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FOUNDRY-CUPOLA GASES AND TEMPERATURES

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FOUNDRY-CUPOLA GASES AND TEMPERATURES.

By A. W. BELDEN.

INTRODUCTION.

Among the investigations that the Bureau of Mines is conducting with a view to increasing efficiency in the utilization of fuels belonging to or for the use of the Government is an investigation of the processes that take place in a foundry cupola during a melt.

Some observations on the results of cupola tests of cokes at the Government fuel-testing plant in St. Louis, Mo., the coke being from coal from many coal fields of the United States, have been stated in a previous bulletin.[a] Especial attention was given to the melting losses that resulted from the use of different grades of coke, light and porous or heavy and dense. These losses amounted in one instance to 52.5 per cent of the iron charged and showed, in convincing manner, the need of exact information in regard to conditions in the fuel bed of the cupola.[b]

Melting losses of iron have been fully appreciated but little understood. The fact that these losses were possible with either light or heavy coke led to the belief that by using small charges so placed that melting would take place in that zone of the cupola where the highest heat and the smallest percentage of oxygen prevailed and by confining all melting to this zone these losses would be eliminated and the economical use of practically any coke produced for metallurgical purposes would become possible. This widening of the field from which coke might be drawn for foundry purposes would serve to place the foundryman in an independent position as regards his source of supply, and would tend to conserve the better grades of coking coals, which are being rapidly exhausted, by making the poorer grades available for mixing with them.

In order to investigate conditions within a cupola, the Bureau of Mines as a first step decided to install a commercial cupola, to sample the gases during their travel from the tuyères upward, and to determine the temperature of the fuel bed.

[a] Moldenke, Richard, The coke industry of the United States as related to the foundry: Bull. 3, Bureau of Mines, 1910, 34 pp.

[b] For description of the tests at St. Louis, see U. S. Geol. Survey Bull. 336.

ACKNOWLEDGMENTS.

Acknowledgment is made of the many courtesies and assistance extended by foundrymen generally, especially by Maj. J. S. Seaman and the Jamison Coal and Coke Co., of Pittsburgh, Pa., and Dr. Richard Moldenke, of Watchung, N. J., secretary of the American Foundrymen's Association. The author is greatly indebted to the personal assistance of his colaborers in the bureau, both chemists and engineers, who, since the beginning of the investigation in 1911, have made many valuable suggestions.

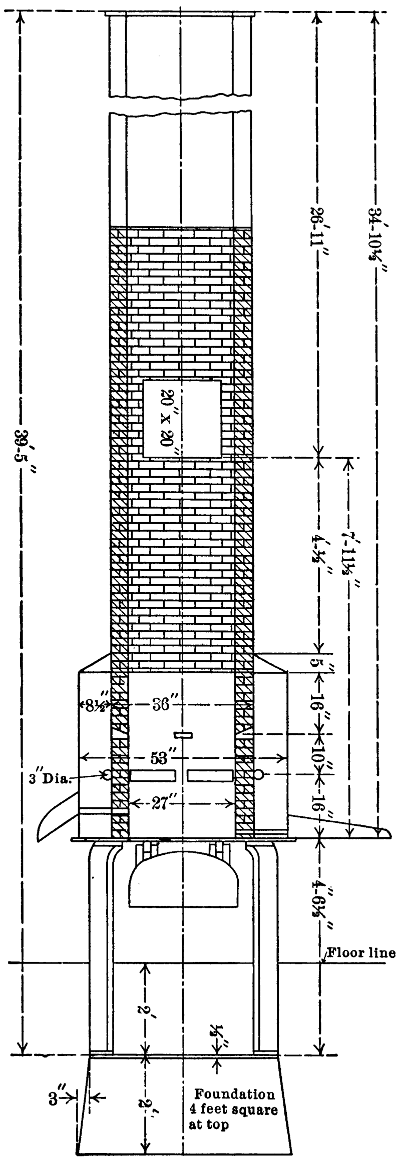
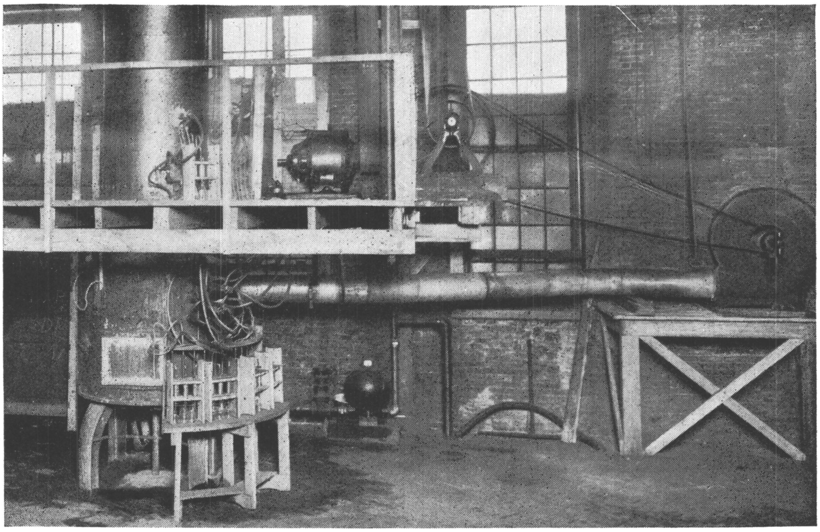


FIGURE 1.—Section of 36-inch foundry cupola.

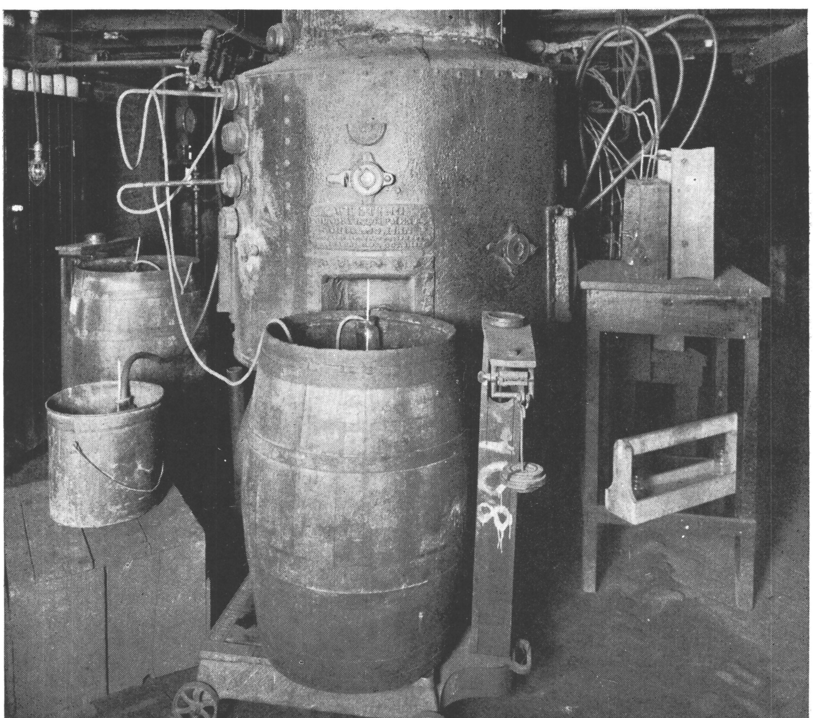
EQUIPMENT.

CONSTRUCTION OF CUPOLA.

A 36-inch standard Whiting cupola was installed. A No. 6 Sturtevant fan was connected to it by a 10-inch pipe 15 feet long. (See Pl. I, *A*.) The cupola is shown in section in figure 1, which gives the several dimensions. Attention is called to a few special features, as follows: Upper and lower tuyères were provided, but the upper ones were not used in any of the tests. The four lower horizontal tuyères measured 4 by 6 inches on the outside and 3 by 13 inches on the inside of the cupola and were 14 inches above the bottom. During tests the sand bottom was brought up to within 3 inches of the bottom of the tuyères in order to save as much coke as possible. The tuyère area was 96 square inches, and the area of the cupola, lined to 27 inches internal diameter, was 573 square inches, a ratio of 1 to 5.96.



A. CUPOLA WITH FAN AND CONNECTIONS.



B. APPARATUS FOR DETERMINING TEMPERATURES.

THEORETICAL SECTIONS AND PLANES.

For the purpose of the investigation the cupola was considered as divided into sections by four imaginary horizontal planes, situated as follows: One inch above the top of the inner opening of the tuyères, and 7, 13, and 19 inches above the top level of the tuyères. These imaginary planes, beginning at the bottom, are designated in this bulletin as *A*, *B*, *C*, and *D*.

Two-inch holes, as shown at *a*, *b*, *c*, and *d*, of Plate II, *A*, were cut through the wind box and inner shell along the lines at which the planes intersected the wall. Through each hole a 1½-inch pipe 10 inches long was passed, the inner end extending 1 inch past the inner shell into the brick lining, the outer end, extending 1 inch outside the wind box, being threaded to take a cap adapted to fit tightly the sample tube when inserted. The 1½-inch pipe was held in place and leakage of air from the wind box prevented by lock nuts inside and outside. The lock nuts were drawn up after proper packing was inserted between the nut and the inner wall of the wind box, thus making an air-tight joint. Around the pipe at the entrance of the inner wall no packing was used, as the brick lining was cut to make a tight fit, and the sample tubes after insertion were well plastered with fire clay at the point where they passed through the brick. The pressure was not sufficient to cause leakage through to the fuel bed, and all air admitted to the cupola passed through the tuyères. On the opposite side of the cupola at points designated as *a′*, *b′*, *c′*, and *d′* in Plate II, *A*, holes were cut at levels corresponding to those represented at *a*, *b*, *c*, and *d*, and were fitted with 3-inch pipes similarly to those just described. The exact location of the holes, considered with reference to the inside of the cupola, was as follows: *a* and *a′*, 1 inch above the top of the inner opening of the tuyères; *b* and *b′*, 6 inches above *a* and *a′*; *c* and *c′*, 6 inches above *b* and *b′*; and *d* and *d′*, 6 inches above *c* and *c′*. Later tests made necessary the insertion of a fifth tube at *e* and *e′*, 7½ inches above *d* and *d′*. All of these tubes except tubes *e* and *e′* passed through the wind box. The distance of 7½ inches instead of 6 inches between *d* and *e* was necessary in order to clear the wind box and avoid the difficulty of making the joint air tight. Subsequent tests showed that this placing of the tube had no material effect on the results.

FAN BLOWER UNSATISFACTORY.

It was decided to use a fan because a fan had been used in former tests, and because a blower causes pulsations in the blast. The fan was driven by two belts from a counter shaft (Plate I, *A*) connected by a single belt to a line shaft overhead. The fan was connected to the cupola by a 10-inch pipe 15 feet long. This pipe was not straight but had two bends of large radius to insure as little resistance as possible to the flow of air. In the preliminary tests a No. 6 Sturtevant fan blower was used and the pressure determined by means of a blast pressure gage, graduated in ounces and using water as the registering fluid. This gage was connected to the wind box, near the top, by means of a rubber tube, as shown in Plate II, *A*. Later, in order to get more delicate readings of pressure, a Pitot tube was installed in the straight part of the pipe, beyond the second bend near the cupola and connected with the gage. One of the main requirements of the investigation was to determine the quantity of air necessary and to insure the delivery of this quantity during each test.

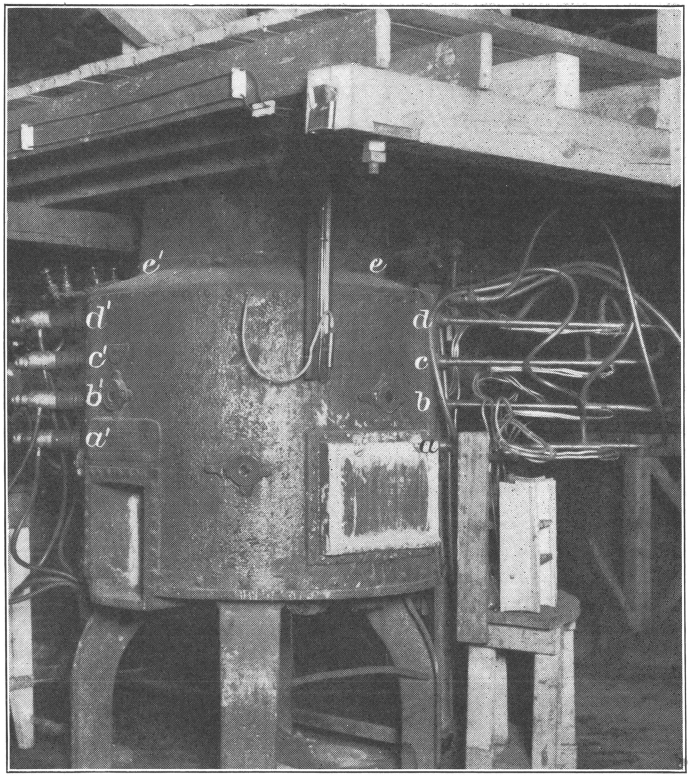
After many attempts to regulate and control the air, the task was found impossible and a No. 2 10-inch by 35-inch horizontal Roots blower was installed.

BLOWER DETAILS.

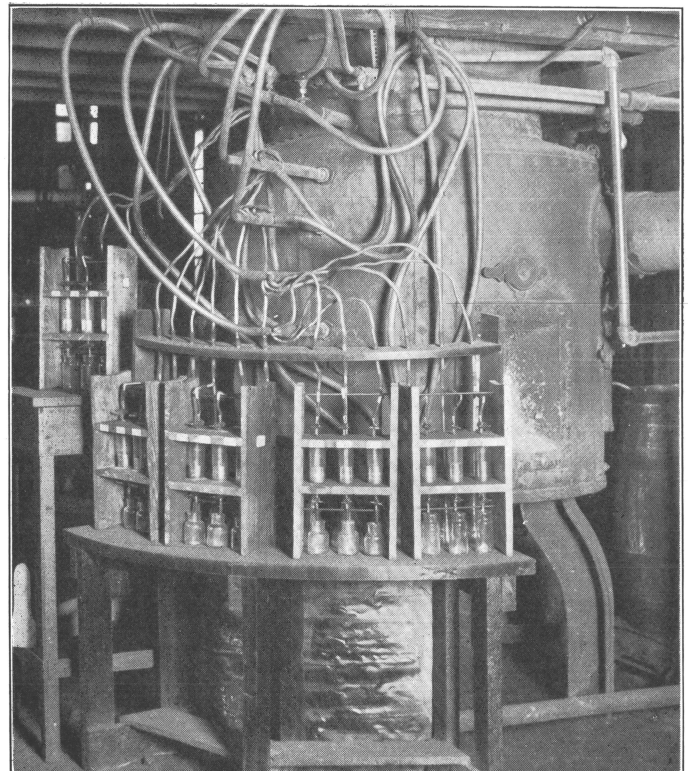
The blower and connections are shown in Plate III. A blower delivers a definite volume of air per revolution when running free, and the loss due to slippage is a definite and uniform quantity under any particular pressure. A reciprocating counter attached to the main shaft of the blower gave an accurate means of determining the revolutions, a Pitot tube connected to a recording pressure gage indicated the pressure at any time or the average over any period of time, and calculation gave the total volume of air delivered. In order to make the tests independent of possible delay and of overload difficulties, use of the line shaft was discontinued and a 10-horsepower motor was installed for operating the blower.

VOLUME OF AIR DELIVERED AND SLIPPAGE.

The blower was tested by the manufacturers at 2, 4, 6, 7, 8, and 16 ounces, and was recalibrated after installation. The curve shown in figure 2 was constructed to show the slippage in revolutions per minute at various pressures from 0 to 16 ounces. The amount of air delivered per revolution when running free was 4.8 cubic feet. The following example shows the method of arriving at the total volume of air delivered. During a 15-minute test the blower made 3,497 revolutions and each revolution delivered 4.8 cubic feet of air, so that the total number of cubic feet delivered was 3,497 times 4.8, or 16,785.6 cubic feet. The average pressure, as shown by a pressure gage connected with a Pitot tube inserted in the air pipe, was 5.3 ounces. The slippage of the blower at this pressure was 22 revolutions per minute. As each slippage revolution represented 4.8 cubic feet loss, the total loss during the test was 1,584 cubic feet ($22\times 15\times 4.8$). Deducting this loss of 1,584 cubic feet from the total air delivered with the blower running free ($16,785-1,584$) gives 15,201



A. VIEW OF CUPOLA SHOWING LOCATION OF TUBES.



B. APPARATUS FOR SAMPLING GASES.

cubic feet of air actually delivered in 15 minutes, or 1,013 cubic feet per minute.

MEASUREMENT OF PRESSURE.

The simple water manometer, used with the Pitot tube, required the undivided attention of an assistant, who made frequent readings over the whole period of the test in order that the average pressure might be determined. After the method of testing had been decided, a Bristol recording pressure gage, making a complete revolution in one hour, was connected with the Pitot tube. (See Pl. III.) A record

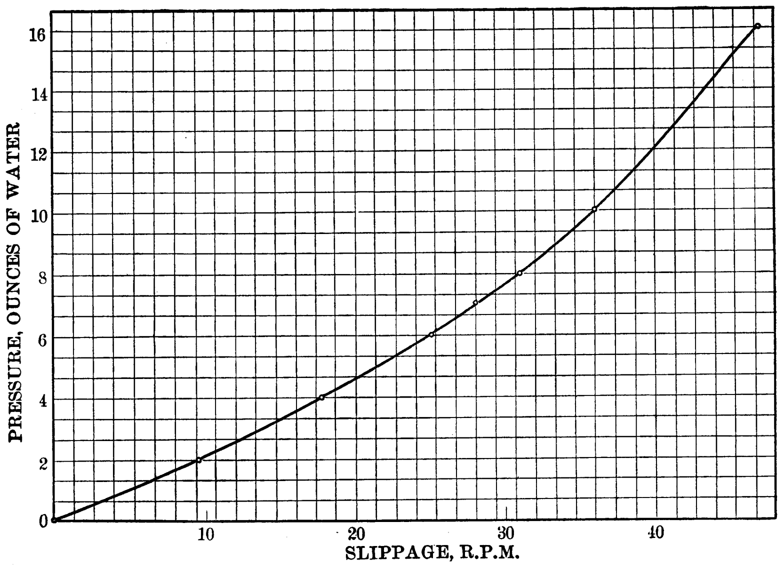


FIGURE 2.—Slippage of blower under various pressures.

was thus obtained which was continuous over the whole period of the test and facilitated the determination of a true average.

PROCEDURE IN TESTS.

CHARGING OF CUPOLA.

In all tests, whether relating to the character of the gases or to the temperatures, the cupola was lined to 27 inches internal diameter. Coke alone, without iron or flux, was used. The investigation being designed to furnish data as to the action of the fuel, it was necessary to consider only that part of the cupola below and including the melting zone. Complications from the use of iron were thus avoided, and the experience of ordinary commercial practice does not indicate that the addition of this material would seriously affect the results obtained from coke alone. The sand bottom was brought up to within 3 inches of the bottom level of the tuyères. The tubes for collecting gas or measuring temperature were put in position. About 24 inches of coke was placed upon sufficient wood to insure proper kindling. The fire was lighted and the coke allowed to ignite and burn until the top showed bright. Coke in small quantities was added from time to time until well above the top tube, each succeeding charge being held until the preceding charge had burned through. After the last small charge had been added, sufficient time was given to insure its burning evenly over the whole surface of the bed, thus indicating that the burning was over and through the whole bed of coke and was not localized as sometimes happens when proper precautions are not taken. The kindling wood was always completely burned before the last coke was added. This last addition of coke brought the top of the charge to within 6 inches of the charging door. The total weight of coke charged was approximately 750 pounds for each test. Ten minutes after the last coke had been added the blast was turned on and was continued for 15 minutes before the test began. The reason for allowing this length of time was to insure uniform conditions over the whole fuel bed, and was more than that necessary in regular commercial practice to cause the appearance of iron at the cupola spout, an indication that melting has begun.

AIR SUPPLY.

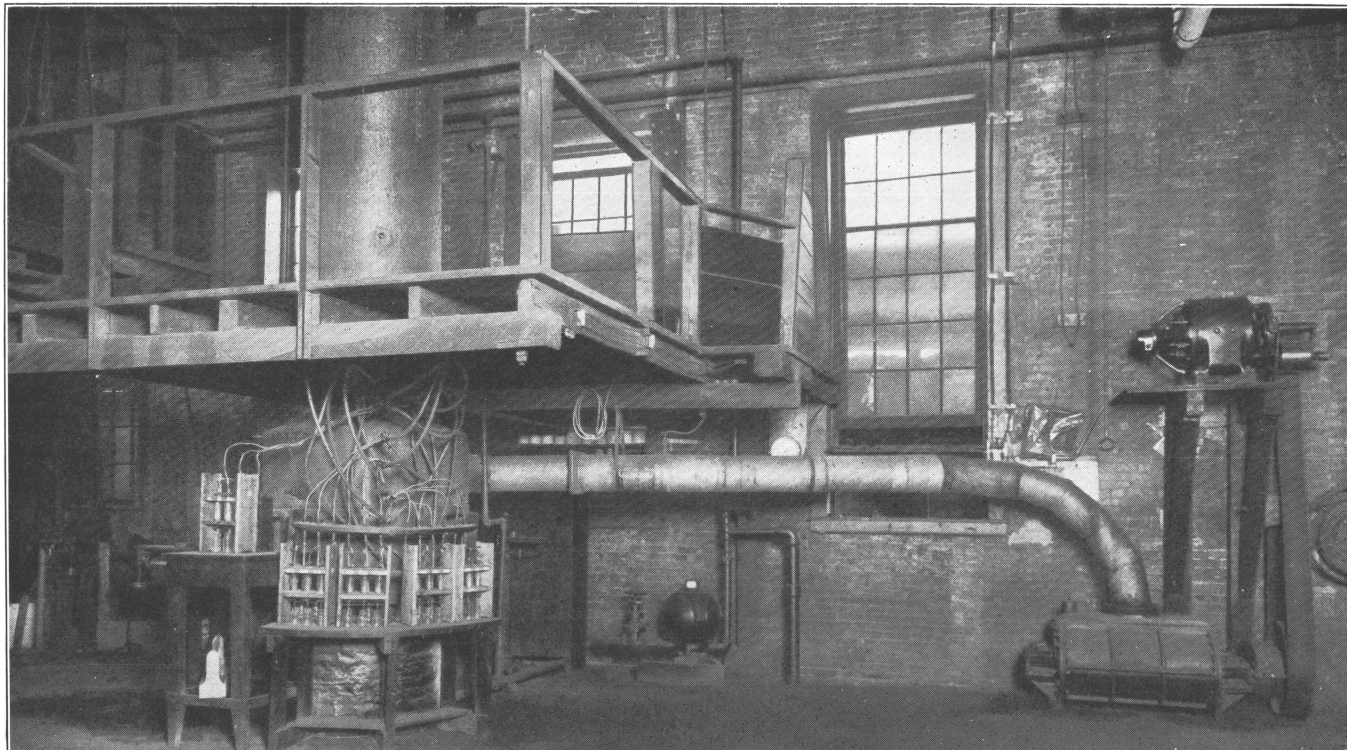
Preliminary tests were made with varying volumes of air per minute, the results suggesting the use of 1,000 cubic feet per minute as a normal condition. As the 36-inch cupola, lined to 27 inches, can melt about 2 tons of iron per hour, 1,000 cubic feet of air per minute checks well with the usual assumption that 30,000 cubic feet of air is required to melt a ton of iron. The varying pressures due to different sizes of coke, the position of pieces of coke with reference to other pieces and the side walls, the effect of slagging and hanging and of other conditions, made impossible the exact regulation of the air supply, but the average of all tests approximated 1,000 cubic feet per minute.

GAS SAMPLING.

In investigating the cupola gases it was necessary to decide on the best method of obtaining samples that would represent the gases in the different cross sections of the fuel bed, and the number of such samples necessary at each cross section, as well as the number of sections.

POINTS OF SAMPLING.

It was decided to consider the fuel bed as being divided by four imaginary planes, located as follows: 1 inch above the top of the inner opening of the tuyères, and 7, 13, and 19 inches above. In subsequent discussion these planes are designated, starting with that



CUPOLA WITH BLOWER AND CONNECTIONS.

1 inch above the top level of the tuyères, as *A*, *B*, *C*, and *D*, and the points from which samples were taken, beginning with the center, as 1, 2, and 3, 2 being $4\frac{1}{2}$ inches from the center, and 3 being 9 inches from the center and $4\frac{1}{2}$ inches from the lining. Figure 3 shows a vertical section of the cupola and the positions of the imaginary planes and of the sample tubes in place. As figure 3 shows, all samples were taken from vertical radial planes that intersected the tuyères, it being assumed that the gases were the same over any other similar area in the cupola because the entrance of the blast was through tuyères, the inner openings of which extended practically the whole way around the interior circumference of the lining. Simultaneous samples taken at other points showed reasonable although not exact agreement.

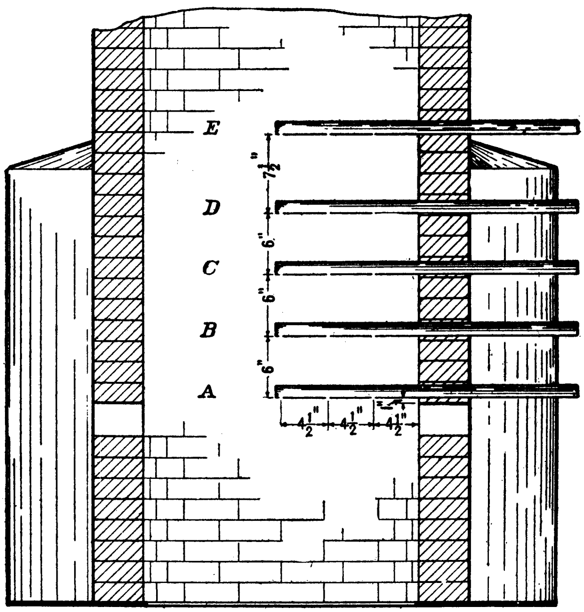


FIGURE 3.—Position of planes and gas-sampling tubes.

The preliminary work showed the necessity of examining the bed above plane *D* (fig. 3), so that examination was made of the gases in a fifth imaginary plane designated as plane *E*. This plane was $7\frac{1}{2}$ inches above plane *D* and $26\frac{1}{2}$ inches above the top level of the tuyères.

GAS-SAMPLING APPARATUS.

The type of gas-sampling tube used in this work is shown in cross section in figure 4. *A* in the figure represents a $1\frac{1}{4}$-inch iron pipe 48 inches long, one end closed by a circular piece of steel welded in. Three $\frac{1}{4}$-inch, $\frac{3}{16}$-inch internal diameter, copper tubes, for the collection of the gas samples (represented by *a*, *b*, and *c*, fig. 4) were brazed into small holes cut through the wall of the pipe and made flush with the outside. These gas-collecting tubes, as well as the inclosing pipe, were kept cool by cold water which entered the outer end through a $\frac{1}{2}$-inch copper tube (*d*, fig. 4) and passed out through a $\frac{1}{4}$-inch iron pipe (*e*, fig. 4). The exit ends of the small tubes, as well as the $\frac{1}{2}$-inch inlet, were held in place and the whole made water tight by brazing.

The gas-collecting tubes were connected by ¼-inch lead tubes to ¼-inch copper tubes leading into the wash bottles. The copper tubes were provided with a T at a point convenient for attachment to the mercury-filled sample receivers. The connection was made by means of a 1-mm. internal diameter glass tube, through which a portion of the gas was drawn off continuously from the larger stream. The wash bottle was introduced beyond the point where the gas sample was taken and served to indicate whether the gas was flowing properly through the tubes. No aspiration was necessary, as the sampling tubes extended into the fuel bed and the positive pressure of the blast forced the gases through the tubes. The portion taken for a sample was drawn from the main flow by the flow of the mercury out of the gas receivers. Details of the apparatus are shown in Plate II, *B*. More complete discussion of the method of sampling and analysis used can be found in Bulletin 12 of the bureau.[a]

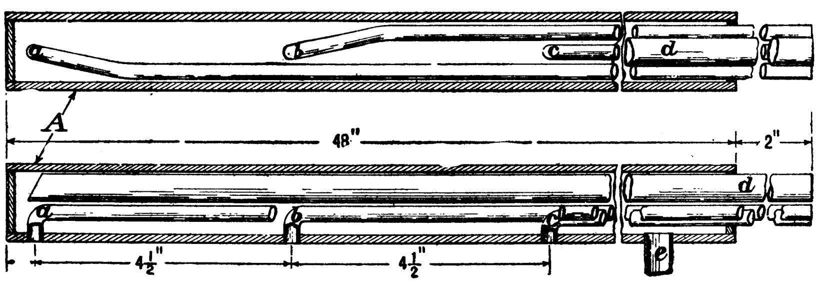


FIGURE 4.—Section of gas-sampling tube.

METHOD OF USE.

The water-cooled tubes were inserted and the cooling water turned on before the cupola was charged. All of the tubes were inserted a distance that brought hole 1, or the hole nearest the inner end of the tube (fig. 3), at the exact center of the cupola; hole 2, 4½ inches from hole 1 toward the lining; and hole 3, 4½ inches from hole 2 and 4½ inches from the lining.[b] This placing of the tubes divided the 13½ inches from lining to center into three equal parts. When the blast was turned on, the bubbling of the water in the wash bottles attached to the ends of the tubes gave evidence of the flow of gas. If the gas did not flow properly, the small tubes were disconnected at the point where they joined the lead tube and a wire was run through to remove the obstruction; or, as later practiced, compressed air was blown through from the end of the lead pipes. The latter procedure had the advantage of clearing the whole system and saved much time.

[a] Frazer, J. C. W., and Hoffman, E. J., Apparatus and methods for the sampling and analysis of furnace gases. 1911. 22 pp.

[b] The points in the fuel bed at the holes here mentioned are subsequently referred to in text and in tables as "locations."

After all the parts had been tested and gas was flowing freely, the mercury-filled sample receivers were attached. Fifteen minutes after the blast had been started the cocks on all the receivers were turned simultaneously and samples were taken for a period of 15 minutes. One set of three samples was taken from each imaginary horizontal plane, a total of 15 samples for each test. On several of the tests a sixth set was taken at a point above the charge, to show the average composition of the gases at that position. (See Pl. I, *A*.)

RESULTS OF ANALYSES.

The results of analyses of the gases from separate tests, as well as the average for the series, are given in table 1, as follows:

TABLE 1.—*Analyses of cupola cases.*

[L. L. Satler, jr., analyst.]

Plane.[a]	Location No.[b]	Test No.— 1.			2.			3.			4.			5.			Average.		
		CO_2	O_2.	CO.	CO_2.	O_2.	CO.	CO_2.	O_2.	CO.	CO_2.	O_2.	CO.	CO_2.	O_2.	CO.	CO_2.	O_2.	CO.
A	1	5.9	0.0	25.1	8.8	0.0	19.5	17.1	0.7	4.9	16.8	0.3	6.0	11.6	0.0	15.5	12.0	0.2	14.2
	2	10.3	9.5	1.6	10.3	0.1	16.9	11.0	0.4	15.5	6.0	0.5	24.2	13.8	0.1	11.6	10.3	2.1	14.0
	3	1.1	19.6	0.0	2.5	18.1	0.0	3.1	17.6	0.0	9.5	10.6	1.1	7.3	13.1	0.3	4.5	15.8	0.2
B	1	7.9	0.0	21.3	15.6	0.5	8.3	12.2	0.0	14.0	14.0	0.0	11.1	15.6	0.3	7.5	13.1	0.1	12.4
	2	18.3	1.3	1.7	11.8	0.1	14.7	13.1	0.3	12.0	9.2	0.0	18.8	10.3	0.0	17.2	12.5	0.3	12.9
	3	10.4	10.1	0.1	14.0	6.2	0.7	8.1	12.4	0.0	12.4	7.8	1.1	12.7	7.8	0.4	11.5	8.9	0.5
C	1	7.0	0.0	23.2	13.9	0.2	10.9	12.9	0.0	13.1	11.7	0.0	14.7	14.1	0.5	10.1	11.9	0.1	14.4
	2	15.0	0.2	8.6	14.2	0.0	13.1	13.8	0.2	11.2	8.2	[c]0.7	19.7	.....	.....	.....	12.8	0.1	13.2
	3	15.2	4.9	0.4	15.0	4.7	1.5	13.2	7.3	0.5	16.6	2.8	1.2	15.1	4.8	1.4	15.0	4.9	1.0
D	1	6.3	0.0	24.0	11.3	0.0	15.3	10.8	0.0	16.3	9.1	0.0	18.9	11.4	0.0	15.8	9.8	0.0	18.1
	2	12.1	0.0	14.8	11.0	0.1	15.8	13.3	0.1	12.3	9.1	0.0	19.8	12.1	0.0	14.2	11.5	0.0	15.4
	3	17.6	0.7	4.1	17.0	0.7	4.9	16.9	[c]2.6	1.8	16.5	0.1	6.9	16.6	0.2	6.4	16.9	0.4	4.8
E	1	6.7	0.0	24.1	9.5	0.0	18.3	10.1	0.0	17.3	7.1	0.3	21.5	9.7	0.0	18.1	8.6	0.0	19.9
	2	10.6	0.0	16.6	10.4	0.0	16.7	.....	.....	.....	8.5	0.0	19.0	10.9	0.0	16.0	10.1	0.0	17.1
	3	16.5	0.3	6.8	15.8	0.0	7.8	16.8	0.0	5.4	12.1	0.2	14.1	14.9	0.0	8.8	15.2	0.1	6.8

[a] Refers to imaginary horizontal plane, see pp. 10–11.
[b] Refers to holes in sampling tube, see p. 12.
[c] Probably due to channel flow of air; not included in average.

As was to be expected, samples of gas taken at different times showed many variations. The flow of the blast after entering the tuyères was probably changing during the whole period, seeking escape inward as well as upward along the lines of least resistance. The largest volume undoubtedly flowed up the side walls, and this, as well as the part penetrating toward the center, was more or less deflected by the obstructions encountered. Effects of such changes were especially noticeable during preliminary work, when coke was charged in varying sizes as received. This explains why more uniform results are obtained in practice by the use of by-product coke or anthracite coal. During some of the first tests, in which large pieces of coke were used exclusively, oxygen persisted through the whole charge and was found in the gas sample taken above the charge. This condition was no doubt due to the fact that the large pieces of coke against the wall allowed a free and practically unobstructed passage to a part of the gases. In the tests the results of which are given in tables 1 to 5 all coke was broken into 3-inch cubes or less. The analyses of samples of the gases present above the charge under the conditions of the tests showed no oxygen, typical analyses being as follows:

Analyses of gases present above cupola charge.

[L. L. Satler, jr., analyst.]

Kind of gas.	Percentage of gas in location—[a]		
	1.	2.	3.
	Per cent.	*Per cent.*	*Per cent.*
CO_2	8.5	10.2	14.5
O_2	0.0	0.0	0.0
CO	20.6	17.8	8.4

[a] Explanation of locations given in footnote on p. 12.

DISCUSSION OF RESULTS.

Figures 5, 6, and 7 have been constructed from table 1. The planes of the cupola from which the gases analyzed were taken are represented as ordinates and the percentages of carbon dioxide, oxygen, and carbon monoxide as abscissas. Carbon dioxide (CO_2) is the product of complete combustion. Carbon monoxide (CO) is the product of incomplete combustion. The oxygen (O_2) of the blast entering at the tuyères comes in contact with hot coke and the burning or combustion takes place, forming CO_2. This reaction produces heat and raises the temperature. If the CO_2 comes in contact with incandescent coke it takes up carbon from the coke and changes to CO. This reaction takes up heat and reduces the temperature.

GASES AT CENTER LINE OF CUPOLA.

Figure 5, representing the conditions at the center line of the cupola, shows the practical absence of oxygen at all sections, the small quantity recorded being within the range of the probable error of the method of analysis or attributable to the chance penetration of some small amount of the blast. The changes taking place in the first 6 inches show an increase of CO_2 and a decrease of CO, and from this point upward a rapid falling off of CO_2 and a corresponding increase of CO.

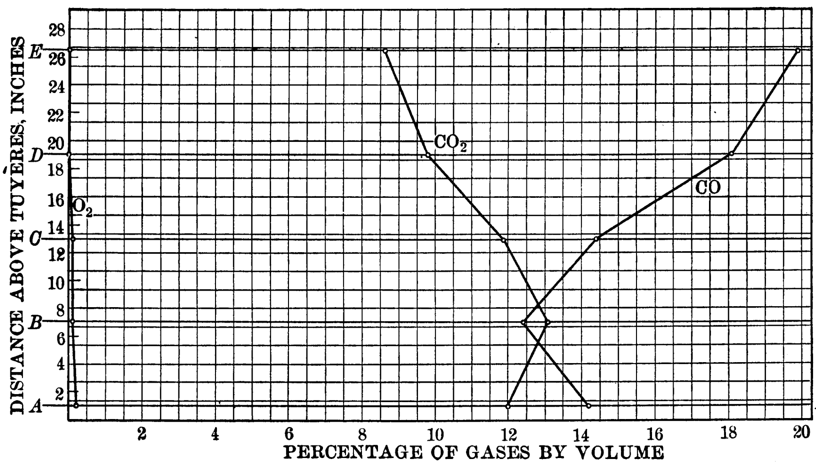


FIGURE 5.—Diagram showing variation in percentages of O_2, CO, and CO_2 at different heights (planes) on the center line of the cupola. Lines *A*, *B*, *C*, *D*, and *E* represent the imaginary planes.

GASES 4½ INCHES FROM CENTER LINE OF CUPOLA.

Figure 6 represents the conditions 4½ inches from the center and by the percentage of oxygen shown indicates the penetration of the blast at plane *A*. As shown in the figure, the percentage of oxygen rapidly decreased, being practically nothing 6 inches above, at plane

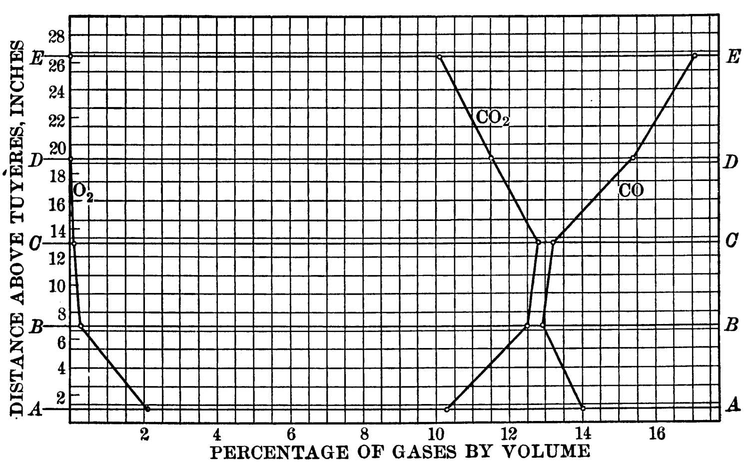


FIGURE 6.—Diagram showing variation in percentages of O_2, CO, and CO_2 at points 4½ inches from the center of the cupola. Lines *A*, *B*, *C*, *D*, and *E* represent the imaginary planes.

B. Comparing the conditions at the center and 4½ inches from the center as represented in the figures, the CO_2 percentages in both cases show the same general increase through the first 6 inches. At 4½ inches from the center there is no material change during the movement through the second 6 inches. From this point upward through the fuel bed the percentage of CO_2 at 4½ inches from the center decreases but not so rapidly as the percentage at the center. The CO percentage 4½ inches from the center decreases in the same general manner as the CO at the center during the passage of the gases through the first 6 inches. Through the second 6 inches no material change takes place. From this point up through the bed the proportion of CO at 4½ inches increases but not so rapidly as that at the center.

GASES 9 INCHES FROM CENTER LINE OF CUPOLA.

Figure 7 represents the conditions 9 inches from the center and 4½ inches from the lining. One inch above the tuyères the oxygen of the blast is reduced by an amount necessary to form 4.5 per cent CO_2, and the formation of CO_2 rapidly increases in the first 6 inches,

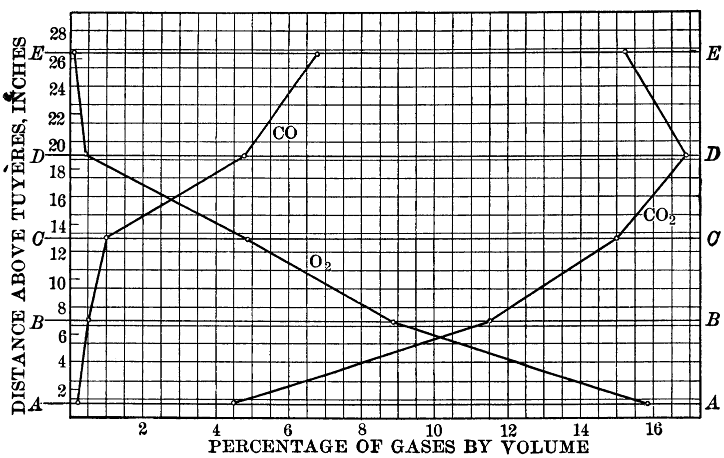


FIGURE 7.—Diagram showing variation in percentages of O_2, CO, and CO_2 at points 9 inches from the center and 4½ inches from the lining of the cupola. Lines *A*, *B*, *C*, *D*, and *E* represent the imaginary planes.

with corresponding decrease in O_2 and with little formation of CO. These conditions indicate a fierce burning and a great rise in temperature. This assumption is borne out by the rapid rise of the temperature at plane *B* as compared to the temperature at plane *A*. (See also fig. 15.)

From plane *B* the oxygen rapidly decreases to practically nothing just above plane *D*. The CO_2 remains practically constant from plane *B* to plane *C*, the CO increasing slightly. During the passage of the gases through the next 6 inches both CO_2 and CO increase. This zone of highest CO_2 content, as yet not materially affected by the rise of CO, is the hottest part of the entire fuel body. This condition is also indicated in figure 15. From this point to the next plane (*E*) 7½ inches above, the CO_2 decreases and the CO increases. The temperature decreases.

The temperature conditions at plane *E* and at plane *C* are nearly the same, but the conditions for melting are materially different. At plane *C* there is a supply of oxygen that would undoubtedly cause oxidation of the metal and resultant loss. Whether the amount of iron melted at this plane would be oxidized sufficiently to affect seriously castings made from the whole tonnage was not determined by these investigations, but if certain conclusions, based on the tests at St. Louis,[a] as to the effect of burned metal on casting are correct, it is safe to assume that the chances favor the production of defective castings.

PROBABLE COMBUSTION AREA.

The broken line in figure 8, represents the upper boundary of the region of gases containing free oxygen.

As indicated in figure 8, the actual combustion of the fuel takes place in the fuel bed around a region having the shape of an inverted cone; the apex of this cone is at the center on the level of the bottom of the tuyères and its surface flares out to the lining at a point 20 inches above. If melting be kept above the base of this cone, no oxidation will occur.

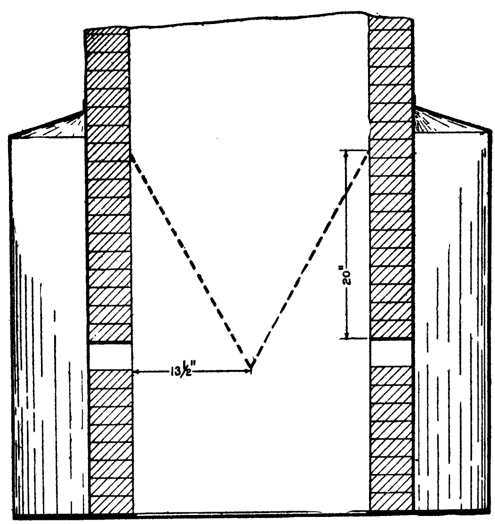


FIGURE 8.—Section of cupola showing upper boundary of region of combustion.

PROBABLE LINE OF HIGHEST TEMPERATURE.

Considering the region of gases highest in CO_2 content and devoid of O_2 (see figs. 5, 6, 7, and 8), and considering the plotted line of highest CO_2 content at each plane as a line of demarcation, the line *ab* in figure 9 shows in cross section the probable shape of the top of the fuel bed as defined by the points of highest temperature.

If it were possible so to charge the cupola that melting would take place along or just above such a line (or, rather, surface) as is indicated in this figure, ideal results would be obtained both as regards temperature and absence of oxidation. Since it is not possible to confine the melting to this irregular region, the best condition for

[a] Moldenke, Richard, The coke industry of the United States as related to the foundry: Bull. 3, Bureau of Mines, 1910, p. 19.

melting is obtained at that section across the whole of the fuel bed that shows the highest temperature together with absence of oxygen. This condition, as shown by the tables of temperatures and of analyses of the gases, exists just above plane *D*, about 20 inches above the tuyères. It is not possible to do all melting at this particular plane, but the melting can be so confined and regulated that none takes place below this plane.

The height of the melting zone above this plane is determined by the physical condition of the coke and the rate of heat absorption of the iron. If the coke is porous, the charges of iron should be small to prevent the coke burning out and letting the iron down into the oxidizing zone before melting is accomplished. If the coke is heavy and dense, or if anthracite coal is used, the charges may be made larger, as the fuel will burn more slowly and give a longer time for melting. In some region above this zone of highest temperature the temperature is still high enough to melt iron but is not high enough to impart heat quickly and to give hot iron. This melted iron passes through the lower zones, although the temperature in these zones be exceedingly high, too rapidly for the absorption of enough heat to raise its temperature materially, and cold iron is the result. The experiments here reported confirm the general opinion that the hot test part of the cupola is where the lining is most burned out. A curved line drawn to represent the burned-out lining corresponds closely with the curves drawn to represent the heat absorbed at the several planes previously described.

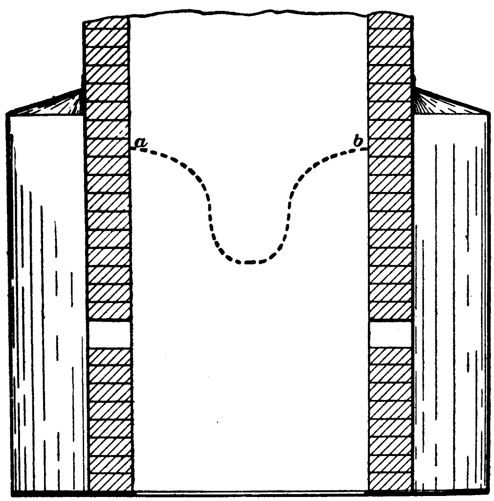


FIGURE 9.—Probable line of highest temperature.

ALTERATION OF CUPOLA LINING.

A study of the data shown in table 1 led to the conclusion that the amount of coke necessary for melting could be reduced by changing the lines of the cupola from the straight to the boshed form. Accordingly the lining was drawn in to 23 inches at the tuyères, tapered to the original lines of 27 inches at 15 inches above the tuyères, and continued straight from this point. It was thought that the blast entering at the tuyères would penetrate farther toward the center of the cupola and a smaller volume of air would escape up the side walls without first coming in contact with hot coke. This, it was hoped, would cause the loss of all the oxygen at a lower point in the fuel bed and would lower the zone at which the iron could be melted without its quality being seriously affected. The zone of highest temperature was expected to follow the zone where oxygen disappeared, as in the case of the straight lining, but no attempt was made to determine whether this relation held.

RESULTS OF ANALYSES OF GASES FROM CUPOLA OF BOSHED CONSTRUCTION.

Table 2 shows typical analyses of gases sampled after alteration of the lining but taken from the same locations as were the gases whose analyses appear in table 1. Table 2 follows:

TABLE 2.—*Analyses of gases from cupola of boshed construction.*

[L. L. Satler, jr., analyst.]

Plane.[a]	Location No.[b]	CO_2.	O_2.	CO.
		Per cent.	*Per cent.*	*Per cent.*
A	1	11.1	1.0	14.3
	2	0.3	20.4	0.0
	3	0.2	20.7	0.0
B	1	14.8	1.2	8.4
	2	11.1	9.3	0.0
	3	2.2	18.4	0.0
C	1	14.6	0.0	10.6
	2	16.0	4.0	0.7
	3	5.4	15.2	0.3
D	1	10.3	0.0	17.3
	2	15.7	0.0	8.0
	3	16.9	3.3	0.7
E	1	7.5	0.0	21.9
	2	13.2	0.0	12.5
	3	17.1	0.5	4.7

[a] See p. 7. [b] See p. 12.

The penetration of oxygen was affected, as may be seen by comparing the analyses with those of table 1, but the oxygen persisted up through the whole bed. The analysis of the gas at the point represented by D3 of the table shows 3.3 per cent O_2, as compared with 0.4 per cent at the corresponding location with the original straight lining (table 1). The drawing in of the lining materially increased the blast pressure (from 3.6 to 5.5 ozs.), and the flow of gas was accelerated to such an extent that the time of contact with the coke was not sufficient to rob the blast of its oxygen.

TEMPERATURES.

DIFFICULTIES OF MEASUREMENT.

Measuring temperatures in the fuel bed of the cupola presents many difficulties and all attempts to get actual temperatures failed. Descriptions of the several forms of apparatus used in the various tests here reported are given somewhat in detail for two purposes: (1) To draw attention to the many difficulties encountered during this part of the investigation, and (2) to render these experiments more serviceable to future investigators. Diligent search of all available literature failed to reveal accounts of attempts to determine the actual temperature in the interior of the fuel bed of the cupola or in other metallurgical operations on the same scale. Measurements have been attempted at points on or near the furnace walls, but not at points over a considerable cross-sectional area.

USE OF PLATINUM-RHODIUM THERMOCOUPLES.

It was first decided to take temperatures by means of platinum-rhodium thermocouples introduced into the fuel bed through clay

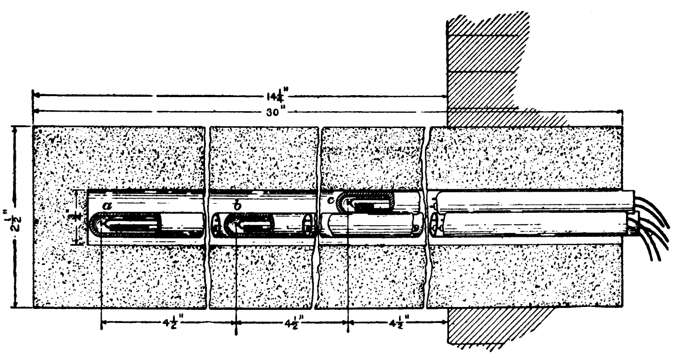


FIGURE 10.—Section of fire-clay tube with platinum-rhodium thermocouples inserted.

tubes, as shown in figure 10. The thermocouples were so placed that readings were obtained at the center of the cupola (*a*, fig. 10), at a point 4½ inches from the center toward the lining (*b*, fig. 10), and at a point 9 inches from the center and 4½ inches from the lining (*c*, fig. 10). The positions of the points are the same as those from which gas samples were taken. The tubes were specially prepared from mixtures of the most highly refractory clays that could be obtained. In plane *A*, just above the tuyères, the tubes stood up well, and direct readings of temperature were obtained. Readings over 15-minute periods, taken each minute, showed an average temperature of 2,593° F., 2,430° F., and 1,576° F., at points represented by *a*, *b*, and *c* of figure 10; the maximum variation at any one point was 122° F. Above plane *A* the tubes were sheared off at their point of entrance through the wall by the movement of the charge. To prevent this shearing a pier of magnesite brick was constructed to support the ends of the tubes. Although the pier prevented shearing, it was of no avail in obtaining readings, as the clay tubes were melted at all planes above plane *B*. At the center of the cupola in plane *B* the thermocouple was melted, indicating a temperature above 3,100° F. As a result of these tests, the use of the platinum-rhodium thermocouples was abandoned.

USE OF OPTICAL PYROMETER AND WATER-COOLED TUBE.

The next step was an attempt to obtain temperatures with an optical pyrometer by observation through a water-cooled iron tube with a glass-covered opening at one end. A cross section of the tube is shown in figure 11. It was fully appreciated that the readings obtained would not represent actual temperatures on account of the cooling effect of the water-cooled tubes, but it was hoped that approximate temperatures showing the temperature differences between planes would be obtained and that they could be expressed in

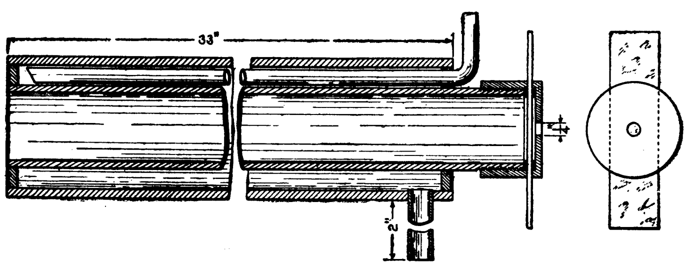


FIGURE 11.—Section of water-cooled iron tube used in taking temperature readings.

degrees of temperature with an explanation as to the limitations of the method. It was thought that at any given point the highest reading obtained during the whole period of the test would approximate the true temperature at that point. However, the averages of five temperature readings made at each of five points at different heights on a vertical line at the center of the cupola proved to be practically the same as were the highest temperature readings at each of the points. It was thought that the true temperatures at the center of the cupola might possibly be as uniform as these readings indicated, since no analysis of the gases taken at any time showed an appreciable amount of oxygen, and therefore indicated that there was no combustion. Further tests with the ends of the tubes at varying distances from the side wall continued to show for all points in any vertical line practically the same average temperature and the same high temperature. It was thought that this condition might be due to the fact that the ends of the water-cooled tubes were in direct contact with the coke.

USE OF CLAY PROTECTING TIPS.

With the hope of further perfecting the apparatus, a clay protecting tip (fig. 12) was placed over the end of each of the water-cooled tubes, extending a distance of 2 inches. This made possible the reading of the temperature of coke that was not in direct contact with the water-cooled tubes. These protecting tips were melted, like the clay tubes, but held up long enough to show the same uniform readings as with the unprotected tubes.

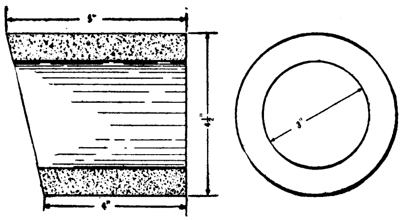


FIGURE 12.—Section of clay protecting tip.

DISCUSSION OF RESULTS.

Tables 3 and 4 show typical readings of temperatures taken through water-cooled tubes with an optical pyrometer. The tables follow:

TABLE 3.—*Temperatures, °F.*[a]

Plane.			
A	*B*	*C*	*D*
2,736	2,827	([b])	2,827
[c]2,862	([b])	([b])	([b])
2,653	2,966	2,934	2,786
2,712	([b])	3,015	2,741
2,736	3,036	2,988	2,692
([b])	[c]3,083	([b])	([b])
2,742	2,939	[c]3,052	[c]2,961
2,800	2,811	3,009	([b])
[d]2,750	[d]2,942	[d]3,000	[d]2,802

[a] All temperatures taken at center of cupola with Wanner optical pyrometer at intervals of 2 minutes.
[b] Cold; not included in total. [c] Maximum. [d] Average.

TABLE 4.—*Temperatures, °F.*[a]

Plane.				
A	*B*	*C*	*D*	*E*
2,584	[b]3,027	2,993	2,579	2,856
2,763	2,939	[b]3,020	2,674	2,786
2,988	2,809	2,925	2,871	2,696
3,020	2,804	2,851	2,570	2,763
2,826	2,971	2,809	2,856	[b]2,914
[b]3,067	2,752	2,687	[b]2,908	2,883
3,060	2,817	2,809	2,826	2,800
2,939	2,773	2,593	2,692	2,800
3,033	2,678	([c])	2,766	2,817
2,671	2,790	([c])	2,874	2,680
2,790	2,955	2,851	2,889	2,797
2,899	2,851	2,674	2,719	2,755
2,934	2,817	([c])	2,730	2,851
[d]2,890	[d]2,845	[d]2,822	[d]2,766	[d]2,800

[a] All temperatures taken at center of cupola with Wanner optical pyrometer at intervals of 1 minute; 2-inch clay protecting tips on ends of water-cooled tubes.
[b] Maximum. [c] Cold; not included in total. [d] Average.

USE OF WATER-COOLED COPPER TUBE.

The tube shown in figure 13 was finally adopted as a device for determining the amount of heat absorbed per minute at different depths in the fuel bed. A ¾-inch copper tube 32 inches long was closed at one end by welding in a circular piece of steel. A ¼-inch tube inserted at one end and extending to the farther end provided a means for circulating water through the tube. This tube was inserted differ-

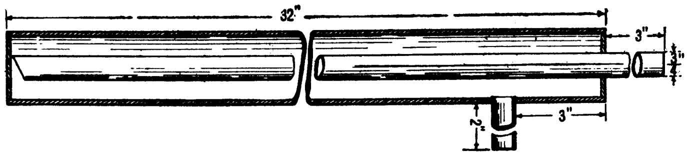


FIGURE 13.—Section of water-cooled copper tube used for determining amount of heat absorbed per minute at different depths of the fuel bed.

ent distances into the fuel bed and the heat absorbed by a measured quantity of water during a definite period of time was determined. The flow of water was kept as nearly constant as possible. The average amount for each test was 150 pounds in all, or 10 pounds per minute. The temperature of the inlet and outlet water was obtained by means of mercurial thermometers. Readings of the temperature of the inflowing and outflowing water were made each minute during a test. These readings were separately averaged. The difference between the average temperatures over a definite period multiplied by the total weight of water circulating through the tube during that period gives the total heat absorbed. This total divided by the total number of minutes of the test gives the heat absorbed per minute. Figure 14 shows how the tubes were placed in the cupola. The copper tubes were thoroughly cleaned before each test and the conditions were made as uniform as possible in all respects. Only two tubes were used during any one test. They were placed at least 12 inches apart in order to prevent a possible reduction of temperature by radiation of heat from coke surrounding one tube to the other tube if the two

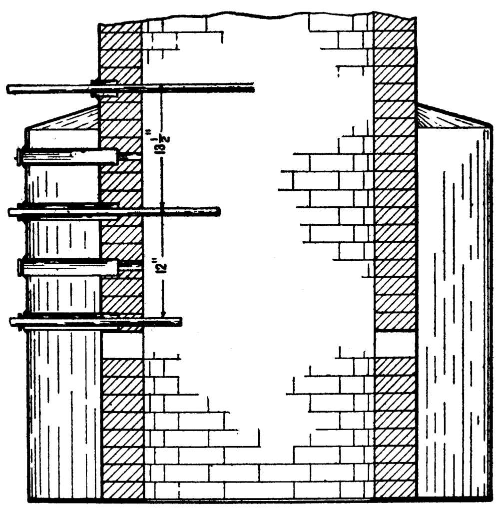


FIGURE 14.—Section of cupola showing location of water-cooled copper tubes.

were in close proximity. Plate I, *B*, shows details of apparatus as used for determining the heat absorbed.

RESULTS WITH USE OF WATER-COOLED COPPER TUBES.

Table 5 shows the heat absorbed per minute at the different planes. The tubes were inserted in the fuel bed to distances corresponding with the points from which the gas samples were taken. For location 1 of the table the tube was inserted 13½ inches (from the lining to the center of cupola); for location 2, 9 inches; and for location 3, 4½ inches. Table 5 follows:

TABLE 5.—*Heat absorbed per minute at different locations in the fuel bed, B. t. u.*

Plane.	Location.	Length of tube exposed.	Test No.— 1.	2.	3.	4.	5.	6.	Average.
		Inches.							
A	1	13½	347.8	304.0	351.2	311.8	292.4	399.4	334.4
	2	9	191.1	161.7	163.3	222.3	199.3	189.5	187.9
	3	4½	20.4	19.5	38.2	21.4	27.7	22.6	25.0
B	1	13½	495.1	506.0	594.1	514.5	559.0	534.5	533.9
	2	9	339.4	344.9	363.1	315.7	343.2	385.1	348.6
	3	4½	158.8	131.4	144.0	118.9	155.1	128.6	139.5
C	1	13½	612.0	615.0	....	541.3	545.9	625.2	587.9
	2	9	362.2	399.0	450.2	457.5	456.8	460.3	431.0
	3	4½	110.3	178.5	186.1	189.8	220.1	238.7	187.3
D	1	13½	598.5	....	606.4	623.3	582.7	651.4	612.4
	2	9	453.3	466.3	449.4	472.0	432.6	449.0	453.8
	3	4½	238.9	242.3	229.6	236.8	243.9	....	238.3
E	1	13½	613.8	587.7	558.6	572.5	609.0	614.5	592.7
	2	9	400.8	425.3	407.0	401.0	401.6	386.1	403.7
	3	4½	244.0	242.1	255.0	202.7	248.1	....	238.5

The heat measurements by the copper tubes show the heat absorbed by the tubes over the whole distance to which they were inserted and not the heat at some particular point in the fuel bed. As in the case of the gas analyses, the observations varied considerably. Allowance being made for the crudeness of the method, the variations are not surprising.

GRAPHIC REPRESENTATION OF RESULTS.

Figures 15 and 16 show graphic representations of the results.

AVERAGES.

Figure 15 gives a graphic representation of the averages of the observations at each location, which are believed to show the relative temperatures of the several planes measured. The heat absorbed per minute is shown as abscissas and the heights (planes) as ordinates. From this figure it will be noted that the greatest amount of heat was absorbed at plane *D*. At plane *A*, with tube inserted 4½ inches, the cooling effect of the blast is evident, the heat absorbed being small.

As the height above the tuyères increases the temperature steadily increases up to plane D. Curve 1, representing the heat absorbed in

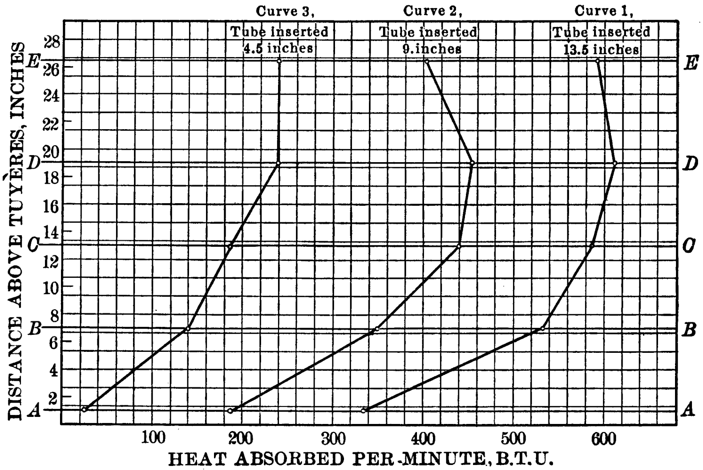


FIGURE 15.—Diagram showing variation in number of British thermal units absorbed at different heights (planes) in the fuel bed. Lines A, B, C, D, and E indicate the imaginary planes.

each section when the tubes were inserted over the whole radius of the cupola, shows that the height above the tuyères where the greatest

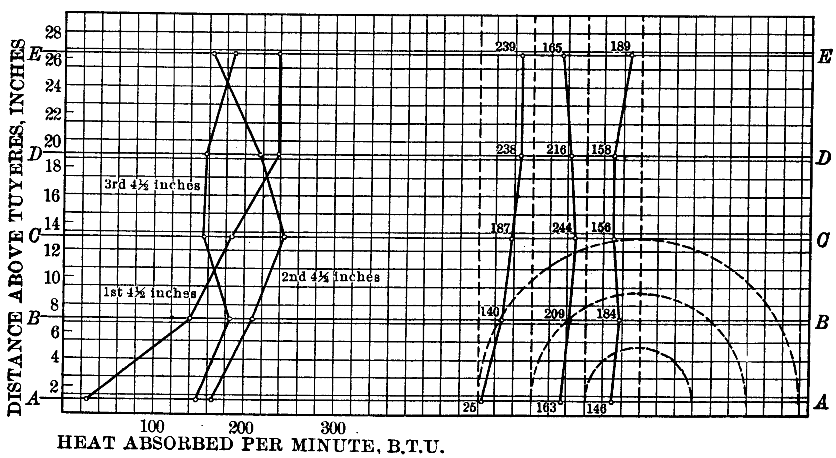


FIGURE 16.—Diagram showing variation in amount of heat absorbed per minute in different regions of cupola fuel bed.

heat existed over the whole cross-section of the fuel bed was at D, 19 inches above the tuyères.

EFFECT OF LOCATION.

The heat absorbed in each plane of the cupola is shown by the curves in figure 16. The figures representing the heat absorbed in the first 4½ inches from the lining are direct determinations.

The figures for the second 4½ inches are obtained by deducting the amount found for the first 4½ inches from the amount found for

9 inches, and for the third 4½ inches by subtracting the amount found for the 9 inches from the total for the whole 13½ inches. In the zone between the lining and a line 4½ inches within, the temperature increased rapidly through the lower 19 inches. Through the next 7½ inches it was practically unchanged.

A comparison with the gas curve shown in figure 7 shows that the temperature followed the increase of CO_2 to plane D, 19 inches above the tuyères. Through the next 7½ inches the CO_2 fell off though the temperature was constant, the amount of CO formed seemingly not absorbing enough heat to reduce the temperature. In the region included between lines 4½ and 9 inches distant from the lining the temperature increased to plane *C*, 13 inches above the tuyères and fell off from this point upward. This temperature curve, when compared with the gas curves presented in figure 6, shows that the increase of heat followed the increase of CO_2 up to plane *C;* then fell rapidly through the next two planes as the CO rose. In the third region, included between lines 9 and 13½ inches from the lining and representing the central part of the cupola, the temperature rose through the first 6 inches, fell off through the second 6 inches, remained constant through the next 6 inches, and finally increased rapidly through the last 7½ inches. Comparing this curve with the gas curves of figure 5, the temperature curve is found to follow the CO_2 curve through the first 12 inches. From this point up through the remaining 13½ inches of the fuel bed, the temperature would be expected to fall considerably since the CO_2 decreases and the CO increases. The actual determination of the heat absorbed shows the reverse to be true. The rapid change of CO_2 to CO absorbed heat and cooled the central part of the cupola below the surrounding portions. The flow of heat from the hotter to the cooler portion increased the temperature of this central part.

As it was not possible to make true temperature measurements at the several points corresponding with the points from which the gas samples were taken, it is not possible to confirm the probable location of the points of highest temperature as shown in figure 9. However, by the use of the curves shown in figure 15, it is possible to confirm the conclusion that the best melting zone is where the highest temperature and an absence of oxygen exist throughout the whole cross section of the fuel bed. An examination of the curves shows that the region of highest temperature corresponds with that region where oxygen is entirely absent across the whole cross section. This region is about 19 inches above the tuyères.

CONCLUSIONS.

The ideal melting region probably corresponds to that lying along and just above the line *ab* of figure 9. This line includes points in the figure representing those points in the cupola having highest carbon-dioxide content together with an absence of oxygen, as determined from analysis of the gases. It is manifestly impossible to confine melting to such a region, and the logical conclusion from the experiments here reported is that the best results are obtained if the iron is melted at that region in the cupola where the highest temperature, together with an absence of oxygen, exists across the whole fuel bed. The bottom of this region in the cupola tested was 19 inches above the tuyères when 1,000 cubic feet of air per minute was being blown. This region will be raised if the blast is increased and be lowered if the blast is reduced. Experimental determination of this region is not necessary. In practice, the bellying out of the lining of the cupola is a perfect index of the position of the melting zone, and this bellying is in the region where temperature is highest and oxygen is absent.

Care must be taken not to melt below the bottom of this region, for, the oxygen of the blast not being entirely removed, the iron will be oxidized or burned. The extent of this burning is dependent on the distance below the proper melting region and the lateral position in the fuel bed. Just below the bottom of this melting region oxygen is still found at the lining and the cross-sectional area of this oxidizing region increases as the distance downward increases until the whole cross section at the tuyères shows the presence of this damaging element. The whole problem of obtaining hot iron, free from effects due to oxygen, is solved by using small charges evenly distributed on the fuel bed,[a] and confining the melting to a few inches above the plane shown by the burning out of the lining to be the hottest plane of the fuel bed. If the first charge of iron is so placed that melting begins, say, 4 or 6 inches above this plane and is completed before any of the iron gets below it, and if the following coke and iron charges are so regulated as to maintain this melting zone, the best possible results will be obtained.

The experiments here reported indicate further that the use of upper tuyères is not only unnecessary but a positive detriment to the production of the best iron. The introduction of air into the fuel bed above the tuyères, even though in small volume, increases the liability of injurious effect from oxygen and serves no useful purpose. The increased tonnage supposed to be obtained by the use of upper tuyères can be produced just as easily by blowing through the bottom tuyères the proper volume of air.

[a] Moldenke, Richard, The coke industry of the United States as related to the foundry. Bull. 3, Bureau of Mines, 1912, p. 22.

PUBLICATIONS ON FUEL TECHNOLOGY.

The following Bureau of Mines publications may be obtained free by applying to the Director, Bureau of Mines, Washington, D. C.:

BULLETIN 1. The volatile matter of coal, by H. C. Porter and F. K. Ovitz, 1910, 56 pp., 1 pl.

BULLETIN 2. North Dakota lignite as a fuel for power-plant boilers, by D. T. Randall and Henry Kreisinger, 1910. 42 pp., 1 pl.

BULLETIN 3. The coke industry of the United States as related to the foundry, by Richard Moldenke. 1910. 32 pp.

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BULLETIN 5. Washing and coking tests of coal at Denver, Colo., July 1, 1908, to June 30, 1909, by A. W. Belden, G. R. Delamater, J. W. Groves, and K. M. Way. 1910. 62 pp.

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