, or in other cases a gang of men, from four to ten or twelve, were put on a long churn drill whose weight was sufficient to make it both drill and hammer in one. Drilling was carried on until the temperature and the physical condition of the material at the bottom of the hole showed that the iron was very close, when the drill was generally removed and a bar was driven by a sledge to break the remaining skull if there were any. In many cases with churn drilling the drill broke through the skull and the iron came without the necessity for driving the bar.

This was the practice in the days of pig beds and hand labor for everything. Now the number of men on the furnace is not sufficient to operate one of these huge churn drills, while the easier drilling produced by the use of the mud gun as just described has made these powerful blows unnecessary, and the hole is drilled out either by light sledging on a small chisel bar, or else a clay auger driven by a compressed-air or electric motor is used. This is held and fed down into the hole by two men. When they see that they are close to the iron the auger is removed from the hole and the skull broken by a steel bar driven by a hammer as just described. This reduces the labor of casting the furnace to a fraction of what it was in the older practice, even with a regularly working furnace; when the furnace was working irregularly under the old conditions there was never any telling how much time or labor would be required to get the tapping hole open. The red-hot material composed, as I have indicated above, of clay, iron, and cinder could be drilled in to a point at which its temperature was so high as quickly to dull the edge of the drills, while it was still so hard and at the same time so tough that to drive a bar through it was often an impossibility. Consequently, it was no uncommon thing to see furnaces require 2, 3, and 4 hr. to drill open the tapping hole, which should have been done when things were working properly in 10 or at most 15 min.

This drilling with a churn drill is by no means a gentle exercise; a few

minutes of it will temporarily exhaust even a powerful gang of men, so in a case of this kind two relays of men must be provided, while the drills are dulled so quickly that two crews of blacksmiths are not always able to keep crews supplied with drills. Of course, these frightful conditions occurred only semi-occasionally, but the impression which they created when they did occur was a lasting one.

The labor and expense entailed by these conditions is the least serious part of the difficulty; the design of the furnace, as I have above indicated, is such that the well or hearth will hold the iron made between two consecutive casts with a safe margin. At the end of an hour this margin, in the old days at least, was likely to have disappeared. The iron would then be up to the cinder notch, while the cinder would be well above the tuyeres, and kept out of these only by the pressure of the blast. The stopping of the blowing engines would have filled the blow pipes and the penstocks and caused hours of delay, yet to continue blowing constantly increased the height of the iron and cinder. Up to a certain point it was considered safe to open the cinder notch and flush the cinder; after that it was certain that the iron would be above the cinder notch, and the question was whether to take the risk of the damage that the iron would almost certainly cause by rising around the tuyeres, or risk the danger of flushing it through the cinder notch with the likelihood of cutting the monkey or the cooler and producing a disastrous explosion. It was one of those conditions in which it was out of the question to stop, and yet to go on was to court destruction. There was nothing for it except, perhaps, to slow the engines down as far as was safe and to hope that the attempts to open the tapping hole would succeed before the catastrophe came, whatever its form might be.

Owing to the vastly better conditions, and the almost perfect control which the mud gun gives us of the tapping hole these bad hours are now very generally a thing of the past. I am sure that no one who has ever been through the experience will regret their passing.

BLOWING IN

The blast furnace is essentially an apparatus which operates not for days nor weeks, but literally for years at a time. It is virtually impossible to operate it at all except on an absolutely continuous basis. The reason why this is so, while not difficult to understand, is not exactly self-evident, and a brief explanation may not be amiss.

We have seen that fundamentally the operation of the furnace consists in maintaining a continuous downward current of solid material which starts in solid at the top and comes out molten at the bottom, and an opposite upward current of gases which attain their maximum temperature a fraction of a second after they enter the furnace, and cool off

progressively as they rise through it, being discharged at the top at a temperature lower than that of the waste gases from even the best boilers, sometimes down to 200°F. These materials exercise a counter-current effect, both physically and chemically, upon one another throughout their passage. This means that the condition at any point in the blast furnace is the result of a floating equilibrium between the heating and reducing action of the ascending gas and the cooling and oxidizing action of the descending solids at that point.

In good practice the conditions in any given zone are practically constant throughout for an almost indefinite time, but the conditions in the individual particles of matter change rapidly from second to second in the case of the gas, and from hour to hour in the case of the stock, and each of these exercises an effect upon the other. For instance, let us suppose that the top gases are discharged from a given furnace at 400°F.; now if we go down a short distance we shall reach a point where these gases are 1000°. They are cooled from this temperature down to 400° by the action of the incoming stock, which they pass on their way up. On the other hand, the stock entering at, say, 70°, descends to this point, and in so doing is heated up, let us say, to 800°.

If the operation be regular and normal the gas will always be about 1000° and the stock always about 800° at this point, but suppose that we ceased to fill the furnace regularly and continuously. When the surface of the charge descended to this point, obviously conditions below this would be just the same, but the conditions above would be very different. The descending stock becomes heated, but without the addition of further charges the temperature of the gas rises steadily until when the surface of the stock column reaches our chosen zone the gases are obviously passing off at 1000°, there being now no stock above this zone (at which they reach this temperature) to cool them any further. Obviously the heat in the gas from 400° to 1000° is gone, permanently lost as far as the furnace is concerned. Now if we begin charging again, the stock which should reach this zone with a temperature of 800°, reaches it instead with a temperature of 70°, and is behind its schedule by as many hours as it takes in normal operation for a charge to descend to this zone, while the heat which should have raised this fresh charge to 800° is, as we have seen, lost, and has left the furnace forever.

The result is that this charge has had several hours less treatment for its reduction and has received much less heat than it should. If the zone to which it fell when charged is not down too far, that is, if the stock line has not been allowed to settle too far, if, in furnace parlance, the furnace be not too far down, and if there be a surplus of heat in the upper part of the furnace, as there generally is in coke practice, then the lost time and heat may be made up; but the further down the furnace is, the more certain it becomes that this will be impossible and that this charge

and those immediately following it will reach the hearth improperly prepared and that the regular operation of the furnace will be upset by this condition, the seriousness of the derangement being in a general way proportional to the amount of time these charges have lost.

We can carry this supposition a step further. Suppose that the top surface of the stock were permitted to descend to the level of the top of the bosh. Obviously the gas would pass off at a temperature of 2700° or 2800°, representing a very large proportion of all the heat developed, and if the furnace were driven at the same rate any stock which entered at this point would reach the hearth in a very short time in such a completely raw condition that its conversion into merchantable iron would be impossible.

If we carried the process a step further, and allowed the top of the stock to decend to the tuyeres, obviously the furnace would be virtually out of commission, the quantity of heat carried off by the gases would have been so great, and the time permitted for the absorption of heat by any incoming charge would be so small, practically zero, that we should have nothing but raw stock in the hearth of the furnace if we charged at such a time.

Now suppose we reversed this process and filled the furnace up completely just as though it were in regular operation, and let us suppose for convenience sake, that this operation could be done instantaneously. Instead of having a furnace full of material in all the stages of reduction and heating, from nothing up to completeness in both respects, we should simply have a receptacle full of cold material, and while the heat generated by the combustion of the coke in the charges at the tuyeres would warm it up, it would obviously be impossible for this amount of heat, without the assistance of that of the gases which had gone before, to complete or even to come anywhere near completing the smelting operation.

This represents in a rough way the conditions which we have on blowing in a furnace. We necessarily fill it with cold stock from bottom to top, and then put fire in at the tuyeres and put on the blast. The material in the bosh instead of being molten is cold, and if we had a burden of the ordinary kind on the furnace it is obvious that we should never get it to the liquid condition so that we could remove it, to say nothing of reducing the iron contained in the charge.

Moreover, there is another large factor which exercises a precisely similar effect. The walls of the furnace weigh many hundreds of tons, and the interior surfaces of these when in operation are at the same temperature as the zone of the furnace which they inclose, and while the outer portions of the walls are not so hot, still the amount of heat contained in the walls in normal operation is enormous; it is probable that it represents the thermal value of the coke burned for a considerable

fraction of a day. When blowing in these walls, of course, are perfectly cold, and it is impossible for the different zones of the furnace to acquire their proper temperature without simultaneously raising that of the walls at these zones to the same point.

To overcome these conditions in blowing in the furnace, therefore, we must charge a great quantity of fuel without any burden whatever. This mass of fuel fills the furnace up to a considerable portion of its height, probably in ordinary practice from one-fourth to one-third. It is clear that when this has burned away, and the material above it reaches the tuyeres, it will have had the benefit of the heat in the gas coming from this great mass of fuel, and that it will have been several hours in its descent while this mass of fuel is burning away. Such superincumbent portions, therefore, will have a vast advantage in time and temperature over the initial coke at the tuyeres. In practice we take advantage of this condition after charging the big "blank" at the beginning of filling, by putting on a very small amount of burden, with an extra large coke charge, two or three times the normal size, and then very gradually increase the burden and decrease the coke charge until finally the furnace is filled. The burden is gradually increased until at the top it reaches a ratio of about 1:1; that is, 1 ton of ore to 1 of coke, which is virtually half of the burden in regular operation. The rate of driving while blowing in is very slow, for reasons to be given later, and the extra time which this gives especially to the upper portions of the charge, combined with the excess fuel, finally brings the different zones approximately to the temperature which they should have in normal operation, and the furnace then begins slowly to produce iron.

After lighting and several hours of blowing cinder appears and is flushed, and after 24 to 48 hr., according to the conditions and the judgment of the manager, enough iron accumulates to make it worth while to cast; during this interval the furnace as it settles is filled with charges carrying gradually increasing burden.

After the first cast the furnace has approached so much more closely its normal conditions of temperature in the different zones that the burden may be increased more rapidly, the only guide being the indication of each cast as it is made, the appearance of the cinder, and the general conditions in the hearth as determined by looking into the tuyeres, but the furnaceman who is satisfied with the way things are progressing, knowing that with normal progress each cast will be hotter than the next, increases the burden in advance so as to prevent making too much high-silicon iron. Where the practice is well standardized, and where there has been previous experience in blowing in with the same materials, it is possible to bring the furnace down on irons of the desired analysis at the first cast, and to increase the burden as needed so as to make nothing else during the blow in.

The tendency in recent years has been to shorten very greatly the period required in older practice to bring the furnace to normal operation.

Leaving the question of burdening we turn toward the next most important question, that of the volume of wind at the different periods of blowing in. This must be very much smaller than the normal blast blown in the furnace in normal operation for two reasons: First, to allow the effect of time to replace in some measure the deficiency in exposure to heat from which the materials first charged suffer, it being obvious that the longer these are exposed to the rising temperature due to the gradually increasing heat of the furnace the more nearly will they reach the condition they should have at the different zones; second, the walls of the furnace are cold, as already described, and time must be allowed for these to heat up, and the blast must be encouraged to travel up them by the use of short tuyeres rather large in comparison with the quantity of blast blown because if relatively high penetration be used, especially with the open mass of coke in the hearth and bosh, the tendency of the blast is to travel to the center of the furnace and to pass up through this region like a chimney, leaving the walls relatively cold. Then as the slag begins to form it runs down, and striking on the sloping surfaces of the bosh is chilled there and so builds up, in some instances forming a shelf-like structure on the bosh walls, which may be highly injurious, if not fatal to the success of the campaign being started.

I knew of one case in which a furnace was blown in on a very large volume of blast for its size, and this was blown through a small number of tuyeres, which gave excess penetration. The furnace worked so badly that at the end of a week it was blown out. When the operators went inside to see what the conditions were they found a shelf built on the bosh walls, the opening through the annular shelf being something like 3 ft. 6 in. in a furnace whose bosh diameter was about 18 or 19 ft.

This seems almost incredible, but the facts were given me by the manager, who certainly had no reason to be proud of the performance, and there is every reason to believe that the story is authentic. The cause in this case is obvious; the high penetration drove the blast to the center and left the walls so cold that the cinder running down over them froze to them, and probably after a short time began increasing the bad effect, which was initially at the bottom of the trouble, by forcing the blast more and more toward the center.

For both these reasons then the quantity of blast used at blowing in is a small fraction of that used in normal operation, probably, in ordinary practice, about a third. This is increased very slowly at first, and at all times more slowly than the burden until the latter has reached about the figure for normal operation at the end of one or two weeks. Then the blast continues to be increased until it in turn has reached its normal amount and the furnace may be said to be in full operation.

LIGHTING THE FURNACE

The practice in this respect has varied over the widest possible range. My father, the late Joseph E. Johnson, told me that the practice of the old Southern charcoal "founders," who were entirely illiterate, was to light the furnace at the *top* and allow the fire to work down through the fuel column to the bottom, filling up above as the charcoal burned away, a process which took a week or two even with those tiny furnaces. Anything more absurd than this performance it is impossible to conceive.

As a result of this and some other practices based on reasoning about as fallacious, the furnace when blown in on one occasion got into such a horrible "mess" that at the end of 3 weeks it was blown out as being hopeless. They filled it and started again, and in a short time it was in worse condition than it was on the first occasion, but this time for shame's sake he insisted that the founder keep on, and they finally pulled the furnace through, rather in spite of that individual than through any help which he gave them.

These events took place in the early seventies, now more than 40 years ago, but considering the changes which have taken place in this as in other departments of this business the time required for the transformation does not appear very great.

After the practice of lighting the furnace at the bottom was established, and up until very recently it was the custom to put a large quantity of wood into the hearth. This practice is still followed at some plants; in one case it is varied by using a carload of charcoal for the bottom of the furnace, this, of course, being very expensive in most localities.

When wood is used it is put into the hearth with the greatest care. In some cases in former times, and perhaps still at some plants, a scaffold or platform of wood was built inside the hearth and the cord wood was carefully placed on top of this, so that when the scaffolding had burned sufficiently to break, the stock was given a sudden drop which started it to settling, there being a tradition, based, I think, on the rather defective practice of an earlier day, that it is very difficult to start a furnace to settling when it is blown in. When the scaffold was not used the wood was stood up vertically in the hearth and built up at least two lengths of cord wood 8 or perhaps 12 ft. or more, a small shaft being left to the last through which the wood, passed in through the tuyeres or tapping hole, could be taken up to the upper ranks, and through which the man who placed the wood could get down when that operation was finished.

In more recent years the tendency has been to discard the use of wood almost altogether. A few sticks placed around the tuyeres with a little kindling between them and the tuyeres are a convenience in getting the furnace lighted quickly. A few pounds of waste soaked in oil, pushed in through the tuyeres and ignited just before the blast is put on will

ignite the coke with the use of no wood at all or at least only as much as may be put through the tuyeres. This saves a great deal of bother and in most cases saves a very considerable expense for cord wood, which costs several times more than coke per unit of heat contained.

One feature of practice in blowing in, due to the dread of having the furnace "hang" at that time, now, fortunately, belongs to a bygone era. It was then believed that the great height through which the stock had to fall in the early stages of filling the furnace tended to pack it solid and prevent the gas from rising, on the one hand, and the stock from settling, on the other. In order to avoid this difficulty, I am told that the practice was one time followed, of lowering the stock into the furnace in tubs at the end of ropes, the tubs being dumped only when they were within a short distance of the stock already charged. I am extremely glad to say that I never had the misfortune to have experience with this operation, which is entirely obsolete as far as I know.

The universal custom now is to charge the furnace from the top (after the wood had been placed, if any be used), exactly as is done in regular operation.

In former times it was customary to allow the furnace to draw, that is, leave the tuyere caps down and let the furnace act like a chimney, its draft, of course, being very greatly impeded by its being filled up with stock, over a period of hours ranging from 2 or 3 up to 24.

I have seen this practice followed a number of times, and I have also seen and used the more recent practice of putting the blast on as soon as the furnace is lit, and I have never been able to see any advantages whatever in the old practice, whereas there are several in the latter. One of these is that the slow fire drawing gradually up through the furnace has the chance to bring some material to a half-molten condition and cause it to stick, while a quick blow-in does not. Another is the elimination of a half day or even a day of lost time and "sneaking" gas.

I have never used the scaffold to cause the settling of the stock, but in recent years I have followed a practice whose benefits I found almost by accident, and that is to give the furnace, for a few minutes after the fires at the tuyeres are well caught, about twice as much blast as it is expected to use for the rest of the blow-in. This drives the fire well to the center of the furnace to start off, and producing a brisk action before any pastiness has had a chance to arise from slow combustion, induces a quick initial settling of the charge, which thereafter proceeds regularly on the reduced blast used for the rest of the blowing-in period. This practice also has an advantage in facilitating "bringing down the gas," as it is called.

BRINGING DOWN THE GAS

When the furnace is first lit the interstices in the stock, the space above the stock line, the downcomer, and the dust catcher, and the flues leading

to the burners on the stoves, boilers, etc., are, of course, all filled with air. Air mixed with furnace gas in a very wide range of proportions is highly explosive, and it was until very recent years considered a difficult feat to bring down the gas without having an explosion of more or less violence, because when the gas began to come through, driving the air ahead of it, the point would finally be reached where the mixture was a combustible one, and the flame striking back from the burners would ignite this mixture, and traveling back from the flue at least throw open all the explosion doors, and at worst burst the dust catcher or blow down part of the boiler settings.

In recent years there have been found two methods for avoiding this trouble which can be practised separately or, still better, together. The first consists of providing at the extreme end of the gas flue, or on each end if it has several branches, an outlet with an explosion door, or other arrangement capable of being easily closed while the gas is passing through it; the burners are all shut off tight, and the bell and other openings into the furnace and gas main tightly closed, all the gas is then forced to pass off at these flue-end openings, from which all fire is carefully kept away. When a solid column of gas appears, which can easily be told, both by its appearance and its odor, the burners on the stoves and boilers are opened one at a time, and the dangerous mixture having all been pushed out of the flues far from these, no explosion can possibly occur. The flue-end vents are then closed and all danger of explosion is over as long as the blast is kept continuously on the furnace.

The other expedient is one first used in the Birmingham district about the first of the present century. It consists in introducing a blanket or cushion of steam into the top of the furnace, dust catcher and flues before or at the time of lighting. This drives out all the air except the small amount in the interstices of the stock, and thereby prevents direct contact of the initial gas with a sufficient quantity of air to produce an explosive mixture. When a sufficient volume of gas has passed to drive this cushion of steam out nothing but practically pure gas is left, and this may be ignited at the burners in safety. It is better, however, and safer to use this method in conjunction with the other by permitting the steam cushion to be blown out at the end vents of the gas flues, and thus securing the benefits of both methods. The steam-cushion method has in recent years been quite widely introduced by Mr. John W. Dougherty.

The benefit of a few minutes of extra blast in connection with bringing down the gas is this. With normal slow driving during the initial period of the operation a very small quantity of gas is formed, which appears to be almost lost in the interstices of the stock, for quite a while, and this, therefore, prolongs the period within which dangerous air mixtures may be made and explosions follow, but with a short sport of extra

blast a considerable volume of gas is formed at once, and sweeping through the furnace drives out the air and shortens the period during which accidents may occur, as well as starting the stock to settling without delay.

WARMING UP THE FURNACE BOTTOM

The bottom of the furnace contains many tons of brickwork which under the very best conditions can only have been warmed to a very slight degree by the drying-out fires previously described, and its temperature is many hundred degrees below the melting point of iron and slag. It therefore has the inevitable effect of chilling these and making the first tapping and flushing of the furnace extremely difficult. It has for a long time been the custom to leave the tapping hole open so as to allow the part of the gas formed at the tuyeres to blow down and pass out through this, thus making a downward current and warming the bottom of the hearth. The tapping hole, however, as built in the brickwork is generally 2 or 3 ft. high, and if left entirely open the tendency of the gas would be to pass out through the top and not go to the bottom as it should. Moreover, it is necessary to have the tapping hole under control so that it can be closed at the first appearance of cinder, as not enough of this flows at first to keep up a continuous flow and chilling it would build up until the hole could neither be opened nor shut without horrible difficulties.

This situation is met in recent years by placing a 4-in. pipe in the bottom of the tapping hole, running it well towards the center of the furnace, and filling up the space around this pipe with clay, sometimes mixed with fine coke braize so that it will not burn too hard. In the best practice this is built out to a convex surface well inside the line of the hearth proper, so that when the time to tap the furnace arrives the final point at which the body of iron is penetrated will be warmed as nearly as possible on all sides and so be made easy to penetrate.

Mr. R. H. Sweetser has introduced an improvement in the use of the pipe by drilling holes in its outer ends through which it may be caught by means of long hooks and pulled out of the furnace when the slag begins to run, thus leaving a clean hole 4 or 5 in. in diameter in the clay which may readily be stopped with clay balls. The pipe is not removed for many hours after the blast is put on the furnace, not in fact until the flow of cinder becomes so large that it threatens to plug up the pipe by progressive flowing and freezing. The gas burns fiercely out the end of this pipe and helps to warm the iron trough outside, a point of very great importance, since it tends to prevent explosions which are likely when the molten iron strikes a cold iron surface.

The whole operation of blowing is one of some complexity, and it is virtually impossible to treat it completely here, there being many details which are neither comprehensible nor interesting, except to practicing furnacemen, who commonly do not need to obtain them from books.

There are, however, a number of points in connection with blowing in which are worthy of mention. The practice of charging cinder saved from a previous blast on the blowing-in charge has been quite extensively followed and has much to commend it. High-temperature operations during the initial stages of blowing in are at a very serious disadvantage as the furnace temperatures are still too low for their accomplishment. We have already seen that the temperature required to form slag is considerably higher than its melting point, therefore a slag which has been completely formed melts much more easily and runs more freely at the temperatures available during blowing in than the substance to be slagged, notably the coke ash, even though the latter have limestone charged with it.

Another reason for the use of slag is that a large volume of molten liquid is much less likely to become frozen and troublesome than a smaller volume of the same liquid, the surface exposed by the larger volume in general being but little greater than that exposed by the smaller, therefore to increase the volume of slag artificially, so to speak, is a benefit and tends to prevent that troublesome occurrence of progressive building up through alternate flowing and freezing of which I have spoken. The practice of adding old slag is not as common as it once was, but its use is well worthy of consideration.

SLAGGING THE COKE ASH

The great quantity of coke used as the initial portion of the blowing-in charge containing about 10 per cent. of ash has in the aggregate several tons of slag-forming material, very largely silica and alumina with but little lime for flux. This alone makes a tough, stringy, hard-working slag. It is very much better on every account to add to the coke as it is charged a sufficient amount of lime to flux this ash to the best advantage. As the first slag should be out of the furnace before any iron comes down it is not necessary that this first slag should have much sulphur-carrying capacity. It can be made much more fusible than the normal coke furnace slag by the use of a considerably smaller percentage of lime, thereby reducing both its quantity and melting temperature, but the slag produced just previous to the carrying down of the first iron should be slag almost of normal lime content, perhaps somewhat lower than this both for safety and because if the furnace is as hot as it should be, less lime is sufficient for desulphurization.

PREHEATING THE STOVES

The blast furnace process as a whole constitutes in a sense a cyclic operation. The blowing engines and the stove supply the blast which drives the furnace and the furnace in its turn supplies the gas which runs

the blowing engines and heats the blast. But when blowing in a single furnace these conditions do not prevail. There is no gas available until after the furnace has been started. It is therefore necessary to fire the boilers with coal to make steam in the way customary where blast-furnace gas is not available.

The stoves present a more difficult problem. We have already seen that under the very best circumstances the material which is down at the tuyeres when the furnace is blown in, is nearly 3000° below the temperature which it should have at that point. The blast is normally 1000° or more when entering the tuyeres. If now when blowing in we add to the effect of the cold stock inside the furnace the effect of blast 1000° colder than that which we should use it is obvious that we shall be a long time building up the temperature we require, and those who had the experience of it know that blast of even 400° or 500° at this time is a great help as compared with cold blast. The stoves being entirely unprovided with grates cannot be fired to advantage with anything but gas, although a bonfire may be kept in the bottom of the combustion chamber by wood pushed through the burner or clean-out openings, and this at least should always be done for several days continuously before blowing in.

Very much better than this, however, is the plan of building a temporary oven outside one of the air or clean-out openings best suited for it, arching it over or covering the top, and connecting its outlet into the stove opening. Grate bars are then placed in the oven and a good coal fire kept in it. The hot gases from this fire pass directly into the stove and if the operation be carried out with a little care and for several days before blowing in, the stove can be in condition to give a blast-temperature of several hundred degrees when it is finally wanted on the furnace. Of course care must be taken to see that the hot gases from the fire do not strike on the steel fittings around the stove openings or any metal part of the stove.

The question of drying out the furnace has already been discussed under the subject of lining in Blast Furnace Construction and need not receive further consideration here.[1]

BANKING THE FURNACE

In the chapter on thermal principles the losses by radiation and cooling water were given in terms of thermal units per ton of iron, and while this is necessary and right for the purpose then in view, it must be remembered that heat losses are proportional to temperature and to time, and under given conditions to nothing else. Hence if we maintained the temperature of all the zones of the furnace exactly as it is in operation, but stopped the operation, made no iron, we should lose precisely as many

[1] See Chapter VI, The Furnace Stack.

thermal units in 24 hr. as we do when the furnace is in full operation. We can put this into a more easily comprehensible form. If the total heat losses be 750 thermal units per lb., and if the furnace produces a ton of iron every 3 min., or 480 tons per day, we shall have a loss of 560,000 thermal units per minute, or in 10 hr. 336,000,000 thermal units. This is as much as is required for the smelting of 25 tons of iron, or in 24 hr. we should lose as much heat as was required for the smelting of 60 tons of iron.

This loss is constant if the temperature of the furnace in all its zones be maintained constant, whether we make 500 tons per day or none, but if we make 500 tons per day the loss only represents 10 per cent. of the heat developed, and this the furnace can stand, but when no heat is being developed the furnace cools off very rapidly and of course the most rapidly in the zone of highest temperature, that is, the hearth. This means that the iron around the edges of the hearth soon begins to freeze and instead of having merely a thin scull of frozen iron to break through, in tapping the furnace, we shall have a scull of red-hot iron many inches in thickness, too hard to drive through, and much too tough and hot to drill except by the most tedious work. The consequence is that if a furnace shuts down for even a few hours in the regular course of normal operation much difficulty is experienced in opening the tapping hole, and the cinder notch, and in removing the frozen iron around the tuyeres which is often low in carbon and therefore tough, almost like wrought iron. Under these conditions operation can be resumed only with difficulty approximately proportional to the length of the stop.

If there be iron in the hearth when the furnace is shut down this quickly freezes solid, filling the hearth with solid material, thus making it almost impossible to put the furnace back into normal operation. Of course the regular tapping hole is frozen solid and cannot be used, the frozen iron in the hearth cannot be removed and the new iron formed when the furnace starts is raised far above its proper level and is continually threatening the cinder notch and tuyeres, while the mass in the hearth being heated only from the top melts very slowly. The furnace must be cast through the cinder notch or even through a tuyere, and in general the difficulties of operation are terrific, nothing being arranged for those conditions.

For this reason if the furnace must be stopped for more than a very few hours provision is always made for it in two ways. First of all by casting and removing as far as possible all the iron and cinder so there will be nothing left in the hearth to freeze. In good practice precautions are often taken in the stopping of the tapping hole; sand or braize is mixed with the clay for "stopping" so that it will not burn too hard. Second, if the stop is to be more than a few hours duration, and if it be known beforehand that it is to be made, a blank of coke is charged at such

a time that it will have descended about to the tuyeres by the time the stop is to be made. This gives an excess of fuel supply which becomes available as soon as the furnace starts up, and the excess heat from this is of the greatest use in restoring normal operating conditions.

Another beneficial feature is that the ore and limestone being absent from this coke charge there is correspondingly less molten material to descend into the hearth and freeze there while the furnace is stopped.

The size of the blank depends upon the length of the stop to be made. For a stop of a few hours duration only a single blank charge of coke may be used. But for a stop for 2 or 3 days a blank many times this size is required, and if the furnace is to be shut down for many days or perhaps several weeks, or indefinitely, as sometimes happens, then the furnace is practically filled altogether with coke.

After the furnace is stopped the greatest pains must be taken to shut off the tuyeres absolutely tight so as to prevent air from entering through them by natural draft. For very short stops this may be done by ramming clay balls through the blow pipes into the tuyeres and packing them in, while for longer stops the blow pipes are taken down, and the tuyeres removed and a tight stop of clay put into the cooler. Of course the cinder notch and tapping hole are kept closed and if there are any cracks which have been blowing gas these should be luted up with clay.

It is surprising the amount of air which will draw into a furnace and the rate at which combustion will go on without blast unless special pains be taken to prevent it. This is objectionable because it burns up coke to no purpose and produces a corresponding quantity of slag in the hearth with the possibility, not to say certainty, that it will freeze there and make trouble on starting up. On long shutdowns the cooling water on the furnace should be cut down to the merest trickle so as to prevent the removal of any more heat by this means than is absolutely necessary.

By following these precautions furnaces have been banked for months and then successfully started up again, but even with the best of management the long period of inaction is likely to bring about the sticking of material on the walls, and the consequent formation of scaffolds. Such material would be scoured off as fast as formed during operation and scaffolds would therefore not occur. Moreover, even with the best of management the hearth builds up and its capacity is diminished, and in general that careful adjustment of all the conditions which the furnaceman may have been months in bringing about is upset, so that it is very rare for a furnace to work as well, for a considerable interval of time after a shutdown as it has before, this interval being in a general way proportional to the length of the shutdown. That is to say, a furnace will quickly recover from the derangement of a 6-hr. shutdown, but it will take in general nearly a day to restore equilibrium after a day's shutdown, and a week or more when the furnace has been banked for several weeks.

The practice of banking furnaces is undoubtedly necessary at times, sometimes for physical and sometimes for financial causes, but for all the above given reasons it is a practice which breeds trouble, very often of long duration, and I believe that most furnacemen, if they knew in advance that a furnace had to be banked for a period of more than 4 weeks, would prefer to blow it out and blow it in again after the desired interval, and in my judgment this would be by far the wiser policy.

BLOWING OUT

We have seen that if the furnace be not kept full, as the level of the stock descends past any zone in the furnace the gas passes off at the temperature which the gas has at that zone in normal operation. In other words, the temperature at that zone is approximately fixed as long as the surface of the stock does not descend below it; if there be stock above it, the gas will give up an amount of its heat roughly proportional to the height heat of the stock above it, but if there be none, then the gas necessarily passes off at the temperature of that zone.

In blowing out, therefore, we lose the heat in the gas which we shall so badly need during the subsequent operation of blowing in, to bring the materials of the charge up to their approximate temperatures at the different zones, but having no means to store this heat we have no recourse but to lose it. But it is worse than this; we not only lose the heat, but the temperature of the gas passing off, starting from a temperature which iron and steel can ordinarily stand without any difficulty whatever, since the bell and hopper have habitually stood it for months and years together, rises as the top of the stock descends, to a temperature which is above the melting temperature of steel itself, and in consequence the gas destroys anything exposed to its action which is not properly cooled.

In the days of furnaces with the center outlet and unlined downcomer, the latter could not be exposed to these gas temperatures without complete destruction and, protection to it being impossible, the entire top rigging of the furnace was taken off, bell, hopper, center outlet pipe, and practically everything of iron above the top of the furnace, this of course being done during a shutdown of a number of hours for this purpose. After this operation was completed the blast was put back on the furnace and the gases allowed to pass out the top at will. They of course instantly burned on meeting the air at the top and a vast flame rising 100 ft. or more in the air was the result, this continuing until the furnace was blown out, that is, practically all the coke charge had burned up.

In more recent years, downcomers being lined throughout with brick, this condition does not exist, for while the bell and hopper are exposed to the gases they can be protected by filling the annular space between them with water and allowing enough to run into it continuously to supply that which boils away, and in consequence the operation of blow-

ing out the furnace is much simplified. It is, however, very desirable to keep down the temperature of the gases as much as possible, and for this purpose water pipes are commonly introduced through the holes provided for the test rod and water is pumped into the furnace through these pipes, so cutting down the gas temperature very materially. I have found, however, that too heavy a column of water descending on the stock would make its way through the coke in spite of the ascent of the gas and so would chill the charge during blowing out. In order to obviate this I preferred to plug the end of the pipe and drill it full of holes for a distance of several feet so as to make a heavy spray of water. This cools the gas much more effectively and prevents the possibility of any solid body of water penetrating the coke.

When provision for cooling the gases in this way is made, and the charging space above the bell filled with water, virtually nothing more is needed but to put on the blast and keep on blowing until all the fuel in the furnace is burned up. It is, however, desirable to have a fairly hot blowout so that the last iron and cinder to be removed may surely be hot enough to be tapped out of the furnace without any difficulty, and for this reason the burden is usually lightened somewhat.

The height to which it is desired to blow down varies according to the opinions of different furnacemen. Some prefer to charge a large quantity of coke braize or poor coke which acts as a sort of piston and enables a little blast pressure to be kept upon the furnace until the charge proper is all burned out, this blowout charge being then shoveled out after the furnace has been cooled down. The iron which lies down below the level of the outer end of the tapping hole cannot be lifted out by the blast pressure on blowing out because there is practically no stock in the furnace to make any blast pressure, and it is very undesirable to have this iron left in the furnace because it represents a decided loss of product and increases by so much the salamander which the furnaceman knows he will shortly have the pleasure of breaking up in the face of very considerable difficulties, even under the very best conditions.

At one plant it is the custom to overcome this difficulty by removing the iron trough previous to the last cast, digging away the brickwork on which it rests, making up a temporary sand runner to some pig beds at a correspondingly lower level and then drilling in at this lower level a foot or two below the level of the regular tapping hole and running in as nearly horizontal as possible. This drains the furnace down to a correspondingly lower level and removes most of the iron which would otherwise be left in a puddle in the hearth to freeze.

RELINING

When the furnace is blown out it is generally necessary to make all repairs needed in the minimum time so as to get the furnace into operation

again and cut off the loss which arises from the continuance of fixed charges whether the furnace is in operation or not, so that such repairs are generally made under pressure. These in general are various kinds of purely mechanical operation and need not be specially described here.

The operation of relining the furnace, generally the principal single item, is ordinarily the same as that of lining, since in most modern practice the old lining is torn out completely. There are, however, many cases in which the major portion of the lining is good and it is necessary only to put in a patch to repair a portion of it. It is obviously not possible to give detailed descriptions of this operation, which depends, as do so many other practical details of this business, on the skill and good judgment of the manager.

REMOVAL OF THE SALAMANDER

There is, however, one operation which is in a class by itself on account of the number of factors involved, and the weight of the pieces to be handled. This consists in the removal of the salamander. The formation and general nature of this has already been described. Its size varies considerably. In a charcoal furnace I have seen the hearth almost perfectly clean and smooth, the iron not having penetrated into the brickwork at all, but in coke furnaces with their higher hearth temperature and slags chemically much more active, conditions are very different. The bottom of the salamander is seldom less than 3 or 4 ft. and may be as much as 8 or 10 ft. below the original hearth level. Its diameter in general bears some relation to the original diameter of the hearth, usually larger than the diameter inside the brickwork and smaller than the diameter outside. This means a mass of metal anywhere from 8 to 20 ft. in diameter. I myself have had experience with salamanders weighing between 250 and 300 tons, this including only the single piece of solid metal in the central mass and not including the smaller but separate pieces lying around it and of course not including any brickwork, nothing but solid iron. I have no doubt that much larger salamanders than this are found in the large furnaces of the present day with their extremely large hearths.

If the hearth jacket is a permanent structure, which is generally the case under modern conditions, it necessitates removing this large mass of metal without disturbing the hearth jacket and, above all, without breaking the latter during blasting.

This of course increases the necessity for more care in handling the explosives required for this operation and incidentally increases the difficulty of hoisting the pieces out of the deep pit so formed.

The following description of the removal of the salamander is condensed from an article in the *American Machinist* which appeared several years ago and from which the illustrations are taken.

Sometimes a furnace works much hotter in the bottom than at others. In the former case the iron and cinder dissolve away firebrick and cut out the bottom to a considerable depth. At other times the furnace will work cold in the bottom and a mass of iron will build up on the hearth. This latter action in the particular case described was probably due to deficient penetration.

The top of the salamander had been about at the hearth level at the blowout previous to this, so it was not removed, the decomposed brick

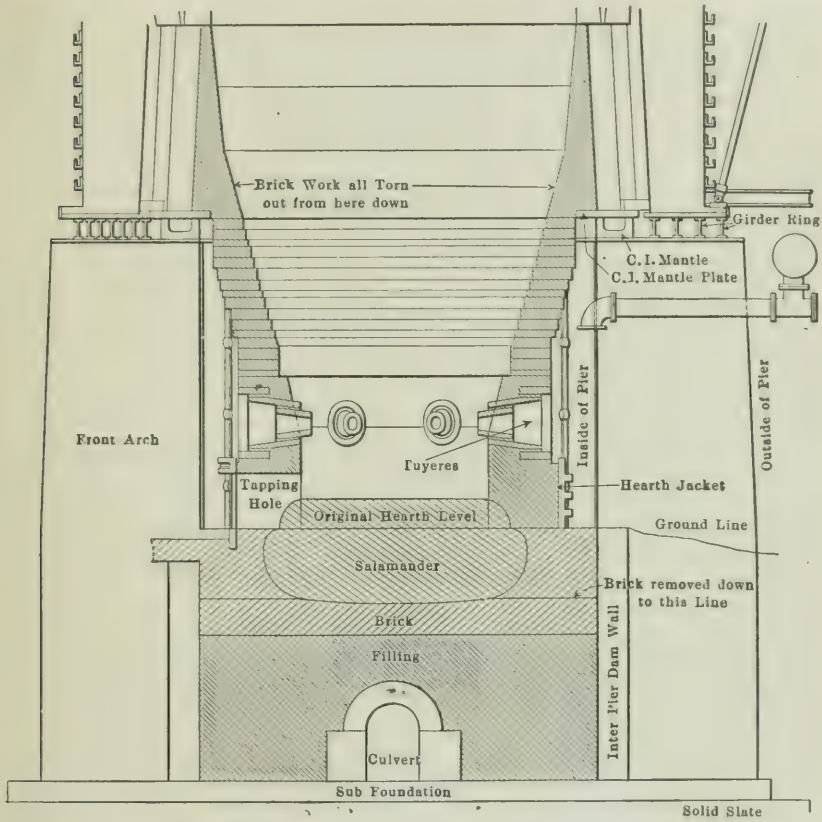


FIG. 90.—Section of the furnace and salamander.

around the edges were dug out and the proper hearth level restored with new brick, the salamander projecting slightly above the bottom in the center. During the blast ending with the blowout under discussion, the furnace had worked "cold" in the bottom and the hearth bottom was constantly high, so that the original salamander was built up by a new part welded to it and, projecting above the hearth level about 18 in. Except around the edges, there was no sign of a crack, the weld being complete and the whole salamander being one homogeneous mass.

Fig. 90 shows the construction of the furnace, which was an old-style brick furnace standing on six huge brick piers. The spaces between these were originally spanned by arches but the upper portion had been rebuilt and heavy I-beams had replaced the arches for carrying the brick shell of the furnace. The location of the original salamander and of the portion welded to it during the last blast is indicated on the drawing. The mass was absolutely solid iron, surrounded by brick, slag, and some detached pieces of iron which constituted difficult but not impossible digging.

After the furnace was blown out and the lower portion of the bosh and the hearth jacket and wall torn away, the furnace bottom was cleaned off and digging was started to expose the salamander proper. This was extremely difficult digging, the firebrick being metamorphosed into a material not unlike granite, while conditions were made much worse, by detached pieces of solid iron up to a couple of tons in weight around the outside of the salamander like partly detached bits of onion peel around an onion.

A steam-driven rock drill was put to work to permit blasting out the material around the salamander and exposing it completely. This blasting removed all that remained of the solid body of brick constituting the furnace bottom shown cross-hatched in Fig. 90, by which the salamander was surrounded. Much care had to be used in this blasting because of the danger of injuring the piers or some of the permanent portions of the structure by flying pieces. The rock drill was also put to work in the apparent crack between the upper and lower portions of the salamander, but soon disclosed the fact that this was not a true crack, and its progress in the solid iron being very slow, the attempt to drill a hole there was abandoned.

No compressed-air supply was available at this plant. There was a small electric plant generating direct current at 250 volts, but the electric drill had not been developed at that time as it since has, so the only form of power available for driving drills was steam.

When the salamander was finally exposed, it was evident that we should have a tremendous job of drilling on our hands and two steam-driven rotary drills were ordered by wire; one arrived promptly but took the whole mechanical force to keep it in operation even part of the time, while the other one, which subsequently proved to be an excellent machine, did not arrive until the job was done. We had, therefore, to settle down to hand drilling. A 12 by 12 beam was run across the furnace between two piers at a convenient height above the salamander, and heavily braced in place. This formed the top support for the drills. The drill bits used were old-fashioned flat bits of high-speed steel, these are better for such work than twist drills because it is virtually impossible to keep the deep holes required perfectly straight, and a twist drill would bind

under these conditions, while the smaller shank of the flat drill enabled it to follow anywhere that the bit led. We had powerful ratchet drills suitable for this heavy work. These were pulled by gangs of three or four men. The drilling proved to be extremely hard, the iron was so low in carbon as to be more like steel than cast iron. The carbon, as I remember it, was about 1.5 per cent. The silicon and phosphorus were also low. A piece of the material was tried in the blacksmith shop and could almost be forged.

We put in 12 holes, 18 in. apart and intended to have them 18 in. deep, but the difficulties in drilling and our impatience were so great that we stopped when some of them were only down about 12 in.

THE USE OF DYNAMITE

The drilling being complete, the blasting was the next step in order, and here precautions of various kinds were needed, first and foremost against the eagerness of the blasters themselves, their saying being "put in what you think is plenty of powder, then add three or four sticks for luck," a procedure likely to defeat its own end in this case.

Another point of vast importance is the grade of dynamite used. As a general proposition it is safe to say that where relatively little breaking power and great throwing power are desired, the lower grades, 30 and 40 per cent., should be used, but where little throwing power and the greatest rending power are desired, the higher grades should be used. The whole business is a matter of time, and the higher grades have a shorter time of combustion than the lower ones. Sixty per cent. was the highest grade we had on hand and this was used throughout.

In work of this kind where the hole is expensive, the cost of dynamite becomes of relatively little importance, and the first requisite is not to run any risk of destroying the hole. This is easily done by putting too much dynamite in the hole at first, filling it up nearly to the top and leaving only a small depth of tamping. The upper portion of the dynamite being relatively little resisted by the top of the hole tends to burst that, and the lower portion of the charge augments the action, so that either the top of the hole may be shivered, or a flat cone of material may be blown bodily out from near the bottom of the hole, destroying it altogether. If, on the other hand, small charges be employed with a large quantity of tamping, the element of time comes in, the dynamite works on the metal at the bottom of the hole before the tamping has time to yield, but the charge being so deep in the piece, no bursting takes place. The metal around the bottom of the hole, however, is compressed and driven outwardly in all directions, not very much at the first shot, but increasingly as the shots are repeated.

This action has two effects: First, compressing the metal and forcing

it outward from the hole, causing it to give way circumferentially, so that the hole not only becomes much larger but deep radial fissures form in the metal that is left, perhaps an inch or two in depth. A line of these have a decidedly weakening effect on the piece which contains them, several times more than that of the holes alone. Second, the enlargement of the hole enables a much larger quantity of dynamite to be put in, and still retain the quantity of tamping with which the earlier holes were fired.

Strict orders were given therefore that only half of a stick of dynamite should be used in the bottom of each hole and that no attention should be paid to immediate results, the object being to crack the salamander as a whole by a number of deep-seated shots and not to spoil the expensive holes by blowing off their tops. Efforts were made to fire the holes simultaneously by using electrical primers and firing them with the regulation hand-operated blaster's battery, but the lead wires became grounded through lying on the salamander and several of the holes failed. This brought about very dangerous conditions and caused loss of time, so we hitched the lead wires to an electric-light socket and could thereby throw such a powerful current through the wires that misfires were entirely eliminated.

Orders were given to swab out the holes with water for the sake of safety and then to load and fire them as fast as possible without regard to the immediate effect produced.

After a few shots, a pocket could be felt in the bottom of the holes and permission was then given to increase the charge as this pocket increased, keeping the same amount of tamping as at first. In a short time cracks could be detected running from hole to hole, and much sooner than we expected the salamander was split in two as neatly as one would split a chestnut log. The halves, of course, each weighed 60 or 70 tons, and could not be handled by any apparatus that we had available. They were therefore drilled with a line of crosswise holes and quartered. These quarters were again broken until the largest piece was estimated to weigh about 15 tons.

We had a set of triplex blocks which were hung to the I-beams over one of the arches; a temporary track was run into the arch; the pieces were chained one by one, and lifted with the blocks; a flat car was run under them and they were lowered on to it and taken to the bone yard.

One unsuccessful experiment was not without its valuable lesson. We had on hand carbons, 1½ in. in diameter by 4 ft. long, to permit burning out bunged-up tapping holes and the like. We thought it might be possible to burn holes in the side of the salamander with this and such an attempt was made. Only direct current of 250 volts being available, a water rheostat was rigged to give some control of the voltage, the carbon was connected to one wire of the circuit, and the other grounded on the salamander. An arc could be formed by touching the carbon to

the salamander and drawing it away but unless this were done very quickly, the flow of current was so great as to throw the circuit-breaker in the power house, the plant being only about 60 hp.

We succeeded in burning a hole 6 or 8 in. into the side of the salamander, but the carbon could not be kept at the proper distance from the iron all the time and when it approached too closely, the overload on the generator produced conditions in the power house that were dreadful

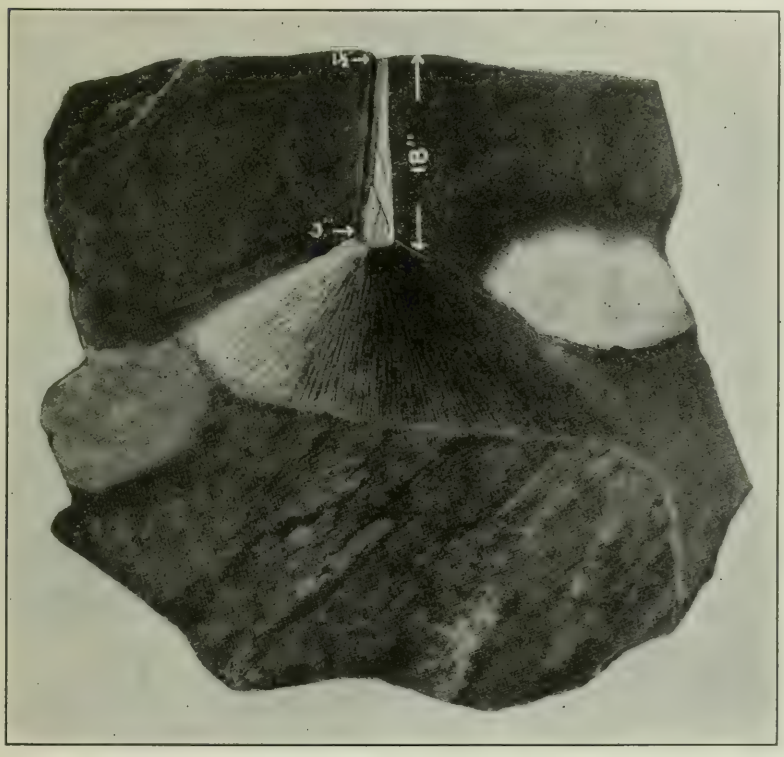


FIG. 91.—Effect of dynamite.

to witness; the circuit-breaker flew out at intervals of a few seconds and the distress of the plant was obvious. This attempt was therefore abandoned.

If we had had available current of 30 or 40 volts and in almost unlimited quantity, holes could have been burned into the side of the salamander by this means, but the side of the salamander is the wrong place for the holes, which must go across the top if it is to be broken the weakest way first, as it should. Moreover, drill holes are vastly to be preferred because they can be placed wherever they are wanted and because they

are of the size desired from top to bottom, a condition which it is not possible to bring about with the electric arc.

The effect of the dynamite at the bottom of the holes was remarkable. It seemed to expand the holes laterally and drive the metal down vertically, so as to produce a perfectly definite cone of separation at the bottom of the hole along which the metal broke in several cases. A sketch of a characteristic piece reproduced at Fig. 91 shows this effect. It also shows the swelling of the drill hole at the bottom and the radial cracks in its walls.

The time required for the job was, of course, much greater than it would be with modern facilities, especially power drills. Ten days were

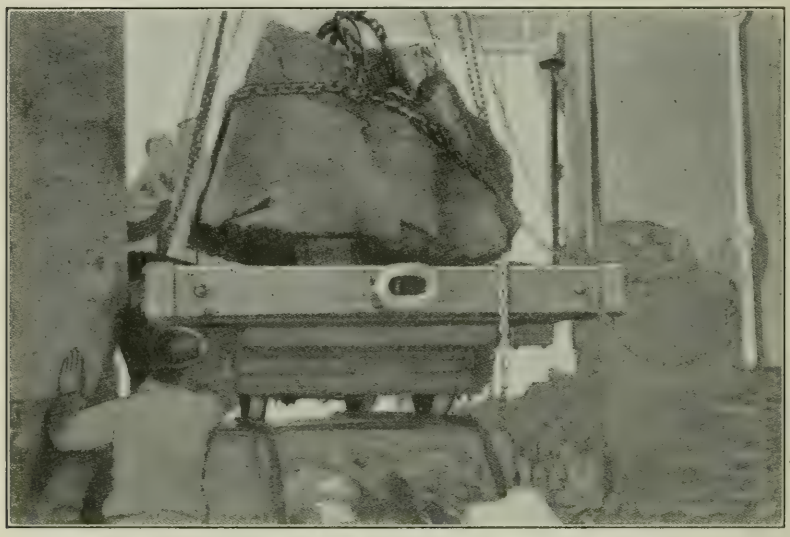


FIG. 91*A*.—A piece of the salamander ready for removal.

consumed from the time the drilling was begun until the last of the salamander was out, and the bottom ready for the bricklayers to go to work. With a good equipment of powerful rotary drills and a crane capable of lifting 30-ton pieces, the time could have been shortened by a half. These modern appliances makes such a job so much easier that it becomes more or less of a routine matter and perhaps not worthy of detailed description. Nevertheless, I believe that our method of the blasting to be the correct one, while a record of how such things can be done without modern equipment may be useful.

Since the time this was written several cases have come to my notice of accidents due to the failure to explode one or more of the holes charged with dynamite. In one case this took place and afterwards a hole fired, presumably by the heat of the salamander, just as the furnace superintendent crawled in through the tapping hole to see what the effect of the

shot had been. By great good fortune he escaped without permanent injury, though both his eyes and hearing were in danger for a long time, and a change of only a minute or two in the time of the accident might have resulted in his being blown to atoms. It is therefore worth a great deal of pains to see that holes do not fail to fire. The wires running to the exploders should be swung up out of contact with the salamander to prevent grounding, and instead of the common battery used for blasting a powerful electric light current should be thrown into the circuit to secure a sufficient volume of current to fire all the holes irrespective of the conditions. Of course vast masses of metal like this hold their heat a long time and the greatest precautions are necessary to prevent the dynamite being discharged from the heat soaking into it from the salamander. The holes as fast as drilled should have water put in them and it is better if this can be kept running constantly so as to cool the metal around the hole for a considerable distance. The heating effect of the blast is great and after each shot pains must be taken to see that this heat is removed before the hole is recharged.

The correctness of the general principle described above has been established by experience subsequent to that operation, using comparatively small charges at the bottom of holes of only moderate depth, by far the great portion of the hole being filled with tamping, and firing all the holes at once. The great tendency of professional blasters is, as intimated above, to overload the holes. This is the worst possible practice in blasting salamanders, for the reason that the expensive and time-consuming portion of the job is the drilling of the holes, and if these be loaded anywhere near full the top of the hole is blown out into a crater and the hole is destroyed. · Moreover, the pieces of iron thrown out of the crater do many times more damage than all the other blasting put together, since they act as projectiles with an enormous charge behind them, whereas the splitting of the salamander itself produces no shock except that of the blast on the air.

CHAPTER XV

BLAST-FURNACE IRREGULARITIES AND THEIR TREATMENT

REGULARITY THE FIRST REQUIREMENT OF SUCCESSFUL OPERATION

The keynote of successful operation of the blast furnace is regularity. I have tried in preceding chapters to make a picture of the delicate equilibrium which must be maintained between enormous forces, and I have tried to show that variations of only 1 or 2 per cent. were enough to affect seriously the results of the operation, while a change of 5 or 6 per cent. might be fatal.

The regularity required is of many kinds. First, uniformity of the stock charged; second, uniformity of its distribution into the furnace; third, uniformity of the blast in temperature and humidity; fourth, uniformity in the distribution of the blast in the furnace; fifth, uniformity in the quantity of blast blown per unit of time; sixth, uniformity in the kind of iron to be produced. It may take days or even weeks to establish the absolute equilibrium which gives best results in cost, quality of product and output, and this cannot be secured at all except by regularity in all these factors. A temporary variation in only one of them may bring about conditions which will necessitate days of careful watching and adjusting in order to restore the furnace to the desired condition.

Undoubtedly the most important kind of regularity is that which leads to regular and uniform driving of the furnace, that is, to steady and continuous working. Many furnacemen have in times gone by, followed the practice of tuning everything up for weeks and then making a sudden spurt in which gigantic outputs were secured, generally assisted by melting up a scrap accumulation of weeks, trusting that this spectacular performance would divert attention from the mediocre work which preceded, and the rotten conditions which followed the conclusion of such a spurt. But it is now well recognized not only by furnacemen but by managers that it is the long steady pull which counts rather than the spurt, and spurting for a record has very seriously declined in favor, to the great benefit of the industry.

THE FURNACE PLANT CANNOT RUN EXCEPT WHEN ALL ITS PARTS RUN

The furnace plant is different from all other large plants in one particular. It has no reserves, no storage capacity, so to speak, at any point on the line so as to permit one part to run and store up a supply of its

particular function that lasts while the function itself is suspended for repairs or the like. For instance, in the steel plant, not counting the mixer, since that may be classed with the bins of the furnace system, there is a storage interval of at least a few minutes before tapping, then after tapping, the steel is poured into ingot molds and these are many hours in making the round trip, though the actual time of pouring and stripping is but a small fraction of this. This means that there is a considerable margin of capacity in the ingot molds. Then there is storage again after the ingots are removed from the molds and put into the soaking pit, and so on, there being some storage capacity, be it great or small, in almost every part of the process, but in the blast furnace this condition does not exist. It is necessary that *all* the parts of the furnace operation be coördinated with one another in the closest possible way.

If the blowing engine stops the furnace stops instantly, and more than that, if the blowing engine stops without the furnace being flushed or cast, the cinder is likely to fill the tuyeres which causes an enormous amount of labor for its removal and a delay of many hours. If the filling apparatus becomes deranged and the furnace can no longer be filled, it may be run for a short time, but if for more than an hour or two, even though filling be resumed at the end of that time, the stock filled immediately after the interruption is deprived of a considerable proportion of the time and exposure to the gas which it should receive, and reaches the hearth in a raw condition, deranging the work of the furnace. Consequently, if the filling arrangements become deranged to any considerable extent the furnace must be cast and the blast taken off. If the stop is to be a long one the tuyeres must be plugged up for reasons already pointed out. If, on the other hand, the arrangenents for disposing the iron or the slag, particularly the former, become deranged, about the worst condition of all arises, especially if the derangement is so great that the iron already in the furnace cannot be tapped out.

If it can be foreseen that the iron cannot be taken care of as made, the furnace may be cast and shut down as before, but in none of these conditions is there any considerable margin of time, and it is true of the blast furnace as it is of no other industrial apparatus within my knowledge, that all the parts must function simultaneously, and stoppage of one stops all.

THE NATURE OF THE IRREGULARITIES

The variety of mishaps which can cause shutdowns of various kinds is almost infinite. They may be divided into two broad classes: First, those in which the derangement affects the furnace itself; second, those in which it affects some of its secondary functions. That is to say, the furnace may be running beautifully, but a breakdown of the filling system shuts it down, or as was the most frequent cause of all within a few years,

a breakdown of the blowing power stops it. These and all similar failures, external to the furnace itself, are more or less mechanical, while plenty of them are serious enough, require enormous labor for their repair, and cause great loss not only in the actual cost of the repairs themselves, but in the loss of time on the whole plant, they do not affect the furnace itself except as the result of a long stoppage, as has been described under that heading.

On account of the variety that is possible in such failures and the fact that the making of repairs in such cases does not differ from that of making similar mechanical repairs in other industries, I shall not attempt to describe them here.

DERANGEMENT OF THE FURNACE PROPER

With the other class of accidents or derangements, those which affect the functioning of the furnace itself, the conditions are very different. They are unlike anything else in industry, and the knowledge of how to handle them and restore the plant to operation would not be given by the most intimate acquaintance with all the other industries in the world. There are several degrees and varieties of these derangements, both as to cause and as to effect produced. The most frequent causes are: (1) heavy slipping; (2) internal explosions; (3) the breaking loose of a scaffold and the descent of the material which formed it into the hearth; (4) the cutting or bursting of a water-cooling member, such as a tuyere, cooler or cooling-plate; (5) breakouts; (6) a mistake in filling, such as charging ore without sufficient fuel to take care of it.

The results of these various causes are, of course, very different when they are not serious, but strange as it may appear, when the results are serious they are practically always the same in a general way, though they vary infinitely in details. They are the chilling or partial chilling of the hearth of the furnace, so that the material can no longer be easily withdrawn in the molten condition; this causes the rest of the various conditions which follow. The reason for this is that a serious derangement from any of these causes brings about either the descent into the hearth of a large amount of insufficiently prepared material, or else a long stoppage of the furnace, which, occurring suddenly and without warning, means that no extra coke can be put into the hearth to meet it so that progressive freezing up occurs, its severity being proportional to the delay.

Slips.—In the chapter on mechanical principles the actions which lead to slipping have been quoted from my paper, "Notes on the Physical Action of the Blast Furnace," and while the mechanism therein described may be subject to infinite variations of detail, in that various circumstances affect and cause such sticking, the universal first remedy is the slacking of the blast so that reduced pressure below may cause the

weight of the suspended material to bring it down. Slipping when almost continuous and not violent is spoken of as "sliding," and when even less violent, but still causing the excessive discharge of flue dust, as "dusting." I give below a further quotation from the same paper which covers those more violent accidents really deserving the name of explosions, which both in this country and others have, in some instances—fortunately only a few—resulted in bursting the furnace shell, or sometimes the bosh structure, with the violent ejection of the contents of the furnace.

Explosions.—"There come, however, occasionally, occurrences of the general type of slips, but of so much greater violence and destructive effect than mere 'slips' that they seem to require a further explanation.

"This seems to be furnished by the fact that the conditions I have described may occur at any point in the furnace, and that the deeper they are the greater is the air pressure, and also the weight of the ammunition in the air gun thus formed; hence the greater the execution.

"But if this occurrence take place so low in the furnace that the cavity formed reaches finally down to the tuyeres, a further condition arises, in which the cavity is filled not with gas but with air; and when the break in the obstruction comes, the incandescent carbon dust always present in the lower part of the furnace from the splitting up of the CO is precipitated (along with the other materials) into an atmosphere of compressed and heated air, giving precisely the conditions requisite to the production of an explosion of great violence, in which case the air gun becomes a powder gun, and is not infrequently burst by the charge. This accounts completely for the observed phenomena of these more violent occurrences.

"As already explained, the 'kicking' due to slips is more violent and prolonged in proportion as the obstruction is deeper in the furnace. But there is still another reason for the shades of increasing violence, which make it most impossible to tell where slips end and explosions begin; that is the varying quantity of unburnt air in the cavity above the tuyeres and the degree of its mixture with other gases. This is due to the gradual decrease in the depth of the layer of coke above the tuyeres. When this is no longer sufficient to burn all the oxygen to CO, CO_2 begins to appear, and when there is not enough to burn it all to this, free oxygen begins to appear, and its percentage thereafter steadily increases. It is evident that the precise point in this series of changes at which the slip takes place will influence profoundly the character of an explosion, and even the possibility of its occurrence."

One case is on record in Germany in which nothing but a stump of the furnace was left after the explosion. Another occurred in the Shenango Valley, soon after the introduction of Mesabi ores, in which the furnace shell was completely wrecked. More recently at a furnace in the Pittsburgh district the bosh was torn wide open without a second's warning. The great steel bands around it, 10 in. by 1¼ in. and only about 1 ft. apart, were ripped in two as if they had been threads cut with a razor

and almost the entire contents of the furnace were discharged through the great opening made, almost half the bosh wall being blown away.

These terrible accidents, accompanied as they so often are by serious loss of life, each occur under different conditions. Fortunately, they are too few in number to be classified broadly and accurately, but in general no two agree very closely. Many explanations have been given for each and every one, and a greater number of theoretical causes have been assigned for the production of the explosion which brings about such terrible results, but after careful consideration of them all I have been unable to find any cause as inherently probable, or with as few practical or theoretical objections as that advanced in the quotation just given.

Certainly if the fuel bed above the tuyeres burns down much below the top of the bosh while the balance of the stock stays suspended above it, we shall have a great cavity filled with an atmosphere containing free oxygen at a temperature well above 2500° and under a pressure perhaps of 20 to 30 lb. If now we precipitate into this a great mass containing a large proportion of incandescent carbon in the condition of impalpable powder, what can we possibly have except a dust explosion under the conditions far more favorable to violence than those which have enabled such explosions to wreck coal mines, flour mills and other industrial operations, almost without number?

Many other reactions have been proposed as the cause of these explosions, but not a single one that I have ever heard advanced will stand the test of representing the conditions truly and being at the same time chemically correct.

Scaffolds.—These can scarcely be treated separately from slips, since scaffolds are one of the most active causes promoting slips. Projecting out from the wall of the furnace they offer support to the charge column and in conjunction with the pressure of the blast from below they support its weight so completely that it ceases to descend until the blast is checked or some keystone of the crude arch formed dissolves away and the mass descends, causing a slip.

Scaffolds are of many and various kinds; it is probable that a large volume could be written concerning this subject alone had anyone the patience to collect all the data available. In general, however, scaffolds confine themselves to the region from the top of the pasty zone downward. Some furnaces which work "tight" are said to have dust scaffolds, but I have always preferred to believe that this was a condition of tightness at a certain zone due to the continuous redeposition in that zone of carbon dissolved at a lower level, according to an action earlier described rather than a fixed scaffold on the walls, though there is no doubt that scaffolds may occur above the pasty zone.

Leaving these we have only to deal with scaffolds formed of molten or semi-molten material. They may be a foot or two thick radially or

they may form a complete floor across the furnace. Of the latter I have heard several times, but fortunately I have never seen it myself. The blast furnace is understood so much better now that those occurrences are becoming very rare if they have not gone forever. But scaffolds from a foot to several feet in thickness measured on a radius are still not uncommon; in plan they may extend from a bare lump on the side of the furnace to a complete ring all around it, almost as regular as if it had been built to a design.

In regard to the latter I can speak with certainty for I have had the unusual experience of seeing in a "live" furnace such a scaffold, just after it had caused its victim to undergo one of the explosions which I have just described, and to throw out its entire contents to a point well below the scaffold. It was an experience that I shall never forget. I was at the time on the upper platform of a steeple-type blowing engine, which was running along quietly enough when suddenly something happened which I have never been able to compare to anything except the blow which an unsuspecting man might receive from a blackjack; he would be knocked to his knees for a moment and then get up and run away. The blowing engine seemed to receive just such a shock, and after a few seconds went on much more easily than before the shock had occurred.

A prolonged roar and a lively fusilade on the engine-house roof announced that something out of the common had happened. On going out to investigate I found that a real explosion had taken place and the furnace top was evidently completely deranged. The furnace was cast and stopped as soon as possible, and when we were able to reach the top we found the bell resting securely in the hopper *on top* of the lip ring instead of beneath it.

Investigation showed that it had been driven upwards with such force as to break the lip ring in two and force it up in the hopper until the bell could pass through it, then the lip ring dropped back to its seat with the bell on top of it. The enormous bell beam built up of heavy plates and angles was bent at a sharp angle, though the forces required to do this must have reached hundreds of tons. Other things were about in a similar condition.

After the top was cleaned off and cooled down enough to work, two of us finally ventured to lean over far enough to look down inside; as several hours had passed all was then quiet and we could see a dull red "ring" scaffold running all around the furnace at a height that seemed up somewhere above the top of the bosh, it seemed to extend out some 3 ft. all around. As the furnace was 21 ft. in diameter this would have left a 15-ft. hole through the center. It may even be that the scaffold was greater and the hole smaller than this.

I take this case to be almost ideal proof of the accuracy of the theory of explosions described in the last section. The whole charge column

taking advantage of some accidental variation, high pressure or the like, evidently came to rest on the top of the scaffold, and being at the top of the pasty zone it held there while the lower portion settled as the coke burned away. In a comparatively short time, 2 or 3 hr. at the most, the surface of the lower portion descended well below the top of the bosh and the height of the fuel bed was no longer sufficient to prevent the presence of some free oxygen in the space above it. Finally, something happened to precipitate the suspended mass above through the central hole in the scaffold and the explosion, which I have so inadequately described, instantly followed.

It is easy to see that a ring scaffold of this kind is the most dangerous that we can have, in spite of its symmetry, because it furnishes such ideal support for the charge column and tends to stop the descent of the latter so completely. A scaffold on one side only tends to check the material on that side and to force the fines over to the far side of the furnace, the lumps running back under it. This produces a very uneven descent of the charge into the hearth and a highly improper distribution of the gas current through the descending charge, but this, though bad enough, is obviously not so serious as the complete suspension of the charge with results like those above described.

The Removal of Scaffolds.—This is a subject concerning which we know far less than we should. Many furnaces which once become scaffolded never work satisfactorily again during that blast, while again others may get rid of the trouble completely and do as good work after as before. In general, there are three methods to be pursued. First, to restore conditions as nearly to normal as possible, running with a comparatively light burden and hoping to melt or wear the scaffold away whatever its position. Second, by careful watching of the working of the different tuyeres to try and locate the position of the scaffold and then try so to direct the filling as to overcome as far as possible its bad effects, or by directing the action of the furnace violently against it to wear it away. Third, by deliberately sacrificing the work of the furnace for a day or two, putting in a light burden with a considerable excess of whatever material will produce the most fusible slag, generally silica with a coke furnace (although silica and fluorspar would be better), lime and fluorspar for a charcoal furnace, and by extra heat and dissolving action scour it bodily off.

For this purpose I have known the ore burden of a coke furnace to be almost entirely replaced by a great quantity of sand. Coke-furnace accretions always contain a considerable quantity of lime, as already pointed out, so when this great quantity of unfluxed silica reaches these accretions in the presence of a great excess of fuel to produce all the heat necessary, it at once tries to satisfy itself with bases by dissolving away the accretion. I have never tried this drastic remedy myself.

On the other hand, charcoal furnaces, especially when they are run on very lean slags, build up on the walls with that fusible but tough and stringy material. This is decidedly more silicious than the most fusible slag, and by lightening the burden and adding an excess of lime for a day or two they may generally be scoured off completely. This I have done more than once.

The Descent of Unreduced Material into the Hearth.—Obviously every time the furnace hangs and then slips we have a condition which deprives a part of the material of some of the time which it should have had for preparation in its descent through the furnace. In the upper part of the shaft where we have the greatest surplus of heat and in general a surplus of reducing power, such a slip is not of much consequence unless it represents hanging for the space of an hour or more.

But as we go further down into the furnace the margins of heat and of reducing power are lower and lower, and the time in which to make up for treatment lost is smaller and smaller, so slips become not only more violent because of the higher pressure from which the furnace is relieved, but more serious, and their effect on the action in the hearth may be disastrous, especially if the shaking up which occurs at that time permits the ore to run ahead of the coke and come down into the hearth ahead of the coke which should accompany it.

Obviously in this case we have material very inadequately prepared in the first place, and yet have no coke appropriated, so to say, to the purpose of finishing the smelting action of the furnace upon it, let alone supplying any deficiencies in reduction. The same is true in the case of the breaking off of a scaffold and the descent of its material into the hearth, the effect can only be in either case to cause a serious deficiency of heat in the hearth with all that implies.

THE CHILLING OF THE FURNACE

In all cases of chilling of the furnace we have an action which is serious in proportion to the amount of incompletely prepared material involved.

If this be small it may be taken up by that latent reserve of heat which the furnace seems to possess, without producing a very serious result. But a very moderate amount of material so precipitated into the hearth brings about a complete derangement, first, the incomplete reduction of the iron which passes into the cinder, turning it as black as tar; second, the cooling of the hearth with its resulting insufficient desulphurization and the consequent ruin of whatever iron may be produced; third, insufficient heating of the slag and iron to permit their discharge from the furnace through the normal apertures in the proper way. Finally, the chilling of a heavy skull of iron, frequently low in carbon, around the whole interior of the hearth and the lower part of the bosh, making the task of drill-

ing in to discharge either iron or cinder very difficult. This is quickly followed by the freezing of the iron in the lower part of the hearth so completely that it will not run no matter how far we may drill into the tapping hole, which is then "lost." This in turn is followed by the freezing up of the iron and cinder around the tuyeres until perhaps only one or two are left sufficiently open for a little blast to pass through. Meantime it having been impossible to withdraw anything from the furnace, and some blast going in continually, combustion continues and more slag continues to be formed, and in the greater quantity because a great percentage of all the iron also passes into it.

We have now a furnace containing many tons of molten material to a height perhaps several feet above the tuyeres, the bottom of the hearth solid with frozen iron in its toughest conditions, and a skull of iron or steel all around the upper part of the hearth and the lower part of the bosh, which prevents our making any opening at the cinder notch for the withdrawal of the cinder which has accumulated. We know that we cannot go on indefinitely, that, for instance, the liquid pressure of the thin, violently active, scouring cinder inside the furnace increases the liability of its breaking out at some point, and the certainty that when it does so the running stream will cut almost anything that comes into its path, will run all over the ground and make access to the aperture almost impossible, that if the engine fails this huge mass of slag will seek its own level in the penstocks and bustle pipe, chilling there and that if on top of present misery a slip occurs it will force the slag into the blow pipes and penstocks, even against the blast pressure.

When this condition is reached the furnace is technically said to be "in a mess." Any furnaceman who has ever passed through the experience will admit that the term is literally as well as technically correct. If he be consulted at the time he will probably express an unfavorable opinion of a man with so little judgment as to enter a business capable of producing such horrible conditions.

These are also the conditions in a general way which result from other causes, a long stop without warning, a mistake in the filling such as charging too little coke, a bad breakout followed by water running from the ditch through the hole made by the breakout into the hearth and standing there for hours because the breakout had effectually dammed the ditch, which happened once in my experience, and various others.

The question is, What course must be pursued to restore those normal conditions which bring profit to the owner and comparative peace of mind to the operator and the crew?

A little consideration shows that no matter what the ultimate cause may have been, the immediate cause of the difficulty is the absence of sufficient heat to bring the materials in the hearth to the temperature at which they will run out, and if my description of the terrors of such a con-

dition were adequate (which it is not), it would perhaps explain my tiresome insistence in earlier chapters on the free-running point as the critical temperature of the furnace and on the vital necessity of enough heat in the hearth to bring about this temperature.

The remedy is then to introduce more heat into the hearth. But our chief method of doing this is to introduce more fuel and we can in general introduce this only at the top of the furnace, and in order to permit its descent into the hearth all the charge in the furnace at the beginning of the trouble must be worked out. This requires from 8 to 20 hr., depending on the rate of driving, even in normal operation, when all the molten material can be removed as formed, in a truly liquid condition; but when the furnace is in a "mess" the possibility of such regular removal has vanished, in fact, we might define a mess as any condition which made the free and regular removal of the molten material impossible.

We must then find means to carry on such removal as best we may until the blank of coke charged to give relief can reach the tuyeres, and this period is prolonged just about in proportion to the difficulty of slag and iron removal. For this reason the wise furnaceman when he sees signs of impending trouble, charges a good blank of coke knowing that even if it does not reach the hearth in time to avert serious trouble it will shorten by so much the weary interval of difficult and irregular flushing and casting.

If the mess arises through a breakout or mechanical breakdown, which causes a long and utterly unexpected stop, he charges the blank the first thing on starting up, and if the difficulty threatens to be a serious one he lightens the burden to a material extent so as to have a reserve of heat to overcome the irregular conditions which will probably persist long after the blank is gone and the furnace once more in operation.

STEPS TO BE TAKEN IN THE EARLY STAGES OF CHILLING

The important question is, What methods are to be used to remove the slag and iron after the regular methods fail?

As the furnace loses its normal supply of hearth heat, the portion farthest from the tuyeres naturally feels the loss first and therefore the iron in the bottom of the hearth, where the regular tapping hole is, freezes so that no iron can be drawn from it; sometimes the drill simply encounters a mass of red-hot tough pasty iron which it cannot penetrate, more rarely it goes half across the furnace underneath the iron in a mass of brick, slag and heterogeneous material which can be drilled but which will neither run nor allow the iron to run.

In such a case the molten iron lies higher up and ordinarily other holes are drilled at successively higher levels until liquid iron is reached or it is found impossible to reach it.

In some rare cases a "dry" hole under the bottom of the skull in the hearth may be shot with dynamite and the scull broken through up into live iron above, which will then flow out. It must be remembered that the hole is between red and white hot and the radiation from it is sufficient to set off the dynamite in a few seconds so this operation is not to be regarded as a safe and harmless pastime. On the only occasion when I used this expedient the hole was drilled well back to the center of the furnace, so there was no danger of damage to the hearth jacket as there would be with a shallow hole; the dynamite was wrapped in rags soaked in thick grout and laid on a little wooden trough or boat so as to keep it from contact with the bottom of the hole; the fuse was cut to burn only a few seconds, it was lit after the charge was placed in the trough and the latter was quickly pushed down to the end of the hole with a long rod, and all hands then retired to a short distance without unnecessary delay, and waited until the explosion came. This was followed by a small river of iron and our troubles were over for that time.

Generally, however, no hole can be drilled at all at the bottom and it becomes necessary to go higher and higher to reach the iron. When the top of the iron notch opening through the hearth jacket is reached and still the skull around the hearth cannot be penetrated the tapping hole is "lost" and it is then necessary to go to the cinder notch.

CASTING THROUGH THE CINDER NOTCH

The construction of the latter is excellently designed for the purpose for which it is normally used, the quick, easy, and safe removal of the cinder. But while water-cooled bronze will withstand molten cinder of almost any temperature, it will not withstand molten iron at all, or, at least, it is likely to fail in a few seconds under a flow of iron, especially the raw, scouring and extremely corrosive material which is produced at such times.

The failure of the water-cooled bronze parts is certain to result in a violent explosion, and therefore before casting through the cinder notch the bronze cinder cooler must be removed. The monkey will probably have been "pulled" already on account of stiff, sluggish slag. If there be an outside iron cinder cooler it must take its chances because it cannot be "pulled." The danger of having this cut is much smaller, and bad explosions are not so likely to follow if it is, whatever risk there may be is further reduced by making up a bed of sand or clay in the bottom of it. An emergency runner of sand is built from the cinder notch back into the iron trough if possible or else to the iron ladles or the pig beds.

One disagreeable consequence of casting through the cinder notch is that the iron cinder cooler, if there be one, or if not the brick surrounding the hole, are cut and roughened by the scouring mixture of iron and cinder,

which is always to be expected under such conditions, and lumps of iron or cinder are left burnt onto the brick or the iron cooler as the case may be. The temporary bottom of sand brick or clay used to pave the bottom of the opening helps to prevent this, but this covering is likely to be knocked off, particularly on the side. These lumps are very difficult to remove when they do become burnt on and unless they are removed the bronze cooler cannot be put back to its proper place. They are, therefore, very objectionable.

In order to protect the hole completely, I have used very successfully the expedient of inserting a piece of common wrought-steel pipe about the size of the inside of the bronze cooler and packing around the outside of it with clay. The pipe may burn up during the first cast through it, but usually lasts several. When burnt up it can readily be replaced, and when normal conditions are restored it can be pulled out and the clay packing around it removed without difficulty, leaving the brickwork or the iron cooler, as the case may be, in perfect condition. This is a small matter, but it may save hours of work and injurious delay in getting back to normal operations.

When all the necessary arrangements have been made the next thing is to drill through the cinder notch if possible. When this can be done the furnace can be kept in fairly steady operation and the life-saving blank worked down to the tuyeres without undue delay, and the trouble is then likely to be pretty well over.

OPENING A CHILLED HEARTH

But if the scull is too hard to drill and too tough to drive—then the real trouble begins. To force an opening we have now available four means, dynamite, the kerosene blow pipe, the electric arc and the oxygen burner.

Dynamite.—If the hole has been drilled back well into the skull so that the latter shows red hot, then the hole can sometimes be shot open with dynamite. The charge should be made up in a cartridge made of a piece of pipe 2 or 3 in. in diameter and mounted on the end of a long piece of small pipe for a handle so that it can be set off instantly when the cartridge has been placed in the hole. This latter is not a particularly pleasant job because the dynamite may be exploded prematurely by the heat of the hole. There is, of course, no time for tamping and much of the force of the shot is lost, but by following up with larger cartridges as the hole swells the scull can sometimes be torn open.

I once saved by this means a furnace which had lost not only the tapping hole and the cinder notch, but also all the tuyeres but two. We shot open a "dead" tuyere, into which we had drilled as far as we could in trying to flush through that, its level was too high to give good drainage

from the other tuyeres, but opening it removed a huge mass of molten and pasty material which had been held up in the bosh by the blast pressure. This gave us time to take further steps and really saved the day.

The closing of this hole was no joke; the drainage afforded was incomplete because only on a level with the tuyeres, so if the blast were taken clear off the cinder came back into our only two remaining tuyeres. Of course, with even very little blast on the big hole left by the destruction of the tuyere, discharged flame and cinder shot about like a small Bessemer converter. We finally checked the blast with the snort valve to the point where the cinder was barely kept out of the tuyeres and reduced the discharge of flame and shot cinder to the point where one of our keepers volunteered to stop the hole, which he did with clay balls and a stopping hook. The job took only 2 or 3 min., but his overalls were practically burnt off him by cinder shot when he finished; it was one of the pluckiest acts I ever saw. Such details will perhaps help to give some idea of the conditions likely to arise during a mess.

The conditions under which dynamite can be used successfully are rare and its use is always highly undesirable because of dangers to which its use exposes the plant as well as the crew, and in consequence it is not often used.

The Kerosene Burner.—Probably the first means developed for meeting these conditions was the kerosene blow pipe. Its use gives such very different results, according to its control, that it has been utterly condemned by some good furnacemen, while it was regarded as a life saver by others, before better means took its place.

Some experience with these blow pipes and some of the principles on which their successful use depends were described in the *American Machinist* 10 or 12 years ago and a portion of the article is quoted here.

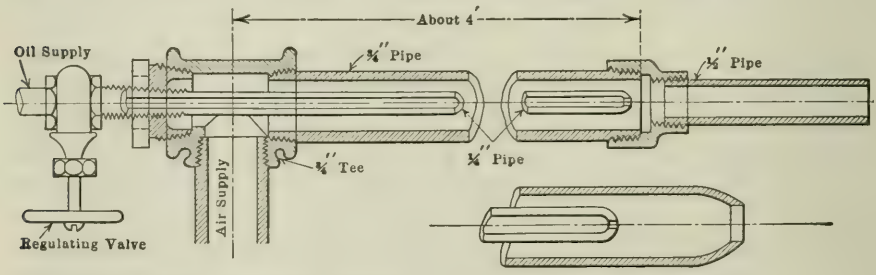


FIG. 92.—First and correct construction burner.

FIG. 93.—First improvement (?) value minus 50 per cent.

"The oil burners shown in Figs. 92, 93, 94 and 95 were made in great haste and in almost total ignorance of the details of their construction, as far as experience was concerned. A piece of ¼-in. pipe was welded shut on one end and a 1/16-in. hole drilled through this end. On the other end of this pipe a long thread was cut, which was screwed into a bushing, filling the rear end of a ¾-in. T. At

the side of the ¾-in. T the air entered through a nipple and hose. The ¾-in. pipe in the front end of the T in the first burner made was about the same length as the ¼-in. pipe inside (about 4 ft. long), and on its end was screwed a reducer, into the end of which a ½-in. nipple, about 4 in. long, was screwed (see Fig. 92).

"This burner was very successful, though used under lighter air pressures than those we subsequently obtained, but having been the first one made, it was, perhaps, natural to think that subsequent ones should be better; so desiring another, the ¾-in. pipe was drawn down by a smith to a conical end or jet much better looking than the reducer and ½-in. nipple, as shown in Fig. 93. But after

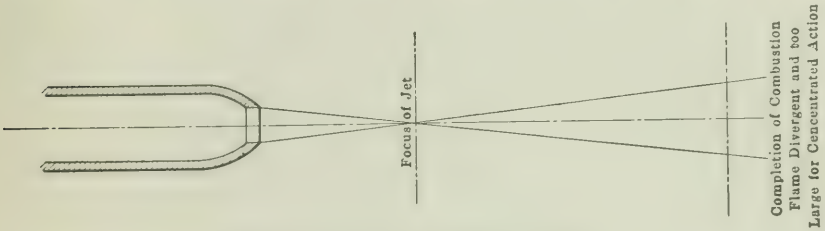


FIG. 94.—Action of convergent nozzle.

full and fair trial, it was found impossible to get the concentration of heat in one place with this that was obtained with the other, for the reason that under the heavy pressure of air the velocity of efflux was so great that combustion was not complete until a point was reached something like 1½ ft. beyond the end of the burner. With the conical nozzle the jet action had ceased, and the lines of flow of the flame had ceased to be convergent and had become divergent within less than a foot; consequently, the flame was without any accurate center, and was quite rapidly divergent at the point where combustion was complete and where the greatest heat should have been if it had been properly concentrated, all as shown by Fig. 94.

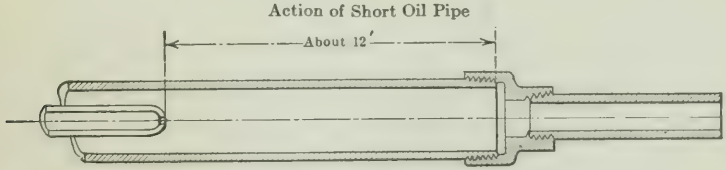


FIG. 95.—Second improvement (?) value minus 100 per cent.

"The ½-in. nozzle by permitting the flow to be approximately parallel, enabled the combustion to be complete within a small area at whatever distance from the burner might be necessary within reasonable limits, and, therefore, focused the activity of the flame much better than the convergent nozzle. This, at least, seemed to be the theory, and these certainly were the facts, as was clearly proven by cutting off the convergent nozzle and substituting for it the reducer and ½-in. nipple.

"Another improvement, shown in Fig. 95, was attempted, with the object of heating the oil further by the action of the ¾-in. pipe upon it before it reached the point of discharge. It should have been stated above that the oil was delivered by

pipe and hose connection from a barrel placed at the top of the furnace, some 70 ft. above, so that there was a very good head to drive it through the 1/16-in. hole, and a sufficient quantity emerged to make a very large flame. The quantity was regulated by a 1/4-in. globe valve on the projecting end of the 1/4-in. pipe, at whose inner end was the 1/16-in. orifice. The operator regulated the action of the blow pipe by opening or closing this valve minute amounts to suit conditions, and also fed the nozzle or drew it back so as to keep the hottest part of the flame in the point where the melting was desired to take place. The improvement which was attempted, consisted in cutting off about 1 ft. of the 1/4-in. pipe which carried the oil, so that the oil had to traverse about a foot of space through the 3/4-in. pipe before reaching the 1/2-in. nozzle, the idea being that it would in this way be preheated more than by simply passing through the 1/4-in. pipe for the same distance.

"The attempt to operate this burner was most exasperating and unsatisfactory. If the valve were regulated to bring the flame to the right condition, it would sustain itself for a brief instant, go out, and be followed by a surplus of oil which reignited against the hot surface and made a detonating mixture with the air with which it had become mixed during the instant of extinction, so that virtually the action of the burner was no more than a series of sharp explosions at intervals of about a second, with, of course, no useful heating effect.

"No regulating of the valve sufficed to cure this most objectionable condition, but finally close observation showed that coincidently with the flashes of reignition there came a few drops of oil in liquid form, not spray, from the end of the 1/2-in. nipple. It was these which supplied the excess of combustible and made the smoky flame accompanying the explosions (which, of course, were perfectly harmless in their nature).

"When this was seen the secret was out. The oil was not driven with sufficient force to throw it entirely into spray at the base of the 1/2-in. nozzle, but some of it ran down and along the bottom of the 3/4-in. pipe, whence it was picked up and carried in waves by the action so familiar to all in such cases, with the result that there was first an excess and then a deficiency of fuel for the air, the supply of which was constant.

"A longer 1/4-in. oil pipe was at once procured, which delivered the oil just at the base of the 1/2-in. nozzle, where the high velocity of the air consequent on the reduction of area caught it and threw it into a perfect spray, so that the action was complete and continuous. This perhaps may be a useful experience for those who have to do with oil burners.

"Another point of much interest in connection with these oil burners came to light during the brief experience, of which mention has been made. This was that the burner did better the deeper the hole in which it was working. The reason was not very far to seek. When the hole was quite deep, say 2 ft., and of comparatively small diameter, the flame which, had it been unobstructed, would have gone perhaps 7 or 8 ft. beyond the end of the burner, was compelled, by striking the object of its attack, to return on its course and come back over the burner itself. The result would have been that the burner would have been heated to a white heat in a very few minutes had it been a piece of "dead" pipe of the same size in the same flame, but as a matter of fact the burners never showed the least inclination to get even red hot, being cooled by the rapid current of air through them. As a result the air must have been heated to a very

considerable degree before leaving the burner. One could even imagine that it may have been 500° or 600°F., though naturally no effort was made to determine the amount at that time.

"Just what the flame temperature in such a case is I do not know. Theoretically, it would probably be 3500°, or perhaps more, but actually would not likely be above 3000°. If, now, the fusion point of the substance to be melted were 2500°, then an increase of 500° in the temperature of the air, giving an increased flame temperature of perhaps 400°, would make the latter 3400° instead of 3000°; and while this is not a very great difference absolutely or relatively, based on the total temperature, when compared with the fusion temperature (assumed to be 2500°), it is seen to be almost twice as great a difference, implying twice as much heat available for melting operations, as well as nearly twice the "thermal head" for causing the heat to flow from the flame to the object being melted. Moreover, it is almost certain that the oil inside of the ¼-in. pipe was somewhat preheated also, and, therefore, its vaporization at its exit from this pipe was much quicker and more complete.

"For these reasons when starting to burn a hole in a flat surface it is well to make an artificial "hole" to start with, by putting a short piece of 6-in. pipe against the surface at the desired point to start and claying up the crack between. When the burner is started the pipe throws the flame back over it and produces this regenerative effect."

Much larger oil burners are sometimes used, in some cases a 2-in. pipe for air and a ½-in. pipe for oil, and in some cases no nozzle is used because it melts away in the intense heat developed, the pipes simply discharging through their open ends.

The necessity of having the focus of the jet coincide with the zone of complete combustion has been shown by all my observations, and it is this fact which makes it so difficult to secure the best results with these burners, because we have four variables to regulate; the distance of the nozzle from the surface to be fused, the velocity of the jet depending on the pressure of the air at the nozzle, the quantity of air depending on the size of the pipe as well as the pressure, and the quantity of oil.

The fact that the volume of air and its velocity which should vary independently, must actually vary simultaneously, is perhaps one of the greatest difficulties. Sometimes it seems impossible for one man to obtain a satisfactory adjustment of all these variables when another will have no difficulty. On one occasion my assistant, the master mechanic, and I all failed to do any good with one of these burners, but the colored pipe fitter came along and did good work with it.

One vital fact to remember is that the best fuel for generating heat to melt iron is the iron itself, not only because of the heat it develops, but because the iron oxide slag formed as a result melts at a much lower temperature than iron. For this reason no burner ever works successfully except with an oxidizing flame. A reducing flame makes a pretty sight and a lot of light, but does no good whatever, whereas an oxidizing flame,

making a hideous roar and showing only a short blue flame, will really cut. After the point of attack is heated to the proper temperature the supply of oil should be reduced to the minimum so as to leave as much oxygen as possible free to burn the iron.

Later and far better methods of burning open chilled tapping holes, cinder notches and the like have laid the kerosene burner on the shelf for most conditions, but for isolated plants caught in a mess without the modern apparatus it is not to be despised.

The Electric Arc.—Heat developed by electricity differs in one important respect from heat developed by combustion. Its temperature of application is from the industrial point of view virtually unlimited, while we have seen that each rise in the temperature of application of combustion heat limits more stringently its availability and effectiveness. Electric heat has then an increasing advantage as the temperature of application rises and this is, of course, greater in fields where the actual amount of heat required is small.

These conditions are exactly those of melting out a frozen cinder notch or tapping hole.

Nearly all blast-furnace plants of importance have an electric plant of some size and very early in the present century it was found that the electric arc could be used in such cases with tremendous advantage, and the practice rapidly spread.

The chief consideration next to having sufficient energy available is that the voltage shall be low. In the description of the removal of the salamander in a previous chapter, the reasons for this are given and need not be repeated here. The voltage preferred for this service is about 50 and at least 1000 amp. should be at hand. Twice as much is better. This gives a short controllable arc and the melting can be done where it is needed.

Alternating current has the great advantage for this service that the approximate voltage needed can be obtained directly from a suitable transformer, whereas direct current must be choked down in voltage through a water rheostat or some equivalent. This is not only wasteful of power, but the apparatus is clumsy and the control not easy. At one large plant a transformer of suitable size and design was located permanently at each furnace so that it was only necessary to connect up the carbon and turn on the current. A hole can be burnt in a short time into any place where there is enough conductivity to carry the current.

The Oxygen Burner.—Modern progress has brought into common use the oxyhydrogen and oxyacetylene blow pipe and developed comparatively cheap methods of producing the gases so that the use of these means for cutting iron and steel as well as that of oxyacetylene for welding is growing at an exceedingly rapid rate. Carloads of oxygen cylinders are now more common than single ones were not long ago. The applica-

tion of this apparatus to frozen cinder notches, etc., was obvious, and it has now come commonly to be preferred to the arc, although the latter continues to be used.

The preferred practice is to use the blow pipe only to bring the surface to be burned up to the temperature at which it will burn in pure oxygen and then direct a stream of the latter against it under heavy pressure. The reflex velocity of the jet keeps the hole clear of the burnt iron formed and rapid action is maintained.

The results which can be obtained in this way are little short of marvelous, instead of its being a matter of hours to burn through a few inches of iron as is the case with the oil burner, it is a matter of a very few minutes. In one case of which I knew, a badly frozen tapping hole was burned through and the iron running in about 6 min. from the time the oxygen jet was turned on. With the great increase in the ease of obtaining oxygen quickly and cheaply, this process seems likely to supersede all the others. It and the electric burner together have done much to remove the terrors which a chilled furnace formerly held for the unfortunate furnaceman.

ADDING ADDITIONAL FUEL IN THE HEARTH

In the most extreme cases of chilled furnaces the material in the hearth is so chilled that the blast has but little effect, in fact, can practically not penetrate the frozen material enough to generate any heat or form any slag. In such cases the materials in the hearth are dry rather than pasty, and can be removed through the tuyeres and cinder notch by pulling out solid lumps of coke, ore and limestone.

In such cases the preferred procedure is to dig a considerable hole into the cinder notch and into the tuyere nearest to it, fill up this space with fresh lumps of coke put in from the outside, then put back the blow pipe into the tuyere. If necessary, kindling or a piece of waste is used to ignite the coke as in blowing in.

A small quantity of blast is then put on; this passes through the coke and burns out the cinder notch, thereby establishing good communication between these two and enlarging the cavity. The furnace is then stopped and the next tuyere is then treated in the same way, and by blowing through this communication from it also is established with the cinder notch. In this way, if need be, one tuyere after another can have reëstablished its communication with the others and with the cinder notch, while much heat is added by the combustion of the coke put into the tuyeres.

Personally, I have never had to fight a furnace that was so badly bunged up as this, but the process has been used by experienced furnacemen who have described it to me.

Another expedient which is well recommended by those who have used it but which I have never tried, is the use of kerosene in the tuyere itself.

A small pipe is put through the peep-hole in the elbow of the penstock and run practically to the inner end of the tuyere. This is supplied with kerosene under pressure from a tank above and the blast turned on. This converts the whole tuyere into a gigantic blow pipe and permits imparting to the furnace a great amount of heat at the point where it is most needed. In this case also, if the bosh is too completely chilled to permit of passage of gas formed, an outlet must be made through the cinder notch or perhaps through another tuyere, as in the previous case.

The details of these operations necessarily vary almost infinitely according to the judgment of the operator and conditions to be met. It is therefore impossible to describe them in detail, but the general outline of the operations is as described.

To summarize, it might almost be said that a furnace is never in vitally serious trouble until it becomes impossible to remove the molten materials from the hearth by the regular methods. When this condition arises, steps available must be taken to remove them by any other means possible, not only once but as often as is necessary to bring down into the hearth a supply of fuel adequate to restore the thermal equilibrium of the furnace, on which its very existence depends. The theory of the remedy is simple but its application is laborious, dangerous and expensive to a degree which cannot be adequately portrayed in print.

WATER TROUBLES

Water troubles are of two separate and distinct kinds, though one kind may, and generally does, lead to the other; these kinds are: First, an interruption either partial or complete in the cooling-water supply of the furnace; Second, penetration of the water into the hearth of the furnace; this may be due, in a broad way, either to the failure of one or more cooling members, tuyeres, coolers, cooling plate and the like, or more rarely to the infiltration of water through cracks in the bosh jacket or hearth jacket, or into the brick direct where it is not protected by metal jackets.

Failure of the water supply may occur in many ways: Failure of pumping plant, the bursting of the supply main, and as regards the individual cooling members, by the plugging up of the supply cocks with vegetable matter, fish or other foreign substance in the water.

These troubles are of two kinds—partial and complete. The effects of the two cases are very different. If the failure is complete, all the more important cooling members are almost certain to be burnt before the furnace can be cast and stopped. This is a calamity of the first order, and whether the failed members can be restored and the furnace put back

into operation after the water supply is restored, or must be blown out for repairs, depends upon the conditions of the individual case.

Complete Failures of the Main Water Supply.—These are among the most terrible of the accidents which can take place around the blast furnace, even if the full supply be restored within a few minutes. The life of the furnace itself depends upon the existence of water cooling, always for the tuyeres, coolers, cinder notch and cinder cooler, and usually for many other cooling members, particularly the cooling plates in the bosh wall, when that type of construction is used. The failure of water on these for more than a second or two is generally sufficient to cause their destruction. The water remaining in them below the drainage level is very often sufficient to cause an explosion when they are burnt, and the small amount drained from the water system into the furnace through those that are burnt is always enough to chill it to some degree; if there is a small amount of water left flowing in the system, this is sufficient in a few minutes to put the furnace out of business for days.

When the water supply is restored after a brief interruption there are still great difficulties to be overcome. If it is known that any member has failed completely, the only thing to do is to shut the water off from it, but the solution of the problem is not generally as simple as this. It is almost out of the question to shut the water off from an active cooling member like a tuyere when the blast is still on the furnace, because under such conditions the member cut off is burnt out completely in a few minutes, and under the very best conditions the blast blows out through the opening with terribly destructive effect. In most cases this is accompanied by a heavy flow of cinder, and not infrequently by iron with its terrific cutting power, which is likely to lead to the destruction of other cooling members as well as cutting the exterior part of the furnace construction, the columns, hearth and bosh jackets, etc. If the first piece to go is a tuyere, such a sequence leads to the destruction of the cooler also in many instances. If, therefore, a number of cooling parts have failed under such conditions, it is absolutely essential to cast the furnace instantly; then the blast can be taken off and the water can be shut off from the failed members without danger of these consequences.

Partial Failure of Main Supply.—When only partial failure of the main water supply occurs, much can be done to reduce the seriousness of the resulting damage. The furnace must be cast and stopped without regard to any consideration except speed. The blast should be taken off the first instant it is safe to do so without filling the tuyeres with cinder. This does not reduce the temperature of the different zones of the furnace instantly, but it does reduce to zero the velocity of the gas currents, and this is of greater importance in diminishing their destructive power than reduction in temperature itself.

Generally the upper cooling members, particularly those above the

mantle, if there are any, lose their water supply first as the head on the system falls. As described under "Construction,"[1] if these are made of iron the water circulation can generally be restored to them even after quite a long stoppage, but if they are bronze they generally melt and must either be replaced or else filled up with grout to form a physical support for the lining resting on them and to prevent the gas from burning out through them.

While the loss of these members is extremely serious, its effects are not so immediate or so disastrous as the loss of the cooling members in the hearth and bosh of the furnace. Here the tuyeres and coolers are subjected to by far the severest conditions, and if there be a partial supply of water remaining it should be diverted to them at the expense of all the other cooling members.

I have been through three partial failures of the main water supply, in each case from the failure of a fitting on the line, the breakage of which permitted the escape of the large part of the water supply and the diminution of the head on the system to the point where it was no longer sufficient to supply all the cooling members. In each case we escaped very serious damage by the same general course of procedure. The great difficulty in each case was to restore the broken fitting without shutting off the water supply completely, so causing the failure of all the members even when the furnace was stopped.

There should always be, and generally is, at every plant, a high-pressure water supply of relatively limited volume for fire service and the like, and this we had in each of the three cases mentioned, but in none of them was this supply nearly adequate for the cooling system of the furnace as a whole. In one case the supply was so limited that after the furnace was stopped the tuyeres were pulled out and the noses of the coolers packed with clay. This eliminated the tuyeres from consideration and permitted us to use the scanty supply available for the coolers and the lower rows of cooling plates. These we connected up by hose lines with the high-pressure supply and by driving the latter for all it was worth we were able to force enough water to these members to preserve them under shutdown conditions, though they would not have lasted 10 sec. with the blast on.

While this emergency supply was being connected, everything possible that could be done in advance toward replacing the failed fitting was made ready. Finally, when all was ready, the emergency supply was connected up, the regular supply shut off and the failed fitting removed, the new one was then inserted, the pipe coupled up and the regular supply turned on. In one case things were getting so hot with only the emergency supply, that as soon as the new fitting was in place, and before any gasket was inserted in the joint, we turned on the regular supply for a

[1] See Blast Furnace Construction in America, Chapter on "The Furnace Stock."

few minutes in that condition. It made a lively spray from the open joint, but sent enough cool water into the cooling members to give us a few minutes' grace, and in that time we slipped in the gasket and tightened up the bolts and then the regular supply was put on to stay.

It is on account of these experiences that I hold to the belief expressed in the volume on furnace construction that two separate supply mains should be provided, each connected independently with the circular main around the furnace through a non-return valve set as close to the circle main as possible. Then in the case of the failure of either main the other will continue to supply the furnace and no difficulty will arise from inability to shut off the break. In some of the cases mentioned the fact that the break was between the stop valve and the circle main caused the principal difficulty.

Obstructions in Pipes.—One of the serious difficulties in a water supply liable to flood conditions is the accumulation of fine twigs, etc., which pass the main screen at the pump intake. These, combined with the silt and mud in the water, make it almost impossible to keep the circulation going on the most exposed cooling parts, especially the tuyeres. Because if the full water supply is diminished even a little, steam is generated and the pressure of this forces the water back into the supply pipe; the discharge then begins kicking and if quick action be not taken the loss of the tuyere is certain to follow within a minute or two, if not within a few seconds.

The best remedy for this difficulty is to have a strainer in the supply line, very much finer than the screen over the main inlet. This must be in duplicate and arranged for quick removal and cleaning; twin strainers are regularly built for this service and some of them are excellent in design and construction. The use of these when supplemented by extra care in times of flood water will cure the worst of the troubles from this source.

In order to guard further against this form of failure, the feed cocks from the circular water main are always made three-way and so arranged that by turning the plug into one position a wire can be run up through the bore of the cock into the supply main and the obstructing particle removed. In cases where this does not suffice to clear the pipe the three-way feature of the cock is useful because by turning it into position to connect the third or spare opening with the supply pipe and connecting a pressure hose onto what is ordinarily the discharge of the cooling member, the water current through that member can be reversed and most obstructions are removed by that treatment.

Certain waters carry in suspension vegetable matters such as the waste of paper mills, and these build up like fish scales in the pipes, in time obstructing them very seriously if not removed. They cannot be flushed out, because like fish scales they lie flat downstream, but by a

strong reversed current they can be ripped off in a few minutes and the pipe entirely cleared.

When the same cooling water is used over and over vegetable growths are apt to occur, much like the green slime seen on stagnant ponds, and these are very troublesome. They can generally be cured by the use of a very small amount of copper sulphate in the water.

Effect of Water upon Furnace Operation.—In Section I, Thermal Principles the subject of moisture in the blast has been treated at some length and the reason for the ruinous effect of water on the operation of the furnace has been explained. It is well, however, to revert to the subject here and to emphasize its vital importance from the purely operating point of view, as distinguished from what might be considered by some the theoretical.

Let us assume a blast temperature of 1200° and a critical temperature of 2750°F., then referring to our diagram of hearth heat available, it will be seen that the hearth heat per pound of fuel with no moisture is 1845 B.t.u. With ½ lb. of moisture it is 1670 B.t.u., and with 1 lb. of moisture it is 1510 B.t.u. One pound of moisture per 1000 cu. ft. corresponds to 7 grains per cubic foot, and is an amount which is very common in the summer months in almost all climates and may readily be exceeded by 30 or 40 per cent. in the South and during July and August in the North. A half pound is a fair average amount for spring and fall conditions in the greater portion of the iron-producing district.

The difference between these amounts, ½ lb. per 1000 cu. ft., represents the difference between fair average conditions and reasonably good conditions. Now, quantitatively, this corresponds to just about 10 per cent. more hearth heat per pound of fuel with the former than with the latter, and this ordinarily corresponds to about 10 per cent. greater fuel consumption with the higher quantity of moisture. This is as compared, not with good conditions of $\frac{3}{10}$ lb., but fair average conditions, on the one hand, while as before stated, the higher quantity taken corresponds only to very fair summer conditions; as between bad summer conditions, say 1¼ lb. of moisture, and the good conditions just noted, the difference is between 1750 and 1430 B.t.u. of hearth heat per pound of fuel, a difference of more than 20 per cent., which corresponds very closely to what has been found in practice in many cases.

Taking our rough figure of 10 per cent. increase in fuel required for ½ lb. per 1000 cu. ft. increase in the moisture in the blast, let us translate this into terms of actual water. On a large furnace blowing, say, 40,000 cu. ft. of air per minute (actual), this would correspond to 20 lb. or a little less than 2½ gal. of water per minute, a very small quantity to cause such a vast difference in fuel consumption. This makes it very clear that a heavy leak due to the failure of a cooling member which may discharge into the furnace in a solid stream 20 or 30 gal. a minute will very quickly

drown the furnace out, while very small leaks are amply sufficient to upset the delicate equilibrium upon which all successful furnace work depends, for on the basis of the above figures ½ gal. a minute corresponds to a reduction of 2 per cent. in the hearth heat, and a change of that amount is usually sufficient to alter the grade of the iron appreciably.

There is one feature about water leaks which may make them even worse than moisture in the blast. The latter is disseminated with absolute uniformity throughout the whole combustion space of the furnace and therefore produces no local irregularity, but when a leak takes place it tends to chill one side of the furnace while the rest goes on undisturbed. This brings about an irregularity which, added to the ruinous effect of the water itself, in whatever form it may be, makes water leakage the worst dreaded enemy of successful furnace operation. I suppose that every furnaceman has had the experience of having a good working furnace begin to work poorly and finally, after endless trouble, finding a small leak in some cooling member, the amount of water passing through which seemed as though it must be absolutely insignificant, and yet when the defective member was replaced by a perfect one, the furnace at once returned to its normal condition and showed every sign that the source of trouble had been removed.

The Leakage of Water into the Furnace.—In striving to maintain the cooling members intact we have to meet conditions perhaps the most severe of any in the operation of the blast furnace. It is absolutely impossible to maintain the furnace without cooling. The water-cooled members must necessarily be very thin or they will burn up in spite of the water cooling, and yet it is absolutely essential that the water must not reach the fire, from whose effects it is protecting the structure. Nothing suffices to maintain these conditions and the satisfactory operation of the furnace which depends upon them, except intelligent construction in the first place, backed up by vigilant and experienced operation.

The inner ends of all the cooling members in the hearth and bosh are in immediate contact with the currents of molten material and gas, while the tuyeres are thrust right out into both and are exposed to the constant wear of the coke and to the drip of the iron and cinder running down the bosh walls. These members, therefore, necessarily fail from time to time, either by wear or by being cut by a particularly active jet of iron striking them from above and perhaps in many other ways. These failures lead to the direct flow of water in the hearth.

Sometimes the flow of water from the failed member is the merest seepage, and in such cases to determine whether a member has failed or not is one of the most difficult tasks in the operation of the blast furnace, for a tuyere may have a hole ¼ in. in diameter burnt in it, through which enough water will flow to chill the furnace in an hour or two, and yet superficial observation does not show the diversion of this

water from the regular discharge of the tuyere, so it does not do to shut off these cooling members indiscriminately, because every one so treated is instantly destroyed when the blast is on, and very soon even when the blast is off the furnace. Those so destroyed must be replaced at great expense in money and far greater in loss of time, to say nothing of labor, before the furnace is in shape to go again.

There is no general method of determining whether a certain member is leaking or not if the leak be a small one. The presence of hydrogen in the gas in large quantities can always be detected by watching the combustion at the stoves and boilers, but while this proves the existence of a leak it gives no evidence as to its location, and sometimes the furnaceman will be hunting for days on the suspicion, or perhaps the certainty, that water is going into the furnace, without knowing where it is coming from. In some cases the plan has been adopted of pulling every cooling member in the furnace, not always at one shutdown, but stopping for a half hour or an hour after every cast and pulling as many as possible, testing these under pressure outside the furnace for leaks and restoring them to place when perfect. This involves an enormous amount of labor, but, as before explained, the destructive action of water on the furnace is so great that a tiny leak is enough to affect the action of the furnace very seriously, and in some cases so destructively that whatever measures are necessary must be used to find it.

Perhaps one of the best methods of determining leaks is to throttle the water supply of the cooling member until the stream from its discharge flows absolutely smoothly, without spatter due to initial velocity, and yet without any break in the stream. By holding a light behind a stream of this kind gas bubbles can generally be seen descending in it if the member is leaking. A necessary feature of this method of test is to throttle the pressure of the water in the cooling member down below the blast pressure inside the furnace, so that the gas comes in through the leak instead of the water going out.

Another method particularly effective in case of a leaking tuyere is to run a rod in through the peep-hole to the nose of the tuyere, leave it for a few minutes and pull it out. In case of anything but a very small leak, the rod is frequently wet on the end.

Very often leaks can be detected by the wetness of the aperture through which the cooling member is inserted. The water is forced back in some rather mysterious way and makes its way out to the outside of the furnace. This is generally an excellent indication, but sometimes the water is so inconsiderate as to travel from the defective cooling member around a half dozen perfect ones and out through the butt of one of the latter, so that it is not safe simply to turn off the water supply from a member which shows wet around the base without investigating further.

There is always a certain amount of gas around the bosh of a furnace,

not coming from any particular region that can be discovered, but nevertheless present all around it; the smell of this gas is altered to some extent by the presence of water going into the furnace, and this sometimes serves for a preliminary indication. The master mechanic of a small plant once said: "If you see old Wash (the colored keeper) get up and begin to walk around the furnace with his nose stuck up in the air, you may as well get ready to change a tuyere after cast."

It is impossible to do justice in print to this subject, so vital to the successful operation of the furnace. Nothing but several years of hard knocks around the plant suffices to impart a satisfactory education on the subject.

In order to prevent the difficulties which arise from the entrance of water into the furnace, various efforts have been made to supply a water circulation in which the pressure should be lower than that in the furnace itself, so that any failure would result in a little gas blowing out through the discharge, but not in the entrance of any water into the furnace. One of the schemes which has probably occurred to many is to pull the water through the cooling members by suction rather than driving it through under pressure, but the practical difficulties of maintaining pipe joints tight against vacuum, and the greater complexity necessary in such a procedure, have prevented it from being put into practical use in this country, so far as known to me.

But while there is difficulty in actually sucking the water through the pipes, much may be done to reduce the pressure required to make it flow. The volume desired should be obtained by large pipes under the lowest possible head rather than by smaller pipes under higher pressure. Above all, the discharge pipe should be direct and as free from bends as possible, because the end of this pipe being open, its frictional resistance is the measure of the pressure which must be maintained on the cooling member to produce the required flow. I do not think that enough attention has in all cases been paid to this important detail.

Another matter worthy of attention is the regulation of the water supply of the different members according to their requirements. It is extremely simple to turn them all on full head and run all the water possible through them, but this not improbably takes more heat out of the furnace than is required; it certainly requires an excessive amount of cooling water, and, above all, it maintains an entirely unnecessary pressure upon the cooling member with consequent liability to heavy leakage in case of failure.

In regard to the tuyeres and very often the coolers, the full-flow policy is generally desirable, because the conditions to which they are exposed in the furnace are so severe that it is a wonder that any amount of cooling preserves them and we cannot afford to take chances of diminishing their water supply, but for many of the other members, a very much smaller

supply of water suffices and they should be throttled down to the point where the water begins to be appreciably warmed in its passage through them, unless this leads to a water supply so small that it is likely to fail accidentally. No member should ever be throttled to this latter degree, because complete stoppage of such a choked water supply is almost sure to take place accidentally sooner or later. In this, as in all matters of furnace operation, there is no substitute for experience and good judgment.

In addition to the penetration of water into the furnace through leaky cooling members, much trouble has arisen in time gone by from water soaking in through the brick work at unprotected points and, particularly where jackets are used, from water entering between the jacket and the brick and thence soaking into the combustion space. It would seem that this action could not occur in view of the pressure of several pounds per square inch existing in the combustion space, but that it does occur most furnacemen know to their sorrow. The explanation probably is that the capillary attraction of the brick is stronger than the blast pressure and so draws the water inward in spite of the pressure outward.

Leaks of this kind can best be prevented by correct design in the first instance. Where steel jackets are used, the greatest care should be taken to see that the upper sheet laps over the lower sheet in every case. The spray trough at the base of the steel bosh jacket, if one is used, should be made amply wide to catch drip and spatter. Where a steel tuyere jacket is used, troughs should be provided above each cooler opening so that any stray water running down is caught in these troughs and guided down over the side of the coolers away from the furnace. The steel tuyere jacket should have a conical base, riveted water-tight to it, to run out over the top of the hearth jacket so as to shed any water which may fall upon it outside the hearth jacket and prevent its running down between the jacket and the brickwork. Above all, if any sort of external spray be used on the hearth jacket, the latter should be made as absolutely tight as a high-pressure boiler, otherwise the water will find its way into the brickwork and working through this, reach the hearth.

After proper construction of this kind has been provided, continuous watch must be maintained to see that water does not break through the defensive armor of the furnace in some unforeseen way and so make its way into the combustion zone.

CHAPTER XV

THE COMBUSTION OF FURNACE GAS

The operation of the equipment of the blast-furnace plant is in general the same as the operation of similar equipment in other industries and therefore needs no special treatment here. There is, however, one exception to this statement, the fuel of the blast-furnace power plant is furnace gas and the combustion of this gas for best results is by no means as simple as it looks. It is perfectly true that furnace gas can be burnt and boilers can be run by the most ignorant foreigner who can be hired, but considering the fact that about half the fuel value of the coke is contained in the gas and that this represents a money value of at least $500 per day per 500-ton furnace and perhaps twice as much, the dollar or so per day saved by the employment of such a man as against a trained and intelligent one, may be a pretty expensive saving. It often has been in the past.

The principles of combustion, particularly of gas combustion, are not nearly so generally understood as they should be and losses aggregating millions of dollars per year have been made by the iron and steel industry through that fact.

Much good work has been done in recent years on this subject and this is well presented by two modern papers. One of these by A. N. Diehl, before the American Iron and Steel Institute, October, 1915, is here presented in abstract, and the other by K. Huessener, before the American Institute of Mining Engineers, February, 1916, presented in full. I am in complete accord with Mr. Huessener as to the undesirability of washing gas for boilers under normal conditions, since the loss of heat through the presence of moisture in the stack gases is much less and the loss of the sensible heat in furnace gas by washing much more important than the advocates of washing have been inclined to admit.

For stoves, on the other hand, clean gas is practically indispensable and the better the combustion practice the more indispensable it is, for the higher the combustion temperature is raised the more effectively any flue dirt present is burnt onto the combustion chamber and checkers, to their early destruction. I think Mr. Huessener might have emphasized more than he did the desirability for automatic control of the draft. Recent experience with coal-fired boilers, where conditions are easier to control than with gas firing, have indicated advantages greater than

would be expected theoretically from the maintenance of a constant draft. It seems likely that automatically controlled fans in the gas main to maintain the needed pressure at the gas burners are a step whose profitableness may before long become apparent.

These valuable papers show the amount of research already expended upon this difficult subject and indicate to my mind the need of a trained engineer to supervise the conditions of gas combustion at plants of even very moderate size; a saving of one or two per cent. of the value of the gas will pay his salary and he may easily make a saving of ten.

ABSTRACTS FROM "MODERN METHODS OF BURNING BLAST FURNACE GAS UNDER STOVES AND BOILERS"

By Ambrose N. Diehl

Assistant General Superintendent, Carnegie Steel Company, Duquesne, Pa.

Requirements of Burner.—There have been very few operators who have not at one time or another put one or more pipes through a stove or boiler burner in order to get the so-called Bunsen effect. In the case of stoves these experiments generally terminated in two results. First, if the air-duct was sufficiently large to effect any decided change, the temperature of combustion was considerably increased and resulted in the flue dust carried with the gas fluxing with the brick in the combustion chamber, and either boring a hole through the same or filling the well with semi-molten or plastic material. Second, the stove from which a high temperature was obtainable, at first, ran down quickly, resulting in the operator's statement that the stove merely had a "flash temperature, but would not carry its heat." The air-pipes generally occupied so much area that the normal supply of gas was decreased in consequence, and an insufficient thermal capacity resulted. These efforts mostly resulted in failure, on account of the foregoing causes, and, instead of burning down stoves by flame concentration, air was allowed to enter through special doors or blow-off valves. In this manner the proper mixing was intentionally spoiled and the consequent flame temperature lowered, to preserve the walls from the subsequent fluxing action. Much of this difficulty is avoided in burning clean gas, and the temperature can be raised to its highest limit.

In the case of boilers, especially if air shortage was the prevailing condition, the placing of pipes or other aspirating devices around or through the burner occasionally resulted in small increases in efficiency, due to supplying more nearly the required amount of air.

Burner Efficiency of 100 Per Cent.—It is apparent that an ideal burner will admit the theoretically correct quantities of air and gas, and completely mix them, thereby producing a maximum flame temperature at the point of ignition. The performance of a burner, on the basis of this ideal condition, may be determined by the observation of flame temperature, and by analysis of products of combustion, both methods being useful in practice. A couple, inserted in the combustion chamber close to the point of ignition, furnishes both

quick and reliable indications for the adjustment of air and gas openings in the burner to continuously produce the best state of combustion. The highest temperature obtained in this way is not necessarily the theoretical maximum, but merely the maximum that can be produced by the burner under the prevailing conditions. The observed temperature will be affected by the radiation from surrounding bodies and the possible presence of CO in the products of combustion. The calculated theoretical temperature will depend on the moisture in the gas and the accuracy of specific heat constants used. Therefore temperature observation cannot be an absolute standard of burner efficiency, and a method based on analysis of products of combustion must be used. If the products analyze carbon dioxide and nitrogen, with no oxygen or carbon monoxide, the combustion is perfect and mixing of the burner may be called 100 per cent. efficient. The next factor to be determined is at what point in the path of the gases this perfect condition should be reached. Theoretically, it is directly at the outlet of the burner or ignition point, and a combination of these conditions would give a theoretical burner efficiency of 100 per cent. Practically, this is very difficult to obtain, and we must assume a point a short distance beyond the burner, but well in front of the first heat absorption surface. It is therefore suggested that, as a standard, a point 2 ft. beyond the point of ignition be adopted as the point at which gas samples shall be drawn for a determination of burner efficiency, a water-cooled sampling tube, of course, being used. The definition therefore becomes: "A mixing gas burner is operating at 100 per cent. combustion efficiency when the analysis of a sample, drawn from a point two feet beyond the point of ignition, shows perfect combustion."

Classification.—Blast furnace gas burners may be classified under six general types as follows:

First.—Rectangular or circular nozzle burner with air added around it or by separate air doors or a combination of both.

Second.—Rectangular or circular burner with air conducted into the gas jet by means of pipes or other openings.

Third.—Burner which subdivides air and gas into separate streams which do not mix in the burner.

Fourth.—Burner into which air is aspirated by means of an air jet at high pressure, as in a steam jet blower, the air from both sources mixing with the gas in the burner.

Fifth.—Burner through which all of the required air is forced and completely mixed with the gas before the ignition point.

Sixth.—Burner to which air and gas are supplied after being perfectly mixed in a fan which admits air on one side and gas on the other, discharging the mixture into a common outlet.

Type 1.—Rectangular or circular nozzle burner with air added around it or by separate air doors or both.

This is the burner in common use in nearly all blast furnace stoves and is exampled by the Spearman-Kennedy burner (Fig. 96). The air is taken in through the clearance space around the burner and through doors in other parts of the stove circumference. The gas and air meet and mix in passing up through the combustion chamber. If the correct quantities have been admitted, the great length of combustion chamber permits the practical completion of burning

before the checkers are reached. Extracts from tests of stoves, using the common burner, made at Duquesne and Edgar Thompson Works, clean gas being used in both, follow:

Item		Duquesne	Edgar Thompson
Type of stove		2-pass central combustion chamber	2-pass
Size of stove		21′ × 96′	22′ × 100′
Heating surface, sq. ft.		39,920	51,192
Cubic contents, sq. ft.		17,974	8,894
Air blown per minute at 62°, cu. ft.		40,580	37,744
Temperature hot blast, deg. F.		1,076	1,200
Temperature stack, deg. F.		612	537.5
Time on gas, min.		198.75	172.25
Time on blast, min.		64.0	60.0
Furnace gas analysis	CO_2	13.06	11.94
	CO	25.78	24.84
	H_2	3.69	4.45
	N_2	57.47	59.77
Flue gas analysis	CO_2	21.30	18.08
	O_2	2.90	4.93
	CO	0.8	0.0
	N_2	75.0	76.99
Heat absorbed by blast (efficiency), per cent.		64.48	58.04
Sensible heat lost in flue gas, per cent.		22.22	23.41
Unconsumed CO loss, per cent.		4.52	0.0
Radiation, unaccounted for, etc., per cent.		8.78	18.45

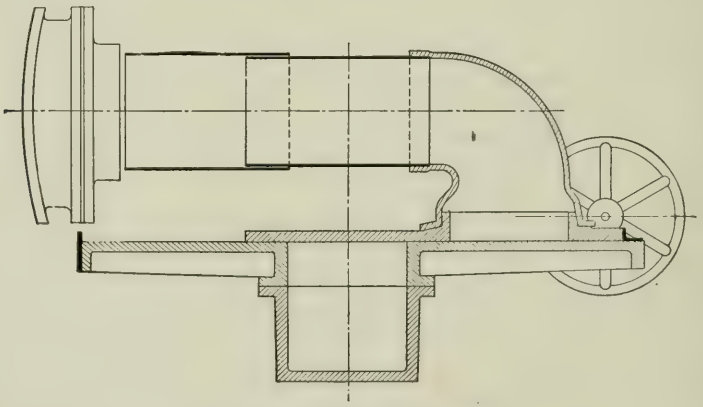


Fig. 96.—Kennedy stove burner.

In these tests the stack analyses are good and the temperature comparatively low. However, both could be somewhat improved by careful regulation, to give approximately as good stack analyses as have been obtained with the use of mixing burners. This point is illustrated by the following figures, from

tests of stoves at Wisconsin Steel Company, where the operation is under constant technical supervision. Clean gas was used.

Type of stove		Kennedy 2-pass
Size of stove		22′ × 90′
Heating surface, sq. ft.		33,000
Air blown per minute at 62°, cu. ft.		35,000
Temperature hot blast, deg. F.		1,165
Temperature stack, deg. F.		761
Time on gas, min.		236
Time on blast, min.		73
Furnace gas analysis	CO_2	15.1
	CO	23.6
	H_2	3.0
	N_2	58.3
Flue gas analysis	CO_2	25.0
	O_2	1.0
	CO	0.0
	N_2	74.0
Heat absorbed by blast (efficiency), per cent.		61.5
Sensible heat loss in flue gas, per cent.		26.5
CO loss in flue gas, per cent.		0.0
Radiation and unaccounted for, per cent.		12.0

The stack analysis here shown is excellent. The high stack temperature is the result of insufficient heating surface, since the combustion is as good as could possibly be obtained in regular operation.

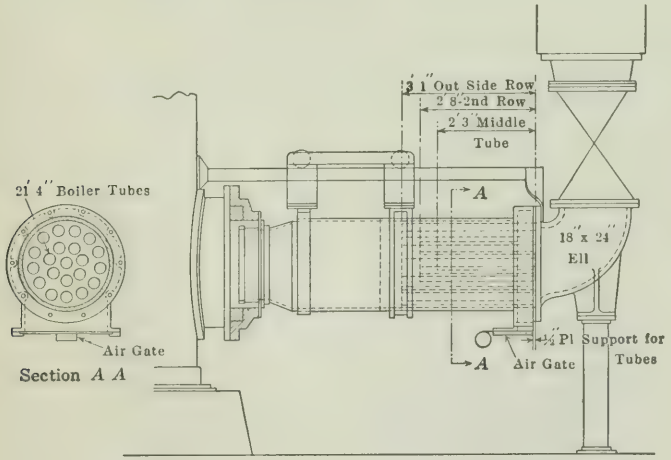


FIG. 97.—Landgrebe burner for blast furnace gas.

Type 2.—Rectangular or circular burner with air conducted into the gas jet by means of pipes or other openings—illustrated in the Landgrebe burner (Fig. 97) developed at the T. C. I. & R. R. Co., Ensley, Ala.

This burner consists of 21-4-in. boiler tubes through which the gas is admitted. The outer row of tubes is the longest, the center tube the shortest, and the middle

row is cut half-way between, so that the gas flowing through the central tube starts burning before any of its neighbors. Surrounding these tubes is an air space formed partly by the outer shell of the burner and partly by a sliding sleeve which tightly connects the main burner with the stove door frame when the door is removed. The ends of the gas tubes are placed about 2 ft. from the door frame. Air is admitted at the back of the gas tubes surrounding them, and at the ends of the latter meets the gas, at which point mixing takes place. To eliminate the necessity of disturbing the relation of gas and air supply, if it became necessary to increase or decrease the flow of gas, a separate gas valve was supplied in the pipe connection to the gas main. This gas valve is simply a cylindrical valve covering a port and consisting of special mechanical features to prevent clogging and leakage and to insure ease of operation. Thus the supply of gas can be regulated at will without disturbing the burner proper. Suitable slides, etc., are provided for regulating admission of air into the air chamber of the burner.

Burners of the above description were provided for two new two-pass side combustion stoves, 22 × 110 ft. which were built and put into service in January, 1912. A series of tests were conducted on these stoves while they were still new and clean, and the results of these tests, through variable, were, on the whole, quite satisfactory.

An exhibit of these tests follows:

Type of stove		2-pass
Size of stove		22′ × 110′
Heating surface, sq. ft.		.....
Cubic contents, cu. ft.		.....
Air blown per minute at 62°, cu. ft.		49,700
Temperature hot blast, deg. F.		1,200
Temperature stack, deg. F.		437
Time on gas, min		205
Time on blast, min		55
Furnace gas analysis	CO_2	10.92%
	CO	32.72
	H_2	1.04
	N_2	54.56
	CH_4	0.16
Flue gas analysis	CO_2	24.40%
	O_2	1.70
	CO	0.0
Heat absorbed by blast (efficiency), per cent		74.1
Sensible heat loss in flue gas, per cent		13.2
CO loss in flue gas, per cent		0.0
Radiaton and unaccounted for, per cent		12.7

Both stack analysis and temperature are excellent and as good as could be obtained with any type of burner, since they are very close to the theoretical possibilities. The secret of success in a burner of this type seems to be the design of air-ports sufficiently large to take care of the quantities required for complete combustion.

Another example of this form is found in the Boynton burner in use at the Lorain Works, of the National Tube Company (Fig. 98).

Air and gas are admitted in horizontal layers as shown in the sketch, this stratification being produced with the idea of obtaining intimate mixture of air and gas at the point of admission.

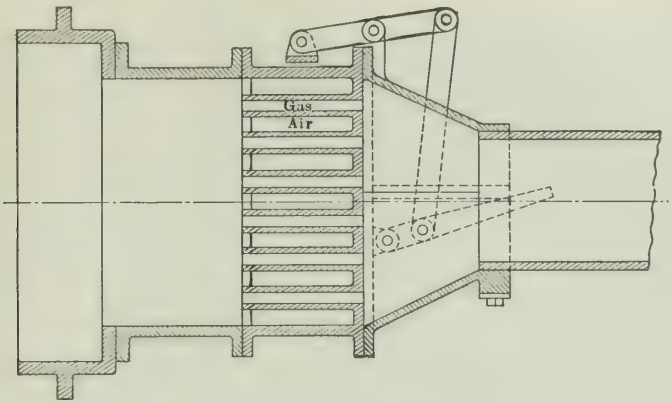


FIG. 98.—Boynton gas burner.

The following analyses, taken without any regulation, and without knowledge of the hot blast men, from seven different stoves operated by three different men, show good operation, but give no indication as to just what point in the stove the completion of mixture takes place or of the resulting stack temperatures.

ANALYSES OF FLUE GAS FROM HOT BLAST STOVES

Date	Furnace	Stove	CO_2, per cent.	O_2, per cent.	CO, per cent.
Oct. 26	No. 2	No. 2	25.0	0 0	0.6
Oct. 26	2	3	26.0	0 0	0.2
Oct. 26	2	4	25.8	0 0	0.6
Oct. 27	5	2	24.6	0 8	0.0
Oct. 27	5	3	25.8	0.2	0.2
Oct. 27	2	1	26.0	0.0	0.2
Oct. 27	2	2	26.0	0.0	0.8
Oct. 27	2	3	25.6	0.4	0.0
Oct. 27	2	5	25.8	0.2	0.2

Of the same type is the aspirating stove burner developed at the Ohio Works of the Carnegie Steel Company, illustrated in Fig. 99. By means of this burner the same blast heats have been obtained with a consumption of 4900 cu. ft. gas per minute as compared to 5740 cu. ft. with the common goose-neck burner. Since stack temperature and analyses on the two burners are about equal, this gain must be credited to the better absorption which is due to faster mixing obtained with the aspirating burner. Comparative tests of these burners follow:

		Common	Ohio works
Type of stove		2-pass	2-pass
Size of stove		21′ × 115′	21′ × 115′
Heating surface	Sq. ft.	53,700	53,700
Cubic contents	Cu. ft.	5,349	5,349
Air blown per minute at 62°F	Cu. ft.	39,600	39,600
Gas burned per minute at 62°F	Cu. ft.	5,740	4,900
Temperature of hot blast	Deg. F.	1,200	1,200
Temperature of stack	Deg. F.	800	780
Time on gas	Minutes	170	170
Time on blast	Minutes	60	60
Furnace gas analysis CO_2	Per cent.	12.9	12.9
Furnace gas analysis CO_2	Per cent.	26.4	26.4
Furnace gas analysis H_2	Per cent.	3.4	3.4
Furnace gas analysis N_2	Per cent.	57.3	57.3
Flue gas analysis CO_2	Per cent.	24.5	24.0
Flue gas analysis O_2	Per cent.	0.0	0.7
Flue gas analysis CO	Per cent.	0.8	0.0
Flue gas analysis N_2	Per cent.	74.7	75.3
Heat absorbed by blast (efficiency)	Per cent.	56.4	59.7
Sensible heat lost in flue gas	Per cent.	29.5	30.3
Unconsumed CO loss	Per cent.	4.1	0.0
Radiation unaccounted for, etc	Per cent.	10.0	10.0

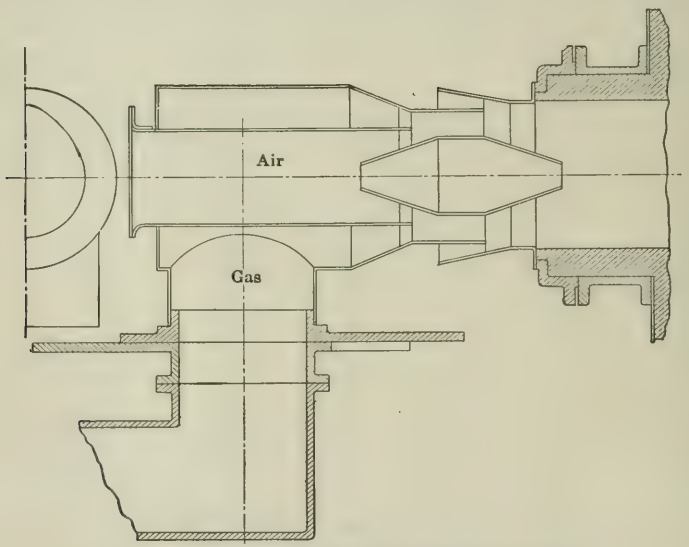


Fig. 99.—Aspirating stove burner (Ohio Works).

Type 3.—Burner which subdivides air and gas into a series of streams which do not mix in the burner.

A stove burner, answering this description, has been developed at the Edgar Thomson Works, Carnegie Steel Company (Fig. 100). This burner consisted

of the usual burner base box carrying the burner base. This burner base is a casting containing the gas and air-admission passages, and ports for the burner, and having a cylindrical seat or face. The burner seat consists of a casting having a cylindrical face fitting onto the corresponding face of the burner base and free to rotate over the same. This casting is provided with gas and air ports, and passages, gear teeth for rotating the same, and flanges for supporting

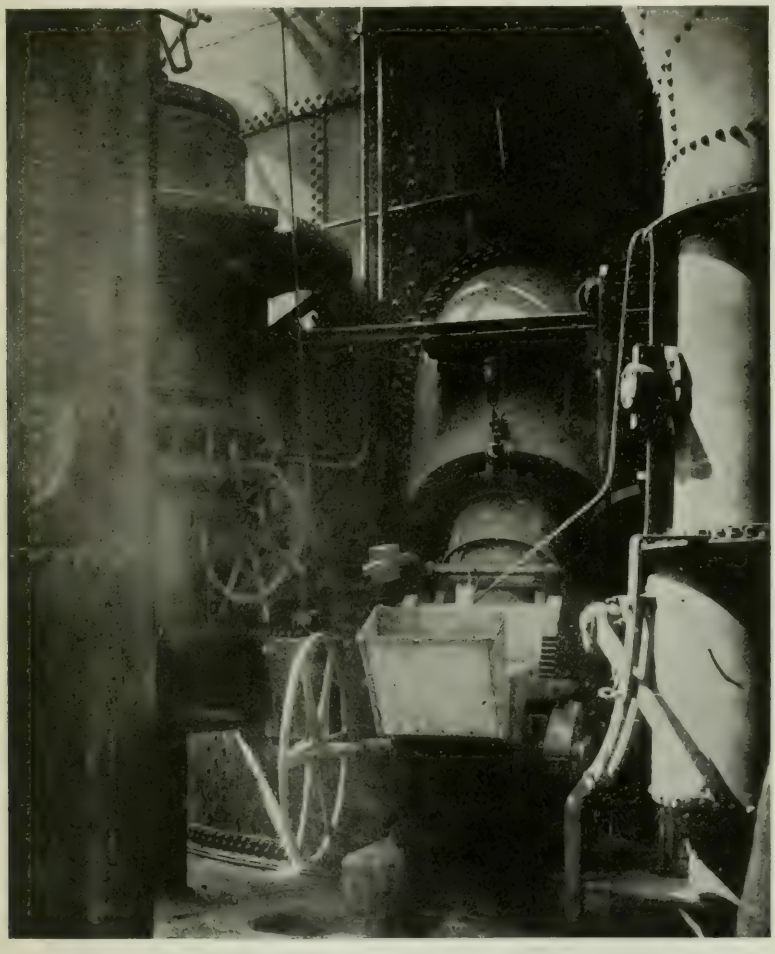


FIG. 100.—Edgar Thomson stove burner.

the burner nose or nozzle. The burner nozzle bolted to the burner-seat casting consists of two concentric barrels, 3 ft. long, forming the gas and air passages. The central or gas passage, 14½ in. in diameter, contains a spirally twisted vane, twisted through about one and one-half turns; the outer or air passage, 4½ in. wide, contains four spiral vanes, making one-half turn each and twisted in the opposite direction from the gas vane. The vanes run the full length of the barrel. The entire nozzle is built of sheet iron and boiler plate. Sliding length-

wise on the outside of the barrel is a short nozzle, actuated by a system of levers and links, and used to complete the connection between the burner and the branch connecting to the combustion chamber. The burner seat and nozzle are rotated in a vertical plane by means of a hand-wheel and gears, the center line of the burner barrel being practically vertical when the gas is off, and making an angle of about 49 deg. with the horizontal when the gas is on the stove. A steel casting is lined with fire brick, leaving a conical opening into the combustion chamber; the central axis of the cone lies in a vertical radial plane through the center of the stove and makes an angle of about 49 deg. with the horizontal, giving as nearly a vertical admission of the flame to the combustion chamber as is possible for a burner at the side of the stove and with the construction of stove tested.

The gas-main supplying gas to the burner was provided with a mushroom type, hand-controlled shut-off and control valve, and a butterfly valve actuated by a pressure regulator.

The following test figures show a decided gain in efficiency over that of the old form of burner mentioned before:

Type of stove		2-pass
Size of stove		22′ × 100′
Heating surface, sq. ft.		51,192
Cubic contents, cu. ft.		8,894
Air blown per minute at 62°, cu. ft.		44,748
Temperature hot blast, deg. F.		1,119
Temperature stack, deg. F.		376
Time on gas, min.		161.8
Time on blast, min.		60
Furnace gas analysis	CO_2	11.78%
	CO	26.38
	H_2	3.15
	N_2	58.67
Flue gas analysis	CO_2	23.60%
	CO	1.87
	O_2	0.45
	N_2	74.08
Heat absorbed by blast (efficiency), per cent.		71.58
Sensible heat lost in flue gas, per cent.		10.50
Unconsumed CO loss, per cent.		9.46
Radiation, unaccounted for, etc., per cent.		8.46

Type 4.—Burner in which air is aspirated by means of an air jet at high pressure, as in a steam-jet blower, the air from both sources mixing with the gas in the burner.

Burners of this form have been placed in use on stoves of the Illinois Steel Company, at South Chicago, but no test data in regard to them is available as yet.

Type 5.— Burner through which all of the required air is forced and completely mixed with the gas before the ignition point.

Burners of this description are in use on the stoves of the Wisconsin Steel Company, at South Chicago, and the American Steel & Wire Company's Central Furnaces, Cleveland, Ohio.

The Wisconsin burner (Fig. 101) consists of a circular gas passage, in the back of which is placed an air nozzle, the air being supplied under pressure by a fan. The old burners on these stoves gave excellent results as mentioned before. However, the heating surface was insufficient, and an additional 4000 sq. ft. of surface was placed in the combustion chamber. After this change, the draft proved insufficient, and forced draft was resorted to in order to furnish to the

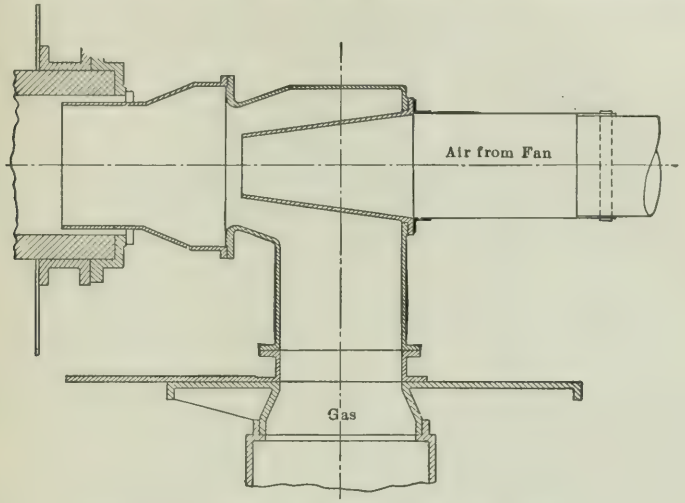


FIG. 101.—Pressure stove burner (Wisconsin Steel Co.).

stove the required quantity of heat. By this means the capacity of the stove was increased, the efficiency being somewhat higher, as shown by the following test extracts, the stack temperature being lower, but the flue gas analysis essentially the same:

Type of stove		Kennedy 2-pass
Size of stove		22′ × 90′
Heating surface, sq. ft.		37,000
Air blown per minute at 62°, cu. ft.		35,000
Temperature hot blast, deg. F.		1,273
Temperature stack, deg. F.		598
Time on gas, min.		148
Time on blast, min.		55
Furnace gas analysis	CO_2	15.1%
	CO	23.6
	H_2	3.0
	N_2	58.3
Flue gas analysis	CO_2	24.8%
	O_2	1.3
	CO	0.0
	N_2	73.9
Heat absorbed by blast (efficiency), per cent.		69.4
Sensible heat lost in flue gas, per cent.		18.6
CO loss in flue gas, per cent.		0.0
Radiation and unaccounted for.		12.0

Type 6.—Burner to which air and gas are supplied after being perfectly mixed in a fan which draws in air on one side and gas on the other, discharging the mixture into a common outlet.

An arrangement of this kind is being developed at the present time, but no specific information is available, so it is impossible to speculate on its merits or shortcomings as a mixing device.

SUMMARY OF STOVE TESTS

Plant	Type of stoves	Size of stove	Cu. ft. air per min. at 62° F.	Burner	Eff'cy	Remarks
Duquesne.....	2-pass	21× 96	40,580	Common	64.5	Average operation.
Edgar Thomson	2-pass	22×100	37.774	Common	58.04	Actual efficiencies probably higher as "radiation and unaccounted for" is excessive.
Edgar Thomson	2-pass	22×100	44,748	Edgar Thomson	71.58	"Radiation and unaccounted for" normal.

SUMMARY OF STOVE TESTS—*Continued*

Plant	Type of stoves	Size of stove	Cu. ft. air per min. at 62° F.	Burner	Eff'cy	Remarks
Wisconsin.....	2-pass	22× 90	35,000	Common	61.50	Small checker area.
Wisconsin.....	2-pass	22× 90	35,000	Forced draft	69.40	4,000 sq. ft. checkers added.
Ensley.....	2-pass	22×110	49,700	Landgrebe	74.10	Very low stack temperature, and biggest stove listed.
A. S. & W. Co. cent. fces.	2-pass	.....	.....	Orr	65.00	Detail data not available.

Remarks.—The combustion chamber of large proportions was originally designed primarily as a receptacle for the flue dust carried in rough gas, and secondarily as a necessary aid to combustion under primitive methods of burning. It was also considered advisable to have the hottest checkers at the top, where material strains are smallest, but no doubt, by suitable precautions in design, this factor could be eliminated. The following points should be observed:

Stove Conclusions.—*First.*—Clean gas should be used when possible.

Second.—Large heating surfaces should be exposed as an aid in lowering stack temperatures.

Third.—Equal drafts and blast distribution over the entire checker area is essential to good practice.

Fourth.—All gas should be consumed in the combustion chamber. The closer the complete combustion is to the burner the better heat exchange is possible.

Fifth.— It is best to add both gas and air at only one point, through the burner, and control them there. Gas and air have channelling tendencies when entered separately.

Sixth.—Forced draft will facilitate flame intensity and act in such manner as to make the combustion of more gas possible in the stove than under atmospheric draft conditions. If the stove is sufficiently large, considerable advantage

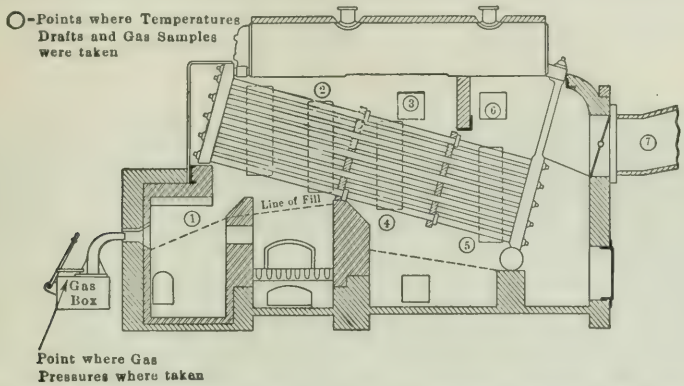


FIG. 102.—B. & W. 250-hp. boiler used in tests on various types of blast furnace gas burners.

can be derived by this method, because greater quantities of gas can be burned in a given time.

Seventh.—It is advisable to make daily flue analyses and have a technical supervision of the combustion.

BOILERS

The average efficiency of a blast furnace boiler plant, using common burners and operating without the aid of technical supervision, is not over 50 per cent. and frequently much lower. The losses of 50 per cent. are distributed about as follows: Sensible heat in waste gases, 36 per cent.; CO in waste gases, 9 per cent.; radiation, 5 per cent. This distribution varies greatly with load, gas pressure and position of stack damper. The average result of 28 8-hr. tests, conducted at Duquesne blast furnaces on several 250-hp., B. & W. boilers (Fig. 102), is as follows:

Stack loss	35.7%
CO loss	8.4
Radiation	5.0
Efficiency	50.9
B.hp	300.0 = 120% builders' rating.

While these tests were conducted under operating conditions, the results may be considered slightly better than a continuous average, as observations were suspended during unusual periods, such as very low drops in gas pressure, etc. Also noticeable bad leaks in settings were patched before testing in many cases.

The following condensed results are quoted to show the variations in the different losses and efficiencies:

		Max. stack loss. Min. eff.	Min. stack loss. max. CO loss	Max. eff.
Per cent. of ratings developed		110	112	125
Furnace gas analysis	CO_2 %	13.4	13.0	13.2
	CO	24.8	25.5	25.5
	H_2	3.6	3.5	3.6
Comb. chamber analysis	CO_2	16.9	19.6	21.2
	O_2	7.5	0.2	1.4
	CO	1.0	8.1	6.1
Stack gas analysis	CO_2	8.1	16.1	18.2
	O_2	14.3	5.9	6.4
	CO	0.0	3.5	0.2
Gas pressure (inches) H_2O		3.5	4.0	3.5
Draft in furnace (inches) H_2O		0.30	0.35	0.42
Furnace gas temperature, deg. F		60	300	60
Combustion chamber temperature, deg. F		1,706	1,690	1,765
Stack temperature, deg. F		628	565	785
Calorific value of furnace gas cu. ft. B.t.u		90.3	92.3	91.0
Sensible heat of furnace gas cu. ft. B.t.u		0.0	4.8	0.0
Total heat of furnace gas cu. ft. B.t.u		90.3	97.1	91.0
Sensible heat lost in stack, per cent		59.1	22.2	34.1
Unconsumed CO lost in stack, per cent		0.0	23.8	1.5
Radiation (assumed)		5.0	5.0	5.0
Efficiency, per cent		35.9	49.0	59.4

The maximum efficiency, as might be expected, occurs with neither a minimum sensible heat loss or CO loss, which is generally the case with high efficiencies. This efficiency of 59.4 per cent. may be considered about the maximum

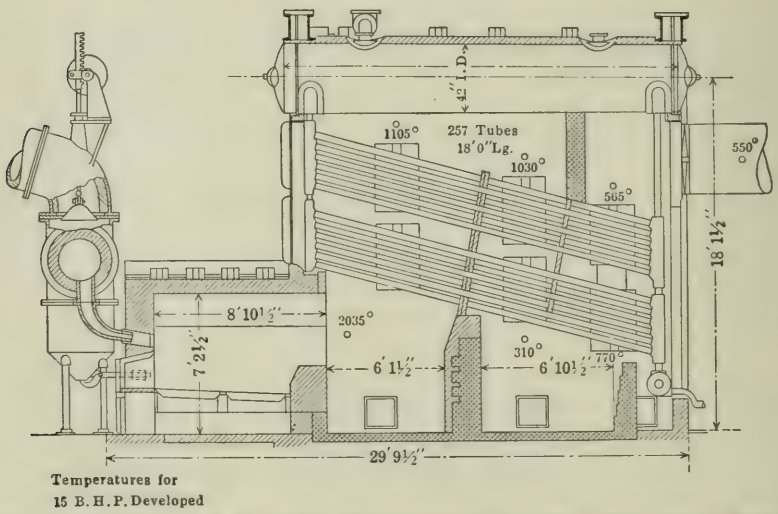


FIG. 103.—500-hp. B. & W. boiler. National Tube Company, McKeesport Works.

under present conditions and equipment, and indicates that, with the attention to details of operation as discussed above, a continuous operating efficiency of about 58 per cent. is possible at rating up to 175 per cent. of full load. It would seem that this is a very low figure, yet it is safe to say that it is exceeded in but very few blast furnace boiler plants. The efficiency of the Duquesne blast furnace boilers at the present time is in the vicinity of 55 per cent., the plant furnishing steam in addition to all blast furnace requirements, electric power

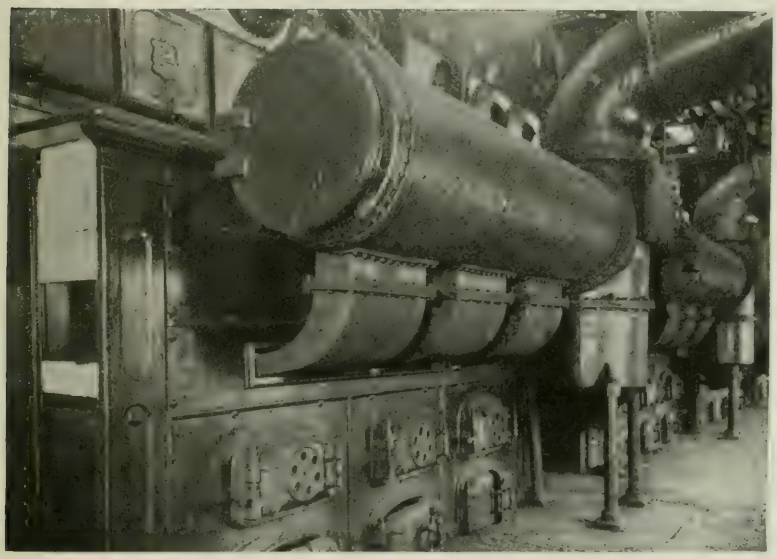


FIG. 104.—McKeesport boiler setting. Wilson regulating valve.

and water pumping, at the rate of 2000 b.hp. per furnace. Twenty-two plants of the United States Steel Corporation, having a total boiler horsepower of 241,504, show an average operating efficiency of 55 per cent.

An example of the high efficiencies that are possible with the old-style burner, coupled with large boilers, long combustion chambers, excellent condition of settings and baffles, sufficient air supply, damper regulation, and close attention is presented in the performance of the 500-hp., B. & W. boilers (Fig. 103) at the National Tube Company at McKeesport, Pa. (see cut on page 388). The observations and calculations at McKeesport were checked by the Experimental Engineering Department of the Duquesne Works, and are shown below:

Per cent. of rating developed		155%
Furnace gas analysis	CO_2	13.0
	CO	25.6
	H_2	3.2
Combustion chamber analysis	CO_2	24.7
	O_2	0.1
	CO	2.0

Stack gas analysis	CO_2	21.2
	O_2	3.7
	CO	0.6
Gas pressure		.....
Draft in furnace		.....
Furnace gas temperature		300°F
Combustion chamber temperature		2,040°F
Stack temperature		545°F
Calorific value of furnace gas per cubic foot	B.t.u.	91.9
Sensible heat of furnace gas per cubic foot	B.t.u.	4.8
Total heat of furnace gas per cubic foot	B.t.u.	96.7
Sensible heat lost in stack		19.0%
Unconsumed CO lost in stack		3.7
Radiation (assumed)		5.0
Efficiency		72.3

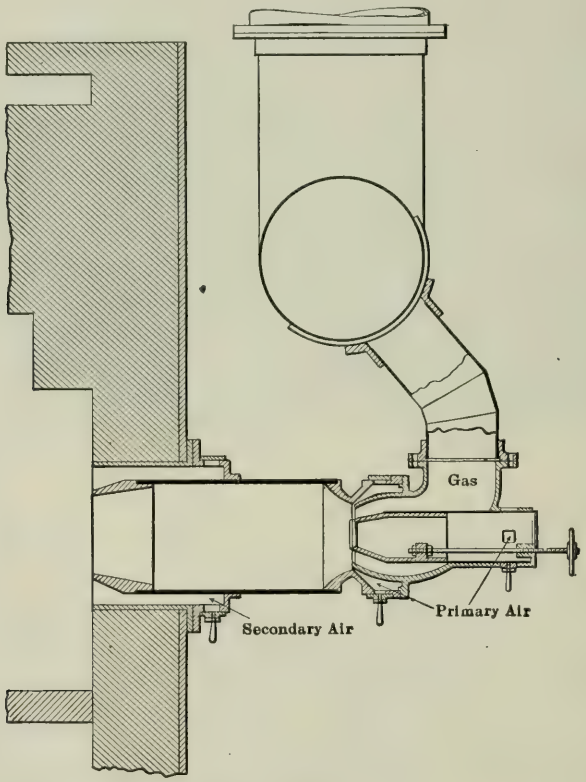


FIG. 105.—Birkholz-Terbeck burner for blast-furnace gas.

The good analyses and high temperature in combustion chamber are attributed to proper air supply and long Dutch Oven, and the good stack analyses and low stack temperature to the excellent condition and attention to the settings and baffles. The average monthly efficiency of the plant, as stated by their

engineering department, is 68 per cent. An excellent gas valve, designed by Mr. J. W. Wilson, assists in the gas control.

Type 2.—Rectangular or circular burner with air conducted into the gas jet by means of pipes or other openings, and auxiliary ports through which additional air is admitted around the burner nose.

Two forms of the Birkholz-Terbeck burner, which is of this type, are shown in Figs. 105 and 106. The form shown in Fig. 106, which is the simpler of the two, will be discussed, as both are the same in principle. The primary air is admitted in a nozzle placed in the back of the burner. Gas from the pipe above passes around this nozzle and mixes with the air in the section of pipe following. The theory is that the gas, in passing through the throat into the larger area of the mixing chamber, has its pressure reduced and thereby induces flow through the air nozzle proportional to the flow of gas. That sufficient air cannot be aspirated in this manner is shown by the provision of a secondary inlet at the nose of the burner, which is affected by stack draft to the same extent as the space surrounding the nose of a common burner, and which probably supplies as much air as the primary inlet. Therefore, this portion of the air is not mixed before the ignition point. No record of gas analyses in the combustion chamber or flame temperatures are available from tests of these burners. However, at the South Works of the Illinois Steel Co., comparative tests which were run simultaneously on two 325-hp. Stirling boilers in the same battery and at the same rating show similar stack analyses and temperatures, and about equal efficiencies for both the Birkholz-Terbeck and the common burners. A large number of tests were run on a 325-hp. Rust boiler, the one in condensed form following, being representative of the general average:

		Common	Birkholz-Terbeck
Per cent. of rating developed		130	130
Furnace gas analysis	CO_2%	14.0	14.0
	CO	25.0	25.0
	H_2	3.6	3.6
Combustion chamber analysis	CO_2%	.....	.....
	O_2	.....	.....
	CO	.....	.....
Stack gas analysis	CO_2%	21.4	22.8
	O_2	3.8	2.8
	CO	0.0	0.3
Gas pressure		0.15	0.7
Drafts in furnace		.....	.....
Furnace gas temperature, deg. F		45	45
Combustion chamber temperature, deg. F		.....	.....
Stack temperature		872	823
Calorific value furnace gas, cu. ft. B.t.u.		91.9	91.9
Sensible heat of furnace gas, cu. ft. B.t.u.		0.3	0.3
Total heat of furnace gas, cu. ft. B.t.u.		91.6	91.6
Sensible heat lost in stack		36.6%	32.8%
Unconsumed CO lost in stack		0.0	1.8
Radiation (assumed), per cent.		5.0	5.0
Efficiency, per cent.		58.4	60.9

At the Ohio Works of the Carnegie Steel Company, tests were conducted on two 400-hp. Stirling boilers fired with mixed rough and washed blast furnace gas. One boiler was equipped with a Birkholz-Terbeck burner, similar to Fig. 106

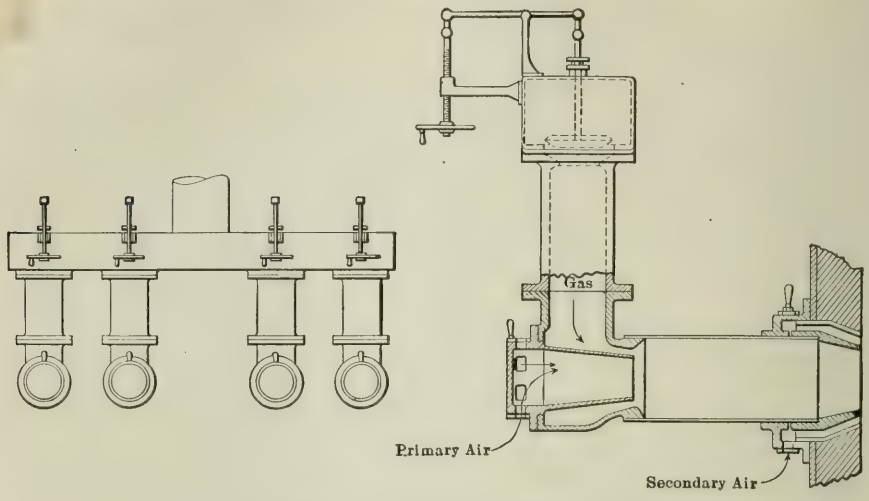


Fig. 106.—Birkholz-Terbeck burner for blast-furnace gas.

(page 390), and the other with the Ohio Works burner, Fig. 107. Continuous tests were run for nineteen days, results being shown on curve sheet A.

The rapid decrease in efficiencies and capacities of both boilers and the high stack temperatures is due to accumulation of flue dust which cannot be blown

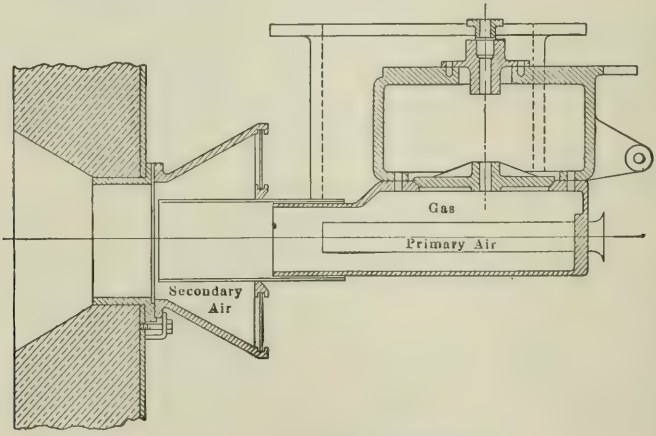


Fig. 107.—Ohio Works burner.

from the tubes, the boilers being too close together to permit free use of good blowing apparatus. Owing to this condition the boilers are taken out of service at frequent intervals and the dust removed.

The following figures are taken from a 24-hr. complete test, run when the boilers were comparatively clean, and indicate that the burners are of about equal merit, the 4 per cent. higher efficiency of the Birkholz-Terbeck being attributed to the fact that the setting of the boiler on which it was tested was in better condition than the other boiler. The data from this test has been used to calculate efficiencies by the indirect method, for sake of comparison with the other tests quoted.

			Birkholz-Terbeck	Ohio works, Fig. 107
Per cent. of rating developed		%	136.5	123.3
Blast furnace gas analysis	CO_2	%	14.4	14.4
	CO	%	24.8	24.8
	CH_4	%	0.6	0.6
	H_2	%	2.5	2.5
Combustion chamber gas Analysis	CO_2	%	....	....
	O_2	%	....	....
	CO	%	....	....
Stack gas analysis	CO_2	%	23.2	19.9
	O_2	%	1.6	4.2
	CO	%	0.6	0.8
Gas pressure		In. H_2O	3.7	3.7
Furnace draft		In. H_2O	.....	....
Furnace gas temperature		Deg. F.	210	210
Combustion chamber temperature		Deg. F.	.....	....
Stack temperature		Deg. F.	790	760
Calorific value of fce. gas per cu. ft.		B.t.u.	92.8	92.8
Sensible heat in fce. gas per cu. ft.		B.t.u.	3.0	3.0
Total heat in fce. gas per cu. ft.		B.t.u.	95.8	95.8
Sensible heat loss in stack		%	28.6	30.8
Unconsumed CO loss in stack		%	3.3	5.1
Radiation		%	5.0	5.0
Efficiency		%	63.1	59.1

Comparative tests at Wisconsin Steel Co., were made on two 350 hp. Stirling boilers side by side, one with the Birkholz-Terbeck and the other with the common burner. The efficiencies were calculated on a basis of Pitot tube measurements of the gas and show decided differences in efficiencies between the boilers equipped with the two types of burners, although the outputs and stack analyses were the same and the stack temperatures only 37°F. different, corresponding to only about 2 per cent. difference in efficiencies. The data from these tests calculated by the indirect method, for sake of comparison with other tests reported in this paper, gives the following results:

BIRKHOLZ-TERBECK AND COMMON BURNER, WISCONSIN STEEL CO. .

First test			Birkholz-Terbeck burner	Common burner
Per cent. of rating developed			127	130
Blast fce. gas analysis	CO_2	%	15.1	15.1
	CO		23.6	23.6
	H_2		3.0	3.0
Comb. chamber gas analysis	CO_2	%	.....	.....
	O_2		.....	.....
	CO		.....	.....
Stack gas analysis	CO_2	%	21.1	20.8
	O_2		3.6	4.3
	CO		0.0	0.0
Gas pressure		Ins. H_2O	.....	.....
Furnace draft		Ins. H_2O	.....	.....
Furnace gas temperature		°F.	267	267
Combustion chamber temperature		°F.	.....	.....
Stack temperature		°F.	615	652
Calorific value of fce. gas per cubic foot		B.t.u.	84.8	84.8
Sensible heat in fce. gas per cubic foot		B.t.u.	4.1	4.1
Total heat in fce. gas per cubic foot		B.t.u.	88.9	88.9
Sensible heat loss in stack		%	25.8	28.0
Unconsumed CO loss in stack		%	0.0	0.0
Radiation loss		%	5.0	5.0
Efficiency		%	69.2	67.0
Second Test.				
Poor regulation on common burner		Eff.	68.4	59.2
Third Test.				
Poor regulation on common burner		Eff.	71.4	59.7

The Bradshaw burner shown in Fig. 108, is supposed to follow the Venturi meter principle. It consists of a rectangular casting, through which gas passes. Air is admitted through narrow openings, top and bottom, the width of the burner. At this point the casting is contracted and the reduction in pressure due to increase in velocity provides the medium for air aspiration.

The casting then flares out to permit expansion from the throat of the burner into the furnace. It is claimed for this burner that there will be aspirated a quantity of air in direct proportion to gas quantity for varying capacities. Experimental proof of this statement has been repeatedly requested from the designers but up to the present time has not been produced. In order to obtain this information, engineers from the Duquesne Works made experiments on Bradshaw burners installed on 500 hp. Stirling boilers (Fig. 110) at the works of the Pittsburgh Steel Company, Monessen, Pa. At the same time comparative tests were made on modifications of the Bradshaw burner, designed by Mr. J. S. Fraser, Supt. of Blast Furnaces.

The makers of the Bradshaw burner state: first, that their best operation is by means of maintaining a constant furnace draft at a point which has been previously determined by test as giving correct air supply; second, that if this

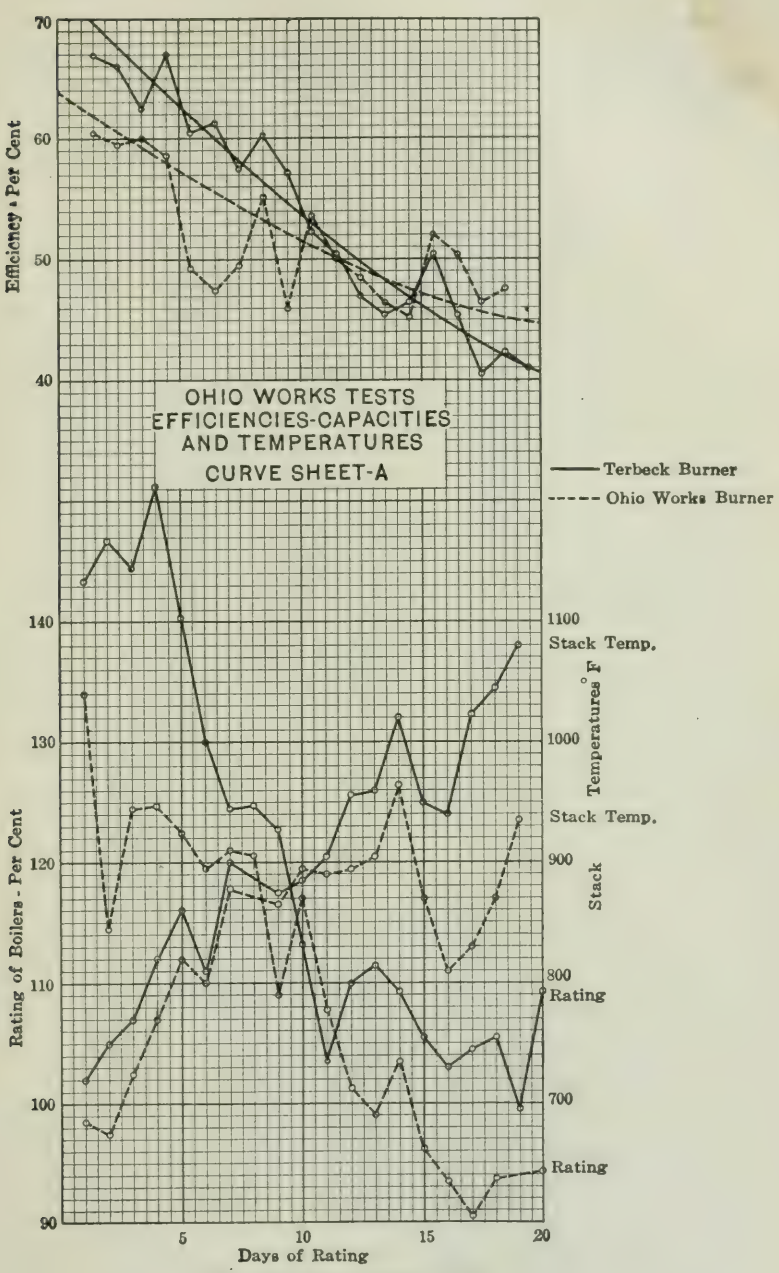


FIG. 108.—Ohio Works tests.

draft is maintained, the proper quantities of air will be drawn into the burner over reasonable limits of gas pressure variation, say from 2 in. to 10 in. H_2O; third, that, without balanced draft, the average efficiency will be about 5 per cent. less than with it.

The experiments were made for this latter condition, in order to investigate the characteristics of the burner without automatic regulation. The damper was placed in a position to give a good gas analysis in combustion chamber

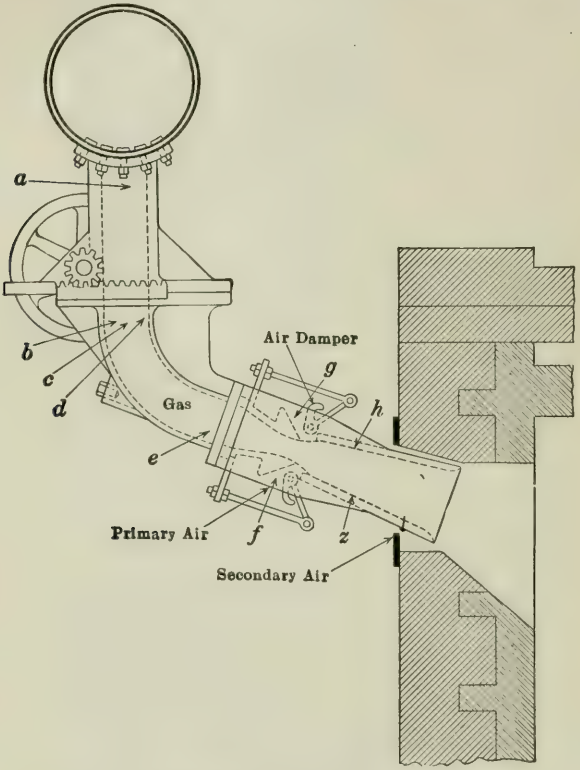


Fig. 109.—Bradshaw burner for blast-furnace gas.

at one gas pressure. Observations were then taken on air drafts and temperatures, with varying gas pressures, with results as shown in Fig. 130, the efficiency over the usual working range of pressure averaging 65.1 per cent.

The boiler test results show that with an increase of gas above the amount for which the original adjustments were made, there results 8.2 per cent. loss due to CO in the stack gases, proving that air in proportion has not been induced. Making due allowance for the 5 per cent. difference between balanced and unbalanced draft, we consider this a fair test of the aspirating possibilities of the burner.

Corresponding observations were made on Mr. Fraser's first modification of the Bradshaw burner which will be referred to hereafter as Fraser burner No 1. The main difference lies in taking air to the contracted portion of the gas jet

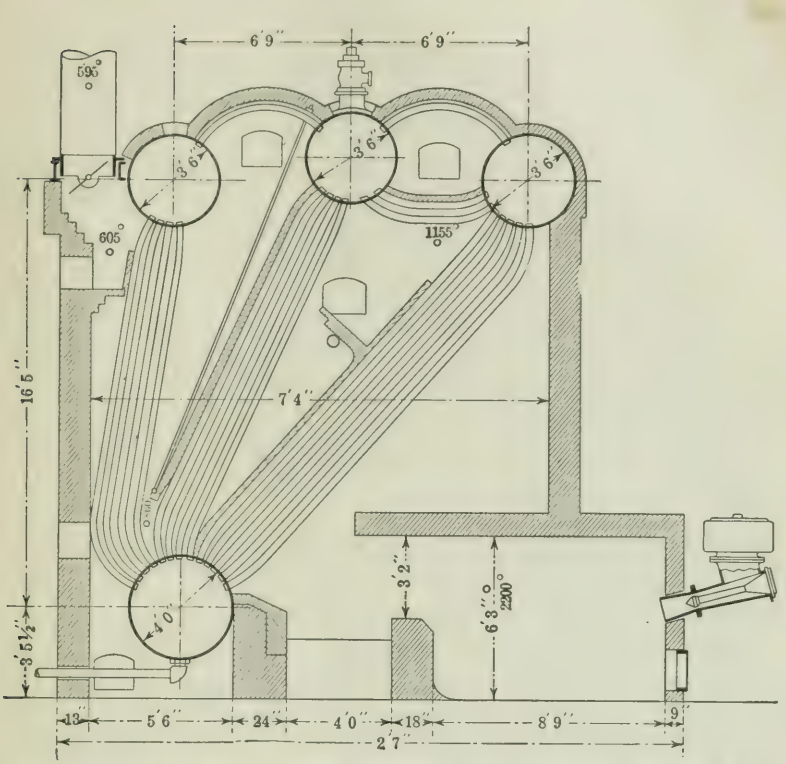
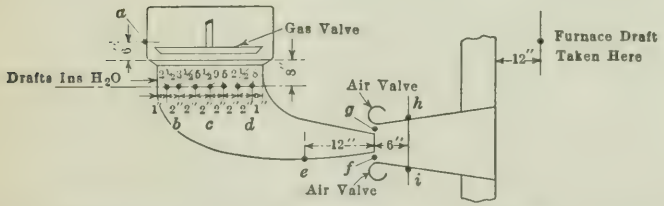


FIG. 110.—500-hp. Stirling boiler, Pittsburgh Steel Company, Monessen, Pa.



Burner Data										Boiler Data									
Mixture Orifice Opening from Gas Valve	Gas Pressure above Valve Point 4	Draft at Points								Furnace		Stack Damper Opening	Stack Gas				Heat Balance				Remarks
													Analysis								
		b	c	d	e	f	g	h	i	Draft	Temp. °F		CO_2	O_2	CO	Temp. °F	Sensible Heat Loss	CO Loss	Radiation	Efficiency	
12	12	2.5	9	.8		.45	.15		.7	.15	2200	½ open	17.8	6.0	.4	575	24.7	2.8	5.0	67.5	Working Conditions
11¾	14	2¾	2.5	1		.40	.55			.20	2255	" "	15.2	8.1	0	550	27.8	0.0	5.0	67.2	Gas Reduced
12	13½	2	2	1¾		.50	.80		.65	.08	2155	" "	17.5	6.0	1.2	580	24.5	8.2	5.0	62.7	Gas Increased
11¾	13	2½	6½	2½		.35	.35		.4	.20	2220	Full	14.2	8.8	0	585	32.0	0.0	5.0	63.0	Gas Reduced
12½	11½	½	¾	-2½	0 to 6		.60	.20	.75	.60	Atm.	Dropped	"	Not taken							Entirely too much Gas

FIG. 111.—Test of Bradshaw burner at Monessen.

TEST RESULTS FRASER BURNER NO. 1

Test number		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.
Per cent. rating developed		.....	.....	.....	.....	.....	.....	.....
Furnace gas analysis	CO_2%	13.2	13.2	13.2	13.2	13.2	13.2	13.2
	CO	27.1	27.1	27.1	27.1	27.1	27.1	27.1
	H_2	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Comb. chamber analysis	CO_2%	21.2	22.8	23.3	23.6	23.9	23.6	24.0
	O_2	3.2	1.8	1.3	0.5	0.3	0.0	0.0
	CO	0.8	0.5	0.6	2.1	1.8	4.2	3.9
Stack gas analysis	CO_2%	.....	.....	17.9	19.2	18.8	19.7	20.6
	O_2	.....	.....	5.7	3.9	4.0	3.3	2.9
	CO	.....	.....	0.2	1.1	1.2	4.1	3.0
Gas pressure, ins. H_2O		.....	8½	13	14	14½	14	21½
Draft in furnace, ins. H_2O		0.35	0.19	0.17	0.12	0.10	0.05–0.07	0–0.05
Fce. gas temperature, °F		.....	400	400	400	400	400	400
Comb. chamber temperature, °F		.....	2180	2230	2250	2300	2085	2150
Stack temperature, °F		.....	.....	570	615	595	540	605
Calorific value fce. gas cu. ft., B.t.u		96.1	96.1	96.1	96.1	96.1	96.1	96.1
Sensible heat fce. gas, B.t.u		6.7	6.7	6.7	6.7	6.7	6.7	6.7
Total heat fce. gas cu. ft., B.t.u		102.8	102.8	102.8	102.8	102.8	102.8	102.8
Sensible heat lost in stack, %		.....	.....	24.8	23.9	23.5	17.6	20.2
Unconsumed CO lost in stack, %		.....	.....	1.4	6.9	7.6	21.8	16.1
Radiation		.....	.....	5.0	5.0	5.0	5.0	5.0
Efficiency		.....	.....	68.8	64.2	63.9	55.6	58.7

inside instead of outside. In this first design the side gas passages past the air box were made too small, resulting in only a small amount of gas passing under the air box.

Test results and observations of drafts and pressures follow. Several tests were run on both boilers, the best results in each case being presented. During these tests the gas valves remained in the same position, and adjustments made to stack damper. Consequently gas pressures indicate pressure in burner and quantity of gas burned.

Draft readings Fraser burner No. 1
Gas pressures

Draft in air ports	Main	Top burner (point A)	Bottom burner (point B)	Fce. draft	Remarks
0.33	9	4¾	1 3/16	0.25	Working conditions.
⅜	14	8½	1¼	.....	Working conditions.
.38	8	4¼	¾	0.28	Working conditions.
½	21	8¼	1⅝	0.05	Working conditions (Damper partly closed.
⅜	21	8½	1¾	+Atm.	Temp. in c.c. dropped. Comb. very poor.)
0.29	7	....	....	.....	Combustion poor.
7/16	13	....	....	0.15	Combustion poor.
11/16	13½	....	....	0.08	Combustion poor.

It will be noticed in the above table that the draft in air ports was small and did not vary with gas pressure, due to the poor aspirating effect of the restricted gas flow.

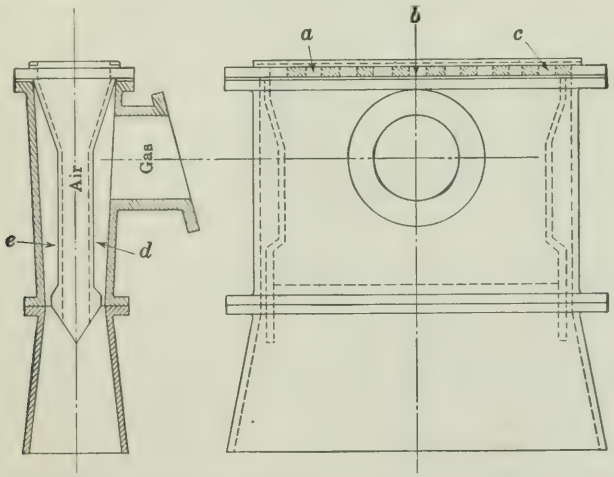


FIG. 112.—Fraser's modification of Bradshaw gas burner.

Fraser burner No. 2 (Fig. 112) was designed to provide ample passage for gas on sides of air box, which resulted in more nearly equal gas pressures at top and bottom of burners. Tests and draft observations follow:

TEST OF FRASER BURNER NO. 2

		No. 1.	No. 2	No. 3	No. 4
Per cent. of rating developed		.....	.....	.....	.....
Furnace gas analysis	CO_2%	13.2	13.2	13.2	13.2
	CO	27.1	27.1	27.1	27.1
	H_2	3.0	3.0	3.0	3.0
Comb. chamber analysis	CO_2%	23.2	24.0	22.6	23.8
	O_2	2.5	0.5	3.1	1.9
	OC	0.6	2.9	0.2	0.7
Stack gas analysis	CO_2%	18.8	18.6	18.7	16.9
	O_2	5.9	4.9	5.4	7.9
	CO	0.0	1.1	0.0	0.0
Gas pressure, ins. H_2O		12½	14½	16½	9
Draft in furnace, ins. H_2O		.08–.10	.19–.24	.05–.07	.31–.33
Fce. gas temperature, °F		360	340	330	330
Comb. chamber temperature, °F		2190	2180	2190	2170
Stack temperatures, °F		645	650	680	605
Cal. val. fce. gas/cu. ft., B.t.u.		96.1	96.1	96.1	96.1
Sensible heat F. gas/cu. ft., B.t.u		6.0	5.7	5.5	5.5
Total heat fce. gas/cu. ft., B.t.u		102.1	101.8	101.6	101.6
Sensible heat lost in stack, %		27.5	26.2	29.2	28.4
Unconsumed CO lost in stack, %		0.0	7.1	0.0	0.0
Radiation, %		5.0	5.0	5.0	5.0
Efficiency, %		67.5	61.7	65.8	66.6
		(Unusual operation conditions.)			(Screens partly closed.)

Damper remained in fixed position and gas valve changed
Draft observations of Fraser burner No. 2

Draft in air ports			Gas pressure			Furnace		Remarks
R.E.	Center	L.E.	Main	Top burner	Bottom burner	Draft	Temp.	
1⅜	1⅜	1⅜	18	4	3½	0.18	2205	(Working conditions.)
2¼	2¼	1¾	17	7½	6	0.05	2255	(Gas added.)
2¼	2¼	1¾	16½	7	5¾	0	2235	(Too much added.)
1⅝	1⅝	1½	17	5½	3½	0.10–0.12	2270	(Working conditions. Gas reduced.)
1⅛	1¼	1¼	10	3	2½	0.17	2165	(Working conditions.)

The tests of Fraser burner No. 2 show an average efficiency of 65.4 per cent. slightly better than shown by the Bradshaw burner under the same operating conditions. Observations of the boilers also indicated very clearly that the

Fraser burner handled greater quantities of gas than the Bradshaw with the same gas pressure. The conclusion to be drawn from these experiments is that the Bradshaw burner, supposedly proportioned with mathematical precision, shows no better efficiencies than the Fraser burner, designed merely with the plain aspirating or injector principle in view, and proportioned by trial to efficiently operate with the pressure and volumes of gas available.

Observations of temperature were made from time to time in the combustion chamber of each boiler from No. 1 to No. 17, as per tables following. This was done by means of a Wanner Optical Pyrometer carefully calibrated and then checked on the work against a standard couple in the furnace of one of the boilers. Two series of stack temperatures are also included.

These figures show that with the same amount of attention and the same pressure conditions throughout the house, the pipe burners (similar to Fig. 107), Fraser, and Bradshaw burners produce about equal results. It might be added that this boiler equipment is kept in excellent condition, the settings being possibly not as tight as on the McKeesport boilers, but much superior to the average installation.

Boiler No.		Combustion chamber temperatures								Stack temperatures	
		Series 1		Series 2		Series 3		Series 4		Series 1	Series 2
		Right	Left	Right	Left	Right	Left	Right	Left		
Pipe Burner 1–5	1	2020	1980	2060	2090	2080	2140	2040	2020	565	640
	2	1975	2060	2050	2060	2140	1900	2150	2080	575	570
	3	....	....	2110	2090	2140	2100	....	....	515	580
	4	1980	1975	....	....	....	....	....	....	...	...
	5	2190	2160	2070	2175	1980	2090	2000	2135	555	560
Fraser No. 2	6	2160	2240	2230	2290	2080	2150	2290	2285	555	550
Fraser No. 1. 7–11	7	2110	2230	2150	2140	2230	2095	2280	2200	595	560
	8	2240	2335	2195	2080	2170	2010	2160	2260	595	560
	9	2340	2260	2225	2265	2115	2125	2305	2270	595	550
	10	2080	2280	2050	2000	2140	2195	2200	2240	565	...
	11	2080	2240	2060	2140	2125	2225	2230	2100	625	...
Bradshaw	12	2200	2200	2230	2080	2230	2090	2260	2180	645	646
	13	2210	2160	2020	2080	2190	2220	2150	2260	595	...
	14	2160	2160	2075	2070	2250	2180	2170	2200	575	630
	15	2240	2175	2060	1950	2230	2115	2130	2140	575	...
	16	2190	2250	2130	2095	2230	2120	2300	2260	655	674
	17	2080	2200	2085	2135	2165	2190	2200	2220	605	...

Type 5.—Burners through which all of the air is forced and completely mixed with the gas before the ignition point.

Due to our own failure to develop an aspirating burner of high capacity and to the lack of evidence that it had been accomplished elsewhere, the investigation of forced draft was the next logical step. The arrangement of burner is

shown on Fig. 113. All the air required for combustion was supplied by a motor driven fan. Air enters the rectangular box at the back of the burner, and after passing through the short pipes, mixes with the gas. From the point where the air and gas meet, they travel together and become thoroughly intermingled before reaching the point of ignition, at the end of the burner. To supply the air theoretically required for complete combustion is purely a matter of speed

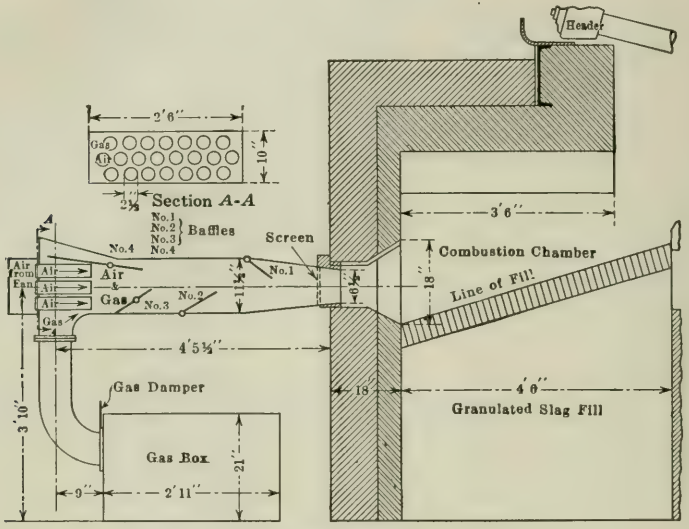


FIG. 113.

of the fan, or control of the air by means of dampers. To thoroughly mix the air and gas is more difficult, but by careful regulation a burner efficiency of 96 per cent. was obtained. During the experiments the air supply was controlled by hand and the maintenance of good combustion required almost constant attention by the testing engineer due to rapid variations in the gas pressure even in the narrow limits of 5 to 7 in. In a working arrangement of forced draft, the speed of motor or engine driving the fan should be controlled by gas pressure. By this method of positive air supply, a burner efficiency close to 100 per cent. may be maintained at any desired capacity.

Results of a representative test on the forced draft equipment on a 250-hp. B. & W. boiler follows:

Per cent. of rating developed		166
Furnace gas analysis	CO_2	14.7%
	CO	25.0
	H_2	3.1
Comb. chamber analysis	CO_2	24.6%
	O_2	0.8
	CO	0.8
Stack gas analysis	CO_2	21.9%
	O_2	3.1
	CO	.....

Gas pressure	2.5
Draft in furnace	½" Pres.
Furnace gas temperature	35°F.
Comb. chamber temperature	2090
Stack temperature	719
Calorific value fce. gas/cu. ft.	89.6%
Sensible heat fce. gas/cu. ft.	–05
Total heat of fce. gas/cu. ft.	89.1
Sensible heat lost in stack	29.9%
Unconsumed CO lost in stack	0.0
Radiation (assumed)	3.5
Efficiency	65.6

Discussion by Henry P. Howland

Superintendent of Blast Furnaces, Wisconsin Steel Company, South Chicago, Ill.

The title of Mr. Diehl's paper covers a subject peculiarly difficult, due to the fact that its consideration is comparatively new and that reliable information is very hard to obtain. In reading the paper one is impressed with the thoroughness and fairness with which the paper has been written. One is further impressed with the fact that there are a great many different gas burners and that many of them do fairly good work.

A year ago at the Wisconsin Steel Company we attempted to increase the efficiency of our gas-fired equipment. Thus far we have installed three pressure burners on our stoves and sixty-six Birkholz-Terbeck burners at our boilers. Our first step in approaching this problem was the installation of checkers in the bottom 25 ft. of the combustion chamber of No. 1 stove. This increased the stove efficiency, but impeded the flow of gas to such an extent that we were unable to use the stove to its full capacity. The next move was the equipping of No. 2 stove with a pressure burner. The air for this burner was supplied through an 18-in. pipe by a No. 9 Sturtevant fan. Having all other air inlets closed we were now able to compel the stove to burn all the gas desired. This type of burner has been expected to effect quite a gas saving by increased stove efficiency. In this we were disappointed.

Saving of Gas Not Effected by Burner Alone.—After several tests of stoves equipped with and without this burner, we were forced to conclude that with equipment such as ours, namely, stoves with large checker openings, small total heating surface relative to radiating surface and poorly insulated shells, the burner in itself will not effect any gas saving. The per cent. of radiation and stack loss remained practically the same. On these stoves the radiation loss per stove increases practically in the same proportion as the work done by the stove. That is, the total radiation loss on the stove system is practically the same regardless of the number of stoves in use. This may be explained on the ground that the increased pressure in the stove as created by the pressure burner tends to raise the shell temperature. Whether this condition would be true in the case of well insulated shells, we had no way of ascertaining.

In the endeavor to cut down the increased radiation and stack loss, due to forcing the stove by the use of the pressure burner, checkers were installed in the combustion chamber of No. 2 stove. Supported on arches located about 6 ft. above the bottom of the combustion chamber, these checkers extend 57 ft. to the top of the chamber. They are built with 9-in. openings and 4½-in. wall, adding 3800 sq. ft. to the heating surface of the stove. When the pressure burner was now used on this stove, both the stack and radiation loss was found to have been reduced to a marked degree resulting in greatly increasing the stove efficiency. By equipping No. 1 and No. 5 stoves in the same manner, we were able to operate with three stoves. The net result is as follows:

October, 1914.—Five stoves in use burning 21,000 cu. ft. of gas per minute and heating the blast (36,000 cu. ft. of air per minute) to 1100°F.

September, 1915.—Three stoves in operation using 16,000 cu. ft. of gas and delivering the same total blast heat.

How large a quantity of gas one of these burners will burn completely has not been determined. With the gas-main pressure as high as 10 in., we were able to force 9500 cu. ft. of gas per minute through the checker-obstructed combustion chamber and burn it completely. Under these conditions, the pressure in the combustion chamber was 3½ in. and at the chimney valve about ¼ in.

Burner Regulation.—This burner lends itself easily to correct regulation. The gas and air mains are equipped with U tubes and regulating valves. The pressures necessary to give complete combustion are ascertained. With the pressure at the required points, the stove tender not only is assured of the required heat, but that the quantity of air supplied is correct. During the past year we have analyzed our stack gases day and night, and find that generally the pressure burner is giving a gas with less than 1 per cent. of either carbon monoxide or oxygen which, compared to our former practice, would be called "complete combustion."

The power required to deliver the air to these burners will, of course, depend upon many local conditions. Delivering 9000 cu. ft. of air per minute at 20-in. pressure requiring two No. 9 Sturtevant fans, the power consumed is, approximately, 45 kw. On the basis of a production of 500 tons per day and ½ cent per kilowatt hour, the power cost thus amounts to 1 cent per ton of iron.

Eliminating the Combustion Chamber.—You have seen that we accomplished the desired gas saving by using the checkers in the combustion chamber in connection with the pressure burner. Due to their location, these checkers are four times as efficient per square foot of heating surface as the original checkers. We have three stoves equipped with the pressure burner, in which the combustion chamber has been practically eliminated. This method of construction has possibilities which may be of value in designing future stoves.

In order to increase the amount of gas passing through the pressure burners, it is necessary to increase the gas-main pressure. The advisability of this practice is doubtful from the standpoint of efficient furnace operation, since it seriously increases the pressure on top of the furnace. We would propose that instead of using the furnace to create this increased pressure, a booster be located in the gas main. The same result could probably be obtained by using an exhauster on the chimney side of the stove. This latter suggestion offers possibly a simpler operating proposition, more especially in view of the probability that with new stoves of proper design, stack heats may be so low as to interfere with the chimney draft.

Hand Regulation of Burner Desirable.—Turning to the problem of boiler burners, we find ourselves inclined to more enthusiasm in favor of some such burner as the Birkholz-Terbeck type than that expressed by the author of the paper. This burner provides an easy, convenient hand regulation of the proper amounts of air and gas for complete combustion, and a mixing chamber for the air and gas before entering the boiler setting. The author has, in our opinion, placed too much emphasis upon variation in boiler house gas-main pressure. At most plants there is no great variation in this pressure from hour to hour or day to day. Consequently, if a ready means for hand regulation is provided and stack gas regularly analyzed there is no reason why reasonably high efficiencies cannot be attained by boiler house operatives.

In the case of the "Common burners," as termed by the author, which are in most general use at the present time, no means is provided for the boiler house superintendency to manipulate or regulate the gas and air mixture, and it is therefore fruitless to provide them with means of analyzing the stack gases.

However, when it comes to comparing by a test the new and old burner, it is always

possible, as suggested by Mr. Diehl, to stick in "a brick or a ball of clay" thereby getting approximately the correct regulation and bring up the efficiency of the old burner much above the regular and usual practice.

Boiler Plant Efficiency with Burners.—Mr. Diehl places the average efficiency of the furnace boiler plant using the "common burner" at "not over 50 per cent. and frequently much lower." We had an excellent opportunity to test nine of our boilers equipped with thirty-six Birkholz-Terbeck burners. Only one furnace being in operation, we carefully measured the gas to the stoves and boiler house, and accurately figured the gas produced by the furnace thus checking our gas input. The feed water and gas was measured for a period of 8 hours. The burners were not touched by any one—in other words, it was a regular operating condition. The result was 68 per cent. efficiency. We believe this represents a big improvement over our practice on these same boilers equipped with the common burner.

We would conclude as follows: For use on stoves we believe the pressure burner to be preferable. Regarding boiler burners, first, the point of automatic regulation, as emphasized by Mr. Diehl, does not seem to us to be vitally essential; second, it should be admitted by all that a big step in advance has been taken in equipping a boiler house with burners capable of easy hand regulation in the place of the so-called "common burner."

Discussion by A. E. Maccoun

Superintendent, Edgar Thomson Blast Furnaces, Carnegie Steel Company, Braddock, Pa.

Mr. Diehl has covered his subject of burning blast furnace gas in stoves and boilers very thoroughly, and has given us details of the various methods in use. As he has pointed out, it was impossible to develop and arrive at an efficient gas burner for this purpose before the use of clean gas under uniform conditions of pressure, moisture, etc., was introduced. The cleaning of blast furnace gas has given the blast furnace operator these conditions, and since its introduction many refinements in the construction of gas burners have been made, and still further refinements will be made in the future to obtain the maximum efficiency possible under our different conditions. We must not lose sight of the fact that in conjunction with any burner the design of stoves or boilers must be adapted to burning blast furnace gas if we are to obtain the best results.

Nearly all burners described are modifications with improvements in details of the old Bunsen or Spearman type of burner. The efficiency of all these burners depends on the thorough pre-mixing of the proper proportions of air and gas, so as to obtain more nearly perfect combustion. This, on some of the newest types of burners, approximates 98 per cent. With the old type of Spearman burner used on the stove test which I outlined in my paper on "Blast Furnace Advancement" before the Iron & Steel Institute in May, 1915, an average stove efficiency of 61 per cent. was shown; but I called attention in this paper that the gas in the combustion chamber burned progressively in vertical layers, that the samples above the burner always showed poorer combustion than at the burner level, and that combustion was not complete until the gases had passed out of the combustion chamber into the dome of the stove. By burner refinements, as described by Mr. Diehl, these conditions were greatly improved, and various long tests made on this same stove under the same operating conditions showed an increase in stove efficiency, the average of these tests showing an efficiency of 71 per cent. This improvement was all due to better mixing of gas at the burner and the use of a burner design that eliminated the burning of gas explosively and the throwing out of flame around the burner.

There are three principal methods of mixing gas used by the various burners described.

First, the velocity mixing type.

Second, the vane mixing type.

Third, the type which mixes by impinging air and gas streams into each other.

Efficient gas burners can be constructed by the use of each of these principles, and as Mr. Diehl has shown, there is no type which has been developed at the present time that we may safely say is the most efficient burner. We may only decide which type of burner is the most efficient after thorough and reliable tests, for at the present time the various types of gas burners have not been tried out long enough in practice, and sufficient detailed tests have not been made, to arrive at any such conclusion.

This paper brings to your attention the various developments being made in the different methods of burning blast furnace gas. We can still look for further improvements to be made along these lines in the future.

MODERN DEVELOPMENT IN THE COMBUSTION OF BLAST-FURNACE GAS WITH SPECIAL REFERENCE TO THE BRADSHAW GAS BURNER

By K. Huessener,[1] Pittsburgh, Pa.

Introduction.—This paper attempts a survey of the principles involved in the combustion of blast-furnace gas in boilers and stoves. I do not expect to be able to give much information which is actually new, since the laws and methods of calculation pertaining to this problem are contained in a number of handbooks; but, so far as I am aware, they have nowhere been treated exclusively with reference to this one problem of gas economy. The road which I follow is less that of strictly scientific research than that of the practical engineer, faced by operation problems which require a quick solution by easily accessible means without a prolonged search in scientific handbooks. For this purpose I give a number of tables and diagrams, as well as the results of many years' practical working experience as combustion engineer, which I trust will prove useful to my readers.

Historical.—Considering the tremendous efforts made during the last 15 years to increase the efficiency of all kinds of power plants, it is highly surprising that until a comparatively very recent period, progress in the economical combustion of blast-furnace gas has been so slow.

The explanation generally put forth, that fuel has been so cheap that it was hardly worth while to bother about this economy, will not hold good, for the greatest trouble was taken to improve the combustion of coal and to reduce the consumption of steam. The most plausible explanation appears to be the general impression, held as an accepted fact, that gas, especially hot, uncleaned, blast-furnace gas, was not a good boiler fuel. Many managers of high repute had tried unsuccessfully to improve the conditions of its use, and the dictum went forth that efficiencies of over 60 per cent., particularly with high loads, were impossible. This was the situation not only in the United States, with very cheap fuel, but also in Europe, where fuel prices are twice and three times as high.

The failure to improve conditions was, to a large extent, due to the type of boilers mostly in use up to the last 5 or 6 years. This also is true for both America and Europe. In America, one-pass boilers of the Cahall, Cook and Wheeler types were used in large numbers, and the boiler capacity was not always sufficiently large so that overload was frequently necessary. While with up-to-date

[1] President, The Huessener Engineering Co., Inc.

combustion arrangements fair efficiencies can be obtained at the present time from these one-pass boilers, they have baffled at least all my efforts to secure that result with an overload.

In Europe 90 per cent. of all blast-furnace boilers were internal-flue horizontal boilers, and as the gas was not cleaned, dirt accumulated in the flues and rendered good efficiencies impossible, however good the combustion itself might have been. The natural expedient in this case was to clean the gas.

In the case of water-tube boilers it was of course possible to remove the dust by the use of soot blowers or steam- or air-blowing lances. This could not be done with the internal-flue boiler, where in order to remove the dust it was necessary to lay off the boilers altogether. With this type of boiler both efficiencies and loads declined continuously, and after one week's working it was impossible to run a boiler on rated load. The natural expedient was to clean the gas; and accordingly in the beginning of the century a number of efficient gas-cleaning plants were developed in Germany. The cleaning of the gas rendered the use of blast-furnace gas in gas engines possible. At a time when cleaning plants, which formed so large an item in the total expenditure over a gas-engine installation, were anyhow considered indispensable and furthermore when an efficiency of 50 per cent. on the gas-fired boilers was considered the best possible obtainable (as was the case 15 years ago), the superiority of the gas engine was hardly open to discussion. In this connection it must be kept in mind that during the first years of gas engines, it was generally accepted that they would not consume more than 14,000 B.t.u. per kilowatt. At this time the best steam engines would still consume 20 lb. of steam per horsepower, equivalent to 26,000 B.t.u. per kilowatt. If then a kilowatt had to be raised at an efficiency of 50 per cent., it meant a consumption of 52,000 B.t.u. for the steam engine, as compared with 14,000 B.t.u. for the gas engine. Since most people considered the gas-fired boiler at that time a thing of the past, little effort was spent for a number of years in improving the combustion arrangement. This development was also held back because the gas-cleaning plant by itself brought about, with the internal-flue boiler, a marked improvement both in efficiency and load, so that an efficient combustion was no longer the all-important factor.

After the gas engines had been in use at a number of places, however, they were found not to be an unqualified blessing; they gave high efficiencies only with high and constant loads, which in iron and steel works loads the blowing engines can furnish, but which could not be maintained in mill work. In 1907, Mr. Hoff, a German iron-works manager of high repute, investigated 32 power plants using gas engines at various German steel works and ascertained that the average load of all of them was only 52 per cent., that, in one instance, it was as low as 32 per cent.; and that it had not been possible in any case to generate a kilowatt with the low consumption of 14,000 B.t.u., a claim put forth by the makers of gas engines.

To-day it is generally accepted that, even at so-called "mixed" power plants, where only the constant load is carried by the gas engines, and the excess load by steam turbines, 18,000 B.t.u. are required for each kilowatt. Moreover, since for gas engines the gas has to be cooled down to atmospheric temperature, we must add to the 18,000 B.t.u. actually consumed the sensible heat which has been taken out of the gas in the washing process; and as this sensible heat represents 8 per

cent. of the latent heat, the actual heat consumption of the gas engine under the most favorable conditions stands to-day at 19,400 B.t.u. per kilowatt. In this country, the General Electric Co. claims that with its steam turbine it can raise a kilowatt with an actual heat expenditure of 19,000 B.t.u.

During this development of the gas engine, great strides were made in the improvement of the steam engine by the advent and development of the steam turbine. The 20 lb. of steam formerly required per horsepower, was gradually reduced to 14 lb. and, in some cases, where very large superheats were used (in Germany one is going as far as 450°F.) to 11 lb. per horsepower.

This concurrent development of steam engine and steam turbine brought about a revival of interest in the perfection of combustion. In the meantime, the waste-heat coke oven, which, up to about 1900, was almost universally used in Germany, gave way to the regenerative coke oven, but this development was generally retarded by the conviction everywhere held that gas was not suitable for boiler firing, and that, unless it could be used in gas engines or sold to gas works, the adoption of the regenerative coke oven would always mean a sacrifice in steam.

The comparative figures in this respect put forth as recently as 1912 by Baron Coppée at the British Iron and Steel Institute Meeting in Brussels were 0.75 ton of steam per ton of coal from the regenerative oven, as against 1 ton of steam per ton of coal from the waste-heat oven.

Burners.—It is a remarkable fact that in Germany the first efficient gas burners were developed for coke-oven gas, although this kind of gas did not represent nearly as important an economical factor as the blast-furnace gas. This is beyond doubt partly explained by the fact that coke-oven gas was always available in a thoroughly clean condition, so that dust troubles were not encountered. After the question of economically burning coke-oven gas had been solved, the inventors of these burners turned their attention to blast-furnaces gas, cleaned and cooled blast-furnace gas being available at a large number of plants. As the difficulty of dirt accumulation in the internal-flue boiler cannot be overcome, even at the present time, it is still held in Europe that for the purpose of obtaining good boiler efficiencies it is necessary to clean the gas.

In both design and appearance, nearly all of the first German burners all followed the Bunsen type, and were mostly round in shape, partly, perhaps, because that shape was obviously the proper one for the circular flues of the internal-flue boilers. The chief disadvantage of the cylindrical burner, namely, the varying friction with the varying gas pressure, did not figure very largely, since, owing to the cleaning plants (which as a rule almost entirely absorb the already low top pressure in European plants), "boosters" to restore the pressure of the gas were necessary anyhow, and provided a fairly uniform gas pressure. The second disadvantage of the Bunsen type of burner, namely, that the number of units varies with the size of the boiler, was of much smaller importance in Europe, since the small (usually 100 to 150 hp.) boilers did not as a rule call for more than two burners. Developments in the United States differed materially from those in Europe. In the first instance, the boilers almost universally used here are water-tube boilers of much larger size, and were all originally equipped with two burners, so that the natural tendency of the American blast-furnace operator and steam engineer was to adhere to the two burners.

The Bradshaw Burner.—A. N. Diehl[1] has described a number of types of American burners, so that I can content myself with a few words about the development of the Bradshaw burner, to which this paper, among other things, is devoted.

G. D. Bradshaw realized from the beginning the difficulty of pressure differences, which would result in differing amounts of friction, and likewise differing percentages of air aspiration. While nearly all the other burners have flat or tapering mixing tubes, he followed the Venturi principle and gave the burner the general shape of a Venturi tube. This principle is as follows:

In the flow of any fluid in a pipe or stream the sum of the static or pressure head and the dynamic or velocity head at any two sections is a constant, if the friction and eddy-current losses between the sections be neglected. That is,

$$h_1 + \frac{v_1^2}{2q} = h_2 + \frac{v_2^2}{2q}$$

where h_1 and v_1 are the pressure and velocity at the first section and h_2 and v_2 the same at the second section. If h_1 be practically the atmospheric pressure, h_2 may be made less than the atmosphere by a proper and not prohibitive change in section between the two points. When a burner embodies this principle, the subatmospheric pressure h_2 may be employed to draw air into the stream of gas. Should the quantity of gas change, the difference between the gas pressure and the atmospheric pressure increases in proportion to the difference in the squares of the former and the new velocities. Since the flow of gas through an orifice is proportional to the square root of the pressure difference, the air drawn in by the suction varies directly with the gas flow, and, once adjusted, the ratio of gas and air is kept constant. All of this is predicated upon a reasonably constant total head, including both pressure and velocity heads. The total head at any point may be kept closely constant by preventing great changes in the pressure of the gas and the draft in the combustion chamber. The gas pressure will vary with the irregular operation of the furnace, but the short path of the gas through the burner and its small losses therein make the combustion draft by far the greater factor in the maintenance of a constant condition within the burner itself. This draft can be held constant by any accepted type of balanced draft regulator.

Figs. 114 and 115 clearly show the general principles of the Bradshaw boiler burner. The gas enters at *A* into the converging section of the burner by which its velocity is gradually increased as it approaches the throat *B*. At *B* are placed the air-inlet openings *C*, which are regulated by the adjustable scroll dampers *D*. From this point onward the burner is diverging and the velocity of the mixture of gas and air is reduced by the expanding tube *E*, which ultimately discharges into the combustion chamber. At *G*, additional secondary air enters around the tube *E*. The burner is designed in such a manner that the velocity of gas and air in the expanding tube *E* is sufficiently high to prevent back flashing. Should a large reduction in the quantity of gas cause back flashing, the return of the gas supply automatically forces the flame back out of the discharge tube.

In the stove burner, where the round shape had of necessity to be adhered to,

[1] See preceding abstract.

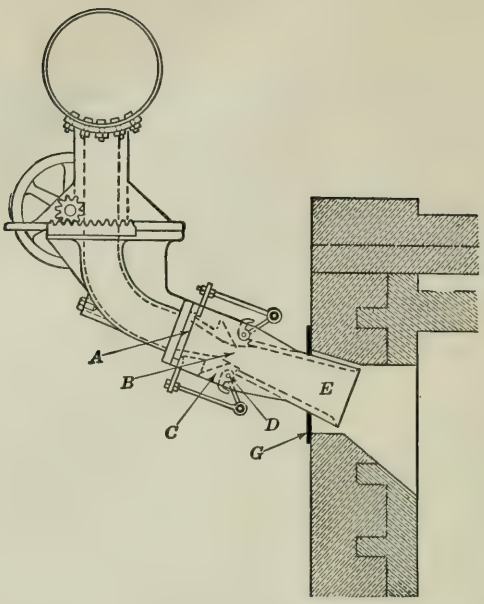


FIG. 114.—Cut through Bradshaw boiler burner.

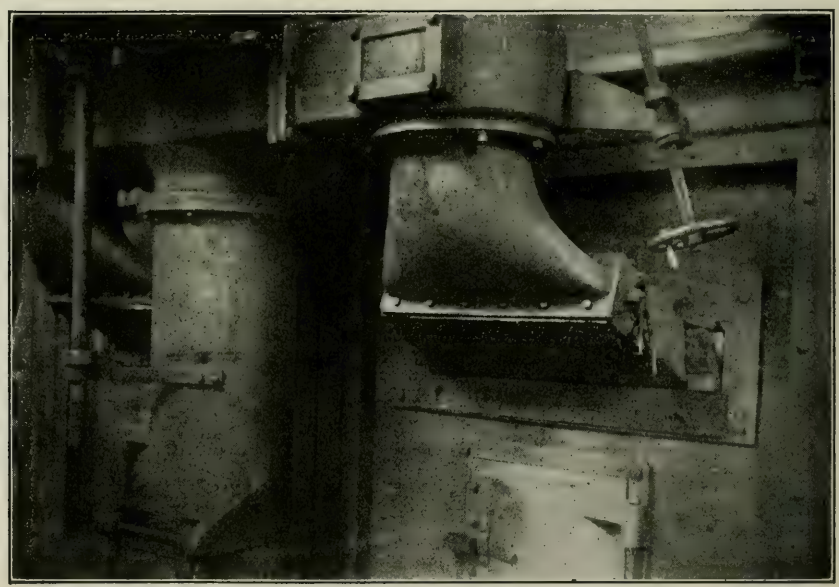


FIG. 115.—Stirling boiler with Bradshaw burner.

Bradshaw secured the operation of the same principle by inserting a bullet-shaped cone in the inside of the burner tube, which also gives him the converging entrance passage of the gas and diverging outlet passage therefrom to the outlet part, as shown in Fig. 116.

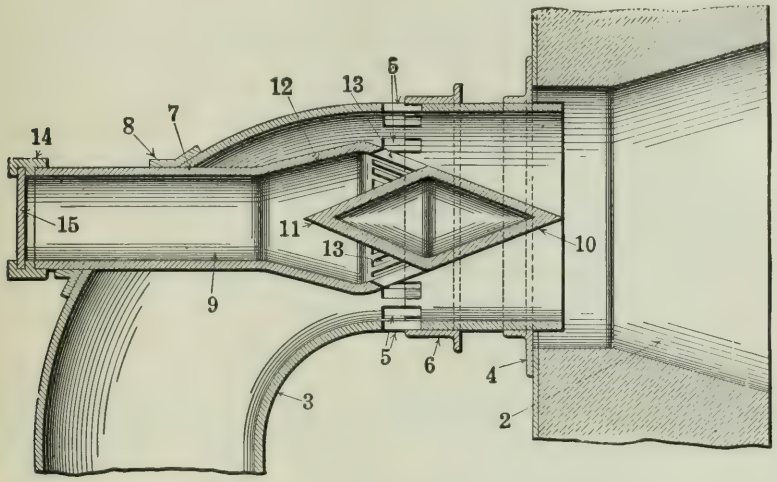


FIG. 116.—Cut through Bradshaw stove burner.

The Bradshaw stove burner is a reversal of the boiler burner in this respect: that the primary air is admitted internally through the air tube 9, as well as externally through the holes 5, shown in Fig. 116. The air regulation is obtained by slide 15 and the annular ring 6. Fig. 117 shows one of the parts of the Bradshaw stove burner. It will be noticed that in other respects both the shape and the general design of the present stove burner are adhered to.

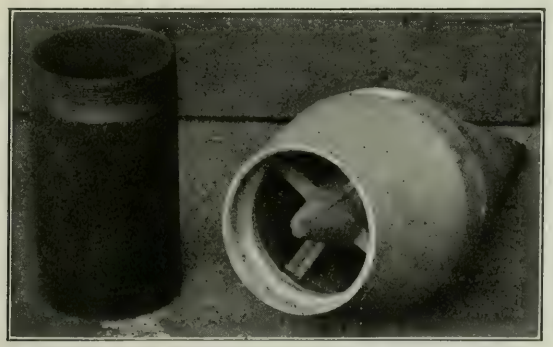


FIG. 117.—Bradshaw stove burner bullet.

Principles of Combustion.—The principles of combustion are of course generally known; but I insert them here as an introduction to a few useful tables concerning the composition of waste gases. The combustion of gas, as everybody knows, is the chemical reaction of the combustibles in the gas with the oxygen

contained in the combustion air. Each kind of gas requires a certain definite quantity of oxygen for complete combustion. If too little air is admitted combustion must remain incomplete; as a matter of fact, it will nearly always be impossible to obtain complete combustion for any length of time, without a certain amount of excess air, since the mixture of gas and air is rarely if ever sufficiently intimate to effect complete combustion unless an excess of oxygen is present. In any case it is not safe to burn the gas with less than from 5 to 10 per cent. excess of air, because the variation in the composition of the gas renders the danger of incomplete combustion too great.

An excess of air is also necessary, because combustion without such an excess of air, particularly if all the air is primary air, has a tendency to be explosive, and creates eddies which interfere with the aspiration effect of the burner.

The volume of oxygen necessary in order to burn completely a given volume of gas is found as follows:

$$\text{Total oxygen} = \frac{(CO + H_2)}{2} + 2CH_4.$$

I mention these three constituents as they are the only ones ever present in blast-furnace gas. The composition of the waste gas providing complete combustion without excess air will then be:

$$\begin{aligned} \text{Final } CO_2 &= \text{Initial } CO_2 + CO + CH_4 \\ \text{Final } H_2O &= \text{Initial } H_2O + H_2 + 2CH_4 \\ N_2 &= N_2 + \frac{\text{Total Oxygen} \times 79.5}{20.5}. \end{aligned}$$

The composition of the waste gas from blast-furnace gas containing 25 per cent. CO, 13 per cent. CO_2, 3 per cent. H_2, 0.4 per cent. CH_4, 58.6 per cent. N_2, when burnt without excess of air will then be as follows:

38.4 parts CO_2
3.8 parts H_2O
116.0 parts N_2

158.2 parts

The theoretical CO_2 on dry waste gas will therefore be 24.9 per cent. As with complete combustion without excess of air each cubic foot of gas will yield 154.4 cu. ft. of dry waste gas of which 24.9 per cent. is CO_2, it is simple to calculate the actual volume of the waste gas from the percentage of CO_2 present.

It will be noticed that in all these calculations the furnace gas has been assumed to be dry. Since, however, fully dry blast-furnace gas never exists, it is in each instance necessary to ascertain the amount of moisture in the gas. This is done by finding the dew point of the gas, that is, the temperature at which the water commences to condense. Fig. 118 shows the amount of water vapor per cubic foot of dry gas, measured at 60°F. and atmospheric pressure, in saturated gas at different temperatures.

Causes of Low Boiler Efficiency.—There are four causes of low boiler efficiency which I will review in the order of their importance: (1) incomplete combustion;

(2) combustion with large excess of air; (3) water vapor in the gas; and (4) deficiencies in the boiler plant itself.

The first three can be combined in one by saying "low combustion temperature." Deficiencies of the boiler plant itself (for instance air leakages in the front part of the boiler) are also frequently the cause of low combustion temperatures. Nevertheless, high combustion temperatures are quite compatible with low efficiencies due to faults of the boiler plants, such as cracks in the rear of the boiler settings, broken baffles, scale, dust accumulations on tubes, etc.

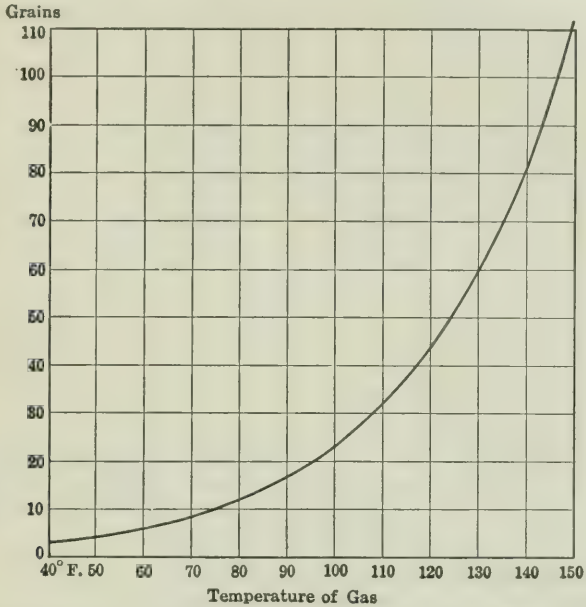


FIG. 118.—Grains of vapor per cubic foot of dry gas measured 60°F. and atmospheric pressure in saturated gas at different temperatures.

Low Combustion Temperature.—It is well known that every gas has a certain highest combustion temperature which is obtained if the gas is fully dry and burned without excess of air. This temperature lies for most blast-furnace gas between 2450° and 2500°F. for cold gas, and between 2.8 and 11.8 per cent. higher for hot gas of a temperature of 200° to 600°F. It must be the aim of the gas engineer to get as near as possible to these theoretical combustion temperatures. If the combustion temperatures are right, the rear temperatures will take care of themselves. It is an accepted rule that for any given gas (provided the same quantities of gas are passed in a given time unit) the rear temperature will always be in an inverse relation to the combustion temperature. This will show at once the importance of combustion with a low excess of air as a large excess will not only increase the volume but also the temperature of the waste gas. All this is predicated on otherwise faultless boiler conditions.

Fig. 119 shows in what manner the efficiencies are affected by unburned CO, giving the losses of both sensible and latent heat through incomplete combustion,

for gases containing 25 and 30 per cent. CO with 0 to 13 per cent. CO in the waste gas, without excess of air.

If the analysis of the waste gas shows excess of oxygen in spite of the unburned CO, both CO_2, and CO must be multiplied by a certain factor which depends on the amount of oxygen varying from 0 to 7 per cent., as shown by Fig. 120.

Example: the analysis of waste gas is

	Per cent.
N_2	74.8
CO_2	20.6
CO	0.6
O_2	4.0
	100.0

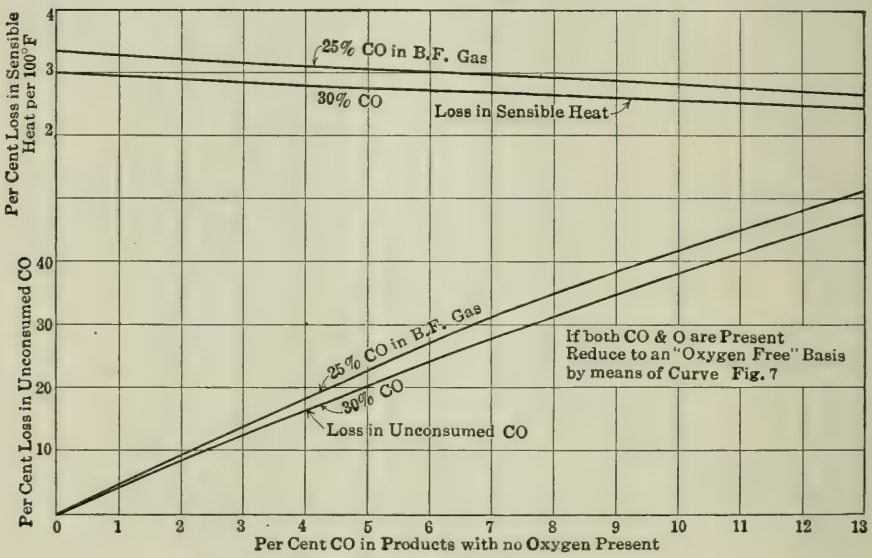


Fig. 119.—Losses through incomplete combustion.

For 4 per cent. O_2, the factor is 1.23 and by multiplying CO and CO_2 by this factor we obtain the following oxygen-free analysis:

N_2 =		73.924 (by difference)
CO_2	20.6×1.23 =	25.338
CO	0.6×1.23 =	0.738
O_2	=	0.0

The loss due to the unburned CO can then be ascertained from Fig. 119 as 2.8 per cent. for gas with 30 per cent. CO, and the total loss through sensible heat 2.98 per cent. for each 100°F. rise in temperature over boiler-house temperature. If stack temperature is 500° F. higher than the boiler-house temperature the total loss is 17.7 per cent. This table is correct for all gas containing CO + CO_2, 38; H_2, 3; and N_2, 59 per cent., the dew-point being 120°F. and the gas temperature 400°F. If used for other gas it must only be considered a rough-and-ready way for ascertaining the approximate stack losses.

Fig. 121 shows how the combustion temperature is affected by water vapor in the gas. It gives the temperature of combustion of blast-furnace gas burned with air at 60°F. and 10 per cent. air surplus, and carrying different amounts of water vapor per cubic foot of dry gas measured at 60°F. and atmospheric pressure.

This curve is particularly interesting, since it answers the question, to what temperature cleaned blast-furnace gas should be cooled, in order to give the best efficiency. It will be admitted that without exceptionally cold water the gas cannot be cooled below 75°F., but even this temperature will not often be obtained, as in most instances it is preferable to use the cooling water from the blast

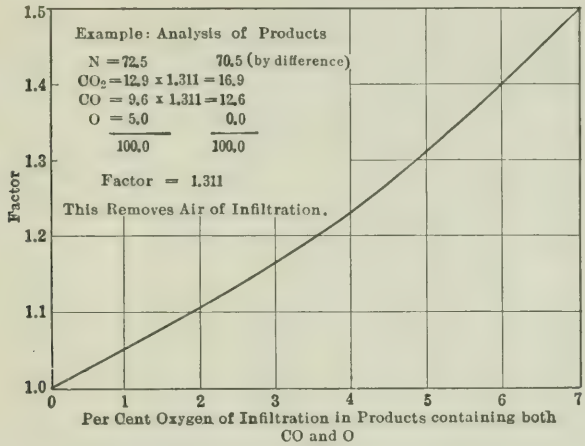


Fig. 120.—Factors for correcting analyses.

furnace for washing purposes so that the possible temperatures will usually lie between 80 and 100°F. The difference in combustion temperature will not be greater than about 40°F. or less than 2 per cent. The heat abstracted by the water vapor in the waste gas is also trifling. Assuming the waste-gas temperature to be 600°F., then the loss as compared with the gas of 70°F. will be as follows, allowing for the gain through sensible heat of the gas at the high temperatures:

Gain in efficiency as compared with gas of 70°F.	
For 80°F. gas temperature	0.06 per cent.
For 90°F. gas temperature	0.08 per cent.
For 100°F. gas temperature	0.03 per cent.
Loss of efficiency as compared with gas of 70°F.	
For 110°F. gas temperature	0.10 per cent.
For 120°F. gas temperature	0.34 per cent.
For 125°F. gas temperature	0.56 per cent.

This shows that as long as the gas temperature is kept approximately at about 100°F. the best possible results will be obtained and that it does not pay to use enormous quantities of water in order to reduce the gas temperature below this point.

Sensible Heat.—A few remarks will here be opportune about the importance of the sensible heat of the gas. The opinion has frequently been propounded that cold, clean gas is always preferable to hot unwashed gas. This is true for stoves which cannot be cleaned while they are working and on which hot uncleaned gas cannot be used to best advantage. If here gas is burned with a small excess of air, the high combustion temperatures will bring about fusing of the dust and consequent slagging in the stoves. In the case of water-tube boilers, however, where a blowing of the tubes about once in every turn will effectually remove the dust from the tubes the proposition is not correct.

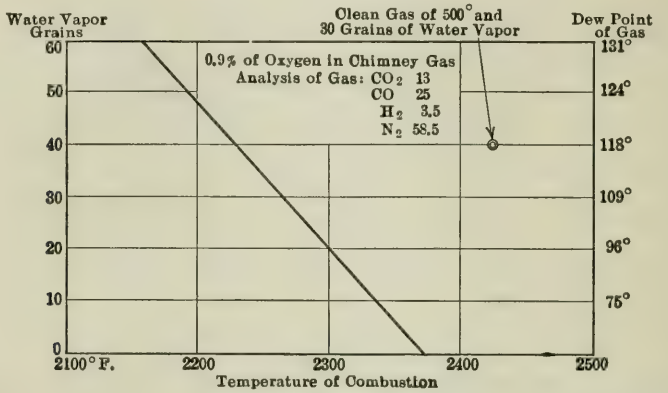


FIG. 121.—Temperature of combustion of blast-furnace gas burned with air at 60°F. and 10 per cent. air surplus gas saturated with different amounts of water vapor per cubic foot of dry gas measured at 60°F. and atmospheric pressure.

In order to be in a position to ascertain the value of the sensible heat in the gas at a glance it will be useful to consult Fig. 122 which shows curves giving the thermal capacity of the various constituents of blast-furnace gas from 60° to 1100°F. This curve together with some of those mentioned above has been kindly put at the author's disposal by A. Steinbart of the National Tube Co., Pittsburgh.

As an example, let us take a gas of the following analysis: CO_2, 13; CO, 26; H_2, 3; CH_4, 0.5; and N_2, 57.5 per cent. at a temperature of 450°F. By referring to the figure we find that each cubic foot of CO_2 contains 9.8 B.t.u., CO, H_2 and N_2, 7.2 B.t.u. and CH_4, 11.6 B.t.u. The total sensible heat is therefore as follows:

CO_2	0.13 × 9.8	1.274
CH_4	0.005×11.6	0.058
Balance	0.865× 7.2	6.228
Total		7.560 B.t.u.

It cannot be sufficiently emphasized that a hot gas containing, say, 107 B.t.u., both in latent and sensible heat, is just as valuable as cold gas of 60°F. containing 107 B.t.u. in latent heat alone—at least as far as gas-fired water-tube boilers are concerned. The loss of sensible heat on account of washing is therefore a net loss

which can in no way be recovered, even if we assume that the cost of washing the gas would be counterbalanced by the cost of cleaning the boilers. In a later part of the paper it will be shown that there is no difficulty in obtaining a boiler efficiency of 75 per cent. and more with uncleaned gas. A boiler efficiency of 75 per cent. on hot gas would correspond with an efficiency of 80.5 per cent. on cold gas and unless this could be exceeded, which I very much doubt, there could be no profit in gas washing.

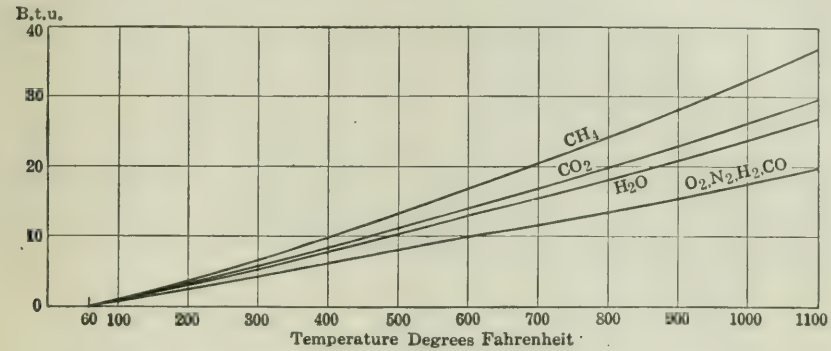


FIG. 122.—Thermal capacity of gas at different temperatures.

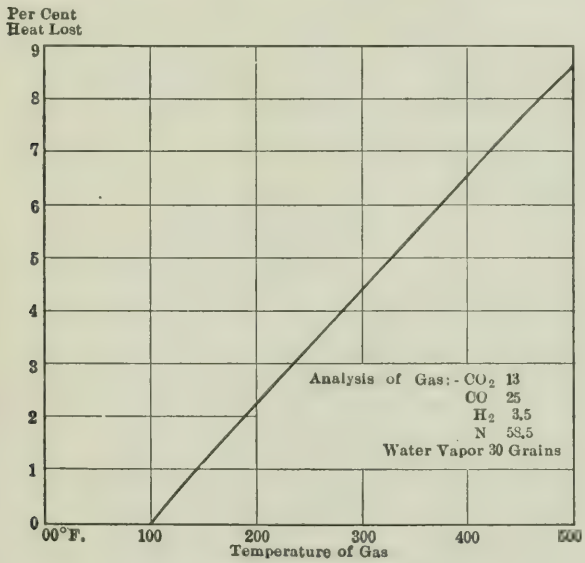


FIG. 123.—Losses through washing.

Fig. 123 shows the losses through sensible heat on account of washing.

Fig. 124 shows how the combustion temperature is affected by the sensible heat when burned with an excess of air both 10 and 50 per cent.

Results published by Mr. Diehl as regards the National Tube Burners at McKeesport are very interesting, as they show that high efficiencies are in exceptional cases compatible with low initial temperatures. I refer to the low-

combustion temperature of about 2100°F. They are in fact lower than they ought to be when the composition of the burned gas is considered. This composition, the same as the stack temperatures, leaves nothing to be desired. I explain these results by the fact that lingering combustion takes place and that the course of the products of combustion through the boilers is so unusually long that this lingering combustion which in 99 out of 100 cases is absolutely fatal to the efficiency of the boilers, does not make itself felt through a concurrence of exceptional circumstances which will rarely be repeated. In any case we have here the extraordinary fact of a burner which itself gives a comparatively low efficiency and yet results in a good boiler efficiency.

Water in Charge.—Hitherto we have only contemplated the effect of water added to the gas after it leaves the blast furnace. From the point of view of combustion alone, it is, of course, immaterial where the water is added, whether in the furnace or in the washing plant. Nevertheless, it will be interesting to note

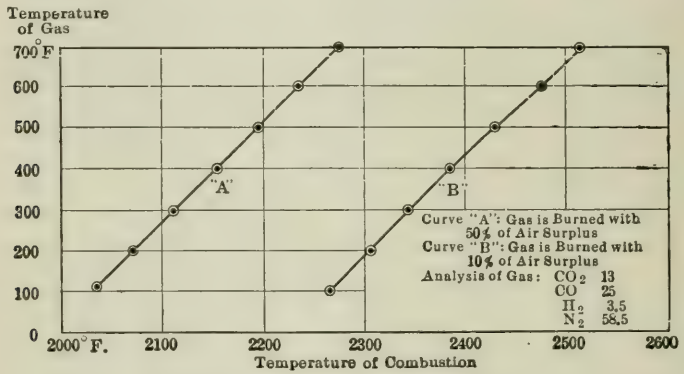


Fig. 124.—Combustion temperature with varying excess of air.

how a wet charge affects the gas economy of the furnace. Let us assume that the dew-point of a certain blast-furnace gas is 130°F. By referring to Fig. 116 we find that each cubic foot of gas carries 60 grains of moisture. This water must not only be evaporated, but also brought to the top temperature of the furnace. Assume the latter to be 400°F. and that each ton of coke is responsible for 150,000 cu. ft. of gas measured at 60°F. and atmospheric pressure. For each ton of coke 9,000,000 grains (1285 lb.) of water must be evaporated and brought to a temperature of 400°F. These must first be raised to 212°F. which will consume $1285\ (212 - 60) = 195{,}100$ B.t.u. The evaporation heat is $1285 \times 966 = 1{,}240{,}000$ B.t.u. The 1285 lb. of water vapor are equal to 27,000 cu. ft. at 60°F. From Fig. 122 we find that the thermal capacity of water vapor from 212° to 400°F. is approximately 4.75 B.t.u. per cubic foot. This heat will be required to raise 1 cu. ft. to 400°F. so that 27,000 cu. ft. will require 128,500 B.t.u. in all. The total heat is thus:

	B.t.u.
To bring water to 212°F.	195,100
To evaporate water	1,240,000
To heat vapor to 400°F.	128,500
Total, per ton of coke	1,563,600

If the calorific value of coke is 12,500 B.t.u., then 125 lb. of coke out of every ton used is employed in heating and evaporating the water.

While it is impossible to eliminate all this moisture, and while its total elimination would result in disturbances in the working of the furnace, owing to high top temperatures, one ought to allow the top temperature to reach the highest point which is compatible with the smooth working of the furnace and not unnecessarily reduce it by damping the ores. For the sensible heat in the gas is just as important a factor for steam raising as the latent heat. With the various types of sintering plants there is no difficulty in recovering the valuable constituents from flue dust. The increased quantity of flue dust due to a dry charge need not deter the operator. That a fairly dry charge can be run has been proved by J. S. Fraser, at Monessen, Pa., who, although using large quantities of Messabi ores, does not damp his ores when charging the furnace.

Other Losses.—To complete the diagrams which are necessary in order to read at a glance the losses through waste gas as revealed by the stack analysis I offer Figs. 125, 126 and 127.

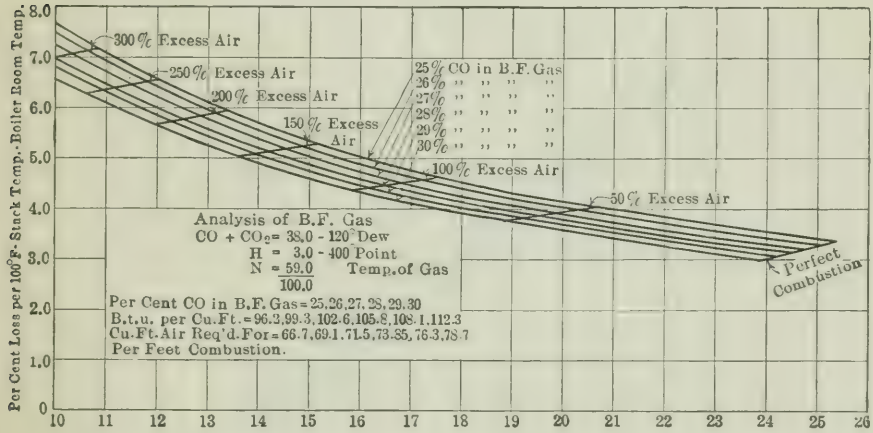


FIG. 125.—Percentage losses through stack gases based on CO_2 contents.

Fig. 125 gives the percentage losses for each 100°F. rise of temperature over the boiler-house temperature, for varying CO_2 in the waste gases from furnace gases containing from 25 to 30 per cent. CO.

Figs. 126 and 127 are useful as checks on the correctness of Orsat tests. Fig. 126 shows the percentages of oxygen and nitrogen corresponding to the various percentages of CO_2 for complete combustion; Fig. 127 the nitrogen and carbon dioxide corresponding to the various percentages of CO for oxygen-free stack gas.

Bad Boiler Conditions.—Bad boiler conditions and the losses resulting are: defective brickwork, causing air leakages; unsubstantial brickwork, causing high radiation and conduction losses; lack of boilerhouses, with the same results; defective baffles; scale; or too short passages for products of combustion. The remedies are obvious.

The whole secret of economy is to be able to know at any given moment what

one is getting and what one ought to get. To start with the latter, blast-furnace operators cannot be too urgently advised to draw up once a week, or at least every month, a carbon balance sheet of their furnaces calculating the quantity of gas from the carbon in the furnace charge. If these balance sheets are to be of any value it will be necessary to take at least one gas analysis a day and also ascertain the dew-point of the gas every day; if the gas is washed, to keep reliable records of the gas temperature as well.

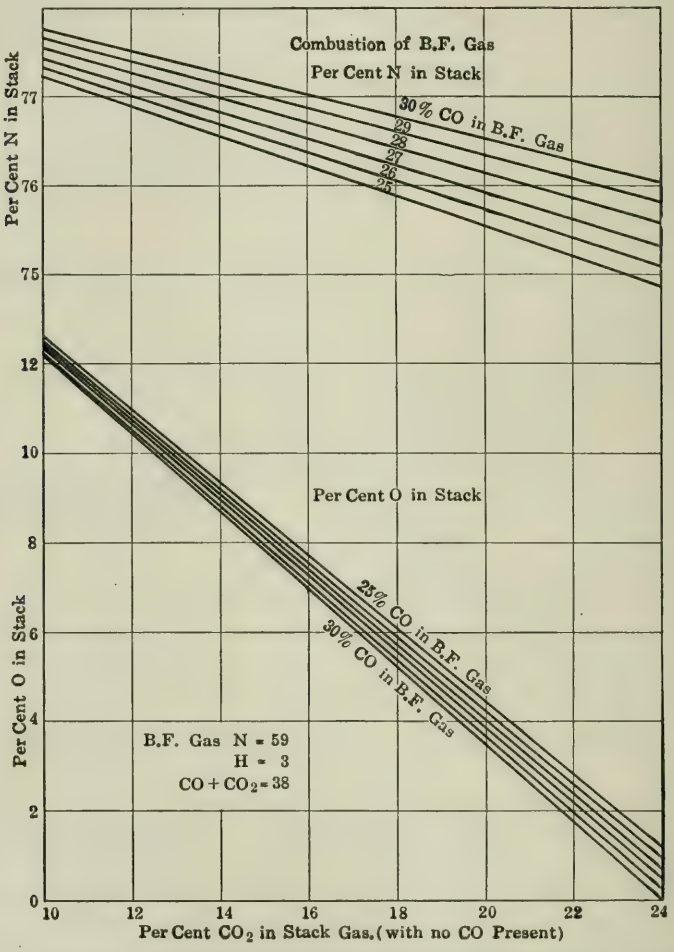


FIG. 126.—Oxygen and nitrogen in stack gas corresponding to various percentages of CO_2 for complete combustion.

Air Infiltration.—How seriously boiler efficiency is impaired by air infiltration is shown by the following experiment made by Mr. Bradshaw at Johnstown. Mr. Bradshaw admitted false air into the boiler at various distances from the burner and before starting his experiment saw to it that he had the boiler and burners in otherwise perfect working condition.

Boiler No. 132, March, 1915

CO_2	Rear temperature	
11.7	626°F.	Gas pressure 4.5 in.
13.0	620°F.	
13.3	616°F.	
18.8	578°F.	
18.8	575°F.	
19.7	577°F.	
15.0	580°F.	Gas pressure 3.5 in.
18.0	545°F.	

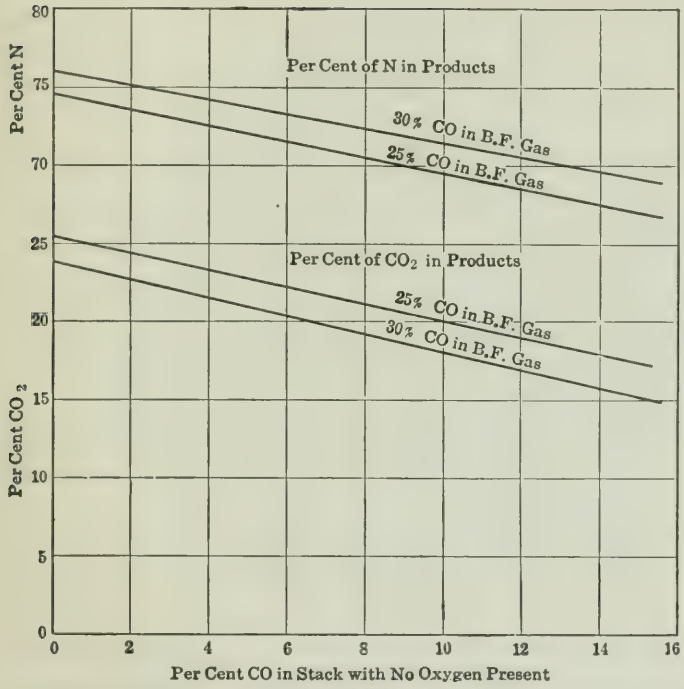


Fig. 127.—Carbon dioxide and nitrogen in stack gases corresponding to various percentages of CO_2 in oxygen-free stack gas.

This experiment shows that air infiltration not only causes a loss, because all this air has to be heated to the stack temperature, but also results in an increase of the latter, or, in other words, reduces the heat absorption capacity of the boiler tubes. This is due to the fact that the thermal conductivity is in direct relation to the difference of temperature between the gases and the outside temperature of the boiler tubes, so that if the temperature of the products of combustion is reduced, the conductivity itself is reduced and less heat is transferred. This again shows how the boiler efficiency is affected by the combustion temperature; and this is also the explanation of the fact that in a good boiler 70 per cent. of the

total evaporation should be done in the first third of the boiler, 20 per cent. in the second and 10 per cent. in the last third. For this reason, air infiltration is a serious factor wherever it takes place and whether or not it interferes with the initial temperature. It is erroneous to assume, for instance, that air infiltration which takes place in the rear passage will only tend to reduce the stack temperatures correspondingly to the amount of heat absorbed by the cold air. In a case where the stack temperature was 550°F. and the CO_2 18 per cent. with complete combustion (the low CO_2 being due to air infiltration in the rear of the boiler), the CO_2 after eliminating this air infiltration, was raised to 22 per cent. without an increase in the stack temperature. This proves that even at this point air infiltration means a net loss to the boiler.

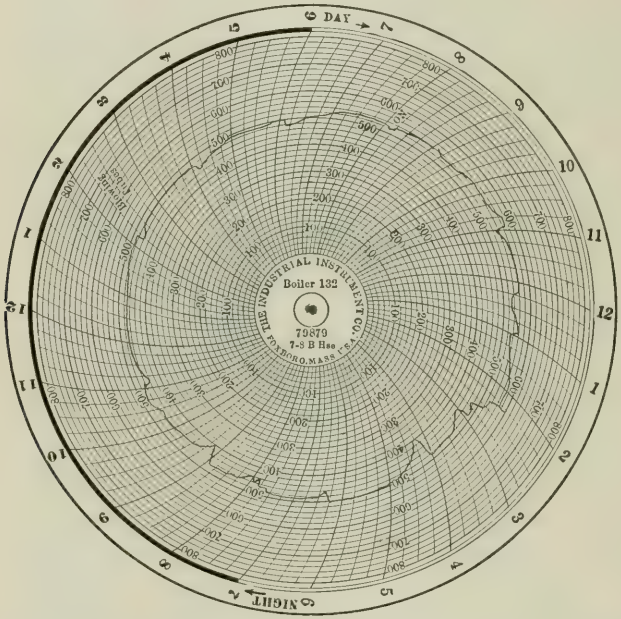


Fig. 128.—Stack temperature chart showing effect of blowing tubes.

Blowing the Tubes.—Another fact which must be constantly kept in mind is the necessity of blowing the tubes. Fig. 128 shows the stack temperature of a gas-fired boiler. The tubes were blown only once in 24 hr. and it will be noticed that as a result of the blowing of the tubes the stack temperatures dropped by 150°. On account of these experiments, the tubes were blown every 12 hr. which resulted in a constant drop of temperature of 100°, a reduction by one-fifth of the loss through waste gas. An experiment made by the Pittsburgh Steel Co. illustrates how the load of the boiler is affected by the accumulation of dirt on the water tubes. When the first test was run the boiler tubes had not been blown for three days and the result was that the maximum average load obtainable from a 500-hp. boiler during 8 hr. was 720 hp. Subsequently the boiler tubes were carefully cleaned and another test of 8-hr. run and the result was that instead of

720 hp. 827 hp. was obtained, with even a decrease of losses through stack gas. In both cases the boilers were run at the maximum load compatible with good efficiency.

Boiler Loads.—A few words as regards the boiler loads may be of interest. We, of course, all know that the official rating of 34.5 lb. per horsepower does not at all represent the actual capacity of the boiler. In this connection it may be interesting to say something about European customs. In England, water-tube boilers of the Stirling or Babcock-Wilcox type are rated for normal working conditions at 4½ lb. of actual steam per square foot of heating surface, which is equivalent to about 150 per cent. rating under the American rules, and the users of such boilers naturally expect to get a considerable overload out of them. In Germany, Belgium, and France, I do not think it would be possible to get an order for a water-tube boiler with a smaller guaranty than 6 lb. actual per square foot of heating surface, so that their rating really represents 200 per cent. of the American rating.

The results obtainable from internal-flue boilers are even more astonishing. I have run boilers of that kind at 8½ lb. actual per square foot of heating surface, equivalent to 9.75 lb. from, and at, 212°F., which would represent an overload of 282 per cent. for American practice. As a matter of fact, the flexibility of a modern boiler is very much greater than is generally assumed, and high efficiencies are quite compatible with loads of 200 per cent. and more. This load depends entirely on the chimney draft; and the limit is not reached until all the dampers are wide open and balanced draft is established in the combustion chamber, at which draft the boilers get all the gas and air which the stack can handle. A very simple and effective means to increase the boiler capacity, which has been resorted to in a good many cases, is to install induced draft. In Europe a number of modern boiler plants have been built without stacks, with fan draft only, and it has been possible to obtain astonishingly high boiler loads.

The maximum boiler load is, of course, to a certain extent dependent on the dust in the gas, and the limit is reached as soon as it is no longer possible to keep the water tubes clean by blowing once every turn. This limit will probably lie at about 180 per cent. At least the Cambria Steel Co. has been able, by blowing once every turn, to run its boiler plant for many months at a load of 165 per cent. while maintaining excellent efficiencies. This load can be exceeded without difficulty if the gas is cleaned. As a rule, the cleaning of boiler gas will only be resorted to if, owing to lack of space, new boilers cannot be installed, since it would be impossible to show any saving even if the boiler capacity should be increased by cleaning, say 20 per cent. Take the case of a 500-ton furnace. With suitable burners, a furnace of this size is capable of generating 5100 rated boiler-hp. per hour. To generate this power at 165 per cent. load, 3100 hp. boiler capacity are required. If the load were raised by gas cleaning to 200 per cent., 2600 rated boiler-hp. would do the work, so that a 500-hp. boiler would be saved. But the gas cleaning would result immediately in a drop in the evaporation of about 7 per cent. or 357 boiler-hp. At $25 per boiler-horsepower per year, the actual loss through cleaning would be approximately $8900 a year which alone would be sufficient to cover the expenditure for an additional 500-hp. boiler quite apart from the cost of a cleaning plant which would require at least another $20,000.

Method of Measuring Economy.—There has been considerable discussion about the means of ascertaining whether or not one is getting good economical results. By some of the operators it is maintained that the only reliable method is to ascertain the boiler efficiency by stack analysis and temperature, and assume a certain percentage for radiation and conduction losses; other operators, and especially a number of steam engineers, hold that this method is all right for occasional tests, but does not answer in cases where large numbers of boilers are operated, and it is used to keep track of the actual results obtained from month to month and from year to year. These men, whose opinion I favor, hold that a monthly figure giving pounds of steam per pound of coke is the one and only reliable method of tracing results. The chief objection to this method of ascertaining the efficiency of a boiler plant is, that a large percentage of the gases are used for the stoves, and in a good many cases some of the gases are also used in gas engines. I hold that occasional efficiency tests are very misleading indeed. It is not very difficult to obtain good efficiencies for a given period of a few hours or days, covered by a test. The main difficulty is to maintain such efficiencies over an indefinite period. I make bold to say that with any kind of a burner, as long as it is possible to admit sufficient air for combustion, we can obtain excellent efficiencies for a period during which a boiler is under constant supervision and is continuously regulated, but we shall first find, that as soon as the supervision is relaxed (as it must be, once the test is finished) the efficiency will fall back forthwith; and second, that the ordinary type of burner will have a comparatively low maximum load, and the stack losses will be much larger with the ordinary type burner at a high load than with a modern type burner, such as the Bradshaw.

The contention that pounds of steam per pounds of coke does not give any reliable information on account of the gas used by the stoves can easily be met. In the first place, as the stoves get the first supply of gas and the boiler only the surplus, there is a very simple method of seeing to it that the stoves always get the same quantity of gas. All that has to be done is to put a pressure gage in the boiler house and instruct the boiler foreman to keep a uniform gas pressure at the stoves, which will bring about a uniform gas consumption. Better still take up stoves and boilers together and equip them both with suitable combustion arrangements, giving the highest possible efficiency. If that has been done, the pounds of steam per pound of coke during any one month give the joint results of both stoves and boiler; and if they fall below that amount which corresponds to the coke ratage, then it must be found out by efficiency tests whether boiler or stoves are responsible for the reduction in the steam output.

If any part of the gas should go to gas engines, a measuring device should be installed and, in ascertaining the results which ought to be obtained, due allowance for the gas consumption of the gas engine should be made. As a rule it will even suffice to take the total output of electricity for the month and allow 18,000 B.t.u. per kilowatt—or whatever the consumption may be in the case.

I reproduce here a table published by S. M. Marshall, late Chief Engineer of the Cambria Steel Co., showing the evaporations to be obtained from blast-furnace gas at the various rates of pounds of coke per ton of iron:

Coke per gross ton of iron, pounds	Cold gas, steam per pound of coke, pounds	Hot gas, steam per pound of coke, pounds
1,736	3.56	3.85
1,800	3.61	3.90
2,000	3.73	4.03
2,200	3.86	4.17
2,240	3.89	4.20
2,400	3.99	4.31
2,600	4.12	4.45
2,800	4.24	4.58
3,000	4.37	4.72

The steam is given in pounds from and at 212°F. Mr. Marshall figures on a very low stove efficiency of only 57 per cent. If this were raised to 75 per cent. the above figures would be increased by 8.95 per cent.

These figures conclusively answer in the negative the question, whether it pays to wash blast-furnace gas for boilers. Take the case of a 500-ton furnace using 2000 lb. of coke per ton of iron. The loss through cleaning is ⅕ ton of steam per ton of coke. If the average value of a ton of steam is 25 cts., cleaning for boilers results in a loss of 5 cts. for every ton of coke used, quite apart from the cost of cleaning, which is only to a very small extent offset by the saving in wages for cleaning boilers

Efficiency Tests.—If the above evaporations are not reached, efficiency tests on both stoves and boilers should be made. The losses sustained are made up in both cases of stack losses, and radiation and conduction losses. The stack losses may be in sensible heat alone if complete combustion takes place, or in both latent and sensible heat if the combustion is imperfect.

Stack Losses.—The stack losses must be ascertained through stack-gas analysis and temperature measurements. The stack gases should show, under total absence of unburnt CO, from 22 to 23 per cent. CO_2 and the temperature, even for high boiler loads, should not exceed 550°F. These results, of course, are obtainable on good modern boilers only, although even with imperfect boilers, like Cook, Cahall and Wheeler, efficiencies of 70 per cent. and more, when running on gas, are obtainable in everyday practice.

With the assistance of Figs. 119, 120, 125, 126 and 127, the stack losses of both stoves and boilers can be easily ascertained. It should not be overlooked, however, that particularly with bad combustion arrangements, the CO_2 is a much varying quantity, so that conclusions should be drawn only from a large number of analyses. It will, therefore, always be advisable to use a CO_2 recorder and take Orsat tests for unburned CO at least every 5 min. for several hours.

Where mixed coal and gas firing is used, a corresponding allowance for the water evaporated by the coal should be made. If there is any doubt as to the amount of water evaporated by the coal, special tests for the purpose of ascertaining the evaporation factor to be used can easily be arranged.

In this connection it may be pointed out that the practice of mixed firing is anything but desirable. Where the boilers are equipped with combustion cham-

bers of sufficient size, and a good combustion arrangement is available, pilot firing, even in the case of the one-furnace plant, is not necessary. The Cambria Steel Co., for instance, has run 20 B & W boilers, equipped with Bradshaw burners and good-sized Dutch ovens, without pilot firing of any kind, in spite of the fact that these boilers received their gas from one furnace only. The heat stored in the combustion chamber was high enough to reignite the gas, even if it had stayed away for 10 min. or more, during a cast or change of tuyere. In this case, however, the furnace boilers were connected up to the mill boilers so that there was no danger of losing the steam pressure. At many of the one-furnace plants, this connection does not exist, and pilot firing cannot be dispensed with, since at any moment it may happen that the gas gives way and the power has to be supplied by coal exclusively. In that case, it should be kept in mind that the boilers are primarily gas-fired boilers and that all that is necessary is to maintain a small fire on the grate. It is essential, that after coal has been thrown on, the fire and ash-pit doors should be sealed up again, to avoid infiltration of air, and that where the boilers are equipped with blowers, these should only be used while actual coal firing is necessary, and sealed up at all other times. If for any reason the gas is not sufficient to carry the load, it is advisable to spread the gas over a certain number of boilers which are not coal-fired except in emergency cases, and do the coal firing on other, separate boilers. In view of the very different conditions under which coal and gas have to burn, the advisability of this procedure is self-evident.

Boiler Construction.—We may inquire next, how boiler efficiency is influenced by the boiler construction as apart from the condition of the setting. It has generally been held that the one-pass boiler, such as the Cahall, Cook or Wheeler, is absolutely hopeless from the point of view of efficiency, and when I first approached the question of improving the efficiency of this type of boiler I did so with no little misgiving. I do not claim that I am in a position to say definitely to what extent a one-pass boiler can be worked economically; but, in experiments made at the Upson Nut Co.'s plant in Cleveland, I was surprised to find that boilers of this type could be run on a 100 per cent. load with very high efficiency. In some cases this was as high as 75 per cent., but all attempts to overload this kind of boiler with any show of efficiency proved futile, in spite of ample draft.

The chief disadvantages of the one-pass boilers are the great difficulty of keeping them air-tight and their very large radiation and conduction losses in comparison with their capacity. In any case, it is interesting to know that it is possible to run a boiler of this kind on gas at rated load with a good efficiency. Where, therefore, ample boiler capacity in one-pass boilers is available, it would certainly not pay to install modern boilers for the purpose of increasing efficiencies.

As regards boilers of the modern type, there can be very little doubt that, from the point of view of efficiency, it does not matter so much which type is used. Equally good efficiencies have been and are obtained on all types of boilers, provided the combustion arrangements are up-to-date.

Boiler House.—A very important feature in the operation of the gas-fired boiler, as we have seen already, is the "morale" of the boiler house. It would be a grave mistake to assume that the adoption of a good combustion arrangement alone would solve the difficulty. That will go a long way toward better efficiencies; but wherever efficiencies in excess of 65 per cent. are desired, the supervision

of brickwork settings and the regulation of the draft are of paramount importance. We have already considered the great influence of air infiltration.

Draft.—The second factor which is of great importance is the draft. That a burner of the type which employs a preliminary mixture of gas and air provides its own combustion air, independently of the chimney draft, is only partially true.

The aspiration velocity of any burner is chiefly dependent on the chimney draft. Mr. Buessel, of the American Steel & Wire Co. of Cleveland, has made some interesting experiments on an installation of Bradshaw burners at the Upson Nut Co.'s plant. He inserted a pipe, flattened at the end, into the air port of the Bradshaw burner and measured the aspiration velocity in this pipe by means of an anemometer. It is evident that owing to the friction in this pipe the figures obtained do not give positive information but they are invaluable as giving the relative velocities for various boiler drafts. With the same amount of gas in both cases, Mr. Buessel found that for a chimney draft of 0.35 in. the aspiration velocity in the air ports was 888 ft. per minute and that after reducing the chimney draft to 0.17 in. it fell to 713 ft. per minute. It is evident that a burner which receives sufficient air for a given quantity of gas at one aspiration speed must have suffered from incomplete combustion for the same quantity of gas at lower speeds. The aspiration velocity stands in a direct relation to the velocity in the mixing chamber, provided that all friction which tends to absorb the aspiration effect is eliminated, as in the case of the Bradshaw burner. In order to keep the relation between gas and aspirated air constant, the pull which is effected on the velocity of the gas and air mixture by the chimney draft must be kept constant, or the quantitative relation between gas and air will be upset. The importance of draft regulation will of course depend on the variation in gas pressure, so that, for instance, at a place where these variations are small, draft regulations will not play nearly as important a part as in places where there are frequent and large differences in gas pressure. Draft regulation is particularly important where it is desired to burn the gas with a very low excess of air; for, with dampers in a stationary condition, an increase in the gas pressure must of necessity result in incomplete combustion. I have found that it is not safe to raise the CO_2 higher than 21 per cent. without automatic draft regulation whereas 24 per cent. can safely be maintained with such regulation. From gas containing 25 per cent. CO the loss through waste gas with 24 per cent. CO_2 at a stack temperature of 560°F. is 17.75 per cent. while with 21 per cent. CO_2 it is 20 per cent. (see Fig. 125). This difference of 2.25 per cent. may not appear important, but it must be kept in mind that with a lower initial temperature the stack temperature in the case of 21 per cent. CO_2 will also, as likely as not, be higher.

Supervision.—Then there is the item of supervision. If the dampers are automatically governed, as for instance by the McLean governing device, and Bradshaw burners are used, then the sole duty of the boiler tender will be to watch the settings. He will not have to watch either burners or dampers. Without automatic damper governing, he will have either to do hand regulation or regulate the air valves for the purpose of maintaining an adequate quantity of air. Such regulation of the air-valves, particularly in large plants, would be practically out of the question.

As regards air-tight boiler settings, it may be useful to know that a very satisfactory coating is obtained by means of whitewash and cement. After several

coatings have been given to the boiler, the settings will get a smooth surface. The falling off of the coating at any part will at once be detected and can be repaired as it occurs.

In addition to watching the draft, even with the most perfect combustion arrangement, it is necessary to check the composition of the waste gas and ascertain the temperatures from time to time. One or two analyses per week for the boilers will be quite sufficient and, at least with the Bradshaw burner, resetting of the air ports will as a rule only be necessary where a change in the iron is made, with a consequent considerable change in the composition of the gas.

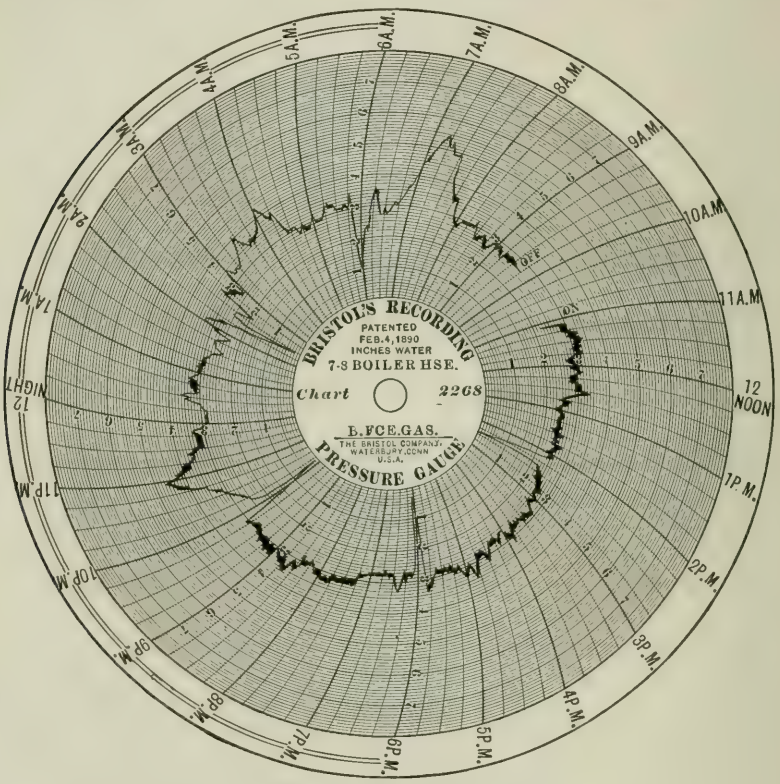


Fig. 129.—Gas-pressure chart.

Results with the Bradshaw Burner.—In conclusion, I wish to say a few words about the results obtained with the Bradshaw burner. I give below a list of 52 stack analyses taken at the Cambria steel works, which show an average of 21.4 per cent. CO_2 under total absence of CO, a stack temperature of 581°F. and a boiler load of 165 per cent. As the gas in question contains 25 per cent. CO and the rise in temperature over the boiler house temperature is about 500°, the total losses through waste gas are 20 per cent., so that the boiler efficiency, even if the losses through radiation and conduction were as much as 5 per cent., would be 75 per cent.

I might mention that with boilers in a boiler house, it is extremely unlikely

that the radiation and conduction losses would be as high as 5 per cent. As far as I am aware, no reliable figures of these losses are available at the Cambria Steel Co. I have personally conducted tests on 500-hp. boilers in England and found that the radiation and conduction losses of these boilers, which were in a boiler house, were less than 2 per cent. The German periodical, *Feuerungstechnik*, published in 1914 a table of experiments made on 12 Stirling boilers, working in various parts of the United States, which showed highest losses of 2.5 and lowest losses of 0.75 per cent. through radiation and conduction.

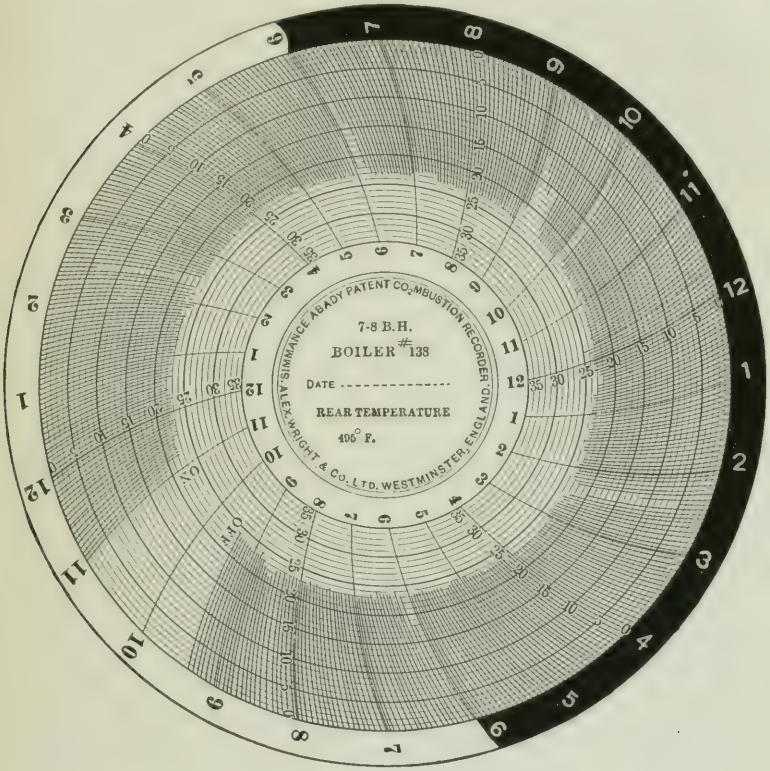


FIG. 130.—Carbon dioxide chart.

It may be of interest to know that the dampers were hand-regulated at the Cambria steel plant, which accounts for the comparatively low CO_2. What can be done with automatic damper regulation is exhibited by the two charts, Figs. 129 and 130, one of which shows the gas pressure, the other the CO_2 in the waste gas, as given by a CO_2 recorder. The correctness of this recorder was constantly checked, and unburned CO was not found in any of the samples.

With regard to Figs. 129 and 130 attention should be given to the uniform CO_2, which runs from 22 to 23 per cent. in spite of the greatly varying gas pressure, *e.g.*, between 6 and 8 a.m. and 10 and 12 p.m. The rear temperature was only 495°F. This is, however, explained by the fact that the boilers were only running on rated

CAMBRIA STEEL CO. ANALYSES AND STACK TEMPERATURES OF WASTE GASES

Boiler No.	CO_2	O	CO	N	Stack temperature	
2–18	20.0	4.5	0.0	75.5	635	Tubes not blown for 24 hr.
2–18	21.0	3.4	0.0	75.6	650	
2–19	21.7	4.0	0.0	74.2	615	
11–126	23.2	2.0	0.0	74.8	445	
11–127	22.5	2.3	0.0	75.2	440	
11–138	21.2	3.2	0.0	75.6	525	
11–137	22.8	1.6	0.0	75.6	525	February, 1915, load 145 per cent. of rating.
11–136	21.6	2.8	0.0	75.6	515	
11–135	20.4	4.0	0.0	75.6	555	
11–129	21.0	3.5	0.0	75.5	515	
11–130	22.0	3.0	0.0	75.0	485	
11–120	21.5	2.3	0.0	76.2	580	
11–121	20.0	3.8	0.0	76.2	570	
11–138	21.4	2.6	0.0	76.0	515	
120	22.6	1.4	0.0	70.0	576	
121	20.7	1.2	1.1	76.8	619	
122	23.3	0.4	0.0	76.3	568	
123	22.6	0.4	0.0	77.0	499	
124	21.0	3.0	0.0	75.7	569	
125	20.8	4.2	0.0	75.0	537	
126	19.5	4.9	0.0	75.6	627	
127	21.6	1.8	0.0	76.6	580	
129	19.4	3.8	0.0	76.6	568	May, 1915, load 165 per cent. of rating, tubes blown 12 hr. before.
130	21.4	0.6	0.2	77.8	610	
131	22.8	2.2	0.0	74.9	518	
132	22.2	1.8	0.0	76.0	565	
133	21.0	2.0	0.0	77.0	655	
134	20.2	1.0	0.0	78.7	610	Continued May, 1915, load 165 per cent. rating tubes blown 12 hr. before.
135	21.6	2.6	0.0	75.8	585	
136	22.6	0.8	0.0	76.6	542	
137	22.8	0.6	0.0	76.6	655	
138	19.8	3.6	0.0	76.6	585	
139	21.0	4.6	0.0	74.4	595	
Average of last 19	21.4	2.08	0.0	76.3	581	
120	23.2	0.8	0.0	76.0	557	
120	22.0	1.3	0.0	76.0	560	
123	22.4	0.6	0.0	77.0	510	
120	20.8	1.8	0.0	77.4	555	
120	21.0	1.2	0.0	77.8	560	
131	20.4	3.0	0.0	76.6	565	June, 1915, tubes blown from 6–12 hr. before taking temperatures 165 per cent. rating.
131	21.4	3.2	0.0	75.4	585	
131	20.8	1.4	0.0	77.8	570	
124	20.6	3.4	0.0	76.0	565	
124	20.8	3.2	0.0	76.0	580	
131	22.6	2.8	0.0	74.6	520	
131	22.6	1.6	0.0	75.8	540	
131	22.8	0.8	0.0	76.4	550	
131	22.3	1.0	0.0	76.7	548	
121	20.4	3.2	0.0	76.4	530	
94	26.0	0.4	0.0	73.6	530	
94	26.2	0.2	0.0	73.6	535	
122	23.2	0.6	0.0	76.2		
129	20.2	4.8	0.0	75.0		

load. The gas in question contained 25 per cent. CO and by referring to Fig. 125 we find that the loss through waste gas was 3.6 per cent. for every 100°F. (stack temperature − boiler room temperature) or a total of 15 per cent., so that the total

boiler efficiency, assuming radiation and conduction losses at 5 per cent., is about 80 per cent.

An interesting test on a large load was run by the Pittsburgh Steel Co. and A. N. Diehl jointly at Monessen. I give below the complete results of this test as they were put at my disposal. It must be kept in mind that this test was for the purpose of ascertaining the highest load compatible with good boiler efficiency, as will be seen from the low draft in combustion chamber of only 0.003 in.

The boiler used was equipped with a modification of the Bradshaw burner designed by J. S. Fraser. As I have already explained, it is rather dangerous to run a boiler on its maximum load, since one is constantly verging on incomplete combustion, as was the case in the present instance. Mr. Fraser's modification which is, as will be seen from Fig. 131, the application of the stove-burner principle to the boiler burner, gave nevertheless excellent results. By comparing the

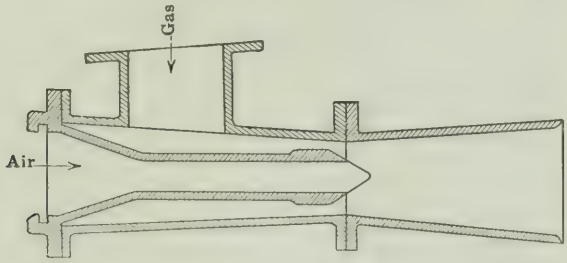


FIG. 131.

analysis in the combustion chamber with the stack analysis it will be seen that there was considerable air infiltration at the back of the boiler, which might of course have been stopped, but for certain reasons this was not done. The total evaporation during 8 hr. was 230,000 lb. water from and at 212°F. which is equivalent to a boiler load of 166 per cent.

The calorific value was stated as 102.8 B.t.u. of cold gas measured at 32°F. This is 97.6 B.t.u. measured at 60°F. for cold gas and 105.2 B.t.u. for gas of 377°F. measured at 60°F.

The average stack losses, in accordance with the readings obtained by Mr. Rhodes of the Carnegie Steel Co. have been, through unburned CO, 1.46 B.t.u.; through sensible heat, 20.32 B.t.u.; total, 21.78 B.t.u. equal to 20.7 per cent.

Assuming the radiation and conduction losses at 5 per cent., the total efficiency is 74.3 per cent., whereas in accordance with Mr. Merwin's figures this efficiency has been 72.3 per cent.

It is interesting to note the astonishingly high combustion temperatures which show that the burner efficiency falls little short of 100 per cent.

The importance of the Bradshaw burner as a coal-saving device was shown very clearly by the results obtained at the plants of the Pittsburgh Steel Co. and the Upson Nut Co. during the tests run to prove guarantees. At the Pittsburgh Steel Co.'s plant, the evaporation in the best months previous to the installation of our burners had been 3.6 lb. per pound of coke. For the purpose of proving guarantees a test of four days was run, which showed a maximum evaporation on one day of 4.42 lb. and an average evaporation of 4.25 lb. per pound of coke.

At the Upson Nut Co., previous to the installation of the Bradshaw burner, the average coal consumption over a year had been 1145 tons per month. This coal consumption was reduced to 100 tons per month, a quantity which is actually required for carrying their boilers over the casts. At the same time the Upson Nut Co.'s is now constantly bleeding considerable quantities of gas.

Conclusion.—Boiler efficiencies depend on both efficient burners and good boiler "morals." If either of the two is lacking, high efficiency will generally be impossible. Boiler "morals" include proper conditions in the boiler plant itself,

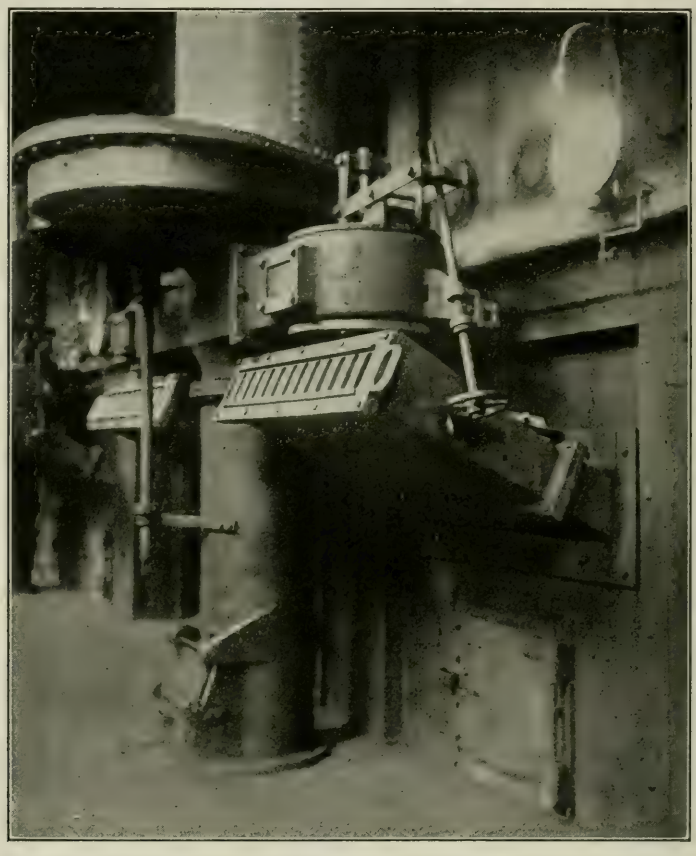


FIG. 132.—Stirling boiler with Fraser's modification of Bradshaw burner.

as well as intelligent working and close supervision. The regulation of a boiler plant should be done, as far as possible, exclusively on the dampers. With otherwise perfect conditions, efficiencies depend on the boiler loads. With a boiler load of 100 per cent. an efficiency of 80 per cent. is possible. With higher loads, it will soon drop to 75 per cent., but as a rule there will be no need to decrease the efficiency any further. Gas washing is profitable for stoves, but almost always results in losses where it is done for boilers. Moisture in the gas does not seriously affect efficiencies, except in the case of entrained moisture,

Tests Made at Monessen

Gas analysis													Rhodes gas analysis								Merwin stack analysis						
							Combustion chamber						Stack														
Time	CO_2	CO	H_2	CH_4	N_2	B.t.u.	Gas main pressure	Temp.	Draft	CO	CO_2	O_2	Temp.	CO	CO_2	O_2	Gas, temp.	Gal. of water	Time	Temp	CO	CO_2	O_2	Draft
9:00	13.6	25.2	2.6	0.2	58.4	99.1	17.0	R 2,320 L 2,410	0.0	0.6	24.4	0.9	600	0.2	20.2	4.7	350	.....	.....	.....	0.2	21.0	3.8	.....
9:30	13.1	26.6	...	...	...	.....	16.5	R 2,310 L 2,400	0.0	...	...	...	590	...	...	...	360	.....	9:00	640	0.2	20.9	3.9	0.76
10:00	13.5	26.2	2.8	0.1	57.4	102.2	17.0	R 2,340 L 2,320	0.0	0.8	24.7	0.3	600	0.3	21.0	3.8	340	.....	9:30	635	0.2	21.2	3.6	0.74
10:30	...	...	...	...	...	.....	17.0	R 2,390 L 2,420	0.0	...	...	...	590	...	...	...	340	23,751	10:00	635	0.2	20.6	3.8	0.75
11:00	13.6	26.5	2.8	0.1	57.4	103.3	17.0	R 2,440 L 2,430	0.0	0.5	24.3	0.6	605	0.0	19.9	4.6	380	.....	10:30	635	0.4	21.4	3.0	0.75
11:35	...	...	...	...	...	.....	17.5	R 2,380 L 2,380	0.0	...	...	...	610	...	...	...	410	23,711	11:00	635	0.3	20.4	4.2	0.70
12:00	12.3	26.9	2.7	0.1	58.0	104.3	17.0	R 2,440 L 2,480	0.0	...	...	...	600	...	...	...	480	.....	11:30	640	0.2	20.8	3.8	0.74
12:40	...	...	...	...	...	.....	15.0	.....	0.0	...	...	...	610	...	...	...	320	24,980	12:00	640	0.3	20.4	3.8	0.74
1:00	12.5	26.6	2.7	0.2	58.0	104.4	17.5	R 2,450 L 2,410	0.0	0.8	24.6	0.4	600	0.3	20.9	3.7	400	.....	12:30	635	0.0	19.8	4.8	0.72
1:25	...	...	...	...	...	.....	15.0	.....	0.0	...	...	...	610	...	...	...	420	23,751	1:00	630	0.2	20.8	3.8	0.72
2:00	13.2	26.5	2.8	0.1	57.4	103.3	17.5	R 2,470 L 2,440	0.0	0.9	24.7	0.2	600	0.3	21.0	3.8	380	.....	1:30	630	0.4	21.2	3.4	0.70
2:30	...	...	...	...	...	.....	16.0	R 2,430 L 2,400	0.0	...	...	...	600	...	...	...	325	22,482	2:00	635	0.3	20.8	3.8	0.72
3:00	12.5	25.9	2.6	0.2	58.8	101.6	15.0	R 2,400 L 2,390	0.0	0.9	24.3	0.3	600	0.3	20.5	3.9	440	.....	2:30	630	0.2	20.6	4.0	0.72
3:30	...	...	...	...	...	.....	17.0	.....	0.0	...	...	...	605	...	...	...	350	22,482	3:00	635	0.3	20.5	4.0	0.73
4:00	12.8	26.4	2.9	0.1	57.8	103.3	16.5	R 2,490 L 2,450	0.0	0.8	24.6	0.4	600	0.3	20.6	4.2	360	.....	3:30	650	0.3	20.7	3.8	0.73
4:15	...	...	...	...	...	.....	16.0	R 2,440 L 2,480	0.05	...	...	...	600	...	...	...	360	23,711	4:00	635	0.3	20.6	3.9	0.71
4:30	...	...	...	...	...	.....	15.5	L 2,500	0.0	...	...	...	600	...	...	...	380	.....	4:30	635	0.3	20.4	4.3	0.71
5:00	11.9	26.4	3.0	0.1	58.6	103.7	16.0	R 2,450 L 2,510	0.0	...	...	...	600	...	...	...	400	24,113	5:00					
Averages.	12.8	26.3	2.7	0.13	58.0	102.8	16.5	R 2,408 L 2,435	0.003	0.7	24.5	0.4	601	0.24	20.6	4.1	377	188,981 + 1,864 + 190,845	Total averages	634	0.25	20.6	3.8	0.75
10:00 a.m.	13.1	26.6	per Chemist Rhodes.																					

which should be avoided. Where gas washing is resorted to, the most favorable temperature from the viewpoint of efficiency is 100°F. It is advisable regularly to draw up carbon balance sheets and keep a check of the results obtained by reducing them to pounds of steam per pound of coke.

I beg to acknowledge the assistance kindly given to me, in the preparation of this paper, by J. S. Fraser and Grant D. Bradshaw, and also by Alfred Steinbart, as author of many of the curves.

PART III
PRODUCTS

CHAPTER XVI

PRODUCTS DEPENDING SOLELY ON CHEMICAL COMPOSITION

The products of the blast furnace may be divided into four broad classes, which in the order of importance and tonnage produced are steel-making irons, foundry irons, puddling irons, and ferro-alloys. These classes are each subdivided into several subclasses. Steel-making and puddling irons and ferro-alloys depend entirely upon their contents of the ordinary elements for their qualities, but foundry irons are required to have certain physical properties also. These physical properties, as will be shown presently, depend upon their content of certain elements for which we have only recently begun to analyze, and, therefore, their qualities are commonly not specified in terms of analysis in these elements, but in terms of analysis in the ordinary elements and physical properties combined. These relations are complicated and difficult; they require a chapter to themselves—therefore, the present chapter will be confined to the description of the other three classes of furnace products.

THE CONTROLLING ELEMENTS

The elements which are always present to some extent and whose quantity controls the qualities of iron as regards chemical specifications, are the same as those given in the chapter on "burdening," silicon, sulphur, phosphorus, manganese and carbon. In addition to these elements, there are present occasionally others, chromium, nickel, arsenic, etc.

In some of the earlier works on metallurgy, analyses of pig iron were given showing appreciable quantities of calcium, aluminium and magnesium, but as previously explained it seems safe in the light of our present knowledge to say that these were reported in error, since it is now absolutely certain that these elements are none of them reduced, or at least dissolved in the iron, by the action of the blast furnace.

STEEL-MAKING IRONS

These may be broadly subdivided into two classes—acid and basic, so-called from the fundamental nature of the steel-making process to which they are applied.

In the acid processes, the lining of the steel-making vessel is silicious, and bases such as lime or magnesia must not be added to the charge because their presence would result in scouring out the acid lining of the furnace. Phosphorus cannot be removed except in the presence of a strongly basic slag, and these processes consequently do not remove any of the phosphorus in the original charge. Therefore, the phosphorus in the pig iron must not only be as low as the desired phosphorus content of the steel, but must actually be lower because the phosphorus all remains while the other metalloids are almost wholly removed, and some of the iron is oxidized and lost in the slag during the conversion process, so that the weight of the steel produced is less by several per cent. than that of the iron charged, and the constant quantity of phosphorus accordingly becomes a higher percentage of this reduced weight.

In the basic steel-making processes, on the other hand, the lining of the vessel is made of basic or neutral materials so that basic fluxes in sufficient amount may be added to the charge, and by the presence of these, the phosphorus may be removed down to almost any limit desired.

The maximum limit for phosphorus in any ordinary steel is 0.09 per cent., and therefore the maximum phosphorus in acid steel-making iron is about 0.08 per cent. In many varieties of steel, the allowable phosphorus is much lower and the phosphorus in the iron must be correspondingly lower.

In basic steel-making irons, on the other hand, the phosphorus may theoretically rise to any percentage without preventing the conversion of the iron into good steel, and actually does rise to 2 per cent. and over in some steel-making irons in regular use in European practice.

No attention is paid to the carbon in any steel-making iron, either acid or basic, and it need not be mentioned again in connection with these irons.

IRONS FOR ACID STEEL MAKING

The three principal varieties of this iron for the standard (acid), Bessemer, acid open-hearth, and "baby" Bessemer.

Standard Bessemer.—Up to a few years ago the acid Bessemer process was the predominating process for the manufacture of steel in this country, but about 20 years ago the basic open-hearth process began to assume greater and greater importance until now Bessemer steel is relegated to a bad second in the race. Practically all rails were formerly made of Bessemer steel, but the superior quality which can be obtained with open-hearth steel has forced the abandonment of Bessemer material for this service, and the Bessemer rails now made are only an insignificant portion of the total rail tonnage. The principal uses left for Bessemer steel are for the manufacture of welded steel pipe, for which it is dis-

tinctly better than open-hearth, and sheet bar for rolling into tin plate. Some Bessemer billets for drawing into wire are also made. The phosphorus specifications in these different classes of material vary, but normally the upper limit is 0.09 per cent. so that the upper limit for the pig iron for conversion into this steel is about 0.08 per cent. In some special cases higher phosphorus than this is permitted, and in many other cases somewhat lower phosphorus is specified.

Sulphur.—Sulphur, like phosphorus, is not removed at all by the acid processes, and, therefore, the sulphur in the pig iron must be somewhat lower than the amount desired in the steel for the same reason as given for the phosphorus. As a general thing the sulphur specification for standard Bessemer iron is under 0.05 per cent. It generally averages somewhat below this in good practice, while in some cases the steel makers desire it somewhat higher, though not much is said about this because sulphur has a bad name, generally well deserved, in the metallurgy of iron.

Silicon.—The silicon in standard Bessemer ordinarily runs from 1 to 1.5 per cent. This depends somewhat upon the Bessemer practice and the class of steel being made. A certain amount of silicon must be present to give the heat required in the Bessemer blow, while too much leads to excessive blowing time and too hot steel. Iron with 1 to 1½ per cent. silicon is about the easiest to make.

Manganese.—The manganese requirements of standard Bessemer are not very strict. Iron can be successfully used running very low in this element, and it can also be used up to 1.5 per cent. or even higher, but the manganese burns out during the blow, and combining with the silicon makes a very thin slag, the effect of which is to produce what the steel men call "sloppy heats," and manganese is not desired much above 1 per cent. on this account. On the other hand, there is a growing belief in the steel business that the best steel cannot be made without the presence of a certain amount of manganese to prevent over-oxidation of the iron, and it is doubtful if an iron running 0.25 manganese, in the long run, would produce as good steel as one running 0.75 per cent. or even higher.

Iron for the Acid Open-hearth.—The quality of the product of the acid open-hearth furnace is, in some way not fully understood, better than that of the basic open-hearth for some purposes. Special forgings, springs, and especially steel castings can be made to much better advantage from this material than from the basic open-hearth, so that it is considerably used in spite of its higher cost.

Phosphorus.—In particular material of this kind the phosphorus specifications are always low, generally around 0.04, and not to exceed 0.05. The iron for this process, therefore, must be down to about 0.03 or 0.035 in phosphorus to make the class of steel desired.

Sulphur.—The sulphur in this class of steel must always be kept low, usually below 0.04 per cent., and for this reason the sulphur in the

iron must practically be no higher than the phosphorus, 0.03 to 0.035 per cent.

Silicon.—The silicon specifications for this material are about the same as those for standard Bessemer. The amount desired varies according to the practice and the conditions. Sometimes it goes as high as 2 per cent., but too much silicon necessitates a longer heat, and is, therefore, not desirable.

Manganese.—Manganese specifications are not commonly given for this class of material. The considerations which control are very similar to those in the Bessemer process, but the danger from sloppy heats does not exist and, therefore, the manganese for the acid open-hearth can go somewhat higher than Bessemer without being objectionable. It should probably be not under 1 per cent. for best results.

IRON FOR THE "BABY" BESSEMER

This process is only used in the production of steel castings, especially those of small size, and for this purpose the steel must be very hot in order to pour well into small molds. Large heats of steel cannot be handled because it would be impossible to pour them quickly enough into a great number of small molds, therefore, the Bessemer vessel used is a small one, normally of about 2 tons capacity. In order to obtain the high temperature necessary, the converter is almost always side blown instead of bottom blown.

Phosphorus.—Phosphorus specifications are practically the same as in the acid open-hearth, 0.04 or 0.05 and under. The loss is considerably heavier in this process than in the acid open-hearth, and, therefore the phosphorus tends to rise much more in the conversion so that the phosphorus in the iron must be at least as low as in the acid open-hearth, 0.03 or 0.035 per cent. and under.

Sulphur.—The sulphur specifications for this iron have to be more rigid than those for the acid open-hearth because the iron must be melted in a cupola for introduction into the converter, and always picks up an objectionable quantity of sulphur in this remelting[1] so that it is very difficult for the steel founder to meet the rigid sulphur specifications without having a very low sulphur iron to begin with. Therefore, iron for this process is desired 0.025 or under in sulphur, though it may be accepted as high as 0.035.

Silicon.—In order to give the high temperature desired, iron for this process must have a high silicon content, never less than 2 per cent., and ranging up to 3 per cent. and over. The burning of this silicon in the converter supplies the heat necessary to bring about the high temperature desired.

[1] The Stoughton oil burning cupola only raises the sulphur about a fifth as much as the coke cupola and is often used in Baby Bessemer works for that reason. Jan. 1, 1918.

Manganese.—There are no manganese specifications for this iron. Much of it is made and used very low in this element, being made from magnetite ores, but it is extremely doubtful whether this is as desirable as an iron containing a considerably larger quantity of this element, for the reasons already given.

IRON FOR BASIC STEEL MAKING

The basic processes for making steel are in a broad way similar to the acid processes except as to the character of the vessel lining used, the vessels used being the Bessemer converter and the open-hearth furnace as in the acid processes. The "baby" Bessemer is not used with a basic lining for reasons not pertaining to the blast furnace, so they need not be discussed here.

When a basic lining is used, a condition is brought about altogether different from that involved in the use of the acid processes. In the latter the presence of silica, caused by the oxidation of the silicon in the iron, makes no difference because the lining of the vessel being acid, this silica has no effect upon it, but in the basic process the silica attacks vigorously the basic lining of the vessel even in spite of the bases added to the charge. The more silicon there is in the iron, the more silica there is produced, and the more extensive is the damage done by its inroads on the lining, therefore, the first consideration in irons for basic steel making is that the silicon shall be low. This, however, brings about other conditions, especially in the basic Bessemer.

The heat necessary to raise the temperature of the molten iron to that of molten steel, some 400°F., is derived principally from the oxidation of the silicon since the oxidation of carbon to CO, the chief product of its oxidation in the converter, generates but little heat above that required for heating the products of combustion, and the nitrogen which accompanies them, to the necessary temperature. A greater amount of heat is required in the basic Bessemer process than in the acid, and when we lower the silicon our principal fuel for the production of this heat is discarded; this must, therefore, be made up by other fuels. The only ones available commercially are phosphorus and manganese, consequently irons for the basic Bessemer process require phosphorus to the extent of 2 per cent. or over, or when this is not available, manganese can be substituted for it to some extent. This process for making steel is not in use in the United States, and complete data concerning the latest practice in regard to it are not available.

Iron for the Basic Open-hearth Process.—The principal specifications in regard to this iron are those in regard to silicon and sulphur.

Silicon.—This element is always desired below 1 per cent. for the reason already explained, and the universal specification for merchant iron of this kind is "silicon 1 per cent. and under," but when the steel

works operate their own furnaces, they take iron running as high as 1.20 in silicon. In general, however, the iron supplied to the basic open-hearth furnaces average about 0.75 to 0.90 per cent. silicon. It is not produced to average much lower than this because with this amount the destruction of the furnace linings is not very severe, and it is practically impossible to produce regularly iron with lower silicon without either increasing the sulphur or the coke and limestone consumption of the blast furnace.

Sulphur.—The universal specification for merchant basic iron is sulphur under 0.05 per cent. Steel works take iron from their own furnaces up to 0.06 per cent. Part of the sulphur is removed by the basic slag, and there is no difficulty in making steel with sulphur 0.03 and under out of iron with sulphur 0.06. Nevertheless, if too much sulphur requires to be removed the cost of conversion goes up, consequently the specifications are held to the limits given.

Phosphorus.—The specifications in regard to phosphorus for basic open-hearth iron are very broad. Iron with Bessemer phosphorus is sometimes used, and on the other hand, iron with phosphorus to 1.85 per cent. is successfully converted into good steel. In this country many of the irons made in the South contain from 0.85 to 1 per cent. phosphorus. These are successfully used in the basic open-hearth furnaces, but they are not regarded so favorably by steel makers as irons containing 0.3 to 0.4 per cent. phosphorus or lower, since when the phosphorus rises above these limits the heats are apt to require longer for complete dephosphorization; this runs up the cost of conversion and so is very objectionable to the steel maker. Where the phosphorus rises much above 0.5 per cent., phosphoric acid becomes an element of appreciable importance in the open-hearth slag, and this being in the form of phosphate of lime may be made to give the slag a commercial value so that what was a liability may become an asset, but this subject can be better treated in connection with the duplex process.

Manganese.—The manganese specifications for basic open-hearth iron are about as broad as the phosphorus specifications, iron being used from that only having a trace of manganese up to that having 1.5 per cent. or more. Formerly but little attention was paid to this, but in recent years steel makers have come increasingly to believe in the protective action of the manganese in preventing the over-oxidation of the iron, and the tendency is consequently to specify manganese 0.75 per cent. or higher.

IRON USED IN COMPOUND PROCESSES FOR STEEL MAKING

In the conversion of iron into steel, the Bessemer process has the advantage of large tonnage per unit of steel-making capacity, and therefore its plant cost is very low. The open-hearth process, on the other

hand, has the advantage of better quality of material produced and of considerably smaller conversion losses because the oxygen for oxidizing the metalloids of the iron is supplied to a very considerable extent by iron ore charged into the furnace, and the iron of this ore passes into the bath and increases the yield. This is particularly true in regard to the removal of phosphorus, since the loss involved in doing this in the basic Bessemer conversion is very high, 15 to 18 per cent.

In order to obtain the advantage of both processes, attempts have been made at various times during the last 40 years to use one type of furnace for one portion of the operation and the other type for the remainder, transferring the metal from one furnace to the other. These combined processes known as duplexing, or triplexing, according to the number of furnaces used, were never very successful until the development of the enormous ladle-handling cranes of the present day made the transfer a matter of a few minutes, and effected it in such large masses of metal that the heat losses were insignificant. This development has occurred only within the last few years so that the evolution of the compound processes for steel making is by no means complete.

The iron for these processes has the least rigid specifications of any. Phosphorus may be present in any amount, and quite high sulphur can be eliminated without much expense. The silicon is eliminated in an acid-lined Bessemer converter, so does no harm unless present in excessive amounts, then it merely increases the time required for blowing. This adaptability to a wide range of irons is one of the causes that has brought about the introduction of the duplex process so rapidly in the last few years.

Silicon.—The silicon for this process is generally desired about the same as that in the Bessemer process, because not only the silicon is eliminated in the Bessemer converter, but the carbon is commonly blown down to between 0.15 and 1 per cent., so that the iron is converted into steel, except for the phosphorus, which is still in the metal and remains to be eliminated. The silicon is wanted about the same as in the Bessemer, about 1.20 to 1.50 per cent., so as to yield the heat to keep the metal molten at the high temperature corresponding to the removal of the carbon. This is the easiest and cheapest iron there is to make from the furnaceman's point of view, and this adds to the commercial desirability of the duplex process.

Phosphorus, Manganese and Sulphur.—Specifications for these are virtually the same as for basic open-hearth iron, and the same general considerations hold in regard to them. There enters at this point, however, the condition mentioned earlier concerning phosphorus.

The duplex process enables the slag resulting from oxidation of the silicon to be separated entirely from that arising from the oxidation of the

phosphorus. As a result the phosphoric acid in the slag can be raised to a very much higher percentage with this process than with the straight open-hearth process.

When a considerable percentage of phosphorus is present, the process may be so manipulated as to raise the phosphoric acid to a point where the slag becomes a commercial asset valuable in proportion to its content of this substance, and under these conditions it may well be that high phosphorus is more desirable than low, because it permits the production of a higher grade or a greater quantity of slag, valuable as fertilizer. I have no knowledge of cases in which the phosphorus has been deliberately raised on this account, but a condition might easily arise in which this would be profitable. Iron containing less than 1 per cent. of phosphorus can be so handled for conversion into steel that a commercial fertilizer of very important value is recovered.

IRON FOR PUDDLING

This variety of iron was formerly of great importance, as puddling represented the sole means of converting cast iron into a forgeable product; wrought iron, and all the standard products now made of steel, such as rails, plates, structural material, wire, etc., were at that time made of puddled iron. This process has, however, in recent years declined to an insignificant fraction of its former greatness, due to the greater cheapness with which steel can be produced and the superiority of that material for most purposes.

In spite, however, of the predictions to the contrary, wrought iron has not died out altogether, but has, on the contrary, in recent years rather arisen in public esteem for certain purposes. Its weldability is admittedly greater than that of steel, and for most forging purposes it is much preferred to steel on that account. Certain rolled products, moreover, are preferred by some consumers when made of wrought iron rather than steel. This is notably true in regards to materials which are required to resist rust, especially sheets for roofing and siding purposes, and welded pipe. The makers of these products in steel have waged a vigorous warfare against the conviction that wrought iron was better, but these products continue to be made of wrought iron and sold at a price considerably higher than that of the steel products.

The specifications for "forge" iron are rather broad and not very definite.

Silicon.—Iron puddles more easily when the silicon is low, but some of the best grades of puddled iron have always been made of comparatively high-silicon iron, No. 2 foundry. The "gray forge" iron, which was the established grade for puddling purposes in the old days, ran from about 0.75 to 1.25 per cent. silicon.

Sulphur.—The sulphur specifications for this iron are not at all strict. Sulphur exercises a less objectionable influence on wrought iron than on steel, and it is probable that the sulphur in the gray forge of the old days ran ordinarily between 0.04 and 0.08 per cent.

Phosphorus.—This iron is notable from the fact that it is desired to contain a certain amount of phosphorus, about 0.3 to 0.4 per cent., and where it is made at the present time, open-hearth slag or some similar material containing phosphorus is charged if necessary, to raise the phosphorus up to this point. Most of the phosphorus disappears in the puddling process, though good puddled iron may contain as much as 0.2 per cent. of this element.

Manganese.—There are no particularly definite specifications for manganese in this iron, but it is understood that the best results are produced when there is a moderate amount of this element present, between 0.5 and 1 per cent.

Carbon.—With this iron, as with the steel-making irons, no attention is paid to the carbon.

FERRO-ALLOYS

Various alloys of iron with other elements are made in the blast furnace. Formerly it was the only means for doing this, but the developments of recent years have shown that certain alloys can be produced to better advantage in the electric furnace, and that some others can be produced therein which the blast furnace cannot produce at all. This has to a certain extent narrowed the field of the blast furnace in regard to ferro-alloys.

Manganese Alloys.—There are two of these, spiegeleisen and ferromanganese varying from each other only in their percentage of manganese. The former was the earliest developed and was largely used in the days of the Bessemer process, especially in rail manufacture; it has been very largely superseded in recent years by ferromanganese.

Spiegeleisen takes its name from the fact that the manganese carbide forms in large flat flakes, half as large as one's thumb nail, which shine like mirrors in the face of the broken pig. Spiegeleisen contains from 15 to 30 per cent. of manganese, depending principally upon the amount of the element present in the ore from which it is made.

The amount of carbon in this alloy varies from 4.5 to 5.5 per cent.

No attention is in general paid to the silicon in this material, although in some cases a special product, high in silicon—6 or 8 per cent.—as well as in manganese, is produced. This is known as silico-spiegel.

Both these products should contain as little phosphorus as possible. The Bessemer limit is usually specified for them, but they may be used containing higher percentages if it suits the conditions of the steel maker in other respects; that is, if the phosphorus in his raw steel is low enough to stand the additional quantity brought in by the spiegel, and the price at which he can buy it is low enough.

Ferromanganese.—The standard alloy of this name contains 80 per cent. manganese, and about 5 to 6.5 per cent. carbon. No attention is paid to the quantity of silicon. Phosphorus is permitted up to about 0.2 per cent. in ordinary practice, the larger quantity being allowed on account of the fact that the weight of the ferromanganese used is much smaller than that of spiegel, owing to the difference in the manganese content.

Ferromanganese is often made containing smaller percentages of manganese than that given. The alloys still go by the name of ferromanganese when the latter element is as low as 40 to 50 per cent., but this is not as desirable, since this alloy is introduced in the solid condition, sometimes preheated, into the molten steel running from the converter or open-hearth furnace into the ladle. It is desirable that the amount of metal so introduced shall be as small as possible, so as to reduce its chilling action on the bath and increase the certainty of its uniform distribution through the metal, and obviously the higher percentage of manganese in the ferro the smaller weight required.

These are very largely the same considerations which have brought about a substitution of ferro for spiegel. When the latter is used, the quantity required is so great that it cannot be introduced solid, but must be melted in a separate cupola and run into the ladle as a liquid. This is more trouble and is out of the question when low-carbon steel is to be made, because the quantity of carbon in proportion to the manganese is three or four times as high in spiegel as it is in ferro, and in order to introduce enough manganese into the steel with the former, more carbon would be simultaneously introduced than could be tolerated for some purposes.[1]

Ferrosilicon.—There are two varieties of this material, blast-furnace and electric-furnace. In the latter, there are very high percentages of silicon—from 50 to 80 per cent.—but these products cannot be made in the blast furnace. Blast-furnace ferrosilicon is practically never made with any more than 15 per cent. silicon. The silicon in the ordinary grades varies from 8 to 14 per cent.

This alloy is notable for the fact that carbon is kept out of the iron by the rise of the silicon, as previously described. This action begins with about 4 per cent. silicon. When this point is reached the carbon decreases to the point where the graphite flakes, instead of appearing continuous in the fracture of the iron, are separated by areas of white, and this action continues as the silicon rises, so that in the higher grades the graphite appears as isolated stars of black in a field otherwise white.

The reduction of carbon and increase of silicon gives the iron a sort of greasy look, and irons containing from 4 to 8 per cent. silicon are called

[1] Recent developments have shown that low carbon steels can be made with spiegel of 30 per cent. Mn. and rapid progress in this direction is probable. Jan. 1, 1918.

"silvery irons", because their color is much lighter than that of normal irons. These irons are to some extent regularly made for foundry purposes, foundrymen using them to raise the silicon in a mixture otherwise too low. For such uses, of course, the phosphorus specifications are unimportant, but most of this is used in certain methods of steel manufacture, and therefore requires to be below the Bessemer limit in phosphorus.

No particular attention is paid to the manganese in this metal.

Ferrochrome.—Ferrochrome was formerly made in the blast furnace but never, as far as I am advised, in America. I am informed on good authority that the maximum amount of chrome that could be introduced into the iron was 30 per cent., no heat obtainable being sufficient to raise it higher than this. The introduction of the electric furnace has brought about the production of alloys much higher in chrome and correspondingly more desirable, so that the blast furnace no longer competes in this field.

Ferro-Phosphorus.—Tinplate when cold rolled in multiple thickness sticks together in the "pack" when the phosphorus is much below the Bessemer limit and as practically all open-hearth steel is far below this limit in phosphorus, it is found desirable to rephosphorize the steel for some tinplate. This is accomplished by the use of ferrophosphorus.

This product is made by a single blast furnace in Tennessee, the raw materials being iron ore, phosphate rock, silica and coke. Phosphorus occurs in great abundance in that region as calcium phosphate and the lime which accompanies the phosphorus is greatly in excess of that needed to flux the impurities of the coke and the iron ore, so silica must be added to flux out the excess lime. The phosphorus content of the alloy produced runs about 17 or 18 per cent. No information is at hand as to its content in the other element.

CHAPTER XVII

THE CHEMICAL AND PHYSICAL PROPERTIES OF FOUNDRY IRONS

Irons were formerly, and to some extent still are, graded by their fracture from No. 1 to No. 6—No. 1 being the most coarse-grained and graphitic iron and No. 6 being a solid white iron entirely without graphite. The No. 2 and 3 grades are nearly always divided into No. 2-X and No. 2 plain, and No. 3-X and No. 3 plain. Number 4 is commonly called "gray forge," No. 5 "mottled," and No. 6 "white," this grading corresponding with the fractures of the iron, and the fracture in turn being supposed to correspond with the softness of the iron in use.

Up to about 20 or 25 years ago chemical analysis was not used to any important extent in determining the quality of foundry iron, and this grading by fracture was the only method available to the foundrymen for determining the suitability of different irons for different purposes, but in more recent years it has been found that this grading corresponded in a general way with the presence of silicon and the absence of sulphur, and chemical specifications came finally to be used as supplementary to the fracture, and now to a very large extent have replaced fracture altogether in the purchase and sale of coke irons. The Eastern Pig Iron Association has adopted the following specifications as corresponding to the three grades first mentioned:

	Silicon	Sulphur
No. 1X	2.75—3.25	0.040
No. 2X	2.25—2.75	0.045
No. 2 Plain	1.75—2.25	0.050

The relations between chemical composition of irons and their physical characteristics are vital in foundry irons and there have been until recently wide gaps in our knowledge of the subject which are not yet completely filled but which have been greatly reduced by investigations made in recent years. In October, 1914, I delivered an address before the Franklin Institute in Philadelphia in which I attempted to embody the latest developments of our knowledge of this subject. The principal recent development was the discovery of the important effects of oxygen on the physical qualities of the irons in which it is contained. These effects are for most purposes highly beneficial, and for others very detrimental, and they explain many facts, the reasons for which have been mysteries previous to this discovery.

Following the discovery, methods were developed for introducing oxygen artificially into iron and some of the results obtained by this process are given as a part of the subject of the quality of iron, and are included in the article above mentioned, which is quoted here practically in full.

These results were obtained by an investigation, directed by me and extending over more than three years, to determine the fundamental facts in regard to cast iron.

Nearly all the chemical work and most of the microphotographs made during the investigations of which this paper is the result were made by Mr. L. Selmi, then chief chemist at the Ashland plant, now chief chemist and metallurgist of the River Furnace Co.'s steel plant. In addition Mr. Selmi gave his hearty and sympathetic coöperation to the whole investigation and rendered invaluable service to it throughout.

[1]Founding is one of the early arts and undoubtedly had its origin at the time of the development of the blast furnace in the latter middle ages. It has made its greatest progress, however, since the methods of using mineral fuel in this furnace have cheapened its product so much that 80 per cent. or more of that product is now nothing more than the raw material for the production of steel. The art of founding was almost ignored by the scientific metallurgist until within comparatively few years. The developments in the manufacture of steel were so rapid and of such vast importance to the whole of mankind that practically all the labors of iron and steel metallurgists were devoted to steel, and the foundryman was left to struggle along as best he could on the basis of his hard-earned, and sometimes contradictory, practical knowledge and experience. A great change in this condition was brought about in the nineties of the last century, for chemistry began to be applied freely in the foundry, and by its aid many facts in connection with the manufacture of iron castings were brought out. Some of these facts the practical men declared were not true, and the conditions of cast-iron manufacture are so complex that many are still in dispute.

In 1900, the closing year of the decade referred to, I published in the *American Machinist* an article in which, to my mind, was made the first definite and coherent statement of the nature of cast iron, particularly in its relation to steel. The following are some quotations from this article:

. . . "the key to the subject lies in considering cast iron and steel not as entirely separate and distinct, but as the same substance, passing by infinitesimal gradations from the chemical and physical properties of one extreme to those of the other. The probable reason that this fact is not more widely realized than it is, is that both of the extreme conditions are 'soft'—soft gray iron and soft or mild steel—while the connecting link between them is the hardest of tool steel

[1]Beginning of quotation from Franklin Institute address.

at one end and the hardest of white iron at the other, with no sharp lines separating them from one another.

"There is no doubt that there could be made in a blast furnace, from the proper materials, an iron containing silicon 0.2, manganese 0.4, phosphorus, 0.03, sulphur, 0.03, combined carbon 2.75 per cent., graphitic carbon, trace.

"But excessively hard crucible steel may be made having precisely the same analysis, and both have practically the same properties. The crucible steel is so hard and brittle that it cannot be commercially rolled or hammered, and is of no value, as well as being extremely difficult to make, while the greatest care and effort, and probably several weeks or even months of trial, would be necessary to produce an iron with the composition given, in a blast furnace, and when produced it would be of little commercial value; so that a material having this composition is seldom or never produced—never commercially—and we are not, therefore, familiar with it, and do not realize the fact, which it is impossible to emphasize too strongly in this connection, that it exists, or may exist, and constitutes a perfect link between cast iron and steel.

"Since soft iron contains the most total carbon (about 4 per cent.) and very mild steel the least (say 0.06 per cent.), while the intermediate stage, the very hard iron or steel just described, contains about the average of these two, roughly speaking, and is so much harder than either as not to resemble them in its properties, this may be thought to weaken or invalidate the above statement; but it does not, when properly considered, for, while the total carbon is high in the cast iron, almost all of it is in the graphite form and only a trace is combined.

"If we say, 'Cast iron and steel are alloys of the chemical element iron with carbon, with a chemical and physical admixture of other compounds, and the hardness of the alloy depends, within commercial limits, upon the amount of the carbon in it, while its tenacity, ductility, and other physical properties depend upon the other substances present, and upon the physical treatment it receives, and the variations produced by these are approximately the same in both,' we shall have a blanket definition of the two substances which covers both quite fully and with substantial accuracy.

"Too much stress can hardly be laid upon the two kinds of carbon in cast iron, the 'combined' being chemically united or combined with the iron to form a chemical compound; the other, the graphitic, being merely interspersed among the grains or crystals of the iron. The most striking proof of this latter is that shown a few years ago, I have forgotten by whom, which consists in brushing with a steel-wire brush the fractured face of a pig of gray iron, one-half of which is protected from the action of the brush; the brushed half becomes perfectly white, like white iron, although the grain, of course, remains as before. The unbrushed half, of course, shows the contrast more plainly.

"Iron, when hot, has a far higher capacity for dissolving carbon and retaining it in combination than it has when cold. The graphitic carbon is probably all in solution at first, although this is not certain.[1] But as the iron cools, if it cools slowly, the graphite is forced out and what is near the surface flies off into the air. It can be seen doing it at a blast-furnace cast when the iron is of the proper composition. The rest is retained, immeshed in the grains of the iron, and probably

[1] We know now that this *is* certain.

gives to gray cast iron whatever toughness and flexibility it possesses, separating the grains or crystals from continuous contact and lubricating their movements.

"Thus hard cast iron, while much less flexible, is much more elastic than soft, as it should be, having much less graphitic carbon in it. The more slowly the iron cools the more graphite crystallizes out of it and the larger the crystals, so that comparatively hard iron, when cast into large masses and allowed to cool for several days, or longer, will show a grain which would put 'No. 1 X' to the blush.

. . . . . .

"The tendency to eject carbon and become softer in consequence, does not by any means stop when the iron is solid, nor until it is down to the lower limit of the red heat at least, and how much lower the writer will not undertake to say. When any casting was made from moderately hard iron which it was required to machine, it was always kept carefully covered up until dead cold, and this was known by experience to be very necessary. Some intentionally 'chilled' pieces, when made of very hard iron, would 'fly' of themselves from the cooling strains set up, but could often be saved by keeping them hot as long as possible.

"When the iron is cooled suddenly, the carbon does not have time to separate out, and remains combined with the iron, making it 'white' instead of gray, because of the absence of the black graphite."

I think that this is a reasonably good presentation in a broad way of our knowledge of the subject to-day. It is a matter of interest that, in the subsequent part of the above article, is to be found the statement that the only reason for the use of charcoal iron, particularly for chilling purposes, was that, charcoal being free from sulphur, iron as low in silicon as desired could be produced in the charcoal furnace without any important simultaneous increase in the sulphur above that in high-silicon iron, which could not be done in coke furnaces until shortly before that time, but that it could be done then at will, and that charcoal iron had accordingly no advantage over coke iron, and was destined to pass out of use. This is probably as good an illustration of assuming that all the facts fit an incomplete theory, and drawing a totally erroneous conclusion in consequence, as can be found anywhere in technical literature. It is my particular purpose now to point out the important respect in which charcoal iron differs fundamentally from coke iron, and to describe the method by which we have succeeded in obtaining, for a modified form of coke iron, the advantages of charcoal iron in a greater degree than are obtainable by it.

In 1901, the year following the publication of my article, Professor Henry M. Howe read a paper before the American Institute of Mining Engineers, in which the theorem of the continuity of the cast-iron-steel series was set forth more elaborately and in far better language than in mine. Professor Howe pointed out that the important question in regard to the carbon in cast iron is not what is the total carbon, nor yet how much is thrown out as graphite, but how much is *left combined*, because it is

upon the quantity of combined carbon in the matrix that its strength depends.

It seemed to me at first that this statement put the matter in a nutshell, and was obviously correct. It will be seen later that Professor Howe's is also an incomplete theory, and that certain other factors enter in of so much greater importance in the final result as almost to eclipse the truth contained in his statement taken by itself.

THE IRON-CARBON DIAGRAM

From the quotations I have made, it is obvious that cast iron must be considered primarily as an alloy of iron and carbon. This is quite proper in a more elementary sense, because carbon is present in iron quantitatively to a greater extent by weight and to a far greater by volume than is any other element. Carbon has, moreover, a more powerful effect, weight for weight, than any other element except one.

The iron-carbon diagram, as applied to cast iron by Guertler based upon researches of Wittorff, is shown in Fig. 133. In Fig. 134 is shown a similar diagram drawn by Upton. Both of these have been obtained through the kindness of Professor William Campbell, of Columbia University. All are probably familiar with the general form of these diagrams. The abscissæ represent percentages of carbon, and the ordinates temperatures. The diagram, within its range, attempts to set forth the changes which occur in any solution of iron and carbon. A horizontal line runs across at the temperature of 1180°C., and two diagonals drawn respectively from the upper right- and left-hand portions meet upon this line at the point corresponding to 4.2 per cent. of carbon in Upton's diagram, at 3.8 per cent. in Guertler's. The diagrams attempt to show not only equilibrium conditions—that is to say, these conditions which prevail after the mass has been allowed sufficient time in cooling to reach a complete state of equilibrium—but also metastable conditions.

The interpretation of certain of the transformations is extremely difficult. I will not try at this point to make an exposition of the complete diagram, but will only call attention to its salient features. Considering Guertler's diagram and starting with a molten solution above the diagonal line on the left-hand side, we have a homogeneous solution—let us assume one whose composition is represented by the line XX. When the temperature falls, the composition remains constant until point A is reached, when, if ample time be allowed for the cooling, a solid freezes out, whose composition at any temperature is given by the intersection of the horizontal through that temperature with the line AB, in the present instance the line JJ_1 shown on the diagram. The metal represented by the point J obviously contains less carbon than that of the whole mass represented by the abscissa of the line XX, and the carbon

rejected by this solution in freezing must go over into the remainder of the solution, and so increase its carbon. If sufficient time is not allowed in cooling through any range, for instance that from JJ_1 to KL, the carbon from the solution is not able to diffuse into the solid and bring the percentage up to that represented by the point K, but tends more to follow the vertical line from J to K. This takes less carbon from the solution and leaves the excess in it greater. We have, therefore, the curious condition that the more rapid the cooling the greater the difference in carbon contents of the first and last frozen portions of the original metal.

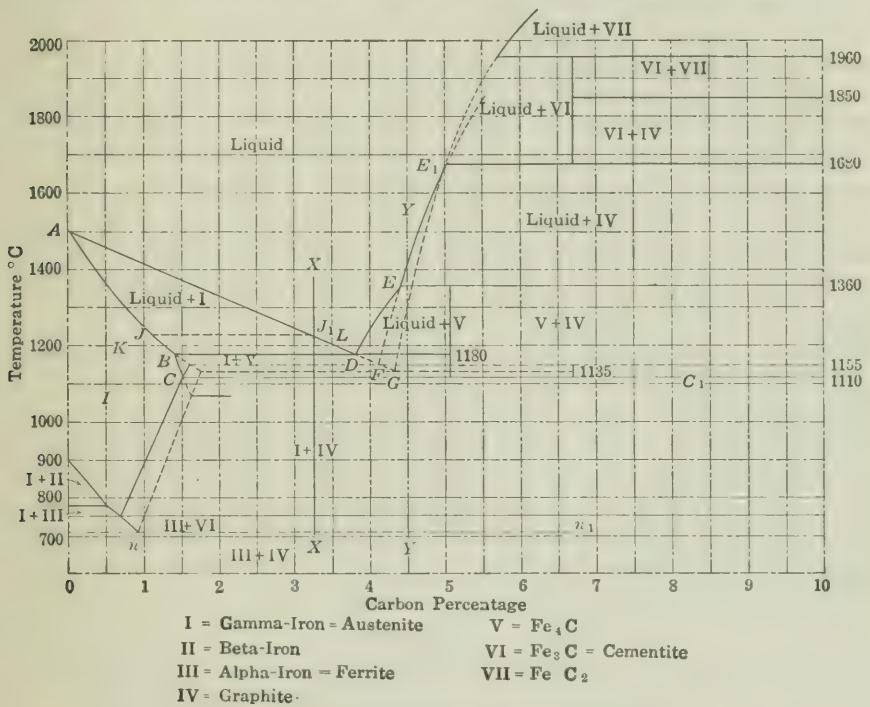


FIG. 133.—Guertler's iron-carbon diagram.

After the metal has fallen in temperature below the line BD, it is entirely solid, but is not yet in its permanent condition, because carbon tends continually to fall out of solution. The method by which this takes place is subject to various conditions, and is not yet fully understood, even among the scientists who deal with this phase of the subject, as will be clearly seen by the difference between the lower portions of Fig. 133 and Fig. 134, which are intended to represent the same set of objective phenomena.

The following brief statement of the possibilities in regard to the transformation of these points is quoted from my reply to the discussion of my paper, "The Effect of Oxygen, etc.," before the Institute of Mining

Engineers, published in its *Bulletin*, June, 1914, and was prepared for me by Professor Campbell, through whose kindness I am able to present here three possibilities based on the work of Guertler (who founds his conclusions upon the experiments of Wittorff and Ruff) and one based on Upton's iron-carbon diagram. According to Guertler:

I. In the stable condition above 1360°C. and 4.4 per cent. C., we can have liquid + graphite.

At 1360°C. the reaction occurs; liquid + graphite = Fe_4C, and in alloys with 4.4 per cent. carbon down to 3.8 per cent. we find Fe_4C crystallizing out from the melt.

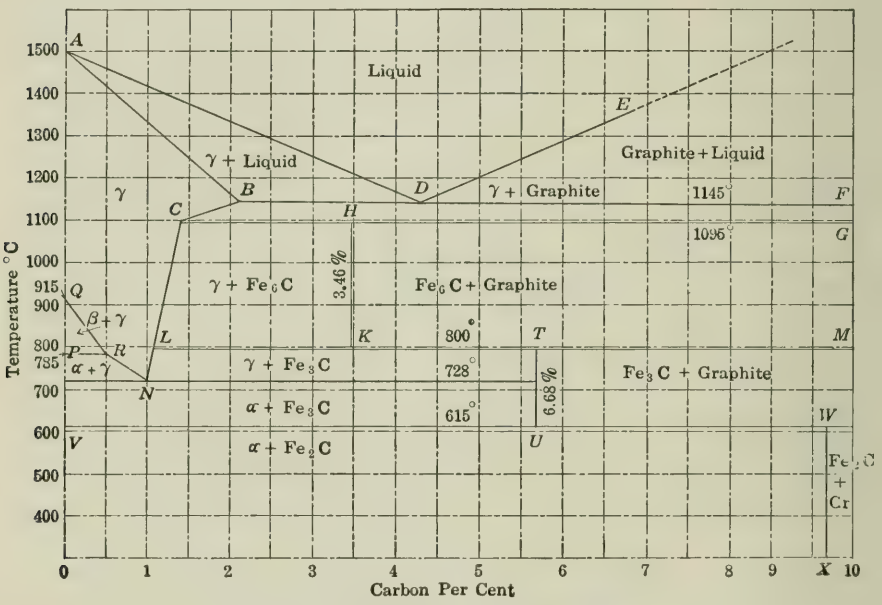


Fig. 134.—Upton's iron-carbon diagram.

At 1180°C. we have the eutectic of austenite + Fe_4C.

At 1110°C. Fe_4C breaks up into austenite + graphite.

At 750°C. the eutectoid of ferrite and graphite forms.

These are equilibrium conditions which are reached only with extremely slow cooling.

II. With more rapid cooling, the reaction at 1360°C. does not occur. Graphite separates from the melt, and at 1155°C. we get the eutectic of austenite + graphite.

III. With more rapid cooling, Fe_3C separates out from the melt and at 1135°C. and 4.3 per cent. carbon forms a cutectic with austenite; then at 710°C. we have the eutectoid Fe_3C + ferrite, commonly known as pearlite.

According to Upton's diagram, white irons are supersaturated solid solutions which are breaking down; and the stable constituents are austenite + graphite above 1095°C.; austenite + Fe_6C or Fe_6C + graphite below 1095°C.; and at 800°C., Fe_3C appears while Fe_6C disappears. At 600°C., F_3C breaks down into Fe_2C. Fe_6C and Fe_2C have yet to be distinguished from Fe_3C under the microscope.

Leaving this for the present, let us consider the conditions represented by an iron-carbon alloy, containing more carbon than that represented by the point *D* on both diagrams. Assume, for instance, iron of a composition represented by the line *YY*. According to both diagrams, when the temperature has fallen to the point where line *YY* cuts the right-hand branch of the curve solidification begins; but in this case it is either Fe_4C, graphite, or Fe_3C which is thrown out of solution.

The relationships expressed by the dotted lines *FE* and GE_1 are too obscure for description at this point, though we may revert to these briefly after examining the action of a few of that infinite variety of alloys answering to the comprehensive name of "cast iron."

In either case, it is well to remember that, when the temperature falls slowly, the iron tends to follow the one or the other of the branches of the curve in cooling. If a hypoeutectic iron—that is, one lying to the left-hand side of the point *D* (for instance, the composition represented by the line *XX*)—selective freezing tends to take place along the line *AB*, with a resulting concentration of carbon in the mother liquor, represented by the distance between the lines *AB* and *AD* on the horizontal line corresponding to the given temperature. But if sufficient time be not allowed then the iron tends to freeze in a purer (that is, lower carbon) condition, with a greater enrichment in this element of the mother liquor.

On the other side of the eutectic point *D* the hypereutectic iron tends in freezing to follow along one of the lines *DE*, *FE*, or GE_1, and in any event this corresponds to the falling out of graphite, or a carbide which, being richer in pure carbon, leads to a direct proportional impoverishment of the mother liquor; and this impoverishment in this case is greater if time is allowed for full equilibrium to be reached, and less if this time is shortened.

When the whole mass has solidified, it is at the temperature represented by the points *D*, *F*, or *G*, and consists of a mixture of different constituents, and the character of this mixture depends upon the original composition of the iron-carbon alloy and its rate of cooling from its initial temperature to that of the freezing point. This mixture generally contains graphite physically enmeshed, if it be a hypereutectic iron.

Below the line CC_1 it is obvious, from the diagrams, that their authors disagree considerably as to the details of the action, but further graphitization goes on, and the solution of pure iron in cementite becomes poorer and poorer in carbon until the line nn_1 is reached, when a very important

transformation takes place. All the solid solution remaining breaks up into pure cementite in detached areas and into pearlite, one of the best-known constituents of all irons and steels, and one which can perhaps best be described by reference to the fact that 0.9 carbon steel, in its unhardened condition, consists entirely of this material. Pearlite is well known as one of the strongest and toughest of the countless combinations of iron and carbon.

Even at this low temperature, 725°C. or 1337°F., barely a dull red, the iron is not yet in equilibrium. The cementite may break down to pure iron and graphite in relatively large masses. Pure iron or ferrite is only about one-third as strong as pearlite, and, of course, when its continuity is broken up by graphite it is thereby further weakened, and the graphite being in large areas, its effect in weakening the whole structure is very great.

The line *DE* of Upton's diagram may be entirely disregarded, since it is well known that the actual line is much steeper and is probably nearly, if not exactly, as drawn on Guertler's diagram, which is more recent than that of Upton and is based on the researches of Wittorff, the most recent and probably the most accurate of any of the investigations on high-carbon alloys of iron.

Upton's diagram is shown principally for the reason that it contains the vertical line *HK*, since it has been found by actual experience that irons with more than a certain quantity of carbon graphitize to a much greater extent than similar irons containing less carbon, and that high carbon irons not only throw out more graphite than do lower carbon ones, but the combined carbon remaining is very materially *less* in the high-carbon irons than it is in the low. The line *HK* indicates such an action, and is, therefore, to some extent in agreement with the observed facts, although I am quite unable to state whether the exact location of the line at 3.46 per cent. carbon is correct.

From the point of view of practical value, two possibilities according to these diagrams stand forth prominently.

1. Graphite can separate directly from the melt. It is held by some authorities that graphite forms only from cementite, that cementite is formed from the melt and then breaks down into liquid and graphite. The fact that this action would thicken up the metal, whereas the irons which evolve graphite from the melt the most freely are the most fluid is met by these authorities by the statement that the graphitization of the cementite is instantaneous. It is impossible to prove or disprove the existence of a phase whose period of existence is zero, so I prefer to omit the hypothesis of the cementite phase. What we surely know is that the graphite is evolved copiously from some irons when they are in an extremely fluid condition.

2. After solidification, according to Guertler and Upton, in certain

areas of the diagram a very slight change in conditions may cause a complete change in the resulting product.

The iron-carbon diagram gives graphically the best information we have concerning the action of alloys of pure iron and carbon, but cast iron is far removed from that theoretical material, as it contains, in addition, silicon, sulphur, phosphorus, manganese, and sometimes oxygen, in vastly varying quantities. There may be also titanium, vanadium, chromium, nickel and perhaps many other elements present, but the first five are the important ones in commercial pig irons. Each of these exercises its principal action upon the carbon and upon its condition, and as a result we would need in practice a complete diagram of the form given for each. To represent graphically, for instance, the effect of carbon and silicon together, we would require a figure of three dimensions, or, in other words, a solid or "glyptic model." In addition, for each percentage of each of the other elements there would be a variation of this model to express all the facts. The effect of three elements would require a model of four dimensions. As matter of fact, however, we have not as yet sufficient information to make a single iron-carbon diagram with absolute certainty, nor do we know very definitely the quantitative effects produced by given quantities of the other elements I have mentioned. We must needs, therefore, confine ourselves to a consideration of the qualitative effects of the above elements on the iron-carbon solution.

THE SHAPE OF THE CRYSTALS FORMED AND OF THE GRAPHITE

Before dealing with the effects of the other elements, I wish to call attention to two profoundly important facts, no intimation of which can be found in the iron-carbon diagram and the effects of which cannot be recorded upon it. They are, however, of vast industrial and, I think, scientific importance, and are also two factors in the final result to which I shall have occasion to refer frequently. The first is the shape of the graphite particles, and the second the form of crystallization in which the iron solidifies.

The shapes in which graphite can occur vary immensely, and have a corresponding effect upon the structure as a whole. Graphite is, to all intents and purposes, a foreign substance in iron. In other words, we could make a steel of the same composition as a good cast iron, counting only the combined carbon, and could by suitable heat treatment bring the combined carbon into the same condition as in cast iron, and have a homogeneous material of the same nature but free from these particles of a virtually foreign substance; this would constitute an impure steel, but would be vastly stronger than the cast iron because of the absence of the "foreign matter."

The smoothness and lubricating qualities of graphite are well known, as is also the fact that it is entirely without physical strength. To intersperse flakes of this material thickly through cast iron can have obviously no other effect than to break its continuity and destroy the bonds with one another of the particles of iron proper.



FIG. 135.—Etched (magnified 38 diameters) spot of spotted iron.

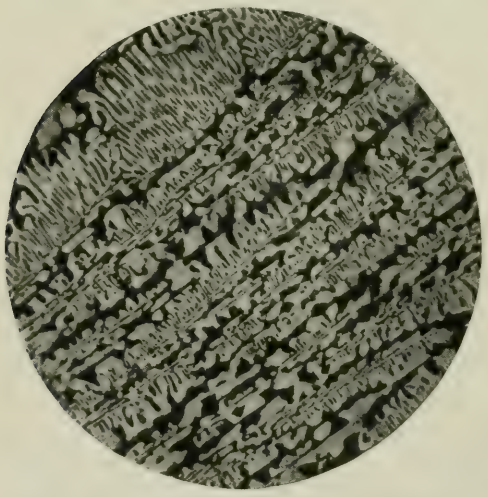


FIG. 136.—Etched (magnified 100 diameters) spot of spotted iron.

Good gray iron contains about 3 per cent. of graphite, and the specific gravity of this is about a fourth that of iron. This corresponds to about 12 per cent. by volume. One of the things which we have discovered is that graphite in some iron is of extreme thinness and of vast extent, while in other iron it scarcely exists except in little round knots or balls. Consider this enormous percentage by volume and the extreme thinness of the plates of graphite, which, judging from the photomicrographs, are probably less than $\frac{1}{1000}$ in. thick, and you will see what an enormous area they must have to make up 12 per cent. of the volume, and what a vast amount of damage they must do to the structure of the iron.

If we were to make up concrete and add to it 12 per cent. by volume of, say, tin scrap in small, irregular pieces, about 1 in. across, and well greased to prevent the concrete from adhering to them, and were to stir these thoroughly through the mass, then pour the mixture into a form, do you think that the resulting concrete would be particularly valuable? If, now, instead of tin scrap an inch across, we used iron balls of about the same specific gravity and in the same proportion by weight, and stirred

those thoroughly through the mass, can you doubt which concrete would be the better?

As to the form of crystallization, the eutectic of 4.20 carbon crystallizes from a pure iron-carbon solution in a series of flat plates, the cross-section of which is similar to that of a number of fern leaves laid side by side, as shown by photomicrographs, Figs. 135 and 136. In certain kinds of iron these plates grow so large as to be plainly visible to the naked eye. When they remain white, they are as smooth as if polished, and shine brilliantly when their surfaces are exposed. If you imagine a series of blocks of mica thrown loosely into a mold, then cement or glue poured in to fill up the spaces between, and the resulting structure subjected to stress, you would not expect to find it very resisting, no matter how good the cement, because the blocks would cleave apart on the smooth faces of the mica. It is the same with iron which has this crystallization. No matter how good its chemical composition may be, even if the combined carbon be of the exact amount to give the greatest strength, the iron will be weak and worthless.

If, on the other hand, even the concentration which comes from progressive freezing results in the formation of little or no eutectic, the solution freezes into a network structure, which I have supposed is the same as that in the steel named by Professor Howe "Primaustenoid." The best illustrations of this structure I have are those shown by Figs. 137 and 138. It will be seen that the structure as a whole is vastly more homogeneous than the eutectic and quite lacking in the lines of cleavage which give the latter its bad qualities, but that such lines of crystallization as do appear are in the form of a meshwork, so that the whole structure, where not absolutely homogeneous, is interlaced together.

These are the two facts which render the amount of graphite, and even the percentage of combined carbon, matters of secondary importance, and which reduce the value of Professor Howe's brilliant generalization on that subject.

The Effects of the Principal Elements on the Qualities of the Iron.—The qualities by which different irons are distinguished from one another are very many. I have classified them as follows: strength, flexibility, elasticity, density or closeness of grain, fluidity, freedom from shrinkage, and machinability. These represent qualities generally desirable, but the importance of some is the greatest in one class of work and of others in other classes of work; in fact, advantages for one class of work may be positive disadvantages for another. These are matters which depend upon the purposes for which the castings are to be used, and need not be discussed in detail here.

Let us return now to the elements of prime importance—carbon, silicon, sulphur, phosphorus, oxygen, and manganese—and consider the effects which varying quantities of each of these may have upon each of

the above qualities of major importance. You will see that we have here a practically unlimited number of combinations, and that it is virtually impossible to do anything more than to discuss the general results of the variations of the elements within the range of practice in different lines of foundry work.

All of these elements must be considered from two distinct points of view, first the effect they would have on the matrix of steel, that is on the iron if no graphitic carbon were present, and second on the state of the graphite, for obviously since every cast iron consists of a matrix of impure steel through which graphite is scattered, its qualities will depend first, upon the strength of the matrix and next upon how much the matrix is cut up by flakes of graphite. Many of the elements exert an effect of their own on the matrix but a more important one on the amount of carbon which remains combined and perhaps also on the shape of the graphite which forms so that their effect is extremely complex.

CARBON

Carbon, as is well known, is the master element of all these which are alloyed with iron to form steel, its importance in the steel industry is so great that the subject of its effects has received more attention than any other in steel metallurgy; books and papers without number have been written about it. The physical aspect, the combinations which form, their relation to the conditions occurring, etc., are shown by the iron-carbon diagram. We need here to touch briefly on the effects of carbon on the mechanical properties of the steel (matrix) which contains it. For this purpose, we may say briefly that carbonless iron is soft, ductile and weak, its tensile strength being only about 30,000 lb. per square inch, while it is so soft and tough that iron with carbon down to 0.04 per cent. can scarcely be turned in the lathe without tearing.

As the carbon rises, the strength and hardness increase, while the ductility as steadily diminishes. The strength is probably a maximum at 0.9 per cent.

The Eutectoid Composition.— This has about three times the tensile strength of carbonless iron, while its ductility, except by special annealing, would be under 10 per cent. instead of over 50, as in the carbonless iron. For cutting tools where little toughness, but great hardness and strength are required, the carbon is sometimes raised to 1.5 per cent., or a little more, but such steel while hard and very strong, has practically no ductility at all and breaks without plastic deformation.

These rough statements give a good idea of the effect of carbon in the matrix of cast iron up to the percentages given, which are as far as steels are made industrially. In cast iron, of course, the combined carbon can be anything up to 4 or more per cent. The effect of further increases



FIG. 137.—Etched (magnified 100 diameters) good charcoal iron, showing meshwork structure.

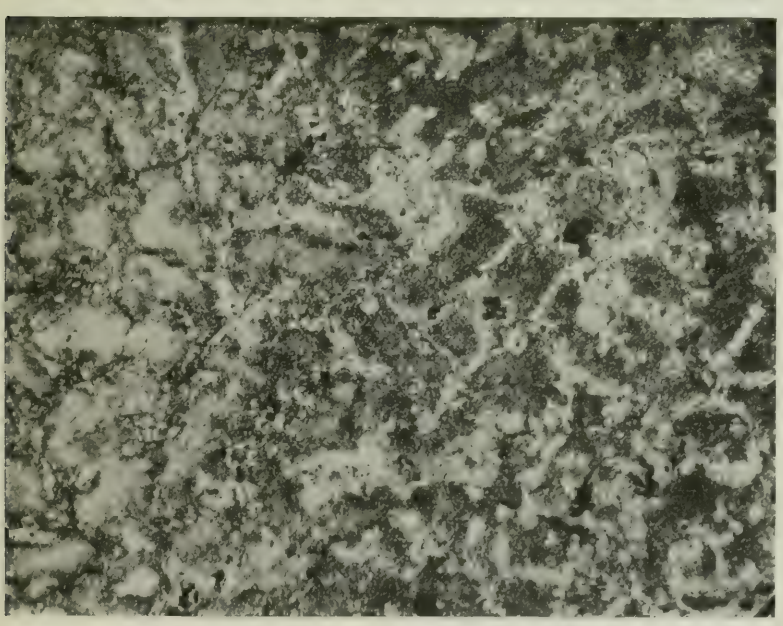


FIG. 138.—Etched (magnified 100 diameters) coke iron with oxygen added. First heat of Johnson iron ever made. (Photograph due to kindness of Prof. William Campbell.)

beyond the limits mentioned is to increase the brittleness so that the strength even in compression is reduced and that in tension very greatly. These direct effects are, of course, tremendously modified by the other conditions now to be described.

The subject of the effect of variations of carbon in cast iron has been neglected far too much. The carbon determination in cast iron is a difficult one, and unless made by a man with considerable experience in this particular work is of no value. Errors to the extent of 1 per cent. of the weight of the iron (not the carbon) have frequently been made by good and conscientious chemists through the difficulty of manipulation and, until recently, through the absence of suitable apparatus for the purpose. At the Ashland plant of the Lake Superior Iron and Chemical Co., where we began the researches the results of which are to be given, we introduced a long silica tube heated by an electric resistance coil, with a pyrometer to control the temperature, and burned the carbon in a stream of purified oxygen, catching the carbon dioxide in barium hydrate solution and determining its amount by titration—practically the same method as used for carbon in steel. We became so convinced of the importance of carbon determinations that we put an extra man into the laboratory in order to obtain one on every cast. Even with this excellent apparatus it took months to learn necessary temperature control and other precautions which must be taken to secure correct results. The difficulties are greatly increased by the fact that one iron will be heated to incipient fusion and sintered by a given temperature, thus sealing up some of the carbon and giving a low result, while another iron at the same temperature may not be hot enough to give off all its carbon and may show a low result on that account. I believe these difficulties of making carbon determinations, and of securing dependable results when they are made, have militated more against the progress of cast-iron metallurgy than any other factor.

The results of variations in carbon and their effect on the form of crystallization were set forth at some length in a paper read by me before the American Institute of Mining Engineers in 1912, entitled "Effect of High Carbon on the Quality of Charcoal Iron."

These investigations were first directed to finding the cause for an occasional cast of "spotted" iron which has enjoyed a reputation for exceedingly poor quality, deficient chilling power and painfully little strength—a reputation which tests showed to be well deserved.

These irons have been noted for a curious peculiarity; ordinarily we expect to see the part of the iron cooled first white and the part last cooled gray, if there be any white or gray at all, which means that the white is outside and the gray is in the center. But in these irons the outside of the pig is gray, while there is a white chilled spot in the center, or just above the center, of the pig (Fig. 141, page 462). This curious

phenomenon has caused much racking of wits in the charcoal-iron business for many years in which we participated during the earlier course of our investigation at Ashland.

Finally, it occurred to me that this spot occupied the position which a segregate would take. An analysis of the spot and other portions of the pig showed that there was indeed a segregation, the spot being decidedly higher in carbon than the rest of the pig, while the iron as a whole contained 4 per cent. or more carbon. In irons of moderate carbon, the portions first frozen are well below the eutectic ratio, but the portions last to freeze have the carbon concentrated in them by the selective action of freezing and therefore crystallize in the eutectic form. It is well known that the evolution of graphite is accompanied by a considerable increase in volume, and, if this be resisted with sufficient pressure, graphitization cannot take place, and the iron must remain white. I have seen a white spot produced in the center of a pig of good iron by cooling the exterior very rapidly. This took away the heat from the outside, while the center still remained hot enough to retain its carbon in the combined condition. The resulting contraction of the outer metal prevented the graphitization of the center, which would have taken place as the temperature fell, by preventing the necessary increase in volume.

It has previously been suggested by Mr. H. E. Field that this spot was caused by the pressure resulting from the contraction of the outer shell of first frozen metal upon it, but, as all pig iron solidifies under these conditions and only a small portion of it contains this spot, this solution is obviously inadequate.

The reason for the automatic formation of the white spot in these spotted irons is probably to be found in two factors:

First, the segregate at the center is the eutectic, and therefore has a freezing point very decidedly lower than the outside, so that the shell is thoroughly solidified and able to exert a considerable pressure when the center begins to solidify.

Second, these spotted irons occur only within a limited range of silicon, from 0.8 per cent. down to 0.3 or 0.4. The former limit of silicon is sufficient to force graphitization, even against the resistance of the external shell. Below the latter limit the iron is practically all white, although in the case of a high-carbon iron it may be heavily specked with primary graphite scattered between the blocks of eutectic plates which constitute the body of the structure.

It is a matter of observation that an iron may show a "spot" if quickly cooled, but will not do so if cooled slowly. For instance, the 1¼-in. test bars made at every cast at Ashland would sometimes show a spot when the pigs did not. This is evidently because of the fact brought out in the explanation of the iron-carbon diagram that the quicker the cooling and the less time allowed for the diffusion of the carbon into

solidified portion of the metal, the greater the carbon concentration in the last frozen portion. Iron which, when slowly cooled, is far enough below the eutectic ratio not to undergo sufficient carbon concentration to show a "spot," undergoes, when quickly cooled, a greater carbon concentration, because there is not enough time allowed for the diffusion of the carbon throughout the mass, and so shows a spot.

The final results we obtained have been briefly mentioned above, and showed that iron of the eutectic ratio crystallizes in smooth, flat plates without cohesion between either the plates in one group or between those of one group with those of another. If the iron is above the

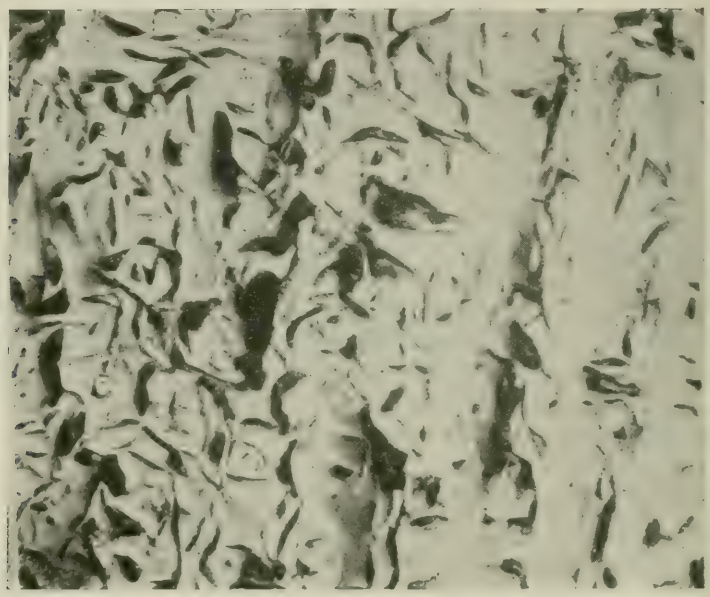


FIG. 139.—Unetched (magnified 70 diameters) high-cleavage iron, showing rows of graphite flakes oriented after eutectic plates from which they were formed.

eutectic ratio—that is, of a composition represented by the right-hand branch of the iron-carbon diagram—the excess carbon above the eutectic ratio falls out in the form of graphite as the iron cools along one of the lines DE, FE or GE_1, and in that event, of course, the whole mass, except the ejected graphite, is at the eutectic ratio at the point of solidification and freezes as a mass of eutectic, perhaps interspersed with the particles of hypereutectic graphite. During cooling after solidification, if the silicon be high enough, it forces the decomposition of the eutectic plates into pearlite, ferrite, and graphite. These are formed in the solid condition and necessarily have the orientation of the plates of eutectic from which they are born, and, in consequence, high-carbon irons,

when they have sufficient silicon to make them gray, have an appearance of high cleavage, especially around the corners of the pigs and at other points where they are quickly cooled. These cleavage planes are black or gray, but are of the same general character as the brilliant white plates, which occur in the same iron when it is white or mottled. They are the result of the breaking down or graphitization of the original eutectic plates (Figs. 139 and 140).

It is obvious that the strength of the iron must be destroyed either by the large flat crystals or the wide areas of similarly oriented graphite into which they may break down.

These spotted irons then are simply irons high enough in carbon for the concentration caused by quick cooling to run up to or above the eutectic ratio and segregate in the last-freezing region. The characteristic crystals formed by its freezing are prevented from throwing off their graphite by the pressure of the envelope of previously frozen iron and so remain white.

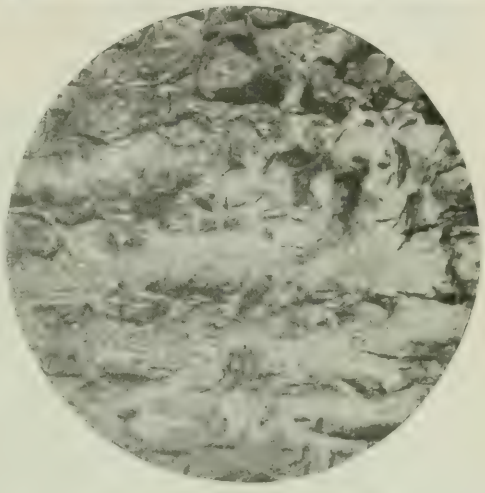


FIG. 140.—Etched. High-cleavage iron, showing rows of graphite flakes oriented after eutectic plates from which they were formed. (Magnified 70 diameters, reduced about $\frac{1}{3}$.)

These high-carbon irons were noted among practical men for very deficient chilling power, a fact amply confirmed by observation of the "chill pig" at Ashland, of which one was cast in every bed, these irons having only a fraction of the chill which they should have for a given silicon. This action may, I believe, best be explained by reference to the well-known law of physics, that a solution of, say, common salt may be cooled below the point at which it can theoretically retain the amount of salt which was dissolved at a higher temperature, and may, if kept quiet, retain the excess to a temperature considerably lower than that of equilibrium; but if a single crystal of salt be dropped into the solution, the excess will instantly crystallize out around it, and the solution will at once drop to the equilibrium ratio. So in iron, if it be cooled more rapidly than will permit it to reach equilibrium, under ordinary conditions more carbon will be retained in combination than the equilibrium ratio would call for, but when the mass is filled with graphite flakes deposited from the molten condition (which, as I have explained, takes place with these irons) these graphite flakes act as centers of precipitation and cause *more* carbon to fall out of the solution

than would do so if there were *less* total carbon present. Thus, by the aid of the microscope and with a little help from the iron-carbon diagram, we find the explanation for the characteristics of these irons easily translatable into terms of analysis, namely, their high carbon content, and so solve this long-standing riddle.

In this connection, it must be pointed out that, while 4.2 per cent. is the eutectic ratio for a pure iron-carbon alloy, the eutectic point is lowered by the addition of silicon, and probably falls to 3.8 per cent.



FIG. 141.—Typical fracture of "spotted iron."

or even lower when the silicon reaches about 2 per cent. or more. On the other hand, other things being equal, the total carbon falls as the silicon rises beyond, say, 0.5 per cent., because carbon and silicon exert to some extent a mutually exclusive action upon each other, exactly as water saturated with calcium chloride will not take up as much common salt at a given temperature as will pure water. So, as the silicon in iron rises, the carbon falls until we reach "silvery iron"—which is much lighter gray than ordinary iron because of the small quantity of carbon present, in spite of its being entirely graphite, the carbon with 4 per cent. silicon

probably falling to below 3 per cent., as against nearly 4 per cent. in coke iron, and sometimes almost 5 per cent. in spotted charcoal iron of about 0.5 per cent. silicon.

On the other hand, the carbon falls from about 0.5 per cent. silicon as the silicon falls, because these irons are made in a colder hearth. The temperature of the iron as produced is not sufficient to enable it to take up its maximum carbon. The fact that at this silicon percentage occurs the maximum carbon is probably also a factor in the occurrence of spotted irons only within a limited range on either side of this point.

While it has been demonstrated that high carbon leads to certain exceedingly objectionable qualities in iron, it is, nevertheless, not to be assumed that high carbon is always bad, or that the lower the carbon the better the iron, since this is far from true. The hardness of chilled iron depends largely upon its content of iron carbide. This compound contains 6.66 per cent. of carbon, so that an iron with even 4 per cent. of carbon is less than two-thirds carbide or cementite. The farther we fall below 4 per cent., the smaller the percentage of carbide which can be formed from the carbon present, and, other things being equal, the softer the chill in the same proportion. In order to obtain the benefit of the high carbon, we must be able to retain the carbon in the combined condition and not have it thrown out as graphite either before or after freezing; this, as will be seen later, we now have a means of doing. For chilling purposes, therefore, the carbon in iron needs to be high. When the carbon falls much below 3 per cent. the character of the metal seems to change. It is probably for this reason that steel scrap, with a mixture of which strong castings can, in good practice, admittedly be made, may only be used in a limited proportion in chilled castings, because, if used to a greater extent, it dilutes the carbon of the whole charge so much as to impair the hardness of the chilled material.

So far as the blast furnace is concerned, we do not need to concern ourselves with carbon lower than about 3.5 in any ordinary range of silicon, since as far as my knowledge goes, furnaces seldom make lower carbons than this under normal working conditions, although a furnace too cold to function properly has often been known to produce what is virtually wrought iron, which, of course, has too high a melting point to run from the furnace and which causes endless trouble in consequence.

The lowest carbon I have ever seen was 3.03 per cent. This was a charcoal iron produced when the furnace was in trouble. Such an iron contains much oxygen-bearing material, which reacts with the carbon and causes the metal to be filled with a great mass of blow-holes, white as silver inside because the CO which blew them prevents oxidation, so that each pig swells up to the section and general appearance of a loaf of well-made bread, and makes the material worthless for commercial purposes. This is known as "Spongy No. 6."

The melting point of the iron-carbon alloys, as may be seen from the diagrams, Figs. 133 and 134, falls from 1500°C. for pure iron to 1180°C. at the eutectic point. The lowering of the melting point taking place along a straight line, being, therefore, proportional to the increase in carbon, consequently if the carbon be lowered to too great an extent, the melting point becomes so much raised as to make the metal difficult to handle in the cupola, and this rise in temperature exerts a certain very detrimental influence on high-class iron, which will be shown later.

For strength alone there seems to be no doubt that a reduction in the carbon is good, even below 3 per cent., but it is probable that only material ranging from 3 to 5 per cent. in carbon should be considered cast iron. By far the major portion of all the iron produced lies within the comparatively narrow limits of 3.5 to 4.25 per cent.

The other elements exert an influence on the amount of carbon which iron can contain, and also on the eutectic ratio, but these influences will be better discussed in so far as they are known, in connection with the elements concerned.

THE CHEMICAL AND PHYSICAL PROPERTIES OF FOUNDRY IRONS

Silicon.—Next to carbon, this is the most important component of cast iron. It varies in ordinary iron from 0.2 up to 4 per cent. Above 4 per cent. the iron passes into the field of "silvery" iron, and from thence to ferrosilicon. It is extremely difficult to make iron containing less than 0.2 per cent. silicon in the coke furnace without having the sulphur run up to prohibitive limits. In the charcoal furnace iron can be produced with silicon as low as 0.1, or 0.15 in good white iron. The lowest I have ever seen it was 0.03, but this was in the spongy white iron of which I have spoken above.

Various investigations have been made as to the effect of the addition of silicon to steel. Sir Robert Hadfield conducted an extensive research on alloys of iron and silicon several years ago; this may be found in the *Journal of the Iron and Steel Institute*, 1889, vol. ii, page 222. The effect of silicon on steel (and therefore upon the matrix of gray iron also, in a general way), within the ordinary limits in which the silicon occurs in foundry iron, was not particularly marked, but when it rose above 3.5 per cent. it diminished materially the ductility of the steel. I have already pointed out that the strength of the matrix of gray iron proper is far less important than the extent to which it is cut up by graphite, and for this reason within ordinary limits we do not need to consider very seriously the relatively slight effect of silicon upon the metal itself (that is, the matrix), but its effect upon the carbon. This, as is well known, is to force the carbon out of the combined condition into the graphitic, and thus action takes place not only above the melting point, but also down to relatively low temperatures.

This is best illustrated by the fact that ordinary coke iron of more than 1 per cent. silicon will not show a white chill when cast against a chill block. Under any ordinary circumstances, this silicon is sufficient to force the graphitization of the carbon, in spite of the sudden cooling. Below this percentage the chilling power of the iron is roughly inversely proportional to the amount of silicon present. The iron begins to show a chill as cast from the furnace a little below 1 per cent. At 0.75 silicon it will show ordinarily ¼ in. of white chill, at 0.5 silicon ½ in. chill, and at 0.25 silicon it will chill clear through a depth of 2 or 3 in., and will show much white in the pig, even when slowly cooled.

The completeness with which carbon is thrown out of the combined condition in unchilled iron is, in a rough way, similarly proportional to the silicon present. With 2 per cent. silicon an ordinary coke pig iron will hardly show more than 0.25 per cent. combined carbon, but the amount left in the combined condition will rise as silicon falls, until when the silicon goes down well below 1 per cent. it may be as high as 1.0 per cent. throughout the mass without the casting being chilled white on the surface. These figures are subject to modification by half a dozen other factors besides silicon, and are correct only in a general way for average conditions. Definite figures are only given with great reluctance to avoid glittering generalities which sound well and mean so little.

Apart from this influence on the carbon, silicon, when it rises above 2 per cent., has the effect of hardening the matrix of the iron itself, so that an iron may be really harder to machine in consequence of having silicon added to it than it would have been with a somewhat smaller amount. There seems to be a certain probability, also, that the portion of the silicon burned out when the iron is melted in the cupola (about 0.25 per cent. in ordinary practice) remains to some extent enmeshed in the iron, and gives rise to that bane of the foundryman's existence—"dirty spots"—in the casting. These, being in the form of silica or silicate of iron, are, of course, very hard, and vastly increase the difficulties of machining the casting which contains them, even though they may not be present in sufficient amount to cause the rejection of the piece.

The effect of silicon on the strength of the iron is, of course, very different in different portions of the silicon range. The amount which converts the iron from white to dense gray increases its strength by turning brittle and crystalline cementite into tough and homogeneous pearlite, even though the latter be somewhat cut up by graphite. But as the silicon content rises further and forces the combined carbon far below the pearlite ratio (say from 0.9 down to 0.2) it weakens the matrix and simultaneously increases the deposition and size of the particles of graphite which interrupt the continuity of the structure, and in both these ways reduces the strength of the iron.

Sulphur.—This is the most troublesome element in the metallurgy of

iron. It is present in the coke with which irons are smelted, in amount from about 0.8 per cent. up to 2 per cent. Probably in present practice it averages 1.10 per cent. Most of this is forced into the slag, but sulphur has an affinity for iron, and it is commercially impossible in coke practice to maintain the sulphur continuously much below 0.025 per cent. in ordinary iron, and only down to that amount by excessive cost in coke and limestone over that required to hold it down to 0.04.

Charcoal is almost free from sulphur, and, therefore, irons with one-half this sulphur *may* be made with that fuel more easily than iron with 0.025 per cent. can be made with coke. At the same time charcoal iron does not average below 0.018 and is seldom below 0.010. This matter has been subject to very wide misapprehension, which has been a hurt and not a help to charcoal iron. The low sulphur of charcoal iron has often been claimed as its principal virtue, with sulphur contents claimed to be "a trace" or "under 0.01 per cent." The latter statement is totally erroneous, since the sulphur in practically all charcoal iron is twice the amount claimed, and is little or no lower than that of a great deal of coke iron. The increase in sulphur in remelting in the cupola is so much greater than that in good iron of either kind that a far greater improvement as regards this element can, in general, be made in the final product by a little more care in buying and analyzing the coke for the cupola, rather than the pig iron. The real virtue of charcoal iron is to be found in a totally different direction, as I shall presently endeavor to point out. Its freedom from sulphur gives charcoal the advantage which it enjoys in producing iron of higher quality than can be produced with coke, except by treatment of the latter after it leaves the furnace, but the low sulphur of the iron itself is not the reason for this superiority.

Sulphur forms with iron a sulphide which has an extremely low melting point, and this sulphide dissolves in the iron itself in varying proportions in such a way that the sulphur exerts a threefold influence: First, it tends to hold the carbon in the combined condition; second, it tends to liquate out into segregated spots and, on account of its low melting temperature, sulphide of iron is extremely likely to bleed or run from the point which remains molten longest, and thereby cause a shrinkage cavity; third, it has an objectionable tendency to produce high shrinkage in the iron, with all the attendant difficulties of casting practice which accompany this condition.

Sulphur also has a very serious tendency to cause cracks in the iron, which is probably a result of the shrinkage. A white coke iron is often made when the furnace is slightly deranged with sulphur, from 0.07 per cent. up to 0.2 or 0.3 per cent. in extreme cases. Such an iron, when quickly cooled with water, will crack up into little cubes like dice, each of whose faces is discolored almost black with a film of so-called "oxide color." White charcoal iron, on the other hand, of even lower silicon is

tough and reasonably strong, and practically never shows this tendency to break up into small pieces with oxidized faces. This statement is important and will bear some emphasis. In making coke iron low in silicon, "basic," we always expected to see the iron do this if the furnace became somewhat cold. On the other hand, in charcoal practice extending over 3 years I never remember to have seen a single case of this, although the charcoal furnace, with the quickness of its kind, was capable of getting into just as serious difficulties as the coke furnace ever did, and did so much more frequently. Conditions are so similar in other respects that it seems certain we must assume that this objectionable tendency to form cracks is due to the presence of sulphur. In the manufacture of chilled cast-iron car wheels the sulphur must be kept within certain limits at all hazards, as otherwise the wheels will crack under the thermal test.

For this poison in the iron we have as antidotes silicon and manganese. The silicon has no tendency to remove the sulphur, but, tending as it does to force the graphitization of the carbon, it resists the tendency of the sulphur to keep it in the combined condition. There is a rough-and-ready rule for the quantitative value of this effect, which is that 10 units of silicon are required to offset the effect of one of sulphur, so that, if the sulphur in the casting be raised 0.1 per cent., the silicon would require to be raised 1.0 per cent., to offset the sulphur. It is almost certain, however, that, while the silicon prevents the action of the sulphur on carbon, it does not prevent its tendency to produce cracks and to increase shrinkage, with all its attendant evils.

The ordinary sulphur specifications for pig iron are 0.05 per cent. for steel-making irons, and 0.04 or 0.035 per cent. for foundry irons. For some special grades, for which a special price is paid, even lower limits are specified. When this iron is remelted in the cupola it always take up some sulphur from the coke in the fuel bed; this amount varies from 0.02,* in extra good practice, to 0.1 or even more, in bad practice, and, while I am not one of those who sneer at the foundrymen, it does seem that they are at times inconsistent, since many of them will make a violent protest if the sulphur in the pig is 0.01 per cent. higher than the specifications call for, and will then buy a cheap coke which will raise it 0.05 per cent. more than would a really first-class coke. I regard sulphur as the most objectionable element with which we have to contend in cast iron, and I believe the foundrymen are absolutely right in leaving no stone unturned to get the sulphur as low as possible in their castings, but sometimes it seems that they put the emphasis in the wrong place.

In this connection, it may be said that the benefits in holding down the sulphur, which may be obtained by the use of lime and a little fluor spar to flux the ash and sulphur of the coke, are not as widely appreciated as they should be.

*It is .01 or less in the oil-burning cupola.

Phosphorus.—The determination of the effect of phosphorus upon steel might almost be said to have been the first fragment of our modern knowledge of metallurgy. The reader may perhaps be familiar with the story that after Sir Henry Bessemer's first successful production of steel on an experimental scale he licensed manufacturers to use the process, but when they came to do so the product was rotten and worthless. His process was condemned, and he himself was subjected to contumely for his claims. He set out to find by chemical analysis the reason for the failure, and discovered that it lay in the phosphorus content of the iron from which the steel was made, and that, by one of those curious tricks of fortune, he had bought for his experiments the only iron in England low enough in phosphorus to make good steel.

Once this was revealed, the ores which would produce iron of low enough phosphorus were located, and by using only these iron suitable for his process was obtained. With the exhaustion of the purer ores, the limit of the phosphorus set for Bessemer steel has gradually risen, until it is now about 0.09 per cent. Dozens of processes have been introduced for making good steel out of material containing much more phosphorus than this, without removing the latter, and it is said this may be done with some success so long as the carbon is low. When the carbon rises, however, such material always becomes brittle, uncertain, and unreliable. This has given phosphorus a bad name.

It has been assumed that because phosphorus was bad for steel it must necessarily be so for cast iron. Here, again, is found ignorance of that fundamental fact that a reduction of the strength of the matrix may be unimportant if a change in those conditions which affect its continuity is simultaneously made. Moreover, cast iron is a brittle material, and is not expected to be used in tension, or only under exceptional conditions, and there is no proof that phosphorus increases the brittleness of the metal until it reaches many times the limit permissible in steel. On the contrary, the Southern irons which carry in the neighborhood of 1 per cent. phosphorus command a premium for foundry purposes.

The effect of phosphorus is probably due to the fact that it forms one or more definite compounds with iron, which have a low melting point, and which dissolve in the iron and lower the melting point of the whole mass.[1] This is different from the effect of sulphur, in which the tendency seems to be for the last freezing portions to segregate after the major portion of material has solidified. The fact that phosphorus contributes to the fluidity of iron is well recognized, and for many classes of castings which require to be made very thin the phosphorus is run up to 1 per cent. or more. There is probably little doubt, however, that this content is high enough to affect the strength of the iron adversely. For general purposes, where strength is more and fluidity less important, phosphorus

[1] J. E. Stead: Iron and Phosphorus, *Journal of the Iron and Steel Institute*, 1900, ii.

from 0.5 to 0.75 per cent. is to be preferred—the latter being only for lighter castings, the former for heavier and stronger castings.

(Since the above was written, I find that the experience of the automobile manufacturers has been that phosphorus must be kept below 0.3 per cent. in their extremely complicated and difficult cylinder castings, as more than this causes a slight liquation from the heavier parts of the castings to the lighter ones and produces porosity at the former points. Castings are more difficult to make with this low phosphorus content and have to be poured considerably hotter than would otherwise be necessary, but this is the only method by which porosity can be avoided. For the ordinary run of thin foundry work, where these very severe conditions do not have to be met, higher phosphorus facilitates the work greatly.)

The effect of phosphorus up to about 0.4 per cent. seems to be to increase the strength of iron. Remelts which I have made in crucibles proved this conclusively. Two remelts were made of the same iron, to one of which phosphorus was added, raising it from 0.13 to 0.4, the other not being changed in any way. This was done on two very different irons with the same result in both cases. The strength of the best bars was materially increased by the addition of the phosphorus, and so were the depth and character of the chill. These are both most desirable qualities for material such as car wheels, but the knowledge that somewhere below 1 per cent. phosphorus begins to make the metal brittle and treacherous debars us from going beyond very moderate limits in this direction for castings in which strength and reliability are the prime consideration.

Oxygen.—I come now to that portion of my subject in which my conclusions are diametrically opposed to the accepted theories of the past. I fear my readers' credulity may be strained to the breaking point. I have referred already to the investigation made at Ashland to determine the reason for the difference in quality of charcoal iron and coke iron. The first results of this investigation were those already described on the effect of high carbon, but, while these explained why some iron was bad, they did not explain why the irons of normal carbon were stronger than the coke irons of similar analysis, in some cases very much stronger.

I went into the investigation with a profound conviction that, next to sulphur, oxygen was the worst enemy of cast iron, but, after several months spent in a vain endeavor to confirm this hypothesis, I suddenly conceived the idea that the *presence* of oxygen, and not its absence, was that which made charcoal iron superior to coke iron. Two years of research were required before sufficient proofs were secured to justify publication of this hypothesis, but these proofs were finally obtained and the results were published in a paper before the American Institute of Mining Engineers, under the title "The Effect on the Strength of Cast Iron Exerted by Oxygen, Nitrogen, and Some Other Elements." The results of

this investigation were at first violently combated by some scientific metallurgists, but are now being more and more accepted.[1]

We found, first of all, that certain irons made when the furnace had been in trouble and working cold were exceedingly strong (sometimes, though not often, almost twice as strong as irons of practically identical analysis made at other times). We found that, after being remelted in crucibles, the strong ones retained and even increased their advantage in



FIG. 142.—Unetched (magnified 100 diameters) electric furnace iron. Note extent and intersections of graphite. Strength of this iron very low, temperature of manufacture very high. Oxygen content zero.

strength over the weak ones. We found, too, after months of trial, how to make oxygen determinations in cast iron; these showed that the strong irons contained oxygen, that the weak irons contained little or none, and that those of normal moderate strength contained an intermediate amount.

By a curious coincidence, a very extensive thermal investigation of the action of charcoal and coke blast furnaces was being simultaneously undertaken for the purpose of bettering the fuel economy if possible. (See "Wet Ore in Charcoal-furnace Practice," Chapter III.) This investigation revealed the fact that furnaces which produce the strong irons are

[1] Prof. H. M. Howe, recognized as the world's foremost metallurgist, has honored my results by publishing in his monumental work The Metallography of Steel and Cast Iron.

those which run with a deficiency of heat in their hearths and so tend to an incomplete deoxidation of the ore—that is, tend to leave a small amount of oxygen in the iron, while those furnaces which produce the weakest irons are those which generate the greatest excess of heat in the hearth and produce the metal at the temperature farthest above its melting point, the electric furnace, which develops practically all its heat in the hearth, and produces its iron at an excessively high temperature, yields the weakest



FIG. 143.—Etched (magnified 100 diameters). Same as Fig. 142. Note complete absence of pearlite and joints in ferrite. These never occur in oxygen-bearing irons.

variety of cast iron made. (See Figs. 142 and 143. Note the shape of the graphite and how it cuts the structure of the iron completely to pieces.)

Photomicrographs of different irons showed the reason for the increase in strength in the strong irons, since the graphite in these irons is relatively round and nodular compared with the graphite in the weak irons, which is thin and of tremendous extent, and cuts the iron like crooked knife strokes in all directions.

In Figs. 144 to 159 are shown strong irons and also weak irons of similar analysis, both before and after remelting. These figures are reproduced from the paper just mentioned. Figs. 144 to 165 show in particular an extremely nodular condition of the graphite, and indicate more plainly than can any words how much stronger these irons must

HIGH SILICON IRON

(All microphotographs ×100, reduced about one-third.)

Good iron (oxygen, 0.27 per cent.).



FIG. 144.—Unetched.

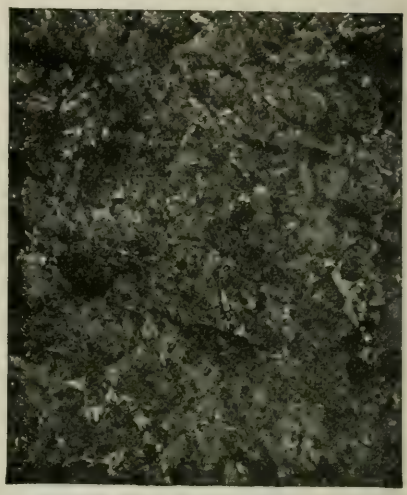


FIG. 145.—Etched.

Silicon, 1.90 per cent. Breaking strength 1¼-in. bar, $\left.\begin{matrix}3000\\3350\end{matrix}\right\}$ lb.

Poor iron (oxygen, 0.009 per cent.).



FIG. 146.—Unetched.



FIG. 147.—Etched.

Silicon, 1.88 per cent. Breaking strength 1¼-in. bar, $\left.\begin{matrix}2500\\2900\end{matrix}\right\}$ lb.

REMELTS OF IRON SHOWN ON OPPOSITE PAGE

(All microphotographs ×100, reduced about one-third.)

Good iron.



FIG. 148.—Unetched.



FIG. 149.—Etched.

Silicon, 1.90 per cent. Breaking strength 1¼-in. bar, $\left.\begin{matrix}3150\\3200\end{matrix}\right\}$ lb.

Poor iron.

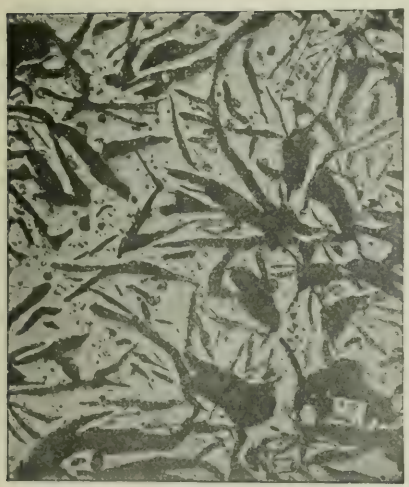


FIG. 150.—Unetched.



FIG. 151.—Etched.

Silicon, 1.88 per cent. Breaking strength 1¼-in. bar, $\left.\begin{matrix}2600\\2700\end{matrix}\right\}$ lb.

MEDIUM SILICON IRON

(All microphotographs ×100, reduced about one-third.)

Good iron (oxygen 0.065 per cent.).



FIG. 152.—Unetched.

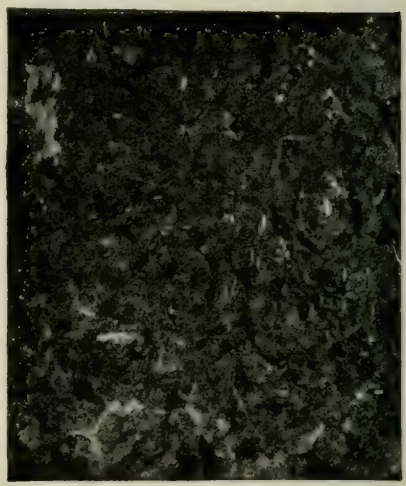


FIG. 153.—Etched.

Silicon, 0.70 per cent. Breaking strength 1¼-in. bar, $\left.\begin{matrix}3400\\3500\end{matrix}\right\}$ lb.

Poor iron (oxygen, 0.009 per cent.).



FIG. 154.—Unetched.



FIG. 155.—Etched.

Silicon, 0.72 per cent. Breaking strength 1¼-in. bar, $\left.\begin{matrix}2500\\2500\end{matrix}\right\}$ lb.

REMELTS OF IRON ON OPPOSITE PAGE

(All microphotographs ×100, reduced about one-third.)

Good iron.

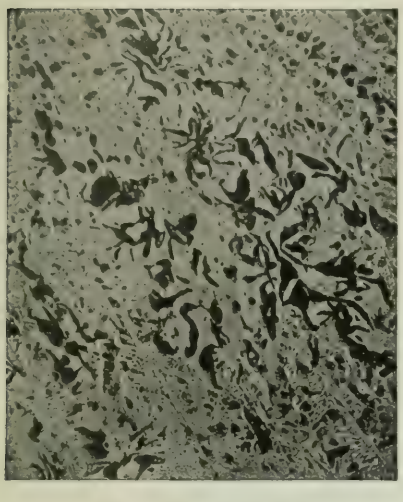


FIG. 156.—Unetched.

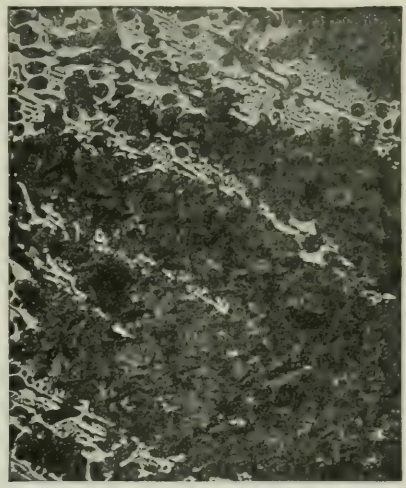


FIG. 157.—Etched.

Silicon, 0.70 per cent. Breaking strength 1¼-in. bar, 4150 lb.

Poor iron.

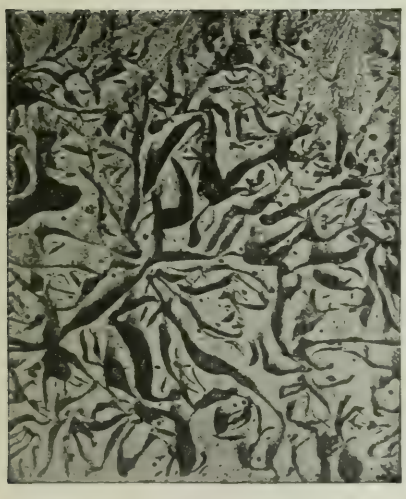


FIG. 158.—Unetched.



FIG. 159.—Etched.

Silicon, 0.72 per cent. Breaking strength 1¼-in. bar, 2750 lb.

necessarily be than those of similar composition containing thin, flaky graphite.

The experiments described in the same paper, and briefly referred to here, are only a selection from the multitude of experiments, carried on throughout the investigation mentioned, all pointing to the same conclusion.

It seems that the effect of the oxygen is fivefold:

First, it tends to throw the graphite into the nodular condition. The theory as to the action by which this takes place has not yet been fully confirmed by scientific investigations, but coördinates so many facts that I am satisfied it is correct, and feel justified in pointing it out here. Observation has convinced me that the irons which contain oxygen have a higher melting point than those which do not contain it. When approaching the freezing point, they do not freeze suddenly, as water turns to ice, but pass through a slushy or pasty stage, which is practically absent in the case of hot-made coke iron. When graphitization begins in the latter it is still liquid, and the graphite forms from the liquid absolutely without any stress whatever upon it, and is therefore free to assume whatever shape it chooses, irrespective of how great the volume and surface of that shape may be, and so following the natural tendency it forms huge flat leaves or plates.

On the other hand the oxygenated irons solidify at a higher temperature, at which little or no graphitization has yet taken place, and by the time they have cooled to the temperature of graphite evolution the iron matrix has become sufficiently solid to be the dominating element in the combination. The graphite forms, but forms only against the heavy pressure exerted by the preformed solid of the metal. In consequence, the graphite must form so as to take up minimum volume and surface. In other words, it must take this spherical form in which it is seen in Figs. 158 to 163.

A confirmation of this theory is that good charcoal irons are noted for their low shrinkage, whereas bad ones are noted for their high shrinkage. This is, I believe, because when the graphite forms in the liquid, as it does in the oxygen-free irons, the iron then solidifies around it and after solidifying shrinks continuously until cold. But when the metal solidifies *previous* to the formation of graphite, the latter forms against the resistance of the metal, which results in an increase of volume of the latter after solidification, and this expansion is deducted from the total shrinkage in the final result.

This theory is not absolutely demonstrated as yet, but it is certainly in accordance with all the facts and is well worthy of an investigation, which I hope will soon be undertaken by some of the scientific metallurgists so as to confirm or refute it.

Whatever may be the facts in regard to shrinkage, the increase in

strength of irons which contain oxygen over those which do not contain it is a matter not open for discussion, nor is the shape into which it throws the graphite.

Second, the oxygen seems to exert another influence by changing the form of the crystallization of high-carbon irons from that of the eutectic, previously shown in Fig. 135, to that of the meshwork structure, shown in Figs. 137 and 138. By this means it increases the strength of the matrix, as well as diminishes the detrimental action due to the graphite.

Third, oxygen seems to act as a brake on the separation of the carbon and to prevent the hard and strong needles of cementite which exist above the last transformation point from breaking down into graphite and ferrite, of which only the latter has any strength at all, and that, much less than any other constituent of iron-carbon compounds.



FIG. 160.—Etched (magnified 70 diameters) coke iron. Note the long, slender bodies of graphite and ferrite side by side formed by the breaking down of cementite crystals.

This action is clearly shown in Fig. 160, a photomicrograph of a coke iron of excellent reputation, exhibiting a number of long, slender plates of graphite with similarly shaped bodies of ferrite on one or both sides of them. These jointly constitute the remains of crystals of cementite by whose breaking down they were formed. The structure is obviously a weak one, not only on account of its shape, but because the graphite and ferrite are so much weaker than the original cementite.

This structure is never seen in irons containing any important amount of oxygen, for the reason that oxygen seems to prevent the iron-carbon compounds from breaking down very far below the pearlite ratio of 0.9 per cent. combined carbon so that they seldom contain any visible ferrite.

I do not pretend to be able to explain this latter fact, but it is a fact

in my own experience, nevertheless. The range of fixed carbon, 0.6 to 0.9 per cent., within which most of the high oxygen irons lie, is that embracing the strongest steels, and this fact is undoubtedly of considerable influence in making these irons so strong, since it makes the strongest matrix.

Fourth, oxygen has an effect on a matrix itself, considered as a steel. This, as is known by the best-informed steel metallurgists, is that it strengthens the steel, but reduces its elongation and increases its brittleness. Undoubtedly the oxygen exercises the same influence on the matrix of the iron, but the results as regards brittleness are the opposite of what they are in steel, because nothing promotes brittleness so much as gashes in the material, such as are caused by flat flakes of graphite, and suppressing these not only increases the strength, but also largely eliminates what might be called incipient cracks, from which breakage might start; and this effect, therefore, reduces the brittleness of the metal far more than the slight effect on the matrix increases it. As a matter of fact, soft irons containing oxygen have not only greater strength, but also a degree of toughness amazing to those used to only ordinary cast iron; they seem almost to bend before breaking.

Fifth, oxygen exercises also a very important influence on the chilling power of the iron, due to its retardant action in the separation of the carbon, and it was undoubtedly for this reason that the use of high-grade charcoal iron was formerly almost universal for car wheels and remains accepted practice to-day for the production of those chilled castings which demand high quality and bring a high price. It seems to be a fact that the presence of oxygen not only increases the chilling power of the iron, but also increases its sensitiveness to chilling influences. An iron containing oxygen, if cast in sand, will retain somewhat more combined carbon than a similar iron not containing oxygen cast under the same conditions, and if the irons are cast against a chilling surface the one containing oxygen will begin to show a white chill at a higher silicon than the other, and will show greater chill for the same silicon as the latter element decreases.

Moreover, the character of the two chills is quite different. The chill of the oxygen-free iron is made up of needle-shaped crystals, or rather crystals shaped like long, slender pyramids, with their axes perpendicular to the chilling surface, their sides brilliantly polished, and making sharp angles with each other in a plane parallel to the chilling surface, so that the crystalline mass has but little strength in any direction in this plane. The chill of the oxygenated iron also shows crystallization normal to the surface, but the crystals, instead of being highly polished, have rough faces, so that they interlock with one another. The chill shades well into the gray at the base, the mottled area containing little stars of graphite in the field of white.

It is impossible to describe in detail, or even to show by photomicrographs, comparative chill structures, but those whose business is the manufacture of high-grade chilled castings have never ceased to use charcoal irons, even though they cost two to three times as much as coke iron of the same nominal analysis, for the reason that, with this iron, they have found by experience they can produce castings of a quality to justify their customers in paying the difference in price.

That the difference between charcoal iron and coke is in the carbon and oxygen I have explained above, and we have proved that it is in those two elements alone, so far as anything is capable of any absolute proof in so complicated a subject, by analyzing not only for all the common elements, but also the rarer ones and for gases such as nitrogen and hydrogen. Hydrogen we found to be absent, but nitrogen we found to be present in varying quantities, but no variation of the quality of the iron attributable to its variation could be observed, and, while we added nitrogen to the remelts by introducing nitrogenous substances, the differences produced even by considerable additions of nitrogen were unimportant.

Here, then, we find, as has so often been found before, that these curious, one might almost say mysterious, variations of quality arise not from variations of one element, but from simultaneous variations of two. We have variations of carbon from well above to well below the eutectic ratio, with the resulting low quality in the first case; and we have, with this, variations in the oxygen whose presence produces greatly improved quality, whether with high or with low carbon. The complexities of the operation of the blast furnace are innumerable; until recently we have not known much about its thermal equilibrium and the variations in the latter produced by different conditions of working, nor the effect of these variations on the carbon and oxygen contents of the iron produced; it is therefore not surprising that the variations in the quality of charcoal iron, as controlled by variations of furnace practice, were so difficult of understanding as to seem positively mysterious.

The analysis of the thermal equilibrium of furnaces, to which I have before alluded, shows that those furnaces which produce good iron run with a relative deficiency of heat in the hearth, while those which produce bad iron run with an excess of heat in the hearth.

Observation both by eye and with the pyrometer shows that irons made under the latter condition are much higher in temperature as they come from the furnace than those made under the former, and this leads to two results—elimination of oxygen (which appears to be a function of temperature more than anything else) and supercarbonization of the iron, because while we know but little concerning the conditions which control the carbonization of iron, we do know that the degree of saturation possible increases with the temperature.

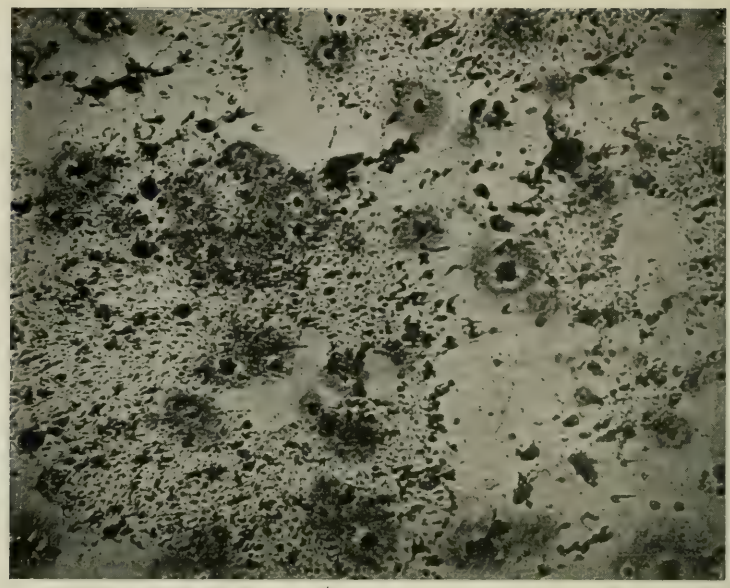


FIG. 161.—Unetched (magnified 100 diameters) "special" charcoal iron, showing finely divided and almost completely nodular graphite.



FIG. 162.—Etched (magnified 100 diameters). Same as Fig. 161.

We find, therefore, that those furnaces which work with excess of heat in the hearth tend to supercarbonization, thereby lowering the quality of the iron, both by giving the weak eutectic structure to the matrix and by cutting it to pieces with large flakes of graphite.

In the case of cold-blast charcoal iron, we have probably a modified condition, the enormous volume of carbon in the hearth tending to carbonize this iron more highly than normal, in spite of its low hearth temperature. We have here, then, a condition tending toward fairly high carbon, but also a condition of low temperature favoring high oxygen, and these are characteristic of iron produced by this process. The carbons are not excessive, ranging around 4 per cent. in good cold blast-iron, while the oxygen is the highest in any standard variety of iron produced, ranging in such samples as we have analyzed from about 0.05 to 0.07.

These two facts are largely responsible for giving this iron its desirable characteristics, because the presence of oxygen seems to prevent the excessive graphization of carbon, even when the carbon content is high. This seems to be in line with the fact above mentioned, that oxygen exerts a general tendency in the direction of preventing the breaking down of the combined carbon into the graphitic form.

Thus, with cold-blast iron, we can secure the benefit of a large percentage of cementite in our chilled castings, without the danger of having this break down into graphite, as happens with high-carbon irons free from oxygen. We are able, therefore, to obtain extremely hard chill along with the extreme closeness of grain and the accompanying physical strength in the gray portion, which oxygen brings.

Manganese.—Manganese has been praised by many as a panacea for almost all the ills to which the foundry trade is liable, whether from too soft or too hard castings. On the other hand, it has been unhesitatingly condemned by many other able foundrymen as the basis of most foundry troubles, particularly with chilled castings.

The effect of manganese on steel has been exhaustively investigated (see "Manganese Steel," R. A. Hadfield, *Journal Iron and Steel Institute*, 1888, vol. ii), but, within the limits in which it is used in foundry practice, it is probable that we can largely ignore this effect on the matrix of the iron, on account of its more important collateral actions. These are important and are two or three in number, also it is certain that the effect of manganese, like that of silicon, undergoes a reversal after it exceeds a certain amount.

Manganese has a greater affinity for sulphur than has iron. It is, in fact, a much more active element chemically than iron in all particulars. As a result, it takes the sulphur away from the iron and forms with it manganese sulphide. It is a general law of metallurgy that a metal will dissolve compounds of itself, but not compounds of another metal with

anything like the same facility. In consequence of this law, the manganese sulphide separates out from the iron and rises to the surface. It may be seen doing this in the ladle under certain conditions, and even where it does not separate out completely, manganese sulphide, not being dissolved by iron, is much less harmful than iron sulphide, which is dissolved by it with the consequences above described.

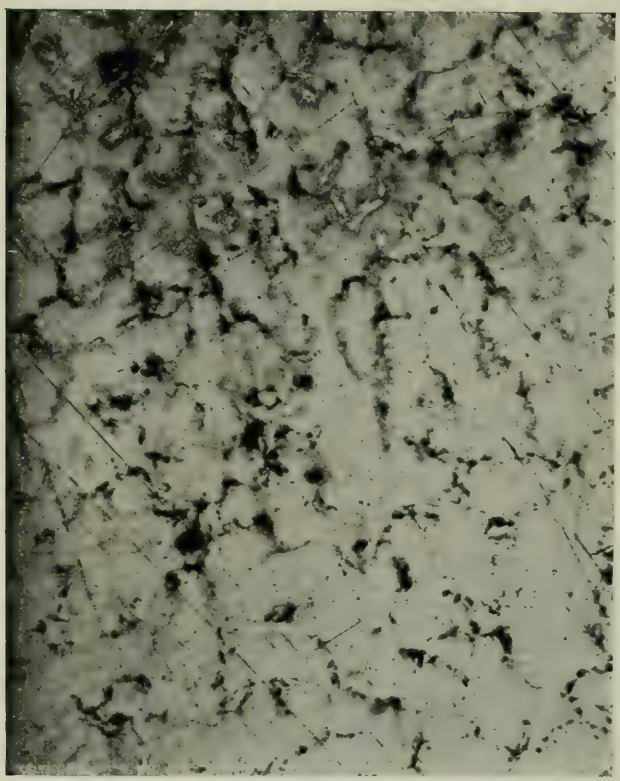


Fig. 163.—Unetched (magnified 100 diameters) coke iron-oxygenated. Same as Fig. 138. (Kindness of Professor Campbell.)

The first effect of the addition of manganese is, therefore, to remove a part of the sulphur. The action is not quantitative, and to obtain the removal of much of the sulphur it is necessary to add several times the amount of manganese sufficient to form manganese sulphide with all the sulphur present. The removal of the sulphur, of course, softens the iron.

The manganese which does not combine with the sulphur combines with the iron, when molten, in the condition of a double carbide.

Manganese, having a higher affinity for carbon than iron, causes an increased absorption of carbon by the metal in the blast furnace even up

to 6 or 7 per cent. in ferromanganese and up to 4 or 5 per cent., in spiegeleisen containing from 18 to 22 per cent. of manganese.

The effect of the manganese itself, after it passes 1 or 2 per cent., is to harden the iron, by holding more of the carbon in the combined condition. This increases the strength of the matrix in ordinary gray irons and also limits the formation of graphite. The result of these actions is that manganese strengthens the iron in addition to increasing its chilling power, and it is used for this latter purpose to make chilling irons harder, as well as to make soft irons softer.

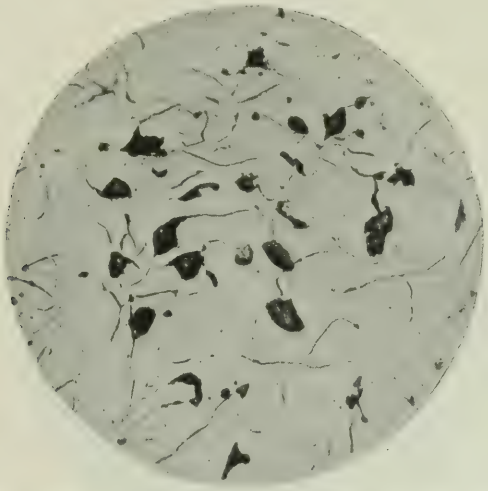


FIG. 164.—Unetched (magnified 100 diameters) oxygenated coke iron, showing nodular condition of graphite.

It is obvious, from what has been said, that these actions are the results of two different sets of effects, one of which predominates in the one portion of the manganese range and the other in the other. The objection to the use of manganese for producing chill is that iron containing much of it crystallizes into large, knife-like crystals with extremely smooth faces, so that the end of a broken pig of spiegel often shows crystals sticking out almost like knife blades, and the whole surface is made up of the faces of intersecting crystals with but little cohesion with one another.

This characteristic probably causes "shell outs" in car wheels, which obtain their chill by the use of manganese, under extra stress, a group of these crystals lose their cohesion with one another, loosen and finally fall out, producing what car-wheel men call a "shell-out." Moreover, the manganese chill is much softer than a straight iron chill, and breaks down under wear.

The activity of manganese as a deoxidizer, as well as a desulphurizer,

is well known, so when manganese is added to metal high in oxygen some of the latter is promptly scoured out; and the chilling power and strength of the metal are thereby reduced. On the other hand, if still more manganese be added, when 1.5 to 2 per cent. is reached, the strength of the iron and its chilling power increase, on account of the direct action of the manganese in throwing the carbon into the combined condition, but in the form of flat plates, as I have just explained.

This conflicting tendency, in conjunction with its effect in removing sulphur and the powerful effect of that element on the quality of the castings, makes it perfectly evident that the rôle of manganese is an extremely complicated one, but, on account of this powerful deoxidizing

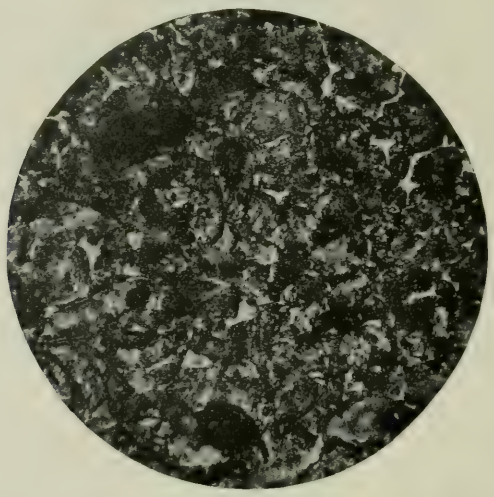


Fig. 165.—Etched (magnified 100 diameters). Same as Fig. 162.

influence, it is my judgment that it should be kept low in all castings where the highest qualities, particularly strength, closeness of grain, and chilling power, are desired, because while these qualities *of a kind* can be obtained by the use of manganese in considerable quantity, the fundamental structure of the iron produced is inherently inferior to the structure produced by the presence of oxygen, and it is a matter of established practice that, in the production of chilled castings, the desired result cannot be obtained by the addition of ferromanganese alone, as at one time was thought to be the case.

Some manganese, perhaps up to 0.5 or 0.6 per cent., is desirable in cupola-melted iron, to hold the sulphur in check, and it may be useful for other purposes in special cases, but for the best castings manganese should generally be kept within very moderate limits. Some of the manufacturers of chilled rolls will not tolerate it above 0.3 per cent.

THE EFFECTS OF TIME

Before discussing the effect of other elements on the iron-carbon alloys, it may be well to discuss the effects of time. The iron-carbon diagram shows chiefly equilibrium conditions, and the time required for the attainment of some of the equilibria it shows is extremely short, while for others it is very long. Hence the diagram cannot tell us what will happen in any case unless the time factor is considered.

The most important effect of time (that is, of the rate of cooling) is its influence on the graphitization of the carbon after solidification. The evolution of graphite during cooling through the molten condition seems to occur only with hypereutectic irons, and this appears to be a function of time, because irons which throw off graphite into the air as they run from the furnace can be converted into good castings from this initial heat only by pouring hot and just as quickly as possible. If poured slowly, the graphite will accumulate at the top of the mold so as to make the whole top of the casting worthless—it will be "worm-eaten" at the best, and at the worst may contain great cavities filled with loose graphite flakes of large size. Whether hot pouring simply causes the metal to set more quickly and thus prevent the concentration of the hypereutectic graphite in the top, or whether the formation of the graphite is actually prevented, I have never determined, but it is probable that both effects play a part.

In regard to the graphitization after solidification, our knowledge is more definite. In this case all the carbon not thrown out as hypereutectic graphite is combined at solidification, and, if the cooling be rapid from that point, the iron will remain perfectly white. But, if the casting be made to cool slowly, it will not only graphitize, but the graphite may form into very large flakes. The best illustration of this is to be found in the salamander taken from the hearth of the furnace after blowing out. This contains huge flakes of graphite an inch or two in extent, and the intersections of the flakes cut the iron into irregular solids quite without cohesion, so that a large lump of salamander can frequently be broken apart with the fingers into pieces of small size, each consisting solely of iron and graphite. Fig. 166 shows a microphotograph of such a piece, and shows why this must be so. The iron in this case has remained just below the melting point for several years.

From this point of view, the action of chilling becomes extremely simple. We merely shorten the time of cooling through the range in which graphitization could take place so as to prevent or diminish this action and leave the carbon in the combined condition. The surface next the "chiller" is the whitest and hardest, because its heat is removed instantly, while that of the metal back of it has to be conducted through the chilled surface and also through the warmed face of the chiller into

the cold metal behind it. This is obviously a much slower operation, and, as a result, more graphitization can occur in the metal behind the chilling face.

In the same way, if the chiller be too light in proportion to the body of the metal to be chilled, a very insufficient chill will result, because the thermal capacity of the chiller is only sufficient to absorb the heat from a thin zone of the molten metal, and this is promptly heated up again by the larger body of molten metal behind, which "draws" the chill already formed, exactly as a blacksmith draws the temper of the quenched edge of a tool.



FIG. 166.— Salamander (magnified 100 diameters) etched. The heavy bands of graphite have completely destroyed the continuity of the structure.

Silicon and time, then, are seen to be the principal actors making for graphitization, while oxygen, sulphur, and manganese are the principal ones resisting it. Of these three, manganese is hostile to the other two, and, if present in sufficient quantity, destroys their effect, while its own effect alone does not give a chill of the character desired. Sulphur gives a hard chill, but an essentially brittle and unreliable one, accompanied by high shrinkage and weak structure back of the chill. Oxygen gives a tough, hard chill, low shrinkage, and the strongest and best structure back of the chill.

CHAPTER XVIII

THE CHEMICAL AND PHYSICAL PROPERTIES OF FOUNDRY IRONS—(*Continued*)

THE LESS COMMON ALLOYING ELEMENTS

Chromium.—The effect of chromium on iron and iron-carbon compounds has also been extensively investigated by Sir Robert Hadfield.[1] The effect of chromium is to harden the matrix of the iron, making an intensely hard but very brittle double carbide of chromium and iron. In low-carbon alloys this makes a very strong, hard steel of low elongation. When the metal contains enough carbon to constitute cast iron, increasing chromium contents throws more and more of it into the combined condition, until, at 2 or 3 per cent. chromium, the metal is entirely white, the fracture being flat, shining, highly polished plates, very similar to those in spiegel, and to those of the weak iron-carbon eutectic previously illustrated. Compare Fig. 167, showing chromiferous iron, with Figs. 135 and 136, showing weak, high-carbon, spotted iron.

There is no doubt that chromium strengthens iron by throwing the carbon into the combined condition and by closing up its grain. It enables a hard chill to be secured, even in spite of the influence of a considerable percentage of silicon; but the structure consisting of these laminated plates has not the staying power of a chill produced by oxygen content without any other substance.

Fig. 168 shows a strong charcoal iron remelted in a crucible with sufficient chromium to raise the content of the remelt to 4 per cent. The structure to which I have alluded is strikingly shown. Test bars made from this mixture were strong, but not by 20 per cent. as strong as test bars made from high-oxygen iron without such an addition. Chromiferous iron, particularly a natural alloy made from certain ores, which contains chromium and nickel to the extent of about 2.5 and 1.25 per cent. respectively, has been urged, in the past, as a substitute for the best grades of charcoal iron. It has only been moderately successful, however, in meeting the claims made for it. It would seem that it is impossible for this alloy to equal the product which I shall presently describe, since this product is far superior in quality to charcoal iron.

Nickel.—Nickel seems to be one of the few metallic elements which produces a truly beneficial effect on the character of cast iron. Its highly beneficial effect on steel has long been understood, but this effect does not

[1] *Journal of the Iron and Steel Institute*, 1892, vol. ii.



FIG. 167.—Etched (magnified 100 diameters) chromiferous pig iron. Note similarity to eutectic structure of (weak) spotted iron, Figs. 135 and 136 (page 454).

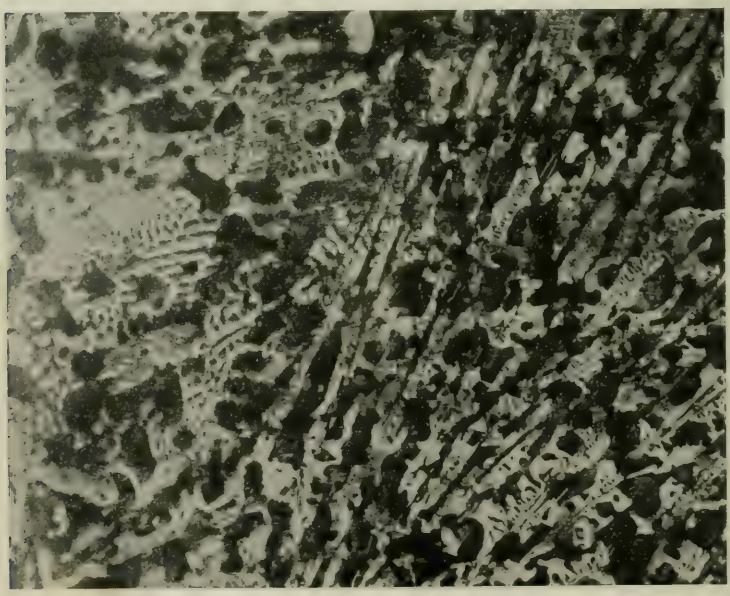


FIG. 168.—Etched (mganified 100 diameters) pig iron with 4 per cent. chromium. Note flat crystals and compare with Figs. 135 and 136 "spotted" poor charcoal iron.

begin until the amount of nickel exceeds 3 per cent. Beneficial results are derived by its presence in cast iron to the extent of only 1 or 2 per cent. It strengthens the iron and improves its chilling power, without appearing to cause any lamination or other objectionable features. These statements are based solely upon some experiments made at Ashland by remelting irons in the crucible with nickel sufficient to give the above-mentioned percentages, and it would be unwise to generalize too widely on such limited data.

It is, of course, not to be overlooked that the expense of nickel for treating cast iron is almost prohibitive. One per cent., or 22 lb., would increase the cost about $7 per ton,[1] and that consideration, taken in conjunction with the fact that even nickel is not able to produce results as good as those obtainable with the new kind of iron presently to be described, makes this an unprofitable field for further research.

For strong, tough irons with hard, wear-resisting chill, no material has apparently been developed as good as an iron containing as much oxygen as its silicon content will permit.

Titanium.—The effect of titanium on cast iron is a much-discussed question, and not nearly so much experience is available for the solution of it as in the case of manganese, but the probabilities are that the action of this alloy also has very contradictory effects, on account of its action on different elements.

An extensive paper on the subject was published by Professor Bradley Stoughton before the American Institute of Mining Engineers in 1912, but the results recorded as to the effect of strength of cast iron, etc., were rather contradictory. One thing, however, seemed to stand out very clearly, and this was that titanium reduced the chill. This is in accordance with what we should expect, for titanium is one of the strongest deoxidizers known. It also has a very high affinity for sulphur and nitrogen. Such effect as nitrogen has is undoubtedly in the direction of producing chill, and therefore, the effect of titanium would tend to remove three elements producing chill namely, oxygen, sulphur, and nitrogen. This amply explains why the chill is reduced, and probably explains also why the results on strength are so contradictory. The titanium removes the highly beneficial oxygen, and it also helps to remove the detrimental sulphur.

The reduction of chilling power which is admitted by advocates of the use of this alloy for cast iron requires the use of more manganese for its restoration, and this is highly objectionable, for reasons already pointed out, and it seems extremely doubtful that any benefit will be found by prolonged experience to result from the use of titanium in cast iron, even in spite of the fact that its action on the matrix of the iron itself may be to strengthen it. Its influence on good castings by removing oxygen is

[1] Prewar conditions.

extremely detrimental, and this is probably not offset by any other beneficent action which it may have; on the other hand, where particularly good castings are not required there is no call for the use of any treating material whatever.

Vanadium.—Following the general custom of claiming a beneficial action on cast iron for any alloying material which has been found useful in steel manufacture, traces of vanadium have been claimed to have a beneficial effect on cast iron. Vanadium, like titanium, is a powerful scavenger. Its advocates formerly claimed that its principal service was not in remaining in the steel itself, but in going out of it with the oxygen, nitrogen, etc., which it removed.

More recently it has been definitely determined that in good practice most of the vanadium remains in the steel and has a highly beneficial effect on it under proper conditions. Under these conditions there is nothing to prevent its being beneficial to cast iron and great claims have recently been made for irons containing traces of this element, but the photomicrographs used to illustrate the claims did not display a particularly meritorious structure, and the results of the physical tests given were so far below the results obtainable with irons containing oxygen as to be beneath comparison with them.

SUMMARY OF THE EFFECT OF OTHER ELEMENTS

As a result of this review of all the metals that are claimed to benefit cast iron, we see that most of them, with the possible exception of manganese, have based their principal claims on being deoxidizers, although some also have merit as desulphurizers, and some have a direct effect in throwing the carbon into the combined condition.

We have already seen, and I trust that I shall be able to show still more clearly presently, that oxygen is of greater benefit to cast iron than any other element at our disposal, with the exception of silicon, and that any addition to the iron which tends to remove oxygen is not beneficial to it, but is highly objectionable, the accepted theories to the contrary notwithstanding.

We have seen, by unmistakable evidence also, that, while some of these metals tend to throw the carbon into the combined condition, the form into which they throw it (or rather the type of crystallization which they induce) is an extremely objectionable one, being inherently weak and brittle, and that the sole benefit which we can expect from the use of these metals is the removal of a portion of the sulphur, for which a small amount of manganese seems to suffice—at least to the extent to which such removal is possible. When this result is accomplished with manganese in moderation, the strength of the iron is not materially impaired, though its chilling power, in the judgment of some expert users, is decreased after the manganese increases above 0.3 per cent.

It seems safe to say, therefore, that, if it were not for sulphur, the more perfectly we dispensed with any of these alloying metals the better iron we should obtain where strength, close grain, and strong, hard chill are the qualities desired.

Remember now the demonstrated fact that the old-fashioned cold- and warm-blast charcoal iron contained much oxygen, and you will understand that the conscientious founder, in his insistence on the use of these materials for high-grade chilled castings, was not actuated by prejudice and ignorance, but by a profound knowledge of his subject, even though he could not explain the reason for the results produced.

It will be clearly recognized that this is a flat contradiction of the tenets of theoretical metallurgy, but we find it necessary in every science to recognize, from time to time, the fact that we have taken a wrong trail and are being led from, not toward, our goal, and the only thing to do under such circumstances is to leave that path and take up the correct course, even though we have to retrace our footsteps in doing so.

A critical examination of the basis of the old theory will disclose the fact that the amount of real evidence on which it rested was small. No work of any amount in determining the actual oxygen present in cast iron by the combustion method has ever come to my attention, except that which we initiated at Ashland, and, while some work has been done by solution of the iron and determining the residual oxide, this method cannot receive much consideration on account of the serious probability of oxidation during solution.

It is true that there is a vast amount of inferential evidence available to the careful observer that oxygen produces a difference. I was convinced that there was oxygen in some iron 10 years before I had obtained any determinations of that element, and the results of the subsequent determinations have shown that I was right, but, because the iron produced was for steel-making purposes, and, when high in oxygen, was generally high in sulphur also (and therefore rejected by the steel works), I considered the effect of oxygen harmful. This was a coke iron, and when I first saw the "special" charcoal iron I condemned it as worthless, because of its strong resemblance to this high-oxygen coke iron. The introduction of the testing machine soon showed the complete fallacy of this judgment.

On the other hand, much has been said as to the burning of iron by overheating it, and its poorer quality when overheated has been attributed to the introduction of oxygen, especially in air-furnace work. The explanation will work just as well if turned the other way around. When metal is overheated in the air furnace the oxygen, of which that apparatus introduces a little, reacts with the silicon or carbon, or both, and goes out, weakening the iron and impairing its quality, just as the exponents of the "burning" theory contend.

The fact that increasing temperature promotes the elimination of oxygen is proved by several facts. The "Experiments on the Over-oxidation of Steel" carried on by Messrs. Shimer and Keachline, and reported by them in a paper before the American Institute of Mining Engineers, showed that, as the temperature went up, less oxygen stayed in. These investigators found less oxygen in steel with only about 1 per cent. carbon and no silicon than we find in cast iron with 3.5 per cent. carbon and 1 or 2 per cent. silicon, because the temperature of molten steel is some 500° higher than that of cast iron.

In the course of my own experience, I have seen a heat in a small converter purposely blown cold until the silicon was removed, but most of the carbon left in. This metal was alive with oxygen. It was exceedingly "wild" when hot, and when cold it was so full of blow holes as to have no strength whatever. The same iron, blown hot, yielded steel of a very high temperature, containing only about 0.06 per cent. carbon, and was absolutely quiet, even before the addition of the deoxidizers, and poured like cream.

All these facts agree with the well-established general law that the affinity of carbon for oxygen increases very rapidly with the temperature. You will see then that, while the view I am offering you is opposed to an accepted theory, it is supported by a vast array of established facts.

THE PRODUCTION OF AN IRON HIGH IN OXYGEN AND THE CHARACTERISTICS OF SUCH AN IRON

When I had obtained what seemed reasonably valid testimony that oxygen was the cause of the good qualities in charcoal iron, I began to experiment with methods of introducing it at will by different ways of operating the furnace, and also by introducing hot ore, mill scale, etc., into ladles and then filling the ladles with iron as it came from the furnace. This yielded no useful result.

After leaving the charcoal-iron business I began to investigate further the conditions under which silicon and carbon were removed from iron during its conversion into steel, in order to obtain a method of introducing oxygen into iron at will without lowering the carbon. I found from the steel men that by starting with a very hot heat in the Bessemer, they could blow the carbon out to a very considerable extent before the silicon was gone, while with a comparatively cold initial heat the silicon would practically all disappear before the carbon began to be removed. Moreover, it seemed perfectly evident that the reason I had been unable to get oxygen into normal irons, either in or outside the furnace, was because, at the temperature at which I was working, the activity of the silicon and that of the carbon were such that they instantly removed the oxygen.

It is, of course, no trouble to resiliconize a bath of metal, and therefore it seemed to me that if I could take metal and reduce it to the condition of the spongy white iron, which we obtained from the furnace when it was so cold as to be almost chilled, and could then mix that with normal iron high enough in silicon to give the resulting mixture the desired silicon contents (all the while keeping the temperature as low as possible), I should reproduce, outside the furnace, the conditions which exist inside it when the rare casts of extra good iron are made. Keeping the temperature low was clearly a vital requirement, because observation of converter practice had convinced me that 0.05 per cent. carbon was more efficacious in removing oxygen at 3000° than was 3 per cent. at 2300°.

Accordingly, therefore, I had preliminary tests made at a steel-casting plant. A heat of metal of 1 per cent. silicon was blown in the side-blow converter, holding the temperature down by stopping the blow and turning down the heat several times. The blow was continued until the carbon flame began to break through, showing that the silicon was gone and the carbon was beginning to go. The blow was then stopped and the vessel turned down. The sample of metal taken from it at that time was, when cold, a white iron full of blow holes, rotten, brittle, and worthless to the last degree. With this was then mixed an equal volume of 2 per cent. silicon iron direct from the cupola, and from that mixture test bars were cast. Test bars had also been cast of the original metal, both the 1 per cent. silicon iron and the 2 per cent., and these broke at approximately 2300 lb. on 1¼-in. round bars on 12-in. centers. Similar bars from the treated metal broke from 4000 to 4300 lb.

Steps were then taken to obtain patents on this process, and in view of the current opinions in metallurgy, there were but few citations from the Patent Office of anything of a similar nature. On the contrary, the patent examiners found my statements and claims so utterly at variance with all the accepted theories on the subject that they were inclined to treat the whole matter as absurd. However, we had at hand a mass of evidence, and when it was presented to them they became convinced that, while there was a conflict between the accepted theories of metallurgy and the facts, it would be better to give precedence to the facts, and let the accepted theories go, so the patents were allowed.

After this a number of furnace companies were approached, with the view of having them undertake the manufacture of the new metal, and, unless one had experienced it, one would not believe with how little enthusiasm the proposal was received. Finally Mr. E. A. S. Clarke, president of the Lackawanna Steel Co., asked me to go to Buffalo to see those in charge of the company's plant there, at the same time accompanying his invitation with intimations of the skepticism of all parties in regard to my process and the results claimed for it. When I reached Buffalo this skepticism was made even more evident and put in

more direct language, but when I showed them the experimental results which I had obtained at the steel-casting plant they waived their doubts for the time being, and consented to make a trial of the process.

At the first attempt, the conditions were not altogether favorable. A plant laid out for the production of steel, with no idea of ever desiring to oxygenate pig iron, may obviously not be ideally arranged for the latter purpose, while blowers, familiar with the necessity of getting a high temperature to produce good steel, found it difficult to blow a heat as cold as possible. Moreover, the iron which was used to mix with the blown metal was lower in silicon than we had expected to get, and this resulted practically in a "mottled" iron. All these conditions militated against the success of the trial.

Nevertheless, test bars made from the treated metal even after remelting, showed an increase of about 20 per cent. in strength over the original iron, and the Lackawanna company then felt justified in making another test and arranging the conditions more in accordance with the requirements of the operation. At this second test we provided a metal of about 2.5 per cent. silicon to mix with the blown metal. The phosphorus was also increased so as to give a result comparable to foundry iron. The metal to be blown was taken from the mixer, mixed half-and-half with the high-silicon metal, and test-bars 1¼ in. round and 2 in. square were cast from the mixture to determine the strength of the iron before treatment. After the converterful of mixer metal was blown the high-silicon iron was added, and additional test bars were made from this mixture.

The 1¼-in. round test bars of the original untreated metal on 12-in. centers broke at about 3100 lb. average, and 2-in. square bars at 13,700 lb. average.

Of the treated metal, the 1¼-in. test bars broke at about 5100 lb. average, and the 2-in. square test bars broke at 22,900 lb. average. The 1¼-in. test bars were a little over size in each case, but about the same amount in each, so that the results are comparable. By a curious coincidence, the increase in strength, based on the average of all the good bars, worked out to exactly 70 per cent. in both cases. Since that time other heats of other silicon have been made, and the strength is in all cases well above 20,000 lb. on the 2-in. square bar.

The first questions naturally asked are: Does the oxygen stay in this iron on remelting, and, if so, why? Why do not the carbon and silicon which are present scour it out, and restore the iron to its normal condition?

The answer to the first is the important one from the commercial point of view, and as soon as we had obtained these results we put some of the iron produced through a cupola as a separate charge. When it came out we raised the silicon with ferrosilicon from 1.26 to about 1.50 per cent. so as to make it comparable with ordinary iron from the cupola.

Even after this treatment with ferrosilicon, which tended to deoxidize it and also to throw out the carbon into the graphitic condition, the strength remained at 21,000 lb. We had previously demonstrated, by an extensive series of remelts of charcoal iron in crucibles, as described in the paper above mentioned, that the oxygen did remain, and that, as I have already stated, an iron which went into the crucible strong came out of it strong. The actual presence of the oxygen after remelting, as well as before, was determined by analysis.

The reply to the second question seems at first sight more difficult, but it is not really so. It seems to be a perfectly general law of chemical action that, while reactions go on in concentrated solutions along certain lines and proceed at least nearly to completion in such solutions, in dilute solutions the same law does not hold. Take, for instance, the cases of manganese and sulphur. It is well known that iron sulphide is broken up by manganese; the sulphur is seized and forms manganese sulphide, leaving the iron. Now, if this reaction proceeded to completion, it should be easy, by adding an excess of manganese, to take out *all* the sulphur. But, as a matter of fact, metallurgists are aware that this is entirely impossible; that each unit of sulphur is harder to remove than the last; and that a point is reached beyond which the addition of further manganese does not reduce the sulphur at all. I take the same to be the case in regard to oxygen, only that the equilibrium point is lower and the influence of temperature is more important, so that, if the temperature be kept moderate, the oxygen will remain to some extent, unless powerful deoxidizers are added.

In this connection I may say that we had an accidental confirmation of the correctness of the oxygen theory, which may not be without interest. By accident, one heat of the new metal was made with iron about 3 per cent. in manganese, so that the resulting mixture contained 1.5 per cent. The strength of this iron was reduced 3000 lb.—*i.e.*, from about 21,000 lb. to about 18,000 lb.—on the 2-in. square bar, as compared with iron identically the same in all particulars, except that the manganese was normal, or about 0.4 per cent.

There are two other questions of interest:

First, in what respect and for what reason is this new material better than the so-called semi-steel (cast iron with a mixture of steel scrap)?

Second, how do we achieve the advantage of high carbon, which, it is my belief, is one of the advantages of cold-blast charcoal iron for special purposes?

The answer to the first may be divided into four portions:

(*a*) The effect of oxygen is to reduce the graphite to a fraction of its injurious area, by changing its shape. This is obviously far superior to a simple dilution of the carbon, which can only reduce the graphite by about a third in the most extreme case.

(*b*) The temperature required for the melting of steel scrap is very high, materially above that of an iron with normal carbon. This requires such iron to be raised to a higher temperature than iron with normal carbon, and facilitates the elimination of any oxygen which it may contain.

(*c*) The use of steel scrap dilutes the carbon and reduces the quantity of cementite which can be formed, so that chilled castings made in this way have not the hardness and wearing qualities of those made of irons with high carbon when the latter is all combined.

(*d*) It seems certain that carbon in proper condition facilitates the machinability of an iron, remembering that carbon in the form of graphite is one of the best lubricants known. It has been demonstrated by experience that an iron of a given strength of matrix machines more easily as it contains more carbon, nor is it necessarily weaker than low-carbon iron, if its carbon be in more nodular form than that in the low-carbon iron.

The answer to the second question is that, by the hot operation of coke furnaces with a limy slag, the carbon can be forced up to or beyond 4 per cent., and by proper operation in treating it we can preserve practically all this carbon, thereby securing an amount equal to that of the cold-blast iron. Whether we shall be able to go beyond this, and introduce additional carbon during or after the treatment, I am not able to say, because we have made no experiments along that line. It seems likely that this will be unnecessary in practice, for most of the users of cold-blast charcoal iron use it in the air furnaces, and reduce the carbon to between 3.5 and 3 per cent. before casting, an amount which we can easily exceed.

We have had a number of tests made by parties who were interested in the purchase of iron. Some of these I am not at liberty to publish, but the representative of one large railroad company has told me privately that he found the strength and chilling power of the iron to be virtually the same as that of one of the famous brands of Eastern charcoal iron. Another railroad company reported that it found the breaking strength of the iron in 2-in. square test bars on 12-in. centers to be 25,000 and some odd pounds; while through the kindness of Mr. Harry B. Swan, of the Cadillac Motor Car Co., I am able to present a table of results of crucible remelts made from this iron.

CADILLAC RESULTS

Analysis	Combined carbon	0.850
	Graphitic carbon	2.650
	Manganese	0.260
	Phosphorus	0.326
	Sulphur	0.039
	Silicon	1.250

Four standard 1¼-in. round test bars of the American Society for Testing Materials broken on 12-in. centers gave the following results:

	A	B	C	D
Transverse strength in pounds	4,505	4,825	4,825	4,875
Modulus of rupture, pounds per square inch	67,300	67,000	67,100	66,400
Tensile strength, pounds per square inch	34,800	33,800	34,100	33,800
Brinnell hardness	202	207	202	196

Charcoal iron showing above 3000 lb. on the 1¼-in. test bar is strong enough to be put into a class of special iron by itself, while one of 4000 lb. strength is very rare. You will see that this iron is about 60 per cent. stronger than the former, and about 20 per cent. stronger than the latter. The closeness of its grain you will see from the samples and from the photomicrographs (Figs. 160 to 163). These latter also show the graphite in this iron to be almost completely nodular, rather than of the flake variety, and show, in the most unmistakable manner, why the iron must be stronger than an iron the same matrix, but with wide flakes of graphite. The effects of oxygen in changing the form of crystallization and in preventing the breaking down of the combined carbon are the same in this iron as they are in charcoal iron, except that warm-blast charcoal iron contains only from 0.015 to 0.3 per cent. oxygen, whereas we have no difficulty in obtaining 0.05 to 0.07 per cent. oxygen, with correspondingly greater effect in these two directions.

The experiments which have been made on actual castings show also that the suppression of the eutectic is more than a scientific hypothesis. One large company found that a certain casting was extremely difficult to make of ordinary iron without having shrinkage cavities along a certain line, but that, when poured from this iron, the castings were absolutely sound at this point. This I believe to be because the iron solidifies all at once as a homogeneous mass instead of passing through a long range of progressive freezing. The last freezing or eutectic portion is altered by the presence of this minute quantity of oxygen into something else with a higher melting point.

Returning now to the iron-carbon diagram, a valuable suggestion has been made by Professor Campbell, to the effect that there are shown by Fig. 134 several paths along which iron-carbon alloys may pass in cooling; that one of these may result in one structure and another in another, and that the presence of a small quantity of oxygen may be the controlling factor which forces the cooling to take place according to one of these paths or another. This suggestion, combined with the diagrams of Guertler and Upton, goes further to account for the facts as we found them in practice than any other that has been made.

The practical question may now be asked: Granted that we have here a new material, what is it good for?

The answer is that it is good where strength, closeness of grain, steam tightness, and wearing qualities are desired. Above all, it is good where chilling power under strict control and hard, strong chill are desirable. Because irons containing oxygen have this peculiarity, they not only begin to show a chill at a higher silicon percentage than do coke irons, but they are also much more sensitive to chilling influences. High-oxygen iron of 1.25 per cent. silicon will show no more white chill than a coke iron if cast in sand, though, of course, it will be much finer-grained. But, if cast against a chilling surface, it will show from $\frac{1}{8}$ to $\frac{1}{4}$ in. white chill, whereas when coke iron reaches the range of silicon within which it will "take a chill" it is with difficulty prevented from chilling, even when cast in sand. With this great strength, with this power of making intricate castings without shrinkage cavities, and with its chilling power under accurate control, it seems that the metal should find its largest field, measured in tons, in car wheels, and tests of it for this purpose are now under way. Outside of that field, the metal is particularly adapted for steam, gas, or ammonia cylinders. As a substitute for, or improvement on, "gun iron" for strong castings, such as are now made from the air furnace, I believe that this metal cast from the cupola will find a large field of usefulness.

It is our hope, also, that with this metal it will be possible to produce malleable castings by melting in the cupola as easily as to produce them from the air furnace, as is done in present practice, because we can supply the carbon of any amount desired, and we can also introduce the oxygen, which it is largely the function of the air furnace to put into the iron now. This statement may seem radical, but I have had made an analysis of malleable iron, and found it to contain 0.13 per cent. oxygen. Moreover malleable iron, which under the microscope is shown to be composed of iron interspersed with little round nodules of graphite or temper carbon, is only a step beyond the metal which I have shown you, and, in my judgment, the new metal will eventually be found to constitute an intermediate step between malleable iron and ordinary cast iron. In malleable iron the carbon is all retained in the combined condition, as cast, and is subsequently graphitized against the resistance of the solid iron by prolonged annealing. The new metal delays graphitization until the structure is sufficiently solidified to resist the formation of the graphite, the resistance being sufficient to force the latter into the forms entirely similar to those in true malleable.

Where castings are made from the maximum percentage of cheap scrap with the minimum of new iron to carry this, a softener is needed, probably in part because of the high sulphur of the mixed scrap; and as this new product tends to produce high combined carbon, and is a strengthener (and to that extent a hardener), it is not recommended for such castings. On the other hand, where a high-silicon strong iron is needed, so that it

may have good machinability and lend itself to rapid manufacture and yet be strong and fine-grained when finished, the ideal material to give these qualities can be made by the new process, and, once the exact combination of strength and machinability desired by the foundrymen is known, that combination can be repeated under conditions of strict control to an extent not possible with any other product.

Iron from the blast furnace has to be taken as produced, not only in oxygen but in the other elements, but, by the use of this process of treatment, we are able to produce iron not only of a given analysis, but with certain physical qualities accompanying that analysis, a degree of control impossible to obtain in iron direct from the blast furnace.

Author's Note.—The above address was written three years ago and is reproduced here with only minor corrections. It is not perhaps in the exact language that would be chosen for presentation in book form, but has been proven correct in all substantial particulars by an immense amount of corroborative evidence. The new metal was produced to the extent of many hundreds of tons which was tried out in the severest service and gave remarkable results. The production of the metal was temporarily cut off by commercial conditions resulting from the war.

PRINCIPAL VARIETIES OF FOUNDRY IRONS AND THEIR COMPOSITION

Foundry irons may be divided according to the kind of castings made into four classes, as follows:

Machinery and general castings, chilled castings, malleable castings and heat-resisting castings, especially ingot molds.

Machinery and General Castings

The range of these is very wide and the specifications for the iron used in making them vary accordingly. It is only possible to cover the subject in a broad general way.

Silicon.—The silicon in machinery castings may be said to vary from 1.25 to 1.5 per cent. in large heavy castings up to 3 or 3.25 per cent. in very small light castings.

Sulphur.—Sulphur in iron for machinery and general castings is almost always an unmitigated evil. It is sometimes used to close up the grain of the iron, but this causes a simultaneous hardening of the surface of the casting, particularly sharp corners and edges, which are easily chilled This greatly increases the difficulty of machining such castings, and the use of sulphur for this purpose is never justifiable.

Sulphur is always imparted to the iron when it is remelted in a cupola for casting, the amount so added varying from 0.03 per cent. in the best cupola practice up to 0.1 per cent. or even more in the worst and averaging around 0.05 per cent. in ordinary good practice.[1] As the sulphur in

[1] The results obtained with the Stoughton oil-burning cupola have been noted earlier.

good castings should be below 0.08, or certainly below 0.09 per cent., it is evident that the sulphur in the iron must be kept under 0.05, and preferably under 0.04 per cent., and these are the ordinary specifications for foundry iron.

Phosphorus.—Phosphorus was formerly considered to be a detriment to foundry castings and it was considered desirable to keep it as low as possible, or at least below 0.3 per cent., but we know now that phosphorus imparts fluidity to the metal and also increases the strength up to certain limits so that in machinery castings phosphorus commonly runs from 0.4 to 0.75 per cent. In some specially thin castings, such as stove plate, it runs higher even—up to 1 per cent. in order to obtain the fluidity necessary to pour these thin shapes, while in automobile cylinders, as noted earlier, it is necessary to keep the phosphorus under 0.3 per cent. in order to prevent spongy spots in the castings. In the ordinary run of machinery castings, however, the phosphorus ranges within the limits given.

Manganese.—Manganese specifications for foundry iron vary between extreme limits. In some cases as much as 2 per cent. is desired for special reasons, while in other cases the lowest amount possible is desired, but these extreme specifications are for special cases and manganese in the iron for ordinary machinery and general castings runs from about 0.6 to 1 per cent.

Carbon.—No attention is paid to the carbon in ordinary machinery castings except where special strength is desired and then the carbon is lowered by adding steel scrap to the cupola charge; this constitutes the so-called semi-steel.

Oxygen.—The relation shown in the previous chapter between oxygen content and strength of castings indicates clearly that when strong close-grained and dense castings are desired, an iron high in oxygen should be used. When a mixture of irons is introduced into the cupola, it is easier to obtain the desired amount of oxygen in the cupola iron by the introduction of most of the oxygen with that portion of the mixture containing first, the least manganese and second, the lowest silicon. As to the absolute quantities of oxygen desirable, we have not as yet sufficient information on which to base exact specifications. Iron with 0.06 oxygen is 50 to 75 per cent. stronger than ordinary coke iron without oxygen, and this strength persists when the iron is remelted in the cupola. The kind of castings desired must control the relative importance to be given to oxygen and the other elements. As a general thing, the strength imparted by a given percentage of an oxygen-bearing iron is more than proportional to the percentage of that iron added. When really good cast-

ings are desired the percentage of oxygen should be as high as commercial considerations permit.

Chilled Castings

Silicon.—Silicon is the element which has the maximum effect in promoting the separation of the carbon from its original combined form into graphite, and as the production of chilled castings consists in keeping the carbon combined with the iron, the silicon must accordingly be low. For car wheels, the principal purpose for which chilled castings are used, the silicon is desired about 0.75 per cent. For other purposes, it falls as low as 0.25 per cent., and for still others rises as high as 1.25 per cent.

Sulphur.—For some kinds of chilled castings where great hardness without much strength is desired, iron with sulphur running up to 0.2 or even 0.3 per cent. is sometimes used as an ingredient of the cupola charge, and in some car-wheel foundries the regular practice is to make car wheels containing 0.18 or 0.19 per cent. sulphur, but this is exceptional and in my judgment bad practice. The chill of the castings should be obtained by lowering the silicon rather than by raising the sulphur beyond very moderate limits. In chilling irons made with coke, sulphur is commonly accepted up to about 0.1 per cent.

Phosphorus.—Phosphorus in chilled material commonly varies between 0.25 and 0.7 per cent. The phosphorus in the iron for this material ordinarily lies within the same limits. For car-wheel purposes phosphorus is not desired above 0.35 per cent.

Manganese.—Extraordinary latitude is used in manganese specifications for chilled materials. Some consumers want the manganese down to a trace while others specify manganese up to 2 per cent. The reason for this appeared earlier and need not be repeated here. In the ordinary run of chilled castings, manganese ranges between 0.4 and 0.8 per cent.

Oxygen.—In the foregoing chapter it has been shown that oxygen exercises a greater influence on the chilling power of an iron than any other element except silicon. When chilled castings are to be made, it is not desirable to obtain the chill desired by lowering the silicon or raising the sulphur beyond certain limits because of the brittle crystalline chill which these extremes cause. By the presence of oxygen in the iron, we can obtain the desired amount of chill without a very low silicon and even in the almost complete absence of sulphur.

Sulphur is the element which causes the greatest degree of brittleness in chilled castings, especially car wheels, and its detrimental effects must be reduced by increasing the manganese which in turn has a very undesirable effect on the properties of the chill. For this reason the best chilled castings will come in time to be made of irons low in sulphur with a moderate amount of silicon, high in oxygen and low in manganese.

Carbon.—It is in the field of chilled castings that the most attention is paid to the quantity of carbon present in the iron. The reasons for this are numerous and complicated, as has appeared earlier, so they do not need to be given here.

Suffice it to say that for some chilled castings the carbon is desired well below 3 per cent., while for many other purposes chilled castings have proven of inferior quality because they did not contain a sufficient amount of carbon to give them the hardness desired. It is probable that the maximum amount which can be used satisfactorily is about 4 per cent.

When the carbon rises much above this point, another set of influences come into play which are likely to destroy rather than to augment the hardening action as explained in connection with hypereutectic irons. In chilled rolls much lower carbon is required, but this is obtained by mixing steel scrap with the charge or by oxidizing part of the carbon in the air furnace.

Malleable Castings

Malleable castings in American parlance are castings which are solid white when cast and then have their carbon converted into fine graphite or temper carbon by annealing at a high temperature. Such castings can be bent cold and have a considerable amount of toughness. When subjected to a tension test they show a considerable elongation and reduction of area which are not shown at all by ordinary casting iron, hence the name malleable castings.

In order to meet the condition that the castings must be white when made, the silicon must be kept comparatively low, ranging from about 1 per cent. for large, heavy castings to about 1.75 per cent. with small castings of light section. More or less of this is oxidized out in the air furnace, in which the iron for these castings is generally melted.

Sulphur.—Sulphur is very objectionable in the malleable process because it tends to prevent the breaking down of the carbon into graphite, which is the essence of the process. The absorption of sulphur in the air furnace is very much lower than in the cupola, but in spite of this the sulphur specifications for iron for malleable castings are as severe as those for ordinary foundry iron, sometimes even more so. For most purposes the sulphur is held below 0.05 per cent. and it is usually desired below 0.04 per cent.

Phosphorus.—The specifications for this element are much closer in the case of malleable castings than in most others. If the phosphorus be too low, the metal has not sufficient fluidity, and if it be too high, the metal is brittle and unreliable when annealed. The phosphorus is, therefore, very generally kept between 0.12 and 0.25 per cent.

Manganese.—The practice in regard to manganese varies in this department of the industry almost as much as in chilling irons, some manu-

facturers desiring it high and others low. The probabilities are that manganese should be between 0.3 and 0.6 per cent. for best results.

Carbon.—The conditions in regard to carbon are very much the same in malleable castings as they are in chilled castings, although the limits through which it is made to vary are not so wide. Some manufacturers will pay a premium for iron with carbon well under 3 per cent., while others accept the carbon as it comes from the furnace without comment. It is my impression that no commercial iron ever contains as little as 3 per cent. carbon when it comes from the blast furnace, and this element can only be reduced to these low limits by treatment outside the furnace.

Oxygen.—It has been definitely ascertained that the presence of oxygen is highly beneficial in chilled rolls melted in the air furnace. The practice in that branch of industry is very similar to that in the malleable industry, and taken in conjunction with the fact that the best malleable is made with charcoal iron, it is probable that oxygen is highly desirable in malleable castings. The fact that its presence tends to throw the carbon into the combined condition in the presence of even considerable percentages of silicon, also indicates that the presence of oxygen is desirable in this branch of the foundry industry.

Ingot Molds and Heat-resisting Castings

In order to resist the expansion and contraction strains brought about by the frequent changes of temperature, iron must have a loose and open structure. The graphite must be in large flakes so that the individual grains of iron can hinge on one another, sliding and bending on the soft graphite. Anything which tends to close up the grain of the iron and reduce the area of the graphite flakes by coagulating them into nodular particles, reduces their ability to act as hinges, and therefore makes the iron more rigid. This means that being unable to bend under the stresses brought about by contraction and expansion when exposed alternately to heat and cold, it soon breaks. Our object, therefore, must be to produce the most graphitic iron.

Silicon.—For reasons which were explained earlier, the maximum amount of carbon is taken up by iron containing about 1 to 1.5 per cent. silicon. Therefore, the silicon in ingot molds is always kept within these limits.

Phosphorus.—Experience has proven that phosphorus exercises a vital influence on the life of ingot molds. Molds made from iron containing more than 0.08 per cent. phosphorus (the Bessemer limit) fall off rapidly in the number of heats they give in service. The reason for this is not fully understood, but it is probably due to the effect of phosphorus in hardening the iron and closing up its grain, as described earlier. For this reason the phosphorus specifications for ingot molds are very

severe and it is in all cases kept as low as commercial considerations will permit, always within the Bessemer limit.

Manganese.—As was shown earlier, there is a certain quantity of manganese which makes the softest iron. An amount either smaller or larger than this will make the iron harder. This amount is roughly from 0.4 to 0.8 per cent., and it is within these limits that the manganese in ingot molds should be kept. If it rises, the silicon must be raised to offset its hardening influence on the iron.

Sulphur.—In order to have the iron as soft and graphitic as possible, it is necessary that the sulphur be kept to the lowest possible limits, and this is always done in practice. Conditions in this respect are greatly bettered by the fact that ingot molds are usually cast from direct metal, that is, metal taken directly from the blast furnace, not cast and remelted as is done with practically all other kinds of castings. There is no doubt the lower the sulphur is kept the better, and it should be always under 0.05 per cent. to secure the best results, preferably lower.

Carbon.—The carbon in the ingot molds should be as high as possible to promote the greatest possible formation of graphite in accordance with the laws controlling its action as already explained. This, however, is a matter whose control is subordinate to that of the other elements, and is accordingly ignored in practice.

Oxygen.—Recent investigations have proven that this element exercises the most powerful influence of any, except, perhaps, silicon, upon the life of ingot molds. It has been shown how powerful is its influence in coagulating the graphite, and it has been found in practice that ingot molds made from iron relatively high in oxygen give only a fraction of the life of those made from an iron of identical analysis except low in oxygen. This is not generally known, but has been proven in practice in the most indisputable way. For this reason, the quantity of oxygen in the iron should be a primary consideration, and to reduce this it may even be justifiable to raise the manganese. If the oxygen cannot be reduced in the furnace to sufficiently low limits, it should receive a treatment outside the furnace in order to bring about this result

PART IV

COMMERCIAL CONSIDERATIONS AND THE FUTURE POSSIBILITIES

CHAPTER XIX

COMMERCIAL CONSIDERATIONS

The object of operating a blast furnace is to make money. This obvious fact should not require to be stated, but as a matter of fact it is for various reasons sometimes apparently forgotten by those who operate, and even more frequently by those who build blast furnaces. There seems to be a certain fascination about the business which inspires in those who are not familiar with it the desire to enter it and were this not balanced by an even more acute desire on the part of many of those who are in, to get out, the business would be worse overcrowded than it is.

Under these conditions it seems desirable to set forth something of the commercial considerations which must govern in the long run, not only for the benefit of the owner or investor, but equally for the higher employees, for if the business be not fundamentally sound they will have an unhappy time and very likely lose the ultimate benefits of many years of hard work.

LOCATION

This is a subject concerning which much has been written and sometimes without consideration of all the factors. There is probably no other large business in which freight on raw materials and finished product plays so great a part. It may be doubted whether freight is less than 25 per cent. of the total cost delivered to the consumer except in a small percentage of the business, it is frequently more than 33 per cent. and even 50 per cent. Under such conditions the question of location in relation to sources of raw materials and markets is vital.

In the *Engineering and Mining Journal* of March 13, 1915, I treated this subject on lines which are believed to be new, and developed the law on which the location of the industry seems to hinge, for it accounts for the facts as no other law seems to do. This article is quoted below.

"The reasons generally assigned for the location of the iron industry have dealt chiefly with the question of whether the ore, of which about 2 tons are required per ton of iron, should be brought to the coal, of which about 1½ tons are

required, or *vice versa*. The coal is frequently coked before shipment and the weight of coke required is only about 1 ton per ton of iron against nearly twice as much for the ore; but many plants have been located much closer to the coal than the ore, nevertheless. This fact has not unnaturally troubled many who have attempted to work out the underlying causes.

"It may be freely admitted that the location of iron-manufacturing centers is a matter of freight charges; but not, as is commonly assumed, of freight on raw material only. Obviously there must be included freight on the finished product to the point of consumption. If we were to consider the establishment of an iron works in a country entirely without such works, knew that each person would consume a given weight of iron per year, and knew also the tonnage of the proposed works, we should know how much population was required to consume the product and from the density of the population in the country we could calculate the average distance the product would have to be hauled to reach the consumer, and the freight for this haul added to the freight on the raw materials would constitute the total freight charge on the product. It is this which should be kept a minimum. It would clearly be an accident if the point which gave the lowest combined value for the three were at either the ore mines or the coal mines.

"The correct location would obviously be the equilibrium point of the three forces acting through the coal mines and the ore mines and the center of population. We could, without much trouble, make a model which would illustrate the action almost perfectly. We need only to put a peg at the center of population on the map of a given district and one each at the ore mines and coal mines, fasten together at one end three pieces of rubber cord of equal length, whose strengths were proportional to the rate of freight per mile of the quantity of material equivalent to a ton of finished product, and attach the free ends to the corresponding pegs; the junction point would be the equilibrium point and would indicate the proper location of the plant. The strength of the forces acting is profoundly affected by the means of transportation available (whether water or rail) and the location of the equilibrium point is obviously influenced to correspond. The sum of the tensions in all three strings measures the disadvantage under which the district must labor.

"We can see this law demonstrated in the growth of our iron-producing centers. At the time of the Civil War, Pittsburgh was nearly the center of population of the country, and it made, for the next 20 years, the vast bulk of the steel produced, although there was a considerable center in eastern Pennsylvania and New Jersey, in which the fuel, the ore and the consuming population, were all close together and the sum of the tensions was small, so it prospered.

"As the West became settled, the center of population traveled West, first to Ohio, then to Indiana, and then to Illinois, where it is now; simultaneously the Chicago district developed as an iron center although its freight on ore is but little less than that to Cleveland and Buffalo while its freight on coal is very much higher; but it is the center of a great consuming district, and its freight on finished product is low enough to make the sum of the string tensions small.

"Later still, Colorado became an iron-producing center, in spite of many disadvantages, because of its location near the center of a consuming district which is far removed from any other source of supply. The sum of its string tensions was high but that of any other iron-producing district is higher in its territory.

"The present construction of a steel plant in Duluth is a further example: The freight on both coal and ore assembled there has been very low for many years; but until the population of the Northwest became large enough to support railroads whose tonnage of steel consumption runs into six or seven figures, it did not pay to build a steel plant there. The freight on the finished product to points of consumption would have been too high.

"At Birmingham the conditions are similar but more marked. The ore and coal are in closer proximity there than anywhere else in the known world, the tension in these two strings is almost nothing but the freight to outside consuming centers was so great as more than to counterbalance this advantage; the tension in the single string was more than that of all three at other iron-producing centers and the district made much pig iron but very little money until a local consuming center was built up

"In the future, the attraction of the center of population will be increased even over what it is now; because the gas, which is a by-product in the production of coke, is of vast value for public heating and lighting and the power which can be produced with surplus gas from the furnace will be increasingly valuable for public utility purposes.

"These products, electric power and gas, are consumed in steel mills in greater quantity than they are produced by its coke ovens and furnaces, so such works are not to be considered as sources of supply for these products and their location will not be so strongly affected; but the merchant furnace will have gas and power for sale and will more and more be so located that it can dispose of them to good advantage without building long pipe or transmission lines; that is, near centers of population.

"That is, in the future, as we grow more efficient there should be an intimate connection between the iron blast-furnace plant and the public utility, and especially the public utility serving large centers of population."

Careful consideration of the history of the iron business in relation to its location will show that a plant must be located in harmony with this general law in order to have a chance of ultimate success. The importance of the by-product oven in relation to the location of the iron industry may well be a little more elaborated.

Large communities use gas in great quantities and are destined to use it in still greater ones as better processes make gas cheaper and so increase its great advantages for cooking and heating. Its use will also grow with the development of the mantle-light (Welsbach) with pilot-flame control giving the convenience of electricity with a source of light as powerful and much more agreeable to many. The candlepower of gas, so important in the days of the open-flame burner, is rapidly vanishing as an important consideration on account of the vastly greater amount of light which may be obtained even with a perfectly non-luminous gas, by means of the incandescent mantle.

The by-product oven yields a large quantity of cheap gas of low illuminating, but high calorific, power, even after the recovery of the by-products from it, and on this account it is destined more and more to be

the source of domestic gas, and this will mean the production in the vicinity of large communities of large quantities of metallurgical coke which being made as a by-product, will be available at lower prices than an equal grade would command in that location under different conditions.

Where the community is large enough and is a manufacturing one, a market for iron will exist and this will lead to the local production of iron in cases where it would be commercially impossible without these favorable conditions.

CONSTRUCTION

Granting that a suitable location has been chosen, the size and construction of the plant next demand careful consideration. The most economical furnace to build and to run on the basis of cost per ton is the large furnace, 22 by 90 ft., if there be a market for its product when run continuously. On the other hand, almost any furnace run continuously makes cheaper iron than one run interruptedly, for the advantage of the large furnace has often been overestimated while the disadvantages of interrupted operation, both technically and commercially can scarcely be overestimated, and it is far better to build a furnace of moderate or even small size and keep it operating continuously, than it is to build a large one and run it intermittently. Some approximate figures of the difference in cost of operation of different sized furnaces will be given later.

When the size of furnace to suit the conditions has been decided many questions as to types of construction remain to be decided, and errors are often made in the decision apparently for lack of a guiding principle.

There is often a disregard of cost. Furnaces are built in the prevailing style whether that style was developed for their conditions or not, and without any regard to whether some simpler or less expensive construction would answer. Gas engines are suggested for isolated furnaces with no market for surplus power. Trestles are built 40 and 50 ft. high and then no use made of the storage capacity so created. Bins are constructed so as to give only half the capacity they might have with the same expense. Elaborate coal and ash handling systems are applied to boilers that should properly be fired with gas 95 per cent. of the time.

On the other hand, the directors are frequently "penny-wise and pound-foolish." In one case within my own knowledge they insisted on building a new furnace of scrap plate and using an old mantle and columns which necessitated the use of lines for the furnace absolutely unsuited to the conditions under which it had to work. The total saving

as compared with building a furnace of new material suited to its work was $10,000. The furnace never did what it was designed to do by a large percentage; the loss per year, due to bad furnace work, was probably not less than $25,000, and at the end of a few years, due to the combination of rotten material and bad lines, the stack fell down bodily in full operation causing a loss of $40,000 to $60,000. Many other instances might be mentioned, none so bad perhaps as this but equally as stupid.

The simple rule by which the value of any construction may be measured is: Find what interest it will pay, indirectly as well as directly upon the investment. There are plenty of justifiable expenditures on which no direct saving can be shown. For instance, to build a modern hearth jacket with water-cooled staves inside a massive steel shell costs several thousand dollars more than to build one of some other types, and one of the latter might go through a blast without a breakout, in which case the return on the money spent for the better one would be nil. But again with the old type, during a blast there might be half a dozen breakouts, each of which might cost as much as the increased cost of the safe construction, with the possibility that the explosions which frequently accompany breakouts might kill one or more men. In such a case it is not only foolish but almost criminal to refuse to make the expenditure which practically makes such things impossible.

In the matter of making expenditures to prevent objectionable occurrences which might shut down the furnace it is necessary to remember that certain charges which in operation, we spread over the cost of the iron made, run on just the same when the furnace is shut down for repairs. When there is no iron being made to carry them therefore we can truthfully say, however it may sound, "We lose the labor and overhead on all the iron we don't make."

These charges on a 500-ton furnace run from $1.25 to $1.50 per ton, therefore, a 24-hr. shutdown on such a furnace means a dead loss, exclusive of profits not made, of $600 to $750. This does not include the coke for banking and restoring the furnace to normal operation, or labor for repairs other than that of the regular crew. On this basis it is obvious that to spend $5000 to prevent a 24-hr. shutdown once a month would be a virtual necessity, whereas to spend the same sum in dull times to prevent such a shutdown once a year would be open to discussion.

Sometimes it is necessary to estimate what is the probability that a given mishap will occur and on the basis of that probability figure what expenditure is justified to eliminate the possibility of its occurrence.

When it comes to savings whose value per ton can be definitely estimated we are, of course on much surer ground. We have only to estimate the saving per year and compare the amount with the investment required.

Even here certain precautions are necessary. Such investments are not like the purchase of a bond in which the principal is secure and a low return is acceptable.

It is obvious that the return on such an improvement must not be less than that expected from the plant as a whole and as this is never less than 15 and should be 20 per cent. for so irregular a business, it is a safe rule to consider very thoroughly any proposed improvement which will not pay for itself in 5 years.

COSTS

Before entering upon any further discussion of commercial considerations we must have a measure of commercial results of which the most important part is the cost sheet. Cost sheets for pig iron are very simple and are virtually standard. Like all other industrial cost sheets those of pig iron are made up of three items, raw materials, labor, and overhead, but unlike most other products, raw materials are far and away more important than both the others put together, and overhead is larger in good plants than labor.

Owing to the fact that the cost of raw materials is fixed by conditions over which the management has no control and that the quantities of each required per ton of iron is subject only to a very limited control, there has come into use a standard of comparisons for costs which consists of the total cost minus the cost of raw materials. This is known as "net cost above materials." This embraces labor, minor supplies, lubricants, relining fund, renewal fund, insurance, taxes, etc. The whole amount varies from $1.25 per ton for large and well run plants to $2.25 for smaller or poorly run ones, in normal times.

Labor varies from 40 to 60 cts. on a large mechanically handled furnace, up to $1.50 for small hand-operated furnaces.[1] The relining fund must be such an amount that at the end of the blast it will equal two to three times the cost of brick for a new lining. Twenty cents per ton on a 500-ton furnace for a campaign of 2 years, or say 700 days, is $70,000, which is about three times the cost of a lining for such a furnace. The renewal and repair fund should equal an amount in 15 years that will rebuild the plant complete except site, as it will practically all wear out or become obsolete in that time, and no profit can be properly shown until this depreciation be provided for.

A typical cost sheet without too much subdivision is shown below in Table XXIII. It will be noted that no interest on the investment is shown. This is probably not correct accounting, but is universal practice in blast-furnace costs. The fact should not be forgotten in considering the profit and loss shown by any blast-furnace operation.

[1] Prewar conditions.

TABLE XXIII.—COST OF PRODUCING PIG IRON DURING FIRST SIX MONTHS OF 1914
FURNACE "A"

Items of cost	Pounds		Rate per gross ton	Cost per ton of pig
Ore	3,791		3.56	6.030
Cinder	453		2.77	0.560
Total ore and cinder	4,244		....	6.590
Scrap used	122		6.00	0.327
Gross metallic mixture	4,366		....	6.917
Total scrap produced	115		6.00	0.308
Net metallic mixture	4,251		.....	6.609
Coke	2,392	net tons	3.10	3.740
Coal	.....		.....	.....
Limestone	1,133		0.80	0.405
Total fuel and fluxes	.....		.....	4.145
Total materials charged	.....		.....	10.754

General superintendence	0.082
Stocking	0.067
Charging	0.045
Casting	0.090
Other producing labor	0.042
Labor in repairs and maintenance	0.028
Material in repairs and maintenance	0.092
Lubricants	0.006
Tools, miscellaneous supplies and expense	0.034
Tuyeres, blocks and cooling plates	0.010
Refractories	0.042
General works expense	0.167
Blowing expense	.....
Steam cost	0.056
Water cost	0.067
Electric light and power cost	0.008
Yard switching expense	0.112
Laboratory expense	0.023
Stable expense	0.008
Shop expense	0.042
Casting machine expense	0.043
Dry air cost	0.052
Reserve for relining	0.250
Reserve for contingencies	.....
Gas credit	.....
Total	11.830
Tons produced	76,432
Daily average production	419
Production since relining	276,739

THE MOST ECONOMICAL SIZE AND RATE OF DRIVING FOR FURNACES

As regards the consumption of ore and stone per ton of iron there is no difference between the smallest and the largest size of furnaces using the same material. In regard to coke it might be thought that the large furnace had the advantage due to less radiation and water cooling in proportion to its output, but as a matter of fact small furnaces working under the same conditions otherwise do as well as large ones and have often done much better. The better control of the charging due to their smaller size seems to offset the advantage of smaller heat losses from the larger ones.

We can therefore consider the cost of different-sized furnaces only as affected by labor cost, interest and depreciation charges, and power cost.

It is not possible to obtain sufficient information for an absolutely correct solution of the question, but by the use of certain reasonable assumptions we can make some illuminating comparisons. In regard to labor we know that there is a certain irreducible minimum no matter how small the furnace or the tonnage produced, and that an increased tonnage does not require a proportionately increased amount of labor. For instance, the size of the cast-house crew does not increase very much between 200 tons and 500 tons output. On the other hand, the labor of unloading raw materials from the cars is practically proportional to the amount of raw material. The engine and boiler-house crew is only one man per shift for a 100-ton plant, but with water tenders, extra oilers, etc., is two or three men in a plant of 500-ton output.

Generally, we may say that the labor for any output is a certain irreducible minimum for minimum output and for each increase in output an additional amount which increases at a slower rate than the tonnage.

Virtually the same thing is true as to plant cost and fixed charges thereon. To build a furnace stack of a certain size and the hoist for it, costs the same irrespective of the tonnage to be produced, while the cost of the stoves for large tonnage is more than for small, but not proportionately more. The cost of bins is, however, nearly proportionate to the tonnage to be handled. The cost of the power plant is left out entirely here, because the charges on it are included in the cost of power.

We have seen in the article on the rate of driving that it is easy to obtain a reasonable approximation to the power required to blow any furnace at a given rate and knowing this we can calculate the cost of the plant very simply at so much per horsepower, or what is simpler still, knowing by the experience of various investigators, C. J. Bacon, H. J. Freyn, etc., what is the cost of power development at furnace plants, including fixed charges, upkeep, labor, lubricants, etc., we can use figures based on their work.

We have, however, two conditions, that where there is a market for surplus power, and that where there is none. In the last case we need

consider only what power *costs* without any allowance for the value of the gas, and in the other, what it is *worth* or might reasonably be sold for. I have taken .25¢ per horsepower-hour for the first, and .5¢ for the second, the latter being a very conservative figure.

The value of the three items, labor, fixed charges and blowing cost, in cents per ton on the basis of the assumptions made, is shown by Fig. 169 for a furnace 80 by 20. The first two items are the same character, a fixed amount plus an amount increasing with, but more slowly than, the tonnage, and these are therefore added together and their sum per ton of iron shown as one curve, a hyperbola descending to the right. The curves

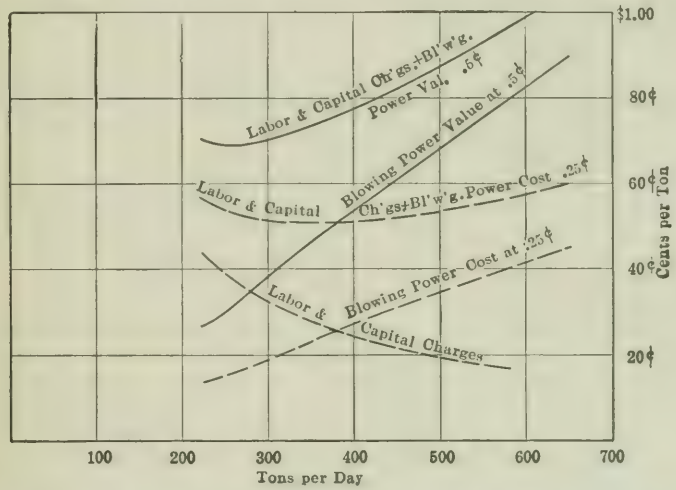


FIG. 169.—Effect of increased production on sum of labor and capital charges + cost of power for blowing at 0.25 c. per horsepower-hour and value of same at 0.50 c. for 20 × 80 furnace.

of power cost and power value ascend almost along straight lines to the right. The sum of the former and that one of the two latter which corresponds to the conditions, shows the sum of these costs for the respective conditions.

These have been calculated for four sizes of furnaces, 17½ by 70 ft., 20 by 80 ft., 22½ by 90 ft. and 25 by 100 ft., both for power cost and power value.

These are plotted on a common basis of daily tonnage in Fig. 170. The solid lines show power value and the dotted lines show power cost in each case.

Several facts show forth very clearly, first, that each curve has a minimum value or point at which the furnace will produce the cheapest iron on the basis of these costs; second, that the cost of the 17½ by 70-ft. furnace is hopelessly higher than that of the 20 by 80-ft., but that the latter

is only a little higher than that of the 22½ by 90-ft., and the 22½ by 90-ft. higher than the 25 by 100-ft. by only 2 or 3 cts. per ton.

In other words, the advantage of large production in lowering cost increases very slowly after the size of furnace reaches 20 by 80 and the tonnage reaches 300, if the cost of the power for blowing be given due weight.

On the other hand, it will be seen that the cost curve of the 22½ by 90-ft. furnace is much flatter than that of the 20 by 80-ft. and that the most economical point can be considerably exceeded with only a slight increase in cost.

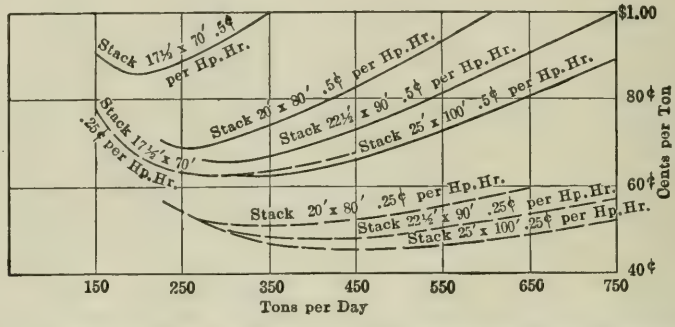


FIG. 170.—Irreducible labor and basic capital charges plus blowing power required at cost of production (0.25 c.) and at selling value (0.50 c.) per horsepower-hour for furnace of different sizes at different rates of production.

THE EFFECT OF RATE OF DRIVING ON PROFITS

It seems likely that cost per ton may at times have received too much consideration and profit per day and per year not enough.

It is very true that during several years out of every ten most furnaces have to figure not how much profit they can make, but how small they can keep their losses, for these cannot be cut short by stopping altogether. Fixed charges consisting of interest, taxes, insurance and some salaries run along just the same, and it pays better to run at a loss that does not exceed this amount than to shut down and break up the organization. But at such times we cannot make all the saving represented by the minimum rate over any higher rate because if we are ever to be able to run at a higher rate, the investment in power plant for that rate must have been made and the fixed charges on it will go on just the same.

When we come now to the question of profits the question is not one of minimum cost per ton, but of maximum profit per day. As a general thing a furnace is not built unless its projector can see a profit of $1.50 as a minimum, for a 500-ton furnace costs with its site and all, complete, about $1,000,000 in normal times, its output is say, 170,000 tons per year, and $1.50 per ton profit on this is $255,000 per year; 25½ per cent. Capital

can be scarcely raised for a smaller return than this in so variable a business.

On the basis of the profit consider the case of the 22½ by 90-ft. furnace on the "power value" basis. The minimum cost for these items is at 300 tons and is $0.65, at 500 tons it is $0.76 or $0.11 higher. The profit on 500 tons per day or 170,000 tons per year at $1.50 as we have just seen would be $255,000, while on 300 tons per day or 102,000 tons per year at $1.50 + $0.11 or $1.61 per ton the profit would be $164,220, which would naturally be less acceptable to the owner than $255,000, even though the cost were lower.

It is very obvious from these considerations that 500 tons per day is not the limit of production from the commercial standpoint, and that it is vastly more important to be able to make double the tonnage in good times than it is to make iron for 11 cts. less in bad times.

During these relatively rare periods when the profit per ton is several times $1.50 per ton these considerations become correspondingly more powerful and the furnace must be equipped to make a maximum production during these periods even though the fixed charges during hard times are somewhat harder to carry, because in this way we secure the maximum return over a long period.

BY-PRODUCTS

There are two important by-products from the blast furnace, the slag and the surplus gas.

Slag.—This finds utilization in three ways at the present time in this country. First, as a raw material for cement manufacture; second, as aggregates for concrete; third, as filling material. In Europe it is also used to make slag building brick and the heat is used to generate steam.

Blast-furnace slag consists principally of the three commonest and least valuable of the components of the earth's crust, silica, alumina and lime; any attempt to utilize it, in order to succeed, must recognize this fact, especially as its composition must be regulated not by the product into which it is to be converted, but principally to suit the conditions of the furnace producing it.

Brick.—The extremely low cost of the natural raw materials for brick manufacture and the high quality of product which can be produced from them has prevented the introduction into the United States of the manufacture on any large scale of slag brick whether cast direct or made by the grinding, mixing and steaming process.

Steam Production from Slag.—A plant has been built and operated in England for the production of power from the waste heat of the slag, a project over which many inventors have dreamed.

The development of the low-pressure turbine made the realization

of this dream much easier. It seemed only to be necessary to permit the slag to flow into an air-tight chamber containing a good volume of water in the bottom, maintain only enough pressure to exclude the air and utilize the steam formed by the direct action of the slag on the water in a low-pressure turbine.

It was found, however, that the acid vapors generated, particularly by the sulphur in the slag, ate up the blades of the turbine so rapidly that this plan was out of the question, so a boiler or evaporator was introduced, made of material unaffected by these acids and the original steam was condensed in this with the production of an equivalent amount of pure steam at a somewhat lower pressure. The slag granulated in the first vessel was continuously removed by a bucket elevator working in a sealed compartment.

The success or failure of any such operation depends upon the price of coal in the district and considering the necessarily high plant cost per horsepower of such an installation it seems inherently doubtful whether the value of the equivalent coal saved would pay the high fixed charges. No plant for the generation of power from slag is in use in the United States at this time.

Slag Cement.—The slag from a large percentage of the furnaces of the largest iron and steel company in the United States is converted into Portland cement. The slag is granulated by a stream of water as it flows from the furnace, the granulated material is dried, ground, mixed with ground burnt lime in correct proportions, the mixture burnt to clinker in a rotary kiln and the clinker ground to cement. The slag must not contain more than 3 per cent. of magnesia in order to make good cement, so the furnaces whose slag is so used are confined to the use of calcite for flux. This converts a waste material from a liability to an asset and with the increasing use of concrete the business seems certain to grow. It is not improbable that better methods of cement manufacture from slag will some day be developed.

Slag for Concrete.—Slag broken up after being allowed to cool slowly forms excellent aggregates for concrete. Being rough and irregular it produces an excellent bond with the cement, and unlike limestone it does *not* swell and go to pieces under the effect of fire. Its use for this purpose will grow with wider appreciation of its value.

Slag Filling.—Slag has been used for reclaiming low land, probably from the earliest days of the blast furnace. In those times it was picked up by hand labor and hauled away cold in carts and wagons, but at present it is either flushed to place with the water used to granulate it or taken molten to the desired location in ladle cars.

When filled to a depth of several feet in the latter way it makes a very solid foundation and is much valued on water-front locations, where cheap transportation has caused the location of so many plants in recent

years and where there is usually much low land which can be reclaimed by filling.

When a railroad fill or dam is desired, end dump ladles are highly desirable as they build an embankment with almost vertical sides and therefore use a minimum of material but with great strength due to its practically monolithic structure.

The Surplus Gas.—In earlier chapters we have seen that with good power-plant and stove practice about one-half the gas produced by the furnace is available for other purposes after the furnace requirements have been supplied. As the gas contains about half the heat energy of the coke from which it is produced we evidently have available in such a case about 25 per cent. of the energy of the coke. This means in the case of a fairly economical 500-ton furnace the heat equivalent of about 125 tons of coal per day. This is evidently an asset of no mean size even where fuel is cheap. How shall we utilize it?

The answer to this question is indissolubly bound up with that of the type of blowing engine to be adopted, already discussed in the chapter on blowing machinery.

When the furnace is operated in connection with steel works, as about 75 per cent. of the furnace capacity is, the steel mill being a heavy consumer of power, the proper and obvious procedure is to convert the heat into power and use it in the steel mill, as is the universal practice in such cases.

The question of the best method to be followed is, however, by no means definitely settled. For those engines in the mill which are steam-driven there is, of course, only one solution, to use the gas for the production of steam, but the power used in mills is increasingly electricity and the question of how best to generate this power and how far to replace the steam engines with electric motors even in the largest sizes is a matter for discussion. The general considerations governing the matter are shown by the following quotations from a lecture before the students of Pennsylvania State College, March, 1915.

"The gas engine is not capable of much change in speed and its economy drops very rapidly as the load falls off, largely because the friction of the engine is very high and almost constant irrespective of the load, so that a friction of 20 per cent. at full load means one of 40 per cent. at half load, and so on.

"This type of engine is also capable of carrying only very slight overloads, that is to say, its most economical load is its maximum load, and any overload capacity is secured only at the expense of economy and at the price of buying a larger engine. In these respects it is at a great disadvantage as compared with either the steam engine or the turbine, both of which have an overload capacity extending far beyond their most economical load.

"On the other hand, the gas engine cuts out entirely the boiler, and above all, it has a heat consumption only about two-thirds or three-fourths of that of the best steam plants.

"It was at one time supposed that this fact was destined to make the gas engine the preferred prime mover for all electric power work, but other considerations came in and this expectation has not been realized; some of the best gas-engine men admit that its day of realization has been indefinitely deferred, where coal is the fuel used.

"Leaving out of consideration altogether the question of first cost and capital charges for the present, let us consider only the operation. Before coal can be used for gas engines, it must be gasified in a gas producer—an apparatus having an efficiency when delivering cold gas (which a gas engine must have) of 70 to 75 per cent., which is almost the same as that of a well-designed and well-operated boiler plant. So on that basis the two are even. But while coal may be burnt under boilers for a few cents a ton, say 15 cts., in large plants, it cannot be gasified for much less than 45 cts., and often 50 cts.

"Now the efficiencies of the producer and the boiler being almost the same, the fuel consumed will be in the same ratio as the heat consumption of the two motors themselves, say as a liberal figure 14,000 B.t.u. for the turbine, and 12,300 for the gas engine, a ratio of 1.17:1. Then if the coal cost is $1 delivered, its cost burned under boilers is $1.15 and gasified $1.45. The fuel cost is proportional, therefore it is $1.15 × 1.17 = $1.34 for the steam turbine and $1.45 for the gas egnine. That is, the heat units used by the gas engine are less, but the money cost of fuel is more.

"This is all based on full-load conditions, and while the cost for both goes up very rapidly for light loads, owing to the far flatter heat-consumption curve of the turbine and its smaller relative size due to its much greater overload capacity, its heat consumption rises much more slowly than that of the gas engine, and as the use factor in public service work is about 30 to 40 per cent., it will be perfectly obvious that the advantage of the turbine over the gas engine will be much greater on the average than it is at maximum load, even on the heat-unit basis. Of course, as the cost of coal rises, the case becomes more favorable for the gas engine, at full load, but it is very doubtful if under any ordinary commercial conditions its practical economy on the average is much higher than that of the turbine.

"When we come to the iron industry we come to a different condition, very much more favorable to the gas engine. This is that the fuel to be used is already gasified by the blast furnace, this gas being in fact almost an ideal fuel for gas engines, and they are, therefore, entirely freed from any charge or loss of heat for gasification, except that the sensible heat of the gas, 6 to 8 per cent. in good practice, must be sacrificed to fit it for gas-engine use.

"The steam plant, on the other hand, is under the necessity of burning this gas under boilers with the same losses as occur in coal firing, excepting that the labor cost is very small. In the past, the economy of furnace boilers has been extremely poor. I have tested boilers on which it was down to 30 per cent. Fifty per cent. was about average practice until quite recently, but just at the present time this subject is receiving great attention and boilers are being operated at an efficiency of 72 to 77 per cent. in regular operation. In this case the full-load fuel consumptions are proportional to 1.17/.77 = 1.52 and (1.00–0.07) = 0.93, or 1.63:1, with the further advantage that the gas engine is enabled to dispense with one whole operation and its attendant bother, the gassification of the coal.

Moreover, the gas engine has in this service a further great advantage. The use factor is about 60 per cent. for electric service in the steel industry, while for blowing engines it is near 80 per cent. Why then are these engines not in universal use in such plants? Here we come to the real milk of the cocoanut.

"We have hitherto said nothing of comparative labor costs and of capital charges. In regard to the former the gas engine has had a bad name. The stresses which it undergoes are tremendous, and breakdowns in the past were frequent and serious, while the uncertainty of the engine's going at all was a decided factor in its early days. But if you remember the prayerful uncertainty with which a man started out on an automobile trip 10 or 12 years ago, not knowing when or how he would return, and consider our present entire disregard of this as an important factor, you will admit that many of the defects of that type of motor have been removed and that its reliability now fairly challenges that of the steam engine, a condition which is rapidly becoming, if it has not already become, true of the larger types which we are considering. Nevertheless, the number of parts and variety of their movements is vastly greater in this engine than in the turbine and the cost of supervision and operation is correspondingly greater; but leaving this question for a few minutes let us turn to that of capital charges.

"These are made up of straight interest and an additional percentage on the investment which is set aside and saved at compound interest, so that at the end of the reasonable life of the plant we may have a sum in the bank equal to the original investment with which we can either pay off the investor or buy a new plant. Any operation which figures its costs on any other basis than this will probably go broke and certainly ought to. Five per cent. at compound interest will equal the principal in about 14 years, which is about all the life we have a right to except from a power plant, for if it is not worn out in that time it has most likely been designed off the map. In other words, later improvements will have then made it commercially undesirable to operate any longer, even though it be not worn out.

"This 5 per cent. added to the 7 per cent. interest rate, which must be figured on industrial plants, gives us 12 per cent. capital charges over and above all operating costs of every kind. This is a minimum figure for plants of this kind. Make no mistake; these are not merely 'bookkeeping' figures, and the shores of commercial history are covered with the wrecks of plants which failed to provide for these charges. No sensible business man will put money into a property which cannot figure on this basis and still show a profit.

"We see, then, that the annual cost of power is made up of fuel, labor, and capital charges equal to one-eighth of the cost of the plant.

"Let me illustrate this.

"I know of a plant where a furnace is blown with two gas-blowing engines which cost about $100,000 apiece, and which with foundation, house, crane and gas-cleaning apparatus and connections erected complete did not cost less than $275,000. They develop together about 2500 hp., or a cost of $110 per horsepower installed. Coal of 14,000 B.t.u. in this region costs about $1 at the plant.

"Steam engines of the best type, with their boilers and all accessories complete could have been installed for $55 per horsepower. These engines would have been required certainly not to exceed 18,000 B.t.u. per horsepower-hour delivered

to the boiler, while the gas engine may get along on 12,000. Counting 8780 hr. per year, the loss of thermal units per year is 6000 × 8780 = 52,600,000 B.t.u. That is a large number of heat units. But how much money does it represent? One ton of coal costs, fired, say $1.15 and contains 2240 × 14,000 = 31,000,000 B.t.u. In other words, it would require 1⅔ tons of coal per horsepower a year to make up the steam plant's deficiencies, or say, $2 worth.

"The difference in fixed charges, on the other hand, is 12 per cent. on ($110-$55) = $6.60 or a net *loss* of $4.60 per horsepower year by the use of the gas engine even with 100 per cent. use factor.

On the other hand, gas-blowing engines are now being built which can be installed for $75 per horsepower, and if these were used in a region where coal cost $2.50 per ton, the cost of make-up coal would be $4.20, and the fixed charges on increased investment be 0.12 × (75-55) = $2.40, a difference of $1.80 in favor of the gas engine under these conditions. This is a little less than 10 per cent. on the additional capital required for the gas engine and might be considered a paying though by no means a startling investment, because owing to the uncertainties of industrial earnings, investors are not commonly interested in them unless they can see a manufacturing profit of about 15 per cent.; and it is obvious that any additional expenditure required should show this return or over to be justified. In this case the amount is 7 per cent. interest plus 9 per cent. net saving or 16 per cent. in all. It is right in this range of conditions that it begins to be good business to install gas-blowing engines, though some authorities would insist that at least 2 to 3 per cent. larger capital charges should be assessed against the gas engine on account of its high rate of physical depreciation, and all the evidence I have indicates that this is correct.

"Turning now to the generation of electric power, we find the conditions different again, because we have on the steam side the turbine with its direct rotary movement and its great capacity, while on the other we have the relatively slow speed of the gas engine and the consequent high cost of its generator with probably greater friction and less efficiency than when connected to a blower.

"For these conditions we may take costs of $70 and $50 respectively per kilowatt installed and heat consumptions respectively of 12,500 ÷ 94 = 13,300 B.t.u. per horsepower for the gas engine, 6 per cent. of the heat of the gas being removed by washing and $\frac{12,000}{0.77}$ = 15,600 per horsepower for the turbine, or 17,700 and 21,750 per kilowatt-hour respectively. The use factor is much lower in electric service than it is in blowing-engine service. If we take 60 per cent. we shall be liberal. This means that on account of peak loads for which it is necessary to provide, the plant in the course of a year will only put out 60 per cent. of its maximum rated power. This factor varies very much in different works, but is higher in all of them than in public service plants.

"The heat consumptions given are about what may be expected under such conditions of loading and are not altered by this condition and neither are the costs, but the financial relations of these two are profoundly altered.

"The excess thermal units per kilowatt-year at full-rated capacity for the turbine above those for the gas engine are 8780 × (21,750 − 17,300) = 39,100,000, and the coal to supply this at 31,000,000 B.t.u. per ton is 1.26 tons at $2.50 per ton. This is worth $3.15, but the use factor is only 60 per cent., so that only

60 per cent. as much coal is required for make-up, and its value drops to \$1.90 while the fixed charges are 12 (70 − 50) = \$2.40.

"In other words, in such a case the saving in coal would not pay all the capital charges on the increased investment, which therefore would be a bad one. Moreover, while the cost of labor and supervision for gas blowers may be no greater than that for steam engines and boilers together, undoubtedly their cost for gas-driven generators is much greater than it is for steam turbines and boilers, and this increased cost would further throw the scale against the gas engine. But as the cost of coal rises, conditions are reached under which the gas engine pays, while as its first cost falls the fixed charges fall also, and tend to make its employment sound from the business point of view.

"It will now be seen, I think, why John Doe in Pittsburgh, where coal is cheap, may be a fool to do what had paid Richard Doe well in Boston where coal is dear, and the engine that is the most economical of coal may be a lot the most wasteful of dollars."[1]

There are certain electrical considerations involved in the very variable load of the steel mill that give the turbo-generator advantages not covered by this discussion, but of great importance and very tangible value in operation. These considerations probably make it desirable, if not essential, that part of the electric power at least be developed by turbo-generators even if the main supply be from gas engines.

One fact cannot be too strongly emphasized. This is that the decision that a certain type of mover is the best for blowing purposes by no means involves the conclusion that the same type is best for electric power developments. One principal reason for this is that the blowing power for each furnace necessarily being separate from that of the others, for reasons of control, the largest blowing unit is limited at the most to about 2500 hp., that being the approximate power required to blow a 500-ton furnace, and for safety it is desirable to have this divided into two units, whereas electric units may be built as large as 35,000 hp., and these larger ones are lower in both first and operating cost than the smaller ones, while they are entirely free from the electrical troubles due to variation in angular velocity to which the gas engine is liable.

The greater reliability and smaller upkeep of the turbine give it an advantage over the gas engine not fully covered even by the necessary allowance in operating costs, because certainty of operation has a cash value from the point of view of the whole works which power cost does not touch.

For the generation of electric power the reciprocating steam engine on account of high first cost of generator and higher operating cost is not to be compared with the turbine in sizes larger than 2000 hp.

[1] Progress in the design of both turbines and gas engines, but especially the former since this was written have lowered the heat consumption to be expected in both cases, so these figures should not be taken as authoritative for the solution of actual problems at the present time.

THE EFFICIENCY OF GAS COMBUSTION

One factor of great importance in the decision as between gas and steam engines is that the efficiency with which the gas is burned under the boilers, while the efficiency of combustion in stoves has an enormous effect on the quantity of gas used for that purpose or left for outside utilization. For many years gas was burnt most wastefully as no attention was paid to the subject, but in recent years it has been carefully investigated and vastly improved. Diehl, Eldridge, Bradford, Boynton, Green, Huessner and a host of others have investigated existing burners and built better ones until the efficiency of boilers using furnace gas has gone from about 50 per cent. to over 70 per cent. in many cases and nearly 80 per cent. in some. With this has gone an increase in the steam produced per boiler which, of course, cuts down the capital cost as well as the fuel cost.

The result is that while the steam motor might have been at a hopeless disadvantage a few years ago, even in spite of its advantage in fixed and operating costs, it might easily beat the gas engine on the same basis to-day.

The general principles on which these improvements have been made are simple, being merely the well-known principles of all good combustion, first, correct proportioning of gas and air on the injector principle so that a change in the rate of flow of one makes a corresponding change in the flow of the other; second, the thorough mixing of the air and gas before they reach the zone of combustion; third, the control of the draft at the outlet to the stack, so as to maintain the rate of flow of the products of combustion at the best velocity without drawing in any excess air.

The establishment of these conditions may require that either the air or gas be put under light pressure by a fan to supply the velocity required for injector action and for proper mixing, also in some cases to give sufficient velocity without excessive stack draft. The expense of operating the fan is insignificant in comparison with the enormous saving made by the improvement in combustion when these principles are correctly applied.

Where a furnace is not operated in conjunction with steel works there may still be a market for the surplus gas. This may be developed in the form of a sale of electric power to the public service company, but the stringent requirements of continuity in that service have made many blast-furnace operators chary of contracting with those companies.

Where the gas cannot be sold in this way it may be sold for heating purposes, but the field is rather limited, because the small heat value of the gas makes its transportation expensive and unfits it for any but relatively low-temperature operations since the combustion temperature of furnace gas is not high.

In spite of these difficulties the enormous potential value of the gas

justifies far greater efforts to conserve and sell its energy than have been made in the past.

In conclusion it is worth repeating that the possibility of disposing of this asset either as electric energy or heat is much greater in the vicinity of a city, and this is destined in the future to induce the location of merchant furnace plants near thickly settled communities to a greater extent than in the past.

COMMERCIAL LIMITATIONS TO FUEL ECONOMY

A few years ago the maximum degree of fuel economy was not only technically desirable, but was commercially necessary for survival; now this is no longer the case. There are conditions in which the commercial results are better with very moderate fuel economy than with the highest. The two developments which have brought about this change are the introduction of the by-product oven and the economic development of power generation with furnace gas, especially the gas engine.

One of the fundamental conditions for the occurrence of this paradox is that there shall be a market for all the surplus power developed. Let us assume, then, the most common case of a combined plant of blast furnaces and steel works in which the latter furnish a market for all the power which can be supplied by the former. Assuming a high cost of coal brings out the facts more clearly; let us then assume that coking coal costs $2.10 delivered at the works. If this were coked in old-fashioned ovens the yield would be about 60 per cent. and the coking cost would be about 60 cts. per ton of coke; coke, therefore, would cost $2.10 \div 0.6 + 0.60 =$ $4.10 per ton, and this cost would represent less than 60 per cent. of the heat value of the fuel. The same coal in modern by-product ovens would yield 70 per cent. of good screened coke, and the coking cost would be about 75 cts. per ton of coke, so that coke would cost $\frac{2.10}{0.7} + 0.75 = 3.75$ per ton. There are, however, some important deductions from this figure. The gas can be sold to the steel works for heating furnaces, the tar and ammonia are recovered (the latter in the form of ammonium sulphate) and sold; while under present and probable future conditions the benzol can be recovered at a handsome profit also.

The value of these by-products varies with the location, but is seldom or never less than $1 per ton of coal. In a region of high-priced fuel such as we have assumed, $1.50 per ton of coke would be a safe estimate. This would reduce the cost of coke to $2.25 per ton; in other words under such circumstances a ton of coke would cost little more than a ton of coal in spite of the loss of weight and the cost of the operation.

Cases exist in which the coke actually costs less per ton than the coal from which it is made, the value of the by-products making up all the losses and paying all the costs of the operation.

Turning now to the utilization of the coke, all the heat energy it contains not consumed in the necessary operations of the blast furnace, is returned in the form of gas, and because this gas contains only a small percentage of its heat in sensible form the efficiency of conversion is very high. Ordinarily the sensible heat of the gas is less than 5 per cent. of the heat of the coke, and we may say that the efficiency of the blast furnace in its double function of iron maker and gas producer is 95 per cent.; or, on a more conservative basis, we can say that since only about 10 per cent. of the total energy of the gas is sensible heat the efficiency of the blast furnace as a gas producer alone is 90 per cent. or better, whereas that of the standard gas producer, measured on the basis of the energy in the cold gas divided by that in the coal, is only about 65 to 75 per cent.

We have already seen that the gas engine has a considerable advantage over the steam turbine in heat consumption, if we start with gaseous fuel; and the tremendous efficiency of the blast furnace as a gas producer enables us to utilize this advantage of the gas engine in regions of high-priced fuel where the saving will pay the fixed charges on the greater investment.

In other words, admitting as we must that there are considerable technical advantages in the use of gaseous fuel for power development, it is obvious that these may be commercially realized much more easily when the gasification is done as it is in the blast furnace with a thermal efficiency of 90 per cent. and without labor and capital charges, than they can when the efficiency of gasification is 65 per cent. and the cost 50 cts. per ton of fuel, as in the gas producer.

If we convert as much of the coal into coke as the furnace can conveniently take and utilize the resulting gas to the full, the sum of the total fuel and power bill measured in dollars plus the fixed charges of a combined plant under such conditions, is smaller than if we work with the highest fuel economy in the furnace and supplement the power required by the use of coal either in gas producers or under boilers. Of course, the ability of the furnace to consume coke is limited and its output of iron decreases, other things being equal, as the coke per ton of iron increases, and if we tried to run the coke per ton of iron unreasonably high the iron output would fall and profits be seriously reduced.

It is worthy of note that the highest fuel economy can be obtained only with very high blast heats, which means a decided increase in the gas required for blast heating. After we have reached the limit of commercial coke economy every such increase in gas consumption for this purpose represents an absolute loss.

It is worthy of note also that these conditions bring about a justification for high solution loss, since we have seen that solution cools down the top gases and reduces the loss due to sensible heat, and it reduces the quantity of blast required per pound of coke and thereby reduces the

pressure required to blow the furnace so that there is a material saving in the power per ton of iron consumed for blowing.

It cannot, however, be too strongly emphasized that where these conditions do not prevail, where the cost per thermal unit of coke is materially higher than that of coal, or where there is no market for all the power which can be produced, or the cost of coal is too low to justify the completest utilization of gas, fuel economy is just as important as it ever was. These are the conditions which generally prevail at merchant furnaces, especially those which buy their coke.

THE DRY BLAST

The fact that the large steel works of the country have generally not installed dry blast plants has led some of those interested in such matters to believe that there was no ground for the claims of fuel economy made for dry blast, but nothing could be further from the facts. The real case of the dry blast depends upon the considerations set forth in the last section. Where it does not pay commercially to run the furnace for maximum economy for reasons there set forth, obviously it may not pay to install dry blast to obtain fuel economy; but, on the other hand, in the many cases where every pound of coke unnecessarily burnt means so much money lost, especially where the climate is damp, the dry blast is commonly a highly profitable investment.

There are special conditions in which furnaces have available more blast heat than they need or can use, and in such cases the only gain from the dry blast is the increased uniformity of operation, and it is a matter for careful consideration whether dry blast will pay or not.

The most marked instance of this kind is the charcoal furnace with high-blast heat and on rich ores. In the case cited in the chapter on thermal principles the hooding in of the air cylinder of the blowing engine resulted in lowering the moisture very decidedly, but did not have any effect on the fuel economy, and the application of the dry blast to another charcoal furnace running under similar conditions did not have any adequate result on the fuel consumption.

On the other hand, practically all the tests made at merchant coke furnaces equipped with dry-blast plants have shown a saving in coke and an increase in product of a value to pay for the dry-blast plant in 2 or 3 years.

It is very unfortunate that dry-blast plants have hitherto not been built in the South where the humidity is high, with the exception of one plant which has not been operated long enough at this writing to demonstrate the advantages of the process in that region. But I have taken records for years at a time which showed a fuel consumption lower by 20 per cent. in the dry than in the humid season, and this represented

only a part of the total saving. For during the humid season the margin of hearth heat was reduced to the point where slight variations were liable to throw the furnace completely off its balance, and the hearth heat per pound of fuel being very small the furnace was not sensitive to changes of burden and was therefore, difficult to keep in regular operation. Serious troubles such as breakouts were very much more common, and as a result the operating costs were very much higher during the humid season. This was so serious that as long ago as 1896 I tried to persuade the owners to install refrigerating apparatus to dry the blast, and was able to show to my own complete satisfaction that it would have been a vastly profitable investment, but no attention was paid to the suggestion by them. This was fully 8 years before the publication of Mr. Gayley's results, and none of us had the slightest idea that anyone else was working on the plan, though I subsequently found that Mr. Gayley had taken out patents on the process 2 years before I started on it.

On another occasion in the Birmingham district, furnaces running on foundry iron fell off in the grades produced in the early spring, a time when ordinarily the humidity is quite low, but the season had been a very warm one, and when I consulted the humidity records I was astonished to find that the humidity had risen enough to account for the increased coke required to restore the grades, a very considerable amount.

Two points in connection with dry blast are of much importance; first, it is the absolute and not the relative humidity on which the possible saving depends; second, the amount of saving possible is susceptible of reasonably accurate calculations. The relative humidity means the percentage of the moisture which the air actually contains measured in terms of the amount it would contain if saturated *at that temperature.* But the amount of moisture which the air contains at saturation increases with great rapidity as the temperature rises.

Referring to the chart given in the chapter on dry blast,[1] it will be seen that at 0°F. this amount is 0.05 lb. per 1000 cu. ft.; at 32°F., 0.27 lb.; at 60°F., 0.8 lb.; at 70°F., 1.13 lb., and at 80°F., 1.6 lb.; therefore the humidity in percentage means nothing whatever unless we know the temperature. On a foggy day with the temperature at 32° the humidity seems excessive, and in fact fog means that the air is supersaturated; while on a summer day with the thermometer at 80° and the humidity 50 per cent. of saturation the air would seem excessively dry, but in the latter case it would contain nearly three times as much moisture per cubic foot as in the former.

We can determine the fuel saving possible in any given case where the humidity during each month of the year is known, by the use of the charts of hearth heat in the chapter on thermal principles (Fig. 3). We first

[1] See Blast Furnace Construction in America.

determine the average absolute moisture in the air for each month, then decide on the point to which it will pay to dry it, and deduct the coke consumption for the second case from that of the first. To do this, of course, requires a knowledge of the blast and critical temperatures, at least approximately, for the given conditions.

The humidity in the air for each month can be obtained from the nearest Weather Bureau Station. It is desirable to obtain it for at least 2 years and average the results. This information (furnished freely by the Weather Bureau officials) forms an excellent basis on which to start, but it is necessary to have in mind that their stations are generally located at the highest point available and that the humidity at the ground level may be locally very much higher, especially on the banks of large bodies of water, rivers, lakes or cooling ponds, where furnaces are usually located. Cooling ponds and rivers in industrial districts in particular are likely to throw off large volumes of moisture, even beyond the saturation point of the surrounding air. Within a few hundred yards this is all absorbed and averaged up in the vast volumes of surrounding clear air, so the results at the Weather Station may not be much affected, but the local increase in humidity in the vicinity of the plant may be of great commercial importance.

For the reason it is well to determine definitely the humidity in the vicinity of the blowing-engine intake over a period of several weeks at least, and compare the results with those of the Weather Bureau. A few weeks will generally give a fair idea of the local increase, but of course it is desirable to have it for a year if possible.

Knowing the coke saving per ton, and the cost of coke, and the tonnage made per day, we can easily figure the saving from this source. A comparison of this with the cost of a dry-blast plant will generally show that at merchant furnaces without a market for their surplus power the saving will pay for the installation in a short time.

In addition to the saving in fuel and the corresponding increase in tonnage which results, there is a saving in smoothing out the irregularities which result from variations in humidity, whose effect, as explained above, may be very serious from a financial point of view. This saving, due to the uniformity, has sometimes been claimed to be greater than that due to the drying itself, and while I cannot subscribe to that view, there is no doubt that it is extremely important, especially in the case of merchant furnaces, where the control of grades is so much more important commercially than at steel works' furnaces.

We can then summarize the status of the dry blast as follows: If first there is a market for heat in the form of combustible gas at a price per thermal unit equal to or better than that for coal, and second, if the money cost of a thermal unit in the form of coke is but little greater than that in the form of coal, the fuel economy in the furnace beyond a

point soon reached has a negative value and a dry-blast plant to promote fuel economy, accordingly cannot ordinarily pay. Or where the furnace has available from hot blast alone more hearth heat than it needs for its conditions (practically, this means only charcoal practice on rich ores), the advantage of the dry blast becomes a very secondary one. But where coke consumption reduced means money saved, and where strict grade control means more money earned, then the dry-blast plant is usually a highly profitable investment.

In conclusion it may be pointed out that the introduction of the by-product oven by reducing the value of coke in comparison to that of the coal from which it is made, and the gas engine by giving to the surplus gas from the furnace a commercial value per thermal unit, in some cases equal to that of the coke itself, have been the principal causes of the non-introduction of dry-blast plants at steel works' furnaces.

CHAPTER XX

THE FUTURE POSSIBILITIES—BLAST FURNACE

That iron is the very basis of our industrial civilization is admitted by the thoughtful, the rate at which it is consumed in industrial countries is enormous and the rate at which this consumption is growing is astounding. For nearly half a century the pig-iron output of the United States has doubled every decade and in 1917 reached practically 40,000,000 tons corresponding to the consumption of about 80,000,000 tons of iron ore.

The consumption of backward countries is destined to grow at a still faster ratio as they emerge into Western methods of living. The iron consumption of China per capita is only about one two-hundredth that of the United States.

China is now using about 500,000 tons of iron per year. It she were using as much per capita as the United States, she would be using 150,000,000 tons per year, over twice the annual production of the whole world to-day. In India conditions are not very different. As those countries with a population jointly far beyond a half a billion begin to adopt Western habits, their consumption of iron must rise by leaps and bounds. The rate at which we are now using up our iron ore is amazing but, when that time comes, the world's resources of this indispensable mineral will be exhausted at a staggering pace. For these reasons the question of a supply for future generations in one vital to the race and is worthy of consideration here, in view of the fact that the changes in conditions which must come about will affect the economics, and through them the technology of the blast furnace.

These conditions of increasing consumption and decreasing reserves have often in the past, particularly about the beginning of this century, been used to create a scare, on the ground that our supplies of usable ore were being so rapidly depleted that their exhaustion would occur within two or three generations. This is a point of view which seems to me preposterous, even leaving out of account the fact that the estimates of the world's iron-ore resources, which were used in reaching this conclusion, were subsequently shown to be entirely inadequate. But the corrections which have since been made push into the future, only by a few brief centuries at most, the time at which the exhaustion of these reserves may be expected. It is then, not here that our fundamental ground for optimism must be found, but in the fact that as we lower the percentage

of iron in the rock which we agree to call "ore" the quantity of such ore increases at a rate out of all proportion to the decrease in iron content.

In considering the decline in iron content, especially as to the rich ores, we must remember that as there are two oxides of iron, containing when chemically pure, different quantities of iron, we must consider them separately. Magnetite, Fe_3O_4, contain 72.4 per cent. of iron, hematite, Fe_2O_3, 70 per cent.

There have been magnetites found containing over 70 per cent. in iron. In one region, a deposit was found, in which there were more than 60,000 tons of ore running 70 per cent. and over. This degree of purity is so rare that this deposit is (historically) famous for its size, but this same district contains millions of tons of ore 60 per cent. and better, tens of millions of ore of 50 per cent. and better, and hundreds of millions of tons containing 30 per cent. and better. This, being magnetic ore and free-milling, is considered as commercially available ore to-day, and while the same thing is not true commercially of hematites, yet to assume that methods will not be found to concentrate these also is to insult the intelligence of posterity. If we were to drop down to rocks containing 20 per cent. of iron, the increase would be still greater.

I believe that this whole matter could be handled accurately upon the the basis of the probability curve, but I am not mathematician enough to do it, nor have I been able to obtain the assistance of a mathematician who could, but such tentative figures as I have, obtained from an authoritative source, indicate that for every million tons of iron ore from 60 to 65 per cent. iron content there are 85,000,000 tons of 30 to 35 per cent., and the increase is even more rapid as we drop below this point, on the mathematical basis of probability.

It is obvious then that we shall never run out of iron-bearing material —we shall simply use leaner and leaner material as time goes on.

This process has already proceeded further than we realize, unless we stop to look up the records of the past. A standard of comparison lies in the fact that when my father made an examination of the famous Chapin mine in 1891, just a quarter of a century ago, he found them throwing 56 per cent. material over the dump as "rock."

The direct result of future change in the same direction will be to increase the cost of pig iron for the reasons elaborated in earlier articles, and this fact must be frankly faced. But we have seen increases in price of pig iron many times greater than that which would result from reducing the iron in the ore from 55 to 30 per cent., but neither the consumption of iron nor civilization was checked by these conditions (if one took only the superficial view they would appear to have been accelerated), and it is, therefore, reasonable to assume that if this condition of high prices becomes chronic for industrial reasons, instead of being spasmodic for

commercial reasons, civilization would scarcely feel the difference, especially as it is a change which will take place with exceeding slowness.

A lowering of the permissible percentage of iron, such as that indicated above, would increase our resources in ore to an extent which the imagination can scarcely grasp, and there is no reason to doubt that the tendency to increased cost, due to the use of leaner ores, would be met by technical and industrial improvements which would minimize if they did not wipe out the increase.

The same thing has happened in other industries. Gold ore worth $10 per ton was probably not commercial 50 years ago; to-day gold is being extracted at a profit from ores which contain values of only $1 per ton. Similarly the copper ores 50 years ago were rich. In the early days of Calumet & Hecla the ore ran 3 per cent. in copper and sometimes 4 per cent. It was also "sweetened" by masses of native copper of such great size that in those early days of little or no equipment great difficulties were encountered in cutting them small enough to be brought out of the mine. Copper in that day commanded a price of 20 to 30 cts. a pound; to-day mines are extracting copper from ore containing 1½ per cent. and less of the metal, and they could sell it, if they wished, at 8 cts. a pound.[1]

If nature has been more generous to the iron industry and endowed it with extensive supplies of ore, capable of immediate use in the furnace without beneficiation, that is no sign that the iron industry and civilization with it, will be extinguished by the exhaustion of these deposits, and the consequent necessity of descending to ores containing only a fraction as much metal.

Advances are to be expected along both industrial and technical lines. Much of the value of the high-grade ores of to-day is made up of two elements—a rarity value, namely, the royalty paid to the owner because of the exclusive ownership of existing deposits, and a transportation value due to the necessity of bringing these relatively rare rich ores to the point of consumption.

If the day ever comes when we drop down, for instance, to 30 per cent. ores, the bodies of these are so vast that exclusive ownership will be almost impossible, and the royalty value will greatly decline or fade away, while, owing also to the relative numerousness of such bodies of material, the chances are that they will be found much closer to the points of consumption than the rich but rare bodies of to-day. This, then, will tend to reduce the transportation values of these ores, or at least will tend to offset the increased cost of transportation, due to the greater number of tons required per ton of iron.

On the technical side, improvements may reasonably be expected along four lines—mining, ore dressing, by-products, and the furnace itself.

Mining.—Cheaper mining is to be expected because we shall be able

[1] In prewar times.

to choose among the most favorably located of the great deposits of low-grade material, and for centuries probably nothing but open-pit work will be done upon them, which will mean a minimum of cost.

Ore Dressing.—In regard to ore dressing, the metallurgy of iron is far behind any other, partly because of nature's hitherto bountiful supply of ores directly available, and partly because the blast furnace, being a willing horse, has often been made to carry an unfair burden. Its proper task is the reduction of iron to the molten metallic state from its oxide; it has also often been made to serve as an ore-dressing apparatus and to separate the iron from the gangue as well, for the good commercial reason that it furnished the cheapest way to do it, if other conditions were right. Most of the science of ore dressing for the iron industry, therefore, lies in the future, and there, as far as this work is concerned, we must leave it, since it is impossible to foretell the lines of development which will follow, and they would be out of place here, if we knew them.

By-products.—It is only within the last 10 or 12 years that we have been accustomed to consider the by-products from the furnace as having any value, but leaving aside for the present the question of the gas, we are coming to an increased realization of the importance of the slag in making cement. As concrete construction grows in relative importance to steel, as well as in absolute importance, and as the quantity of slag per ton of iron increases, which it necessarily must from the use of leaner ores, we must look for a wider and wider application of this slag to the production of cement. We may even hope that the present method of manufacture, which theoretically at least seems very crude, will in time to come be improved, revolutionized perhaps, so that what one furnaceman has been accused of dreaming—tapping iron out of the iron notch and cement out of the cinder notch of the blast furnace—may almost come to pass.

If the cinder can be converted into cement with a profit which will only pay for handling the gangue of the ore and the limestone to flux it, the furnace of the future will obviously be relieved of a heavy part of its increased burden.

The Possible Development of the Blast Furnace.—Turning now to the furnace itself, whatever we say or suggest must be taken in the light of prophecy and subject to all the errors and discounts to which all prophecy is subject, because if there were means whereby we could increase the economy of the furnace beyond the present possibilities when running on lean ores, obviously it would not be a matter for the future, but would be in process of being done to-day.

Turning back to the chapter on commercial considerations, it is easy to believe that the furnace of the future will feel no particular pressure on account of fuel consumption until the latter has risen beyond the point at which the furnace gases will supply all the heat and power requirements of the associated steel mill, except, of course, at isolated merchant furnaces having no such market for their power. The question as to how we shall

reduce the fuel consumption, when this point is passed, is the ultimate question which the industry must answer, and though it is a long way in the future for us, there are visible, even to-day, means whereby it may be done. Of course, the possibilities of hotter blast and all the other lines along which present developments are progressing will have been pretty well exhausted by that time; we must look for a more radical solution.

THE INDUSTRIAL PRODUCTION OF OXYGEN

This, in my judgment, is to be found in the modern industry of separating the oxygen from the nitrogen of the atmosphere by purely physical means, and using this instead of air to blow the furnaces of the future. This idea is not novel in the industry. Experiments were made in the direction of enriching the oxygen content of the blast in Belgium a year or two previous to the breaking out of the Great War, but no important results were obtained, or at least those published were unimportant because the degree of enrichment was too small to produce any marked change. Some American furnacemen have taken the ground that no gain was to be expected on theoretical or practical grounds. If that contention be correct, the fundamental principles of the blast furnace, as set forth in a former chapter are wrong, the explanations of known phenomena made on the basis of these principles are incorrect, and there is scarcely a chapter in the book which can be accepted without the most drastic revision. If, on the other hand, the thermal principles set forth are correct, then we may proceed to show quantitatively the effect which oxygen in different proportions would have upon the thermal relations in the hearth and bosh of the furnace.

Fig. 171 is a diagram giving the quantities of hearth heat obtainable per pound of coke (counting 0.85 lb. of fixed carbon burned in the hearth) with dry air blast at 1000°F., and with a mixture of equal weights of oxygen and nitrogen at atmospheric temperature. This diagram shows that at low critical temperatures there is but little advantage in the oxygen blast, but as the critical temperature rises the advantage increases from a few per cent. to several hundred per cent. The study of this diagram shows us what changes may be made in the thermal operation of the furnace by the use of blast rich in oxygen.

There are many who will doubt the possibility of obtaining the supply of oxygen which would be required for such a use, but the process of separating air into its component oxygen and nitrogen on an industrial scale by distillation from liquid air is now in actual operation at Niagara Falls, separating many thousand cubic feet of air per hour.

Those who remember the ridiculous claims made for liquid air, in the later eighteen-nineties, and their subsequent utter collapse, are inclined to deny the commercial possibility of that operation, on theoretical grounds, but this is not correct. The theoretical power for effecting the

separation, figured on the basis outlined by Ostwald, the great apostle of physical chemistry, amounts to only 1 hp. per 6 cu. ft. of oxygen produced per minute. A modern 500-ton blast furnace requires 45,000 cu. ft. of air or 9000 cu. ft. of oxygen per minute, which would require, on the theoretical basis, 1500 hp. for its production, as against the 2500 hp. now necessary to blow the furnace.

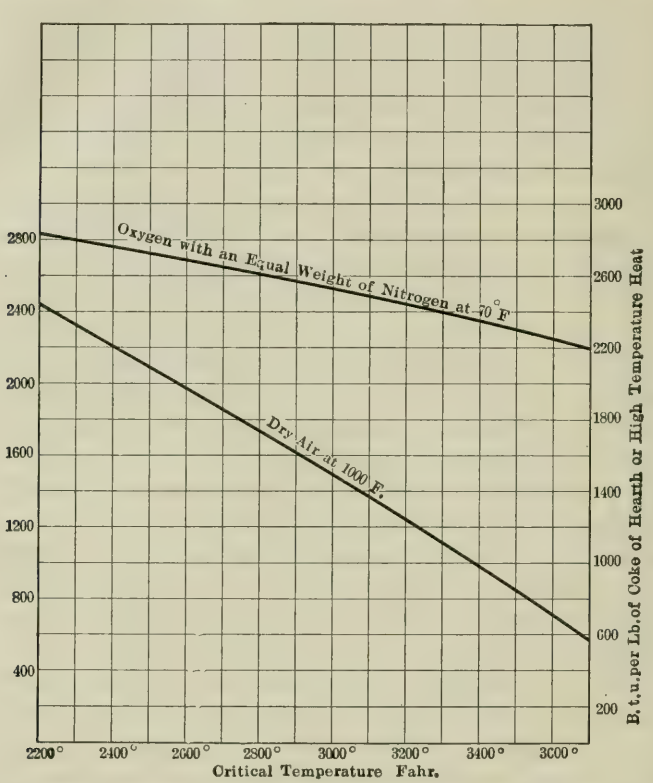


FIG. 171.—Hearth heat per pound of coke (counting 85 per cent. fixed carbon burnt in hearth) at different critical temperatures with blast of dry air at 1000° F., and with dry blast of equal weights of oxygen and nitrogen at 70 °F.

The best performance of any actual air-separating operation to-day requires about seven times the theoretical amount of power, so we are still far from being able to replace existing methods on the power basis. Processes are under development, however, which promise to reduce this power requirement by one-half or two-thirds; in other words, we hope to produce oxygen at an efficiency of 50 per cent., based on theoretical power, and there is no fundamental reason why we should not do so. Even this, it will be said, is no improvement over present conditions, and on the power basis alone that would be true. But this question cannot be decided on the power basis alone, for two reasons:

1. The heat consumption of the blast under present blast-furnace conditions is not limited to power alone.

2. The result in the furnace itself must be considered.

In regard to the first point, it must be remembered that blast must not only be compressed, but it must be heated, and this operation requires about four times the heat required to supply power for compression; then there is the heating equipment, which costs as much as the power plant, all of which would be saved by the use of oxygen. This brings us to the second point, the effect of oxygen in the furnace itself.

It will be seen that for the average condition, 2750° critical temperature, the hearth heat with the ordinary hot blast is about 1800 B.t.u. per pound of coke, while with the 50 per cent. oxygen blast, it is 2625 B.t.u.; in order words, we can raise the amount of hearth heat obtainable from a given amount of coke nearly 50 per cent. by the use of a blast containing one-half oxygen. If the critical temperature be higher the advantage is still greater.

Let us remember that it has been shown in the chapter on thermal principles that the rapid increase in fuel consumption with leaner ores comes principally from the increased slag to be melted, and the volume of slag increases with enormous rapidity as the percentage of iron in the ore declines. The average Lake Superior ore of 52 per cent. iron produces about ½ ton of slag per ton of iron. Ore of 38 per cent. iron and 38 per cent. silica produces about 2¼ tons of slag, which at 0.33 ton of coke per ton of slag means an increase of 0.6 ton in coke. On the same basis, an ore containing about 25 per cent. iron Fe, 48 per cent. SiO_2 and 15 per cent. Al_2O_3, would produce 5 tons of slag per ton of iron which, on the basis of 0.33 ton of coke, would demand an increase of almost 2 tons in the coke required to make a ton of iron, working under present conditions. If the total coke per ton of iron became 3 tons with ordinary hot blast, on the basis of the hearth heat developed, it would drop back to 2 tons with half oxygen blast.

But we must consider the development of shaft heat as well as hearth heat. With lean ore and half oxygen blast, we should require more than under present conditions, for two reasons:

1. The larger quantity of slag-forming materials to be heated to the critical temperature in the shaft.

2. The smaller quantity of nitrogen present to carry heat from the hearth up into the shaft.

But we have seen in discussing thermal principles that a reduction of the amount of fuel required to smelt a given weight of iron automatically increases the amount of heat available in the shaft, because a larger proportion of the CO present at the top of the bosh is oxidized to CO_2 by the oxygen of the ore, with a correspondingly greater development of shaft heat.

We have seen further that solution loss is one of the prime causes of insufficient shaft-heat development, as well as of insufficient hearth-heat development.

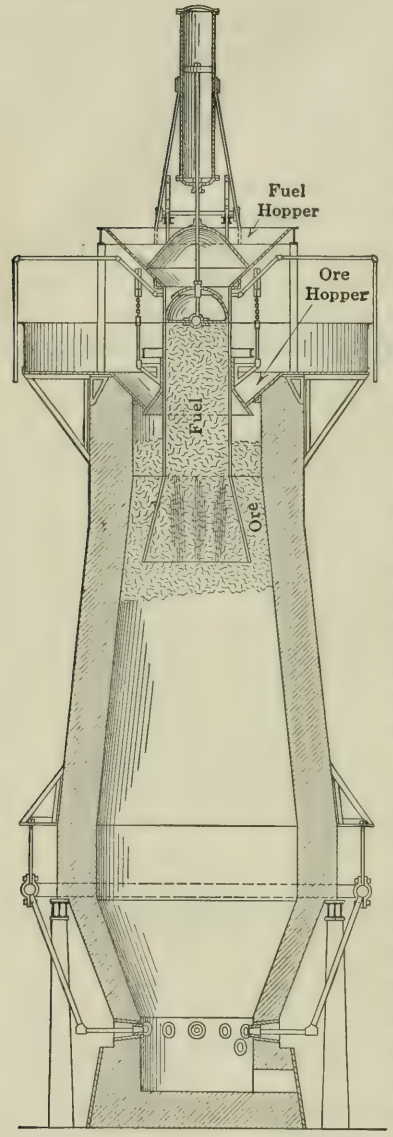


FIG. 172.—Proposed design of blast furnace for oxygen blast.

In order to eliminate this loss more or less completely, especially in the upper regions of the furnace, where the concentration of CO_2 and the solvent action on the coke are the greatest, I have suggested a construction in which the fuel should be fed down through the center of the furnace, and for some distance down kept from contact with the ore, while the gas was made to travel the last portion of its journey through the ore alone, thereby eliminating its alternating contact with ore and fuel, the prime cause of solution loss with the present process.

This design is shown by Figs. 172 and 173. The water-cooled steel mantle with a fluted bottom is supported from the top of the furnace, its top is sealed and no escape of gas permitted therefrom. The fluting is intended to promote a quick and intimate mixture of the ore and fuel in the lower regions of the furnace.

It is hardly necessary to say that this scheme has never been tried, nor has the use of oxygen blast in any percentage calculated to produce revolutionary results. The whole idea must, therefore, be counted as a dream, for the present, but in considering the possibilities of the future, as we now are, it is well to remember that incredulity has discredited the wisdom of the race many times oftener than credulity, and allowing that the supply of oxygen can be obtained, which is a possiblity now almost appearing within sight over the horizon, there is nothing in the principles of furnace operation, as we know them, to cast doubt upon the possibilities of such a design.

Objections will naturally occur to the thoughtful, but they are more apparent than real. Perhaps the first would be the difficulty of maintaining the furnace structure in the intense heat produced by the combus-

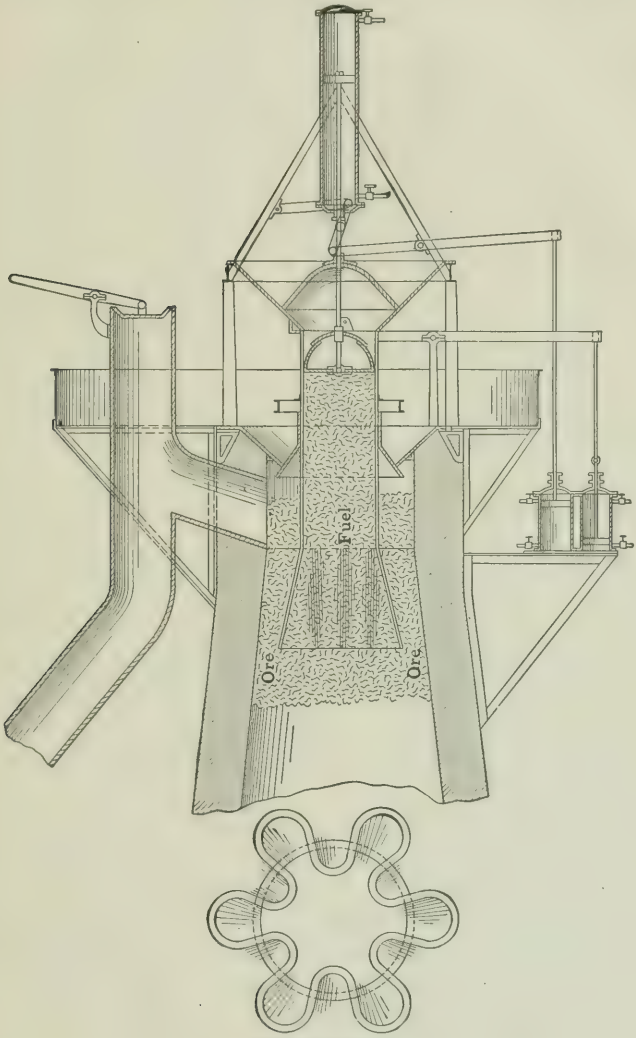


FIG. 173.—Details of Fig. 172.

tion of carbon in oxygen, but the answer to this is easy. We do not desire or intend to produce any higher temperature than we now have. We propose merely to generate more high temperature heat, and then give it enough more work to do to bring the temperature back to where it is

to-day, always remembering that, in the broad sense, the temperature prevailing in any zone of combustion is proportional to the amount of heat developed, divided by the thermal capacity of the materials present.

Another objection will be that the reduced area available for the passage of the gas, that is an ore column without any coke, will not permit the furnace to be blown at any speed worthy of consideration. Here, again, appearances are in error, because a blast containing one-half oxygen has a total volume less than one-half that of air containing the same quantity of oxygen. If by the use of oxygen we reduce the fuel consumption to two-thirds, the gas per ton of ore becomes approximately one-third what it would be with atmospheric blast under the same conditions, and this can, therefore, pass out through an area one-third as large.

On the other hand, such a process has some advantage over the existing furnace in other respects besides fuel consumption. First, the production as a by-product of a large quantity of pure nitrogen, and it is reasonable to believe that this would, to a large extent, come into use for fixation purposes. Second, because the fuel does not require to be penetrated by the gas column, but should be made as impervious as possible to it; a part of the fuel could be charged as coal, not coke, and this would save a corresponding proportion of the coking cost, and the investment for ovens.

There are other advantages over the present process if we could make this dream true. Not the least, perhaps, would be the elimination of the stoves and the consumption of gas required to heat them. The furnace would not need to have so large a volume on account of the much smaller volume of gas passing through it and the correspondingly greater concentration of the latter in active components. The furnace gas would be richer on account of the elimination of the nitrogen, in spite of being more diluted with CO_2.

Of course, we do not know that the blast furnace, the oldest industrial apparatus still in the service of man, will survive the changes which the future is to bring. Other methods of smelting iron have been proposed, and while they have in the main failed, a careful study of the thermal principles will show that they need not necessarily fail on theoretical grounds: But if the blast furnace remain our best, or even our only servant for the conversion of nature's stores of iron to our use, it is evident that there are long strides in sight which it may take, and that when these are taken it will be possible for us to use commercially as ores what we should now dismiss as rock, and that the supply of raw material thereby placed at our disposal is so enormously enhanced that we can more easily foresee the failure of civilization from other causes than from the failure of its supply of iron and steel.

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