Bulletin 2

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JOSEPH A. HOLMES, DIRECTOR

NORTH DAKOTA LIGNITE

AS A

FUEL FOR POWER-PLANT BOILERS

BY

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By D. T. Randall and Henry Kreisinger.

INTRODUCTION.

Importance of the work.—The tests described in the following report were made by the United States Geological Survey in cooperation with the United States Reclamation Service, which, in connection with its Williston project, had erected a large pumping plant at Williston, N. Dak., and had installed steam boilers with furnaces designed to burn a "brown lignite" that was mined on adjacent government land. The tests are deemed important because the lignite deposits of the Northwest are so extensive and the distance of the region from other coal fields is so great that a large portion of the United States, including parts of North Dakota, South Dakota, and Montana, may be greatly benefited by any improvements in the methods of utilizing this local fuel supply. The desirability of getting all available information regarding the methods of using similar lignite is obvious.

The lignite in this field is low in heating value, some of it containing nearly 45 per cent of its weight moisture, and it is difficult to burn in the furnaces commonly used for the better grades of coal, but the tests have shown the possibility of designing suitable furnaces for burning it profitably. The results of tests of lignite on the hand-fired grates under a Heine boiler at the fuel-testing plant at St. Louis were not fully satisfactory in themselves, but showed the necessity of observing certain conditions for efficiently burning this fuel. They indicated that strong draft and a large combustion chamber are essential to insure the burning of the large quantity of gas that is driven off with the moisture from the fuel bed.

The results of the tests made at Williston, set forth in this report, show that this fuel, though generally considered unsatisfactory, may be used with fair economy under boilers that generate their full rated capacity. In fact, when the number of heat units available is considered the results compare very favorably with those of better grades of fuel.

Personnel.—The tests were made under the personal direction of Henry Kreisinger, who was assisted by F. E. Woodman, of the Geological Survey, and C. E. Draper, electrical assistant of the Reclamation Service. The furnace temperature measurements were made by J. K. Clement and the flue gases were sampled and analyzed by E. J. Hoffman, both of the Survey. The chemical work on coal and ash was done at the chemical laboratory of the Geological Survey at Pittsburgh, Pa., under the direction of F. M. Stanton. The computations were made at Pittsburgh under the direction of Lauson Stone.

Acknowledgments.—Credit is due to A. A. Storrs and G. O. Sanford, the Reclamation Service engineers directly in charge of the Williston project, who had all changes made in the boiler-plant equipment that were necessary for the tests. J. M. Fine, engineer in charge of the power plant, and John G. Cunningham both rendered valuable assistance in connection with the operation of the boiler under test.

Related investigations.—The fuel researches of the Geological Survey, which had their beginning under an appropriation made by Congress on February 4, 1904, for testing fuel at the Louisiana Purchase Exposition, embraced not only the field study of mineral-fuel deposits, but also analyses and tests to determine the quality of the deposits, their adaptability to specific uses, and the methods by which they could be utilized to best advantage. In the course of these investigations the Survey collected and analyzed thousands of samples and made a great number of tests, such as washing, briquetting, coking, steaming, and producer-gas tests, to ascertain the fuel value of the peat, lignite, or coal under fixed conditions, its relative suitability for a given purpose, and the possibility of increasing its efficiency. Results of these tests are given in many of the bulletins listed at the end of this report.

The act of Congress of May 16, 1910, which established a Bureau of Mines, transferred to this bureau the work of analyzing and testing fuels that was being carried on by the Geological Survey. The act became effective July 1, 1910. Hence the Bureau of Mines is publishing a considerable number of reports, of which this is one, dealing with investigations made by the Geological Survey prior to that date.

Objects of the tests.—The primary object of the tests was to show that the lignite coals of North Dakota are suitable for making steam. The secondary objects were to determine the effect of the size and the weathering of coal on economy and to determine whether anything is gained by superheating the steam used in the Argand steam blowers.

FUEL, APPARATUS, AND METHODS.

THE FUEL TESTED.

The fuel used on the tests came from the government mine located within about 500 yards of the power house. The mine is working the middle seam of the three known beds. The coal is a "brown lignite," containing about 40 per cent of moisture and 7 to 8 per cent of ash. It is therefore considered low-grade coal. In most of the tests the coal was burned soon after being mined. It was delivered in run-of-mine form to the power plant, where it was crushed either by a power crusher or by hand.

APPARATUS USED.

THE BOILER.

The tests reported in this bulletin were made with one of six Stirling boilers installed in the power plant of the Williston irrigation project of the United States Reclamation Service. This boiler was located at the north end of the boiler room and was designated at the plant as No. 6. Boilers Nos. 5 and 6 were erected as a single battery.

Plate I shows two sections of the boiler and the setting. The boiler proper is of the standard Stirling water-tube type, consisting of three steam drums, one mud drum, and three nests of tubes. The baffles are inserted in the usual places.

THE FURNACE.

The furnace is of the semigas-producer type and has an external resemblance to the so-called Dutch oven. The most striking features in the construction of the furnace are the deep-set grate and the contraction of the space between the bridge wall and the end of the prolonged fire-brick arch. As shown in the plate, the grate is 21 inches below the lower edge of the firing door. The object of this construction is to enable the fireman to carry a thick fuel bed and still see its condition at the top. The side furnace door shown in the plate, used in removing clinkers, is only 7 inches above the grate.

The furnace is designed to work on the gas-producer principle. The solid fuel is gasified on the grate and the gas passes through the space under the arch into the combustion chamber, where most of the gaseous combustible burns. The necessary air for combustion is added through the openings A in the bridge wall. This air is preheated to 200° to 300° F. in coils P, and forced into the furnace under a pressure of 0.5 to 1 inch of water. Owing to the location and direction of these air openings, the air is blown in jets into the comparatively slow-moving body of combustible gas, thereby causing considerable stirring, so that the gases and the air form a fairly homogeneous mixture. A small quantity of air is also added through the openings R in the roof of the furnace. This air consists only of leakage through the outside wall into the air space which completely envelopes the fire-brick lining of the Dutch-oven part of the furnace. Although there is some combustion above the fuel bed, the greater part of the gases burn below the contracted arch and back of the bridge wall, after air has been added through the openings A and R. With rates of combustion exceeding about 25 pounds of coal per square foot of grate the flames extend even into the space above the arch.

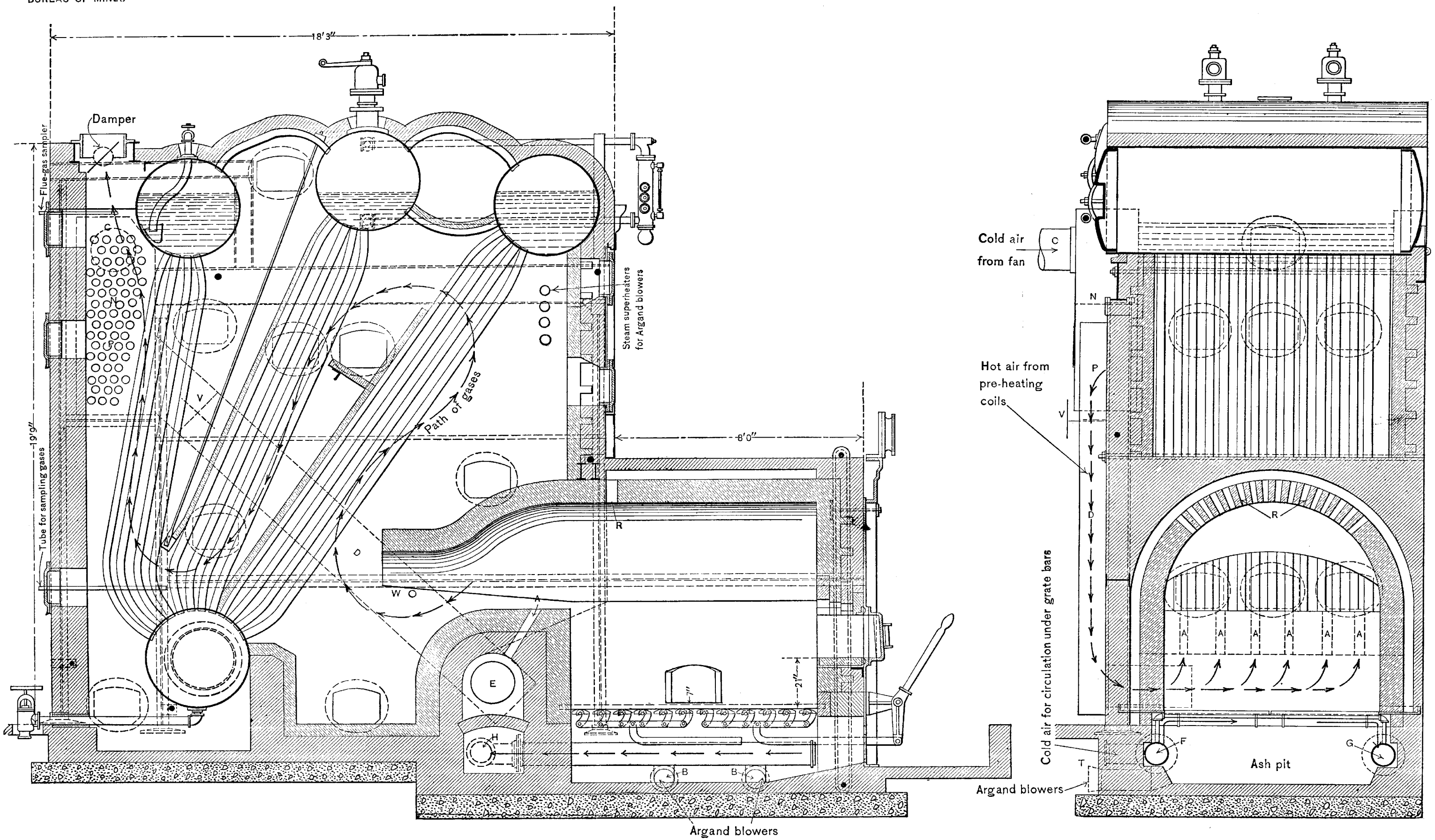
The air added through the bridge wall is forced by a fan blower through the duct C into the upper half, N, of the preheating coils. Through these coils the air passes to the other side of the boiler setting, where it is turned by means of a metal-sheet chamber into the lower half, P, of the preheating coils, through which it flows back to the same side of the boiler from which it started; it there enters the air duct D, which takes it into the upper tunnel in the bridge wall. A damper V placed in the upper part of the air duct D serves to regulate the amount of air to be put through the bridge-wall opening.

THE GRATE.

The furnace is equipped with a rocking grate consisting of two rows of grate bars. Each row is connected with two shaking levers in such a way that by shaking one lever alternate bars in the row are rocked. Figure 1 shows top and cross-sectional views of a grate bar. Each grate bar is supported by a 2-inch pipe, through which cold air circulates; the object is to keep the grate bars and the ash immediately above them cool, so that the ash will not fuse and adhere to the bars. Cold air from the fan blower is brought through a special air duct into the large pipe F, from which it flows through each grate-supporting pipe into the pipe G, as indicated by the arrows in Plate I. Pipe G takes the air into the lower tunnel H in the bridge wall, through which the air flows into the pit T, and is thence blown by the Argand blowers into the ash pit. The pressure in the ash pit varies from 1 to 2 inches of water; the pressure whereby the cold air circulates through the supporting bars is only about 0.5 to 1 inch of water, so that the circulating air can not be discharged from the supporting bars (pipes) directly into the ash pit.

STACK AND BLOWERS.

Boiler No. 6 has a steel stack in common with boiler No. 5. Each boiler has a separate damper placed in the brick gas passage immediately below the hood of the stack. The path of gases through the boiler is indicated in Plate I by the long curved arrow. The boiler is operated with "balanced draft"—that is, the ash pit is kept under pressure higher than the atmospheric and the uptake under a pres-



VERTICAL SECTIONS SHOWING DETAILS OF BOILER SETTING.

sure a little below atmospheric; the furnace is, therefore, just about at atmospheric pressure. This condition permits the opening of the fire doors when firing without allowing outside air to enter.

A coil used for superheating the steam used by the Argand blowers is inserted in the space above the arch, directly under the first steam drum.

Ordinarily, the steam used in the two Argand blowers is taken from the same boiler the blowers are operating. However, on these

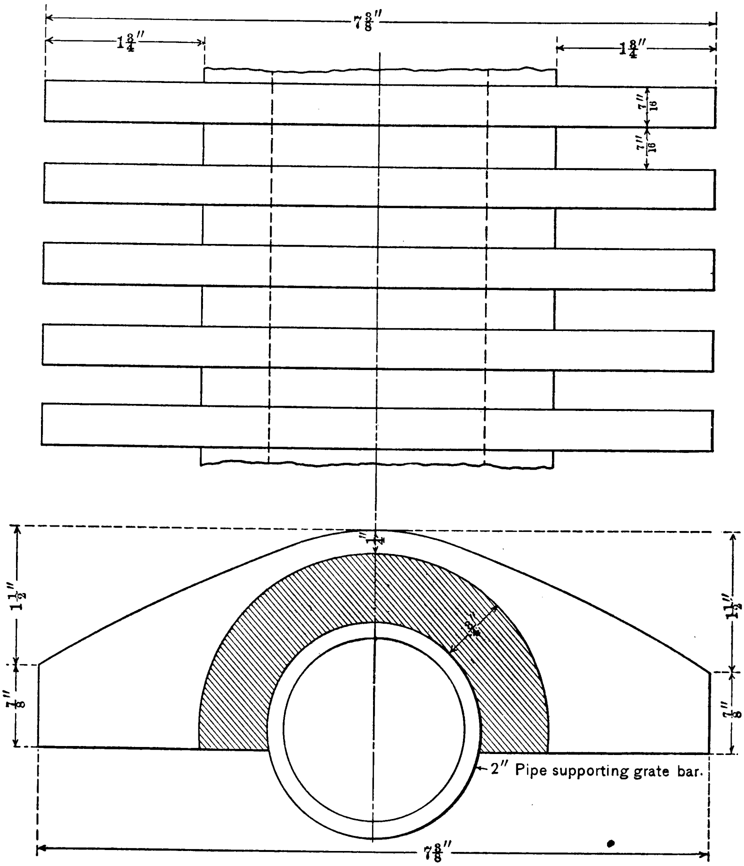


FIGURE 1.—Top view and vertical cross section of grate bar, showing construction.

tests, in order to determine the amount of steam used by the blowers, the steam was supplied by an independently operated small locomotive boiler of 20-horsepower capacity. The connections between the locomotive boiler and the blowers were such that the steam could either be made to pass first through the superheating coils inserted in the main boiler setting or could be used directly in its saturated state.

DIMENSIONS.

Table 1 gives the principal dimensions of the furnace, the boiler, and the grate.

TABLE 1.—*Principal dimensions of furnace, boiler, and grate.*

Furnace:	
Width in front ... feet..	6.6
Width back of bridge wall ... do....	7.5
Length ... do....	8
Height ... do....	7
Roof of furnace:	
Length (straight portion) ... do....	8.5
Length at sides ... do....	15.8
Length in middle ... do....	15.3
Height in rear above bridge wall. inches..	23
Number of openings [a] ...	16
Size of openings ... inches..	2 by 4.5
Width of partitions ... inches..	2
Bridge wall:	
Width at base ... feet..	5
Width on top ... do....	3
Height ... inches..	40
Number of openings [b] ...	6
Size of openings ... inches..	5 by 2.5
Side door:	
Lower edge above grate ... inches..	7.5
Height ... do....	17
Width ... do....	19
Firing door:	
Lower edge above grate ... inches..	21
Height ... do...	14.75
Width ... do...	19.75
Chimney:	
Height above grate ... feet..	155
Diameter ... inches..	54
Boiler:	
Builders' rating ... horsepower..	258
Water-heating surface ... square feet..	2,587
Diameter of steam drums ... inches..	42
Length of steam drums ... feet..	10.33
Diameter of mud drums ... inches..	42
Length of mud drums ... feet..	8.83
Number of tubes ...	209
Diameter of tubes ... inches..	3.25
Grate:	
Width ... feet..	6.6
Length ... do....	8
Width of grate bars ... inches..	7.4
Width of rib ... do....	.44
Width of air space ... do....	.44
Depth of air space ... do....	1.75

FLUE-GAS SAMPLER.

Figure 2 shows a flue-gas sampling device placed in the uptake about 18 inches below the damper. Plate I shows the location of the sampler with respect to the boiler in a vertical section. The gas sampler is a standard $\frac{3}{4}$-inch iron pipe closed at both ends with caps and having two rows of small ($\frac{3}{32}$-inch) holes 4 inches apart drilled in a staggered way on two sides of the pipe. This $\frac{3}{4}$-inch pipe connects in the middle to a $\frac{1}{2}$-inch pipe which extends out of the setting and leads down to within 3 feet of the floor, where it is connected to a steam ejector. Figure 3 shows the steam ejector and connections. The sample of gas for chemical analysis is taken through the pet cock, as shown in the figure. The object of the steam ejector is to induce a continuous stream of gas to flow from the uptake through the sampling apparatus. The construction of the $\frac{3}{4}$-inch pipe placed in the uptake permits of drawing the gas from a large area, so that the sample drawn represents fairly well the average composition of all the gases passing through the uptake.

METHODS OF CONDUCTING TESTS.

Starting and closing.—A modification of the "alternate method" was used in starting and closing tests. The standard method was

[a] Openings in roof of furnace are 6.5 feet from front of furnace.
[b] Openings in bridge wall are 9 inches from front of bridge wall.

altogether out of question. The fuel bed is considered to be in its best condition when it is 18 to 22 inches thick; when a new fire is started with wood it takes several hours to get the bed built up and the fire in a good running condition.

Generally, a fire was started with wood about 4 o'clock in the morning and the bed was gradually built up until about 8 or 9 o'clock, when it was 16 to 18 inches thick. At this time the furnace was well heated and in condition for starting a test. The grates were then shaken and all ash removed from the ash pit. At the time of starting and at the time of closing each test the height of the fuel bed was estimated as accurately as possible by sighting over the bottom of the opening of the firing door to see how far the upper surface of the fuel bed was below this line. This estimate of the fuel bed was made independently by at least two observers; if the observations did not agree, the average of the estimates was taken for record. Usually C. E. Draper and Henry Kreisinger did this estimating.

At the end of test 2 the fuel bed was burned down to the same height as at the start. It was thought that only an inappreciable amount of clinker would be found in the fuel bed, but, after closing the test and burning the fuel bed down still farther, a quantity of clinkers amounting to several hundred pounds was found on the grate. It was evident that to neglect these clinkers would introduce considerable error in the results of the tests; therefore, on all subsequent tests corrections for the clinkers were made by closing the test with the fuel bed 3 to 4 inches higher than it was when the test was started. This method of making allowance for clinker was necessary because the clinkers could not be pulled out during the test on account of the grate being so far below the firing door. Care was taken also to have the height of water in the boiler and the steam pressure as nearly as possible the same at the close as at the start.

Ash and refuse.—Immediately before starting each test the grate was shaken and the ash pit was cleaned out. A few minutes before closing the test the grate was again shaken. After closing the test all the ash was removed from the ash pit, weighed, and charged to the test. The fuel bed was then burned down to about 12 to 14 inches and the clinkers were pulled out, partly through the side door and partly through the firing door. This process of pulling out the clinkers was very difficult, as the firing doors were high above the grate and there was not enough room on the side of the boiler for handling the fire tools through the side door. The removal of clinkers took from one to two hours. Only the larger pieces of clinker could be pulled out; smaller pieces fell through the grate into the ash pit with free ash and hot coal and could not be separately recovered. Frequently during the process of pulling clinkers large pieces were so broken as to be much reduced in size before removal. Coal, ash, and small pieces of clinker falling into the ash pit were not weighed. The method of obtaining the weight of ash and clinker was very crude, but it was the best that could be used under the circumstances. Taking all factors into consideration, it is estimated that only about one-half to two-thirds of the total weight of clinker originally present on the grate was removed, weighed, and charged to the test.

Weighing and sampling fuel.—Coal was weighed in a wooden box which was placed on a platform scale. The box was 4 feet long by 3 feet wide by 14 inches deep, and held about 500 pounds of coal. One side of the box was removable for convenience in shoveling. The time of firing and the weight of coal at each charge were regularly recorded.

Each time the box was filled a sample of coal amounting to about a shovelful was collected by taking a little at a time.

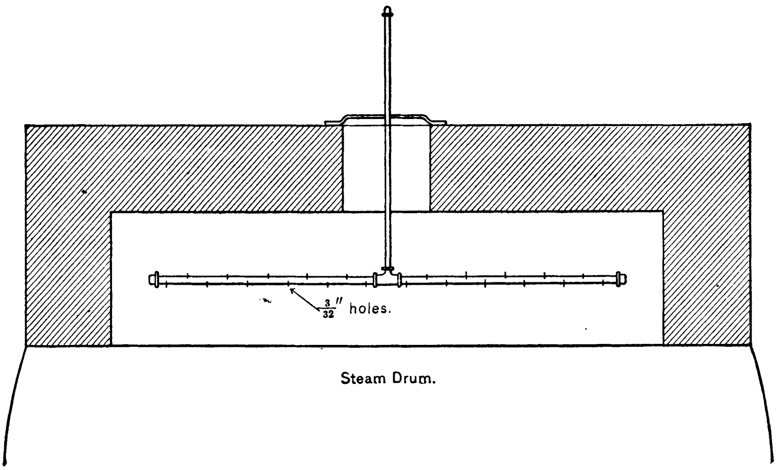


FIGURE 2.—Section through uptake, showing location of flue-gas sampler.

Feed water.—Water was measured in a specially constructed cylindrical tank, which held 1,293 pounds of water, at 60° F. The tank was about 2½ feet in diameter by 5 feet high and had a funnel-shaped bottom which permitted quick emptying. The top of the tank was contracted by means of an inverted funnel to a neck 5 inches in diameter. This narrow neck at the top of the tank reduced the error which might have been introduced by any possible difference in the water level when filling the tank.[a] The measuring tank was placed on a wooden platform about 7 feet high and emptied into a plain cylindrical suction tank placed on the boiler-room floor. This suction tank was of larger capacity than the measuring tank. Water was fed from the suction tank into the boiler by an injector (1½-inch), the overflow from which was run back into the suction tank. The

[a] For details of construction of a similar tank see Professional Paper U. S. Geological Survey No. 48, 1906, p. 309.

capacity of the suction tank was determined for every inch of the height of water. The time of each emptying of the measuring tank was recorded.

During the tests all pipe lines except the injector were disconnected from the boiler. In disconnecting the blow-off pipe from the main line its end was left exposed so that it was at all times visible. These arrangements made it impossible for any water to get into the boiler, except that which was measured and fed into the boiler with the injector, or for any water to get out of the boiler except in the form of steam through the steam main. During each test the rate of combustion was kept as constant as possible, the drafts being changed if necessary. A scale was attached to the gage glass of the test boiler and the height of the water was read at regular twenty-minute intervals.

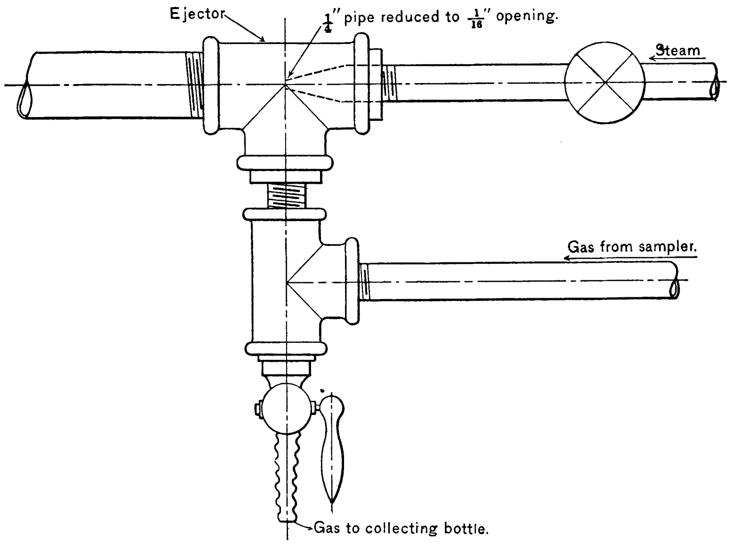


FIGURE 3.—Steam ejector, showing its location at the end of the pipe leading from gas sampler in stack.

Flue-gas sampling.—Samples of flue gas were collected and analyzed for CO_2, O_2, and CO with an Orsat apparatus. Each regular sample was collected through the sampling device (illustrated in figures 2 and 3) during a period of about thirty minutes, so that the analysis of the sample represented the average chemical composition of the gas during that time.

Occasionally a sample of gas was taken with a $\frac{1}{4}$-inch iron pipe through a hole in the lowest middle door in the rear of the boiler setting. The end of this sampling pipe was placed halfway between the mud drum and the baffle between the second and third nests of boiler tubes.

Temperature measurements.—Except as otherwise stated, temperatures were taken for record at regular twenty-minute intervals. Attempts were made at first to measure flue-gas temperatures in the uptake at the place where the regular gas sample was taken, but owing to the close proximity of the air-preheating coils and the steam drum, the thermometer gave very low readings. The upper half of the preheating coils received the cold air from the fan. These coils were therefore much colder than the flue gases going up the chimney. The thermometer being close to these cold coils radiated heat to them and consequently showed much lower temperatures than the flue gases passing by it, so it was decided to put a thermometer about 4 feet above the damper in the hood of the stack. The thermometer readings were too low in this position also, because the hood was much colder than the gases and of course the thermometer radiated heat to it. Moreover, the two boilers in the battery had a stack and hood in common so that the colder gases from boiler No. 5, under which only a very low fire was generally kept, mixed somewhat with the gases from the test boiler. In spite of these cooling effects the thermometer in the hood of the stack read 100° to 200° F. higher than the thermometer at the point below the damper. It is an open question how much too low the indicated temperatures in the hood were, but there can be no doubt that the gases leaving the boiler setting were hotter than is shown by the record of thermometer readings. The thermometer used for this purpose was a large mercury thermometer made especially for measuring flue-gas temperature.

The temperature of water was determined at each time of emptying the tank by means of a thermometer immersed therein.

The temperature of the preheated air which was fed into the furnace through the bridge wall was measured with a mercury thermometer inserted in the air duct D (Pl. I) about 5 feet from its lower end.

A thermometer cup was placed in the steam pipe leading from the superheater to the Argand blowers and a mercury thermometer was used for measuring the temperature of the superheated steam used.

Furnace temperatures were measured with a Wanner optical pyrometer. The measurements were made through a hole (W, Pl. I) bored in the side wall just back of and a little above the bridge wall.

Steam.—Steam pressures were recorded at regular intervals from a standard gage which was calibrated and could be read within 1 pound. A throttling calorimeter for moisture determinations was attached in the approved way to the steam pipe leading from the boiler to the steam header. The steam used by the Argand blowers was furnished by a separately operated locomotive boiler. The water fed into this boiler was weighed and charged to the blowers.

Measuring drafts.—Gas pressures (drafts) were measured on all tests, in the ash pit, over the fuel bed, in the uptake, and in the preheated-air duct by means of Ellison inclined tube manometers, and readings were taken at regular twenty-minute intervals.

ACCURACY OF DATA.

Perhaps the greatest error introduced in the data of the tests was in estimating the height of the fuel bed and in allowing for the clinkers in the fuel bed at the end of the tests. It is not probable, however, that the error in any test was over 2 inches in the net thickness of fuel bed.

The grate area is approximately 54 square feet, and 1 cubic foot of lignite weights about 50 pounds, so that a difference of 2 inches in the height of the fuel bed would be equal to 9 cubic feet, or $9 \times 50 = 450$ pounds of coal.

About 28,000 pounds of coal were burned during each test. An error of 2 inches in estimating the height of the fuel bed would therefore be equal to about 1.6 per cent of the total coal used. The estimated height of the fuel bed might be either 2 inches too low or 2 inches too high, so that there is a possibility of the results of tests given in this report being 1.6 per cent too high or too low. Thus, for instance, if the boiler efficiency item 72.1 is given as 60 per cent, the margin of doubt is $0.60 \times 1.6 = 0.96$, or about 1 per cent either way. In other words, the boiler efficiency may be anywhere from $60 - 1 = 59$ to $60 + 1 = 61$ per cent.

The flue-gas temperatures as recorded, on account of conditions already stated, are very likely too low; but such error affects only the heat balance and not the economic results. A flue-gas temperature that is too low lowers items 2, 3, and 4 of the heat balance and raises item 6 by the same amount. It does not affect the evaporation or the boiler efficiency.

Thus, for example, in test 4 the stated flue-gas temperature is 436° F. It is possible that the actual temperature was 50° F. higher, or 486° F. If so, the corresponding four items of the heat balance for the two temperatures are as follows:

TABLE 2.—*Values of items of heat balance corresponding to different degrees of flue-gas temperature.*

Flue-gas temperatures (°F.).	Items in heat balance (expressed in percentage of heat in 1 pound of combustible).			
	2	3	4	6
As stated, 436	9.47	4.60	12.62	11.78
Hypothetical, 486	9.80	4.83	15.10	8.74

The second line is perhaps closer to the true values than the first one.

DATA AND RESULTS OF TESTS.

TABULATED ITEMS.

Fifteen tests were made. In tests 8, 9, 10, and 12 saturated steam was used in the Argand blowers; for all other tests superheated steam was used. In tests 5, 6, and 7 coal crushed by hand was used; coal for all other tests was crushed by crusher. Coal used in test 13 was exposed to wind and sun for forty-eight hours. Coal used in test 14 was exposed twenty-four hours. The averages of the principal items of observed data and the calculated results are given in Table 3. The computations embodied in the table were made according to the method explained in Bulletin 23.[a] This method is in practical accord with the recommendations of the American Society of Mechanical Engineers. The figures in parentheses at the heads of columns in the table are the item numbers of the society's code for steaming tests.

The economic results of the tests are given in columns 51–53, 56, and 66–69 of Table 3.

The three different efficiencies (columns 67–69) express three different ratios. Item 72.1 (column 67), efficiency of boiler, is the ratio of the heat absorbed by boiler to the heat of the combustible ascending from the grate. It is the efficiency of the furnace and boiler, but not of the grate. Combustible falling through the grate is not consumed and is excluded from this efficiency. Item 72.1, expressed in percentage, corresponds to column 78 under "Heat balance," where the value in British thermal units is stated.

Item 73 (column 68) is the combined efficiency of the boiler, furnace, and grate. It is the ratio of the heat absorbed by the boiler to the heat in all the coal fired on the grate. Item 72.1 multiplied by the efficiency of the grate gives item 73.

The column 69 of Table 3 shows the "over-all efficiency of the steam-generating apparatus," including the ash-pit blowers. This efficiency is the ratio of the heat absorbed by the boiler minus the heat of steam used in ash pit, divided by the heat of the coal fired on the grate, and is equal to item 73 minus the heat of steam used in ash-pit blower, the heat being expressed in percentage of the heat in dry coal.

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[a] Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coals and related investigations, September 1, 1904, to December 31, 1908. Bull. 23, Bureau of Mines, 1912, pp. 46–57.

TABLE 3.—*Summary of observed data and calculated items of 15 steaming tests made with North Dakota lignite, October 8–29, 1908.*[a]

Test No.	Time of test.		Condition of fuel.	Average pressures.			Draft (inches of water).			
	Date, October, 1908.	Duration (hours).		Barometer (inches of mercury).	Steam, above atmosphere (lbs. per sq. in.).		Below atmosphere.		Above atmosphere.	
					At gage.	To ash pit.	Stack.	Furnace.	Ash pit.	To bridge wall.
1	**2** (1)	**3** (2)	**4**	**5** (11)	**6** (11.1)	**7**	**8** (12)	**9** (13)	**10**	**11**
1	8	3.18	Fresh [b]	28	141.4	....	0.61	0.12	0.66	....
2	10	13.77	do. [b]	28.18	134.6	67.9	.15	.75	.90	0.17
3	11	10.47	do. [b]	28.33	131.9	77.9	.23	.10	1.40	.16
4	12	14.75	do. [b]	28.16	133.1	49.7	.13	.11	1.42	.17
5	14	14.25	do. [c]	27.54	133.9	51.2	.18	.14	1.55	.13
6	16	11.13	do. [c]	27.69	130.7	68.9	.24	.15	1.78	.32
7	17	12.70	do. [c]	28.19	134.8	63.6	.11	.09	1.32	.42
8	19	10.00	do. [b]	27.72	135.1	58.3	.24	.13	.93	.27
9	20	12.95	do. [b]	27.12	131.0	64.5	.21	.16	1.67	.33
10	21	14.67	do. [b]	27.75	131.6	69.6	.16	.12	1.37	.38
11	22	10.03	do. [b]	28.30	135.2	105.9	.41	.21	1.74	.36
12	23	11.00	do [b]	28.21	135.0	104.8	.32	.18	1.83	.73
13	26	13.42	Weathered [d]	28.13	131.4	92.0	.30	.20	1.78	.46
14	27	12.73	do. [e]	27.96	131.3	86.6	.27	.17	1.95	.54
15	29	12.12	Fresh [b]	28.31	133.5	82.7	.31	.17	2.35	.43
15A	29	8.13	do. [b]	28.31	133.2	....	.38	.20	2.27	....

Test No.	Average temperature (°F.) of—								Fuel (total weights in pounds).		
	Atmosphere.		Preheated air to bridge wall.	Steam to ash-pit blowers.[f]	Feed water in tank	Calorimeter.	Flue gas.	Furnace.	As fired.	Dry.	Ash and refuse.
	Outside.	Fire-room.									
1	**12**	**13** (16)	**14**	**15**	**16** (18)	**17**	**18** (21)	**19**	**20** (25)	**21** (27)	**22** (28)
1	71	85	....	446	55	299	442	1,791	6,350	....	258
2	44	75	271	557	54	291	373	2,181	30,729	17,897	1,540
3	59	83	279	533	53	292	457	2,171	29,000	16,527	1,558
4	66	84	240	455	54	291	436	2,014	27,998	15,606	2,198
5	70	88	251	532	56	287	474	2,145	28,000	16,895	1,170
6	49	72	246	488	60	276	519	2,160	28,340	16,536	1,103
7	40	66	217	463	57	291	494	2,122	27,101	15,705	781
8	45	68	241	327	51	291	521	2,080	28,000	15,725	1,986
9	45	67	218	332	55	285	472	2,109	28,500	15,837	1,665
10	37	68	207	332	43	285	462	2,148	28,000	15,764	1,586
11	39	69	242	....	39	286	570	2,073	28,000	15,994	1,997
12	46	65	210	336	48	290	549	2,165	30,000	17,271	1,084
13	50	65	197	483	54	276	500	2,115	30,000	17,469	1,309
14	51	75	210	507	48	288	528	2,161	27,997	16,129	1,075
15	33	66	223	549	41	280	526	2,120	31,672	18,167	2,391
15A	35	67	....	....	38	282	555	2,156	21,659	12,424	1,635

[a] Code numbers (in parentheses at the top of certain columns) refer to corresponding items explained in Bull. U. S. Geol. Survey No. 325, pp. 151–153. See also Prof. Paper U. S. Geol. Survey No. 48, pt. 2.
[b] Crushed by crusher; 20 to 30 per cent slack.
[c] Crushed by hand.
[d] Coal exposed to wind and sun for forty-eight hours.
[e] Coal exposed to wind and sun for twenty-four hours.
[f] Condition of steam used in ash-pit blowers: Saturated in tests 8, 9, 10, and 12; superheated in all other tests.

TABLE 3.—*Summary of observed data and calculated items of 15 steaming tests made with North Dakota lignite, October 8–29, 1908*—Continued.

Test No.	Total combustible[a] consumed (lbs.)	Fired per hour (lbs.). Dry fuel. For grate.	Fired per hour (lbs.). Dry fuel. Per sq. ft. of grate.	Fired per hour (lbs.). Combustible.	Refuse in dry fuel (per cent).	Proximate analysis (per cent). Fixed carbon. In moist coal.	Fixed carbon. In combustible.	Volatile matter. In moist coal.	Volatile matter. In combustible.	Moisture in fuel as fired.	Ash in fuel. As fired.	Ash in fuel. Dry.
1	**23** (30.1)	**24** (46)	**25** (48)	**26** (47.1)	**27** (31)	**28** (32)	**29** (32*a*)	**30** (33)	**31** (33*a*)	**32**	**33**	**34**
1.....	....	....	....	....	....	....	....	....	....	....	....	....
2.....	15,423	1,300	23.99	1,120	8.60	28.01	54.99	22.93	45.01	41.76	7.30	12.53
3.....	14,068	1,579	29.13	1,343	9.43	26.01	52.30	23.72	47.70	43.01	7.26	12.75
4.....	12,909	1,058	19.52	875	14.08	24.00	49.48	24.51	50.52	44.26	7.23	12.97
5.....	14,860	1,186	21.88	1,043	6.93	27.56	51.02	26.46	48.98	39.66	6.32	10.47
6.....	13,909	1,486	27.42	1,250	6.67	25.75	50.96	24.78	49.04	41.65	7.82	13.40
7.....	13,428	1,237	22.82	1,057	4.97	25.82	51.72	24.10	48.28	42.05	8.03	13.86
8.....	13,237	1,573	29.02	1,324	12.63	24.86	50.79	24.08	49.21	43.84	7.22	12.86
9.....	13,648	1,223	22.56	1,054	10.51	24.65	50.45	24.22	49.55	44.43	6.70	12.06
10.....	13,678	1,075	19.83	932	10.06	25.28	50.98	24.31	49.02	43.70	6.71	11.92
11.....	13,038	1,595	29.43	1,300	12.49	24.96	50.76	24.22	49.24	42.88	7.94	13.90
12.....	15,164	1,570	28.97	1,379	6.27	26.17	51.34	24.80	48.66	42.43	6.60	11.46
13.....	15,164	1,302	24.02	1,130	7.49	28.22	54.96	23.13	45.04	41.77	6.88	11.82
14.....	14,281	1,267	23.38	1,122	6.67	27.94	54.56	23.27	45.44	42.39	6.40	11.11
15.....	15,584	1,499	27.66	1,286	13.16	27.41	53.93	23.42	46.07	42.64	6.53	11.38
15A...	10,656	1,528	28.19	1,311	13.16	27.41	53.93	23.42	46.07	42.64	6.53	11.38

Test No.	Sulphur, separately determined (per cent). In moist coal.	Sulphur. In dry coal.	Sulphur. ([b])	Ultimate analysis (per cent). Carbon. Dry coal.	Carbon. ([b])	Hydrogen. Dry coal.	Hydrogen. ([b])	Oxygen. Dry coal.	Oxygen. ([b])	Nitrogen. Dry coal.	Nitrogen. ([b])
1	**35**	**36** (41)	**37** (41*a*)	**38** (37)	**39** (37*a*)	**40** (38)	**41** (38*a*)	**42** (39)	**43** (39*a*)	**44** (40)	**45** (40*a*)
1..........	....	....	....	....	....	....	....	....	....	....	....
2..........	0.42	0.72	0.82	60.15	68.77	4.35	4.97	21.18	24.22	1.07	1.22
3..........	.60	1.07	1.22	59.76	68.49	4.32	4.95	21.04	24.12	1.06	1.22
4..........	.79	1.42	1.63	59.36	68.20	4.29	4.93	20.90	24.02	1.06	1.22
5..........	.63	1.04	1.16	61.36	68.53	4.42	4.94	21.62	24.15	1.09	1.22
6..........	1.29	1.39	1.61	59.09	68.23	4.27	4.93	20.80	24.02	1.05	1.21
7..........	1.71	1.86	2.16	58.45	67.85	4.23	4.91	20.56	23.87	1.04	1.21
8..........	1.00	1.09	1.25	59.67	68.48	4.31	4.95	21.00	24.09	1.07	1.23
9..........	1.20	1.30	1.48	60.09	68.33	4.34	4.94	21.13	24.02	1.08	1.23
10..........	1.01	1.10	1.25	60.32	68.48	4.35	4.94	21.23	24.10	1.08	1.23
11..........	1.53	1.68	1.85	58.54	67.99	4.24	4.92	20.59	23.92	1.05	1.22
12..........	1.22	1.32	1.49	60.48	68.31	4.36	4.92	21.30	24.06	1.08	1.22
13..........	.96	1.05	1.19	60.41	68.51	4.36	4.94	21.28	24.14	1.08	1.22
14..........	.84	.92	1.04	61.00	68.63	4.41	4.96	21.47	24.14	1.09	1.23
15..........	1.18	1.31	1.48	60.55	68.32	4.38	4.94	21.30	24.04	1.08	1.22
15A........	1.18	1.31	1.48	60.55	68.32	4.38	4.94	21.30	24.04	1.08	1.22

[a] For explanation of method of computing this item see p. 27.
[b] Accompanying 100 per cent of "combustible" (coal, moisture and ash free).

TABLE 3.—*Summary of observed data and calculated items of 15 steaming tests made with North Dakota lignite, October 6–29, 1908*—Continued.

Test No.	Water fed to boiler (pounds).										Evaporation.	
	Total.	Equivalent evaporated from and at 212° F.							Actually evaporated.[a]		(d)	Factor of.
		Total.	Per hour.	(b)	Into dry steam.	Per pound of fuel—			Total.	Per hour.		
						As fired.	Dry.	(c)				
1	**46** (57)	**47**	**48** (63)	**49**	**50** (61)	**51** (69)	**52** (70)	**53** (71.1)	**54**	**55**	**56** (68)	**57** (60)
1	18,410	22,285	6,990	2.70	22,227	3.50	......	......	18,362	5,774	2.90	1.2105
2	94,187	114,004	8,234	3.18	113,377	3.69	6.33	7.35	93,669	6,802	3.07	1.2104
3	82,450	99,847	9,494	3.67	99,407	3.43	6.01	7.07	82,087	7,840	2.84	1.2110
4	78,050	94,456	6,372	2.46	93,984	3.36	6.02	7.34	77,660	5,265	2.79	1.2102
5	88,404	106,810	7,445	2.88	106,094	3.79	6.28	7.14	87,812	6,162	3.16	1.2082
6	78,520	94,507	8,397	3.25	93,457	3.30	5.65	6.72	77,648	6,976	2.77	1.2036
7	82,043	99,059	7,757	3.00	98,514	3.63	6.27	7.34	81,592	6,425	3.03	1.2074
8	73,179	88,810	8,836	3.42	88,357	3.16	5.62	6.68	72,806	7,281	2.61	1.2136
9	82,137	99,287	7,614	2.94	98,602	3.46	6.23	7.22	81,570	6,299	2.88	1.2088
10	87,126	106,407	7,200	2.78	105,619	3.77	6.70	7.72	86,481	5,895	3.11	1.2213
11	80,162	98,287	9,725	3.76	97,540	3.48	6.10	7.48	79,553	7,931	2.86	1.2261
12	88,875	108,134	9,773	3.77	107,508	3.58	6.22	7.09	88,360	8,033	2.96	1.2167
13	92,103	111,435	8,210	3.17	110,176	3.67	6.31	7.27	91,062	6,786	3.07	1.2099
14	87,195	106,038	8,281	3.20	105,413	3.77	6.54	7.38	86,681	6,809	3.11	1.2161
15	79,135	96,845	7,911	3.06	95,887	3.03	5.28	6.15	78,352	6,465	2.50	1.2238
15A	59,557	73,065	8,908	3.44	72,422	3.34	5.83	6.80	59,033	7,261	2.75	1.2268

Test No.	Composition of refuse (per cent).			Heat value per pound (B. t. u.).		Steam (per cent).		Horsepower developed.		Efficiency (per cent).[e]		
	Carbon.	Earthy matter.	Clinker.	Dry fuel.	Combustible.	Moisture in.	Quality of.	In boiler.	Per cent of rated.	Of boiler and furnace.		Over all.
										Alone.	Including grate.	
1	**58** (44)	**59**	**60** (29)	**61** (50)	**62** (51)	**63** (54)	**64** (56)	**65** (65)	**66**	**67** (72.1)	**68** (73)	**69**
1	......	......	......	......	......	0.35	99.74	202.6	81.0	......	......	......
2	15.10	84.90	28.3	10,121	11,570	.75	99.45	238.7	95.5	61.35	60.39	......
3	22.85	77.15	47.0	10,098	11,573	.60	99.56	275.2	110.1	58.99	57.47	......
4	30.60	69.40	39.4	10,075	11,576	.68	99.50	184.7	73.9	61.23	57.70	52.59
5	22.75	77.25	20.6	10,397	11,612	.94	99.33	215.8	86.3	59.38	58.33	53.59
6	37.24	62.76	43.1	10,026	11,578	1.49	98.89	243.4	97.4	56.05	54.42	49.98
7	12.98	87.02	60.3	9,936	11,534	.74	99.45	224.8	90.0	61.46	60.94	55.52
8	23.45	76.55	47.4	10,116	11,610	.69	99.49	256.1	102.4	55.56	53.65	49.81
9	16.79	83.21	46.5	10,190	11,587	.93	99.31	220.7	88.3	60.17	59.04	53.70
10	13.04	86.96	49.7	10,222	11,605	1.01	99.26	208.7	83.5	64.24	63.30	57.88
11	36.64	63.36	34.9	99,949	11,554	1.05	99.24	281.9	112.8	62.52	59.21	54.46
12	11.68	88.32	49.8	10,258	11,585	.79	99.42	283.3	113.3	59.10	58.86	54.04
13	18.39	81.61	55.8	10,238	11,610	1.53	98.87	238.0	95.2	60.47	59.52	54.36
14	5.25	94.75	63.5	10,330	11,621	.80	99.41	240.0	96.0	61.33	61.14	55.82
15	21.56	78.44	38.8	10,271	11,590	1.36	99.01	229.3	91.7	51.24	49.64	......
15A	21.56	78.44	38.8	10,271	11,590	1.21	99.12	258.2	103.3	56.66	54.81	......

[a] Corrected for quality of steam.
[b] Per hour per square foot of water-heating surface.
[c] Moisture and ash free.
[d] Apparent, per pound of coal as fired.
[e] Figured from chemical analyses of ash and coal.

TABLE 3.—*Summary of observed data and calculated items of 15 steaming tests made with North Dakota lignite, October 8-29, 1908*—Continued.

Test No.	Average thickness of fuel bed (inches).	Average intervals between firings (minutes).	Dry chimney gases.					Heat value of 1 pound of combustible (B.t.u.).	Heat balance.[b]		
			Per pound of combustible (pounds).	Analysis (per cent).[a]					Absorbed (1) by boiler (B. t. u.).[c]	Heat lost in dry flue gases (4).	
				CO_2.	O_2.	CO.	N_2.			B. t. u.	Pr. ct.
1	**70** (81)	**71** (82)	**72**	**73** (84)	**74** (85)	**75** (86)	**76**	**77**	**78**	**79**	**80**
1......	9-10	5.6	....	10.43	7.34	1.49	80.74	....	....	....	......
2......	19	4.6	16.94	10.04	9.04	.10	80.82	11,570	7,098	1,212	10.47
3......	22	3.3	15.19	11.11	7.34	.19	81.36	11,573	6,827	1,363	11.78
4......	18-20	5.0	17.29	9.79	9.27	.05	80.89	11,576	7,088	1,461	12.62
5......	17	4.9	15.04	10.83	7.99	.58	80.60	11,612	6,895	1,392	11.99
6......	22	3.6	14.29	11.18	7.42	.79	80.61	11,578	6,490	1,533	13,24
7......	22-24	4.2	13.54	12.40	6.37	.23	81.00	11,534	7,088	1,390	12.05
8......	18-20	3.5	13.88	12.23	6.45	.19	81.13	11,610	6,451	1,509	13.00
9......	22	4.2	14.48	11.49	7.60	.36	80.55	11,587	6,972	1,407	12.14
10......	20	5.0	15.09	11.06	8.20	.32	80.42	11,605	7,455	1,427	12.30
11......	20	3.1	15.30	10.92	8.26	.23	80.59	11,554	7,223	1,837	15.90
12......	18-20	3.2	13.58	12.14	6.46	.52	80.88	11,585	6,847	1,577	13.61
13......	22	3.9	15.82	10.40	8.74	.43	80.43	11,610	7,021	1,652	14.23
14......	22	4.1	14.84	11.50	7.83	.12	80.55	11,621	7,127	1,613	13.88
15......	18-20	4.8	13.75	11.44	7.03	1.03	80.50	11,590	5,939	1,518	13.10
15A....	18-20	4.8	14.15	11.54	7.12	.58	80.76	11,590	6,567	1,657	14.30

Test No.	Heat balance.								Boiler supplying steam to ash pit.				
	Loss due to moisture.				Loss due to incomplete combustion of carbon (5).		Loss in escaping hydrocarbons, radiation, and unaccounted for (6).		Time used (hours).	Used for Argand blowers.			
	In the fuel (2).		Formed by the burning of hydrogen (3).							Steam (pounds).		Heat in form of steam (per cent).	Evaporation (per cent).
	B. t. u.	Pr. ct.	B. t. u.	Pr. ct.	B. t. u.	Pr. ct.	B. t. u.	Pr. ct.		Total.	Per hour.		
1	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**
1......	......	......	......	......	......	......	......	......	......	......	......	......	......
2......	967	8.36	528	4.56	69	0.60	1,696	14.66	......	......	......	......	......
3......	1,049	9.06	540	4.67	117	1.01	1,677	14.49	......	......	......	......	......
4......	1,096	9.47	533	4.60	35	.30	1,363	11.78	14.60	6,853	469	5.11	8.69
5......	892	7.68	540	4.65	354	3.05	1,539	13.25	8.37	4,206	503	4.74	8.34
6......	1,033	8.92	556	4.80	457	3.95	1,509	13.03	9.55	5,494	575	4.44	7.58
7......	1,050	9.10	551	4.78	125	1.09	1,330	11.53	12.13	6,966	574	5.42	8.69
8......	1,127	9.71	560	4.82	106	.91	1,857	16.00	8.83	4,365	524	3.84	7.03
9......	1,123	9.69	549	4.74	211	1.82	1,325	11.44	9.87	5,651	573	5.34	8.92
10......	1,083	9.33	547	4.71	195	1.68	898	7.74	13.47	6,841	507	5.42	8.68
11......	1,116	9.66	567	4.91	142	1.23	669	5.78	9.12	5,824	639	4.75	7.51
12......	1,061	9.16	564	4.87	285	2.46	1,251	10.80	10.53	6,962	661	4.82	7.83
13......	1,017	8.76	556	4.79	276	2.38	1,088	9.37	9.30	5,496	591	5.16	7.59
14......	1,038	8.93	560	4.82	72	.62	1,211	10.42	12.22	7,252	594	5.32	8.50
15......	1,059	9.14	561	4.84	573	4.94	1,940	16.74	......	......	......	......	......
15A....	1,070	9.23	567	4.89	332	2.87	1,397	12.05	......	......	......	......	......

[a] Hydrogen and hydrocarbons not determined.
[b] Heat-balance items (designated by numbers in parentheses under this heading) are explained in Bull. U. S. Geol. Survey No. 325, p. 153.
[c] The percentage of heat absorbed by the boiler is shown under item 72.1, column 67 of this table.

OBSERVERS' NOTES.

Density of smoke.—The visible smoke during all the tests was very light and appeared to be composed mostly of water vapor. At the top of the stack hardly any smoke was discernible, the color of the smoke becoming apparent only at a distance of 15 to 30 feet from the top of the stack, where a density was observed that would be denoted on Ringelmann's chart as between Nos. 0 and 1.

Test 1, October 8.—Test 1 was short and for that reason is not considered accurate. The fuel bed at the start was comparatively thin (about 6 inches), and when thickest was only 9 to 10 inches. Samples of coal and ash of this test were not sent for chemical analysis.

Test 2, October 10.—Test 2 was run with superheated steam in the ash-pit blowers. Fire was run at low rate of combustion two days before starting the test and the fuel bed was apparently in good condition when the test was started. The fuel bed at start was about 17 inches thick; average for the test about 20 inches. The grates were shaken eleven times during the test. The fire had burned down at the close to the same level as at the start. In computing results 650 pounds was added to the weight of coal as correction for the clinkers in the fuel bed at the end of the test. Fairly uniform conditions prevailed during the test.

Test 3, October 11.—Test 3 was run with superheated steam in the ash-pit blowers. Fire was cleaned about 1 or 2 o'clock in the morning and the boiler was run at 60 to 75 per cent of rated capacity until test started. The fuel bed was about 13 inches thick at the start and 18 inches at the close; average for the test about 20 inches. During the test about 165 pounds of coal was fired at intervals of two or three minutes, spreading the coal over the entire fuel bed. The grate was shaken ten times during test. Uniform conditions prevailed during the entire test.

Test 4, October 12.—Test 4 was run with superheated steam in the ash-pit blowers. The fuel bed was about 16 to 17 inches thick at the start and about 20 to 21 inches at the close; average during test about 20 inches. The grate was shaken eight times during the entire test. Coal was fired in charges of 160 pounds at intervals of four or five minutes, spreading it over the entire grate area. Uniform conditions prevailed during entire test. Clinkers were more troublesome than in tests 2 and 3. This was probably due to the fact that the coal contained about 30 per cent of slack. The fuel was apparently of inferior quality as compared with that of tests 2 and 3. Clinkers were heavy and fused to the brick on the sides of the furnace.

Test 5, October 14.—Test 5 was run with superheated steam in the ash-pit blowers. Coal used on this test was crushed by hand and contained very small percentage of slack; it was mostly in pieces 3 to 6 inches through. Sulphur appeared, distributed in thin layers. The fuel bed was about 15 inches thick at the start and about 18 inches at the close. The grate was shaken eight times during test. Fire was apparently in good condition during the entire test. Coal was fired in charges of 165 pounds at fifteen-minute intervals. From 3.30 to 5 o'clock the fan forcing the air into the furnace through the bridge-wall opening was out of repair and ran too slowly, so that not enough air was supplied to burn the gases; this resulted in high CO content in the flue gases.

Test 6, October 16.—Test 6 was run with superheated steam in the ash-pit blower. Coal used on this test was crushed by hand and was wet from rain when fired. Sulphur appeared in rather large quantities, distributed in thin layers. The fuel bed was about 17 inches thick at the start and about 20 inches at the close; average during test about 22 inches. The grate was shaken five times during the test. Until about 3 o'clock the test was somewhat irregular; after that it ran smoothly. The grates were not shaken after 1.35 o'clock, and the fire remained in good condition. Coal was fired in charges of 165 pounds at four-minute intervals. The percentage of CO in the flue gases, as shown by analysis, is high when the air pressure to bridge-wall openings is low; when the pressure is increased CO drops.

Test 7, October 17.—Test 7 was run with superheated steam in the ash-pit blowers. Coal used was crushed by hand. Sulphur appeared in large quantity distributed in thin layers. The fuel bed was 17 inches thick at the start and 22 inches at the close; average for the test about 23 inches. The grate was shaken four times during test. Little free ash was found in the ash pit at the end of the test. The grate seemed to be entirely covered by clinkers, and no more ash could be shaken down by rocking it. When pulled the clinkers had a very strong SO_2 odor. The fire was unmanageable during the last one and one-half hours, and the test could not have been run much longer.

Test 8, October 19.—Test 8 was run with saturated steam in the ash-pit blowers. Coal was crushed by crusher, was very wet, and contained 20 to 30 per cent of slack. The fuel bed was about 16 inches thick at the start and about 20 inches at the close; average for the test 18 to 20 inches. The grates were shaken five times during the test. Attempts to shake clinkers through the grate resulted in shaking a large amount of fine coal into the ash pit. In cleaning after closing, large and thick pieces of clinker were found on the grate.

Test 9, October 20.—Test 9 was run with saturated steam in the ash-pit blowers. Coal was crushed by crusher, was wet from rain, and contained about 20 per cent slack. The fuel bed was 15 inches thick at the start and 20 inches at the close; average for the test 20 to 22 inches. After 5 p. m. the fire seemed to be in bad condition on account of clinkers, preventing free passage of air through the fuel bed.

Test 10, October 21.—Test 10 was run with saturated steam in the ash-pit blowers. Coal was crushed by crusher. Fire was started at 3 a. m., with the burning coal left on the grate after cleaning. The fuel bed was 18 inches thick at the start and 22 inches at the close; average for the test about 20 inches. Coal was fired in charges of 165 pounds at five-minute intervals.

Test 11, October 22.—Test 11 was run with superheated steam in the ash-pit blowers. Coal was crushed by crusher; the appearance of the coal was good. The fuel bed was 14 inches thick at the start and 18 inches at the close; average for the test 20 inches. The grates were shaken eight times during the test. Strong SO_2 odor came out of the ash pit when grates were shaken. Coal was fired in charges of 165 pounds at three-minute intervals. This test represents the highest capacity which can be developed with this apparatus and fuel without great decrease of efficiency.

Test 12, October 23.—Test 12 was run with saturated steam in the ash-pit blowers. Coal was crushed by crusher. The fuel bed was 14 inches thick at the start and 18 inches at the close; average for the test 18 to 20 inches. The grates were shaken five times during test, only very little at a time, so that not much fine coal was shaken into the ash pit. Coal was fired in charges of 165 pounds at three-minute intervals.

Test 13, October 26.—Test 13 was run with superheated steam in the ash-pit blowers. Coal used had been exposed to wind and sun for forty-eight hours and was crushed by crusher. The fuel bed was 13 inches thick at the start and 17 inches at the close; average for the test about 21 inches. Coal was fired in charges of 165 pounds at intervals of four or five minutes. The grates were shaken six times during the test. One of the ash-pit blowers was stopped during the first three hours of the test.

Test 14, October 27.—Test 14 was run with superheated steam in the ash-pit blowers. Coal used had been exposed to sun and wind for twenty-four hours; the portion fired after 5.30 contained about 20 per cent of slack. The fuel bed was 13 inches thick at the start and 18 inches at the close; average for the test 21 inches. The grate was shaken four times during test. Coal was fired in charges of 165 pounds at four-minute intervals.

Test 15, October 29.—Test 15 was run with superheated steam in the ash-pit blowers, steam being supplied for this purpose by the main test boiler. One object of this test was to determine whether the clinkers could be made to fall into the ash pit by frequent shaking of the grate and the fire thereby continually maintained in good running condition. At 9.45 a. m. one of the shaking bars on the left side of the grate became disconnected from the grate bars, and after that only the other (alternate) grate bars on the left side could be shaken. As a result of the frequent shaking of the grate much fine coal fell into the ash pit and the amount of refuse was increased considerably. At 6.50 p. m. the fire became unmanageable, on account of clinkers on the grate, and the test had to be stopped. The fuel bed was 18 inches thick at the start and 22 inches at the close; average for the test 22 inches.

Test 15 has been separated into two parts. The first four hours have been considered as preliminary. The intention was to run ten hours after that, but clinkers so accumulated on the grate that the second part of the test had to be stopped at the end of eight hours. The data of the two parts appear separately in Table 3. The whole test, including the preliminary part, is represented in the line opposite test number 15; the data of the last eight hours (omitting the preliminary four hours) are given in the line opposite 15A.

INTERRELATION OF DATA.

EFFECT OF VARYING RATES OF COMBUSTION.

Figures 4 and 5 show graphically the relation between the data taken during the tests and the calculated results. Each symbol on the chart represents one test. The hollow circles show tests made with saturated steam in the ash-pit blowers; solid circles show tests during which the ash-pit blowers were operated with superheated steam. The tests made with hand-crushed coal are represented by solid squares; coal on all other tests was crushed by a crusher. The two tests represented by triangles were made with coal weathered twenty-four and forty-eight hours.

Curve C of figure 4 shows the relation of the rates of combustion to equivalent evaporation per pound of dry coal. Although the symbols do not fall closely along a single line the general indication is that as the rate of combustion increases from 19 to 29 pounds of dry coal burned per square foot of grate per hour the equivalent evaporation per pound of dry coal falls from 6.4 to 5.8. This drop in evaporation when the rate of combustion increases is caused to some extent by less perfect absorption of heat by the boilers; but the principal cause, as will be shown in connection with figure 5, is less perfect combustion of the gaseous fuel. This curve also shows that hand-crushed coal does not give any better results than coal crushed by the crusher; it further shows that the use of superheated steam in the ash-pit blower does not improve the evaporation. The two tests made with the weathered coal show evaporation slightly above the average; the improvement, however, is rather small and hardly decisive. On examining the chemical composition of the coal of these two tests it is found that the weathering reduced the moisture but little, and that more could probably be gained by longer weathering.

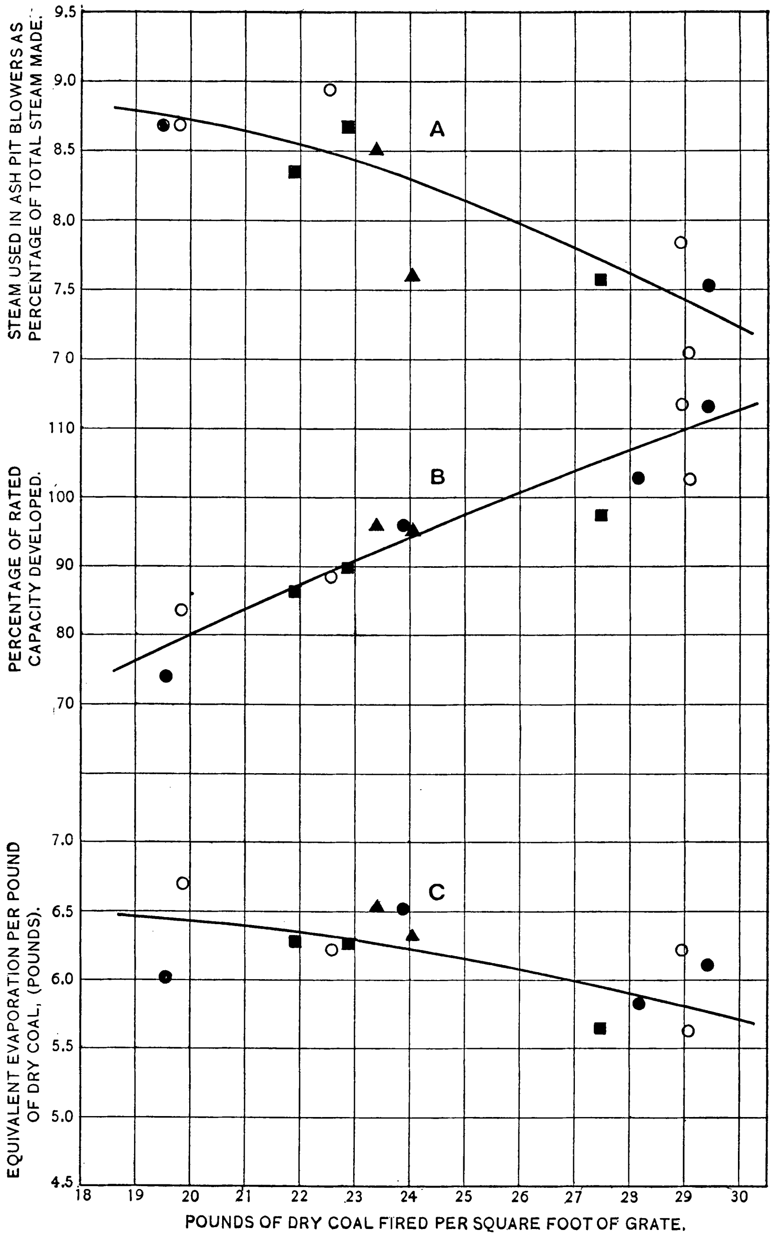

FIGURE 4.—Curves showing relations of rates of combustion to: A, Steam used in ash-pit blowers; B, percentage of boiler's rated capacity developed; C, equivalent evaporation per pound of dry coal fired.

Curve B of figure 4 shows the relation of the rates of combustion to capacity. The indication is that the capacity increases almost directly with the rate of combustion. This of course is reasonable, because when more coal is burned more heat is liberated in the furnace, and more heat is absorbed by the boiler.

Curve A representing the relation of the rate of combustion to the consumption of steam in ash-pit blowers shows that as the rate of combustion increases less steam is used. The actual drop in the consumption of steam is greater than the apparent as shown by the curve because of the fact that as the combustion increases the total steam made per pound of coal grows less, the basis of measuring the steam becomes smaller, and the consumption of the steam consequently appears larger than it really is. The curve indicates that as the rate of combustion increases from 19 to 29 pounds of coal per square foot of grate per hour the amount of steam used in the ash-pit blowers drops from 8.6 to 7.4 per cent of the total steam made. This drop is perhaps contrary to what would be ordinarily expected. In fan blowers the steam consumed would increase approximately as the square of the rate of combustion. The smaller consumption of steam by the Argand blowers at higher rates of combustion is undoubtedly due to a much increased efficiency of the blower at the higher speed. To get higher rate of combustion more air must be supplied to the ash pit; this is attained by increasing the steam pressure immediately back of the small orifices of the blower. The increased steam pressure causes the steam discharged through the orifices to move at higher velocity, resulting in an increased air supply. As this higher velocity of steam makes the blower more efficient, it seems that the blower could be made more efficient at lower speed by making each orifice in the blower smaller; this change would retain higher pressure back of the orifice and thus increase the velocity of steam issuing from it. The objection to small orifices is that they are liable to become clogged, particularly if saturated steam is used. Perhaps fewer openings, of larger size, would increase the efficiency of the blowers without giving serious trouble on account of the openings becoming clogged. It may be noted that the amount of steam used during a given period in the blowers is too high and that considering the already great abundance of moisture in the coal steam is not needed in the ash pit. This suggests the possibility that the same results could be accomplished with much less expenditure of steam by the use of a fan blower.

Curve A shows that the consumption of steam in the blower is about the same whether saturated or superheated steam is used. There seems to be no advantage in the use of superheated steam other than that of lessening the chances of clogging the openings in the blowers.

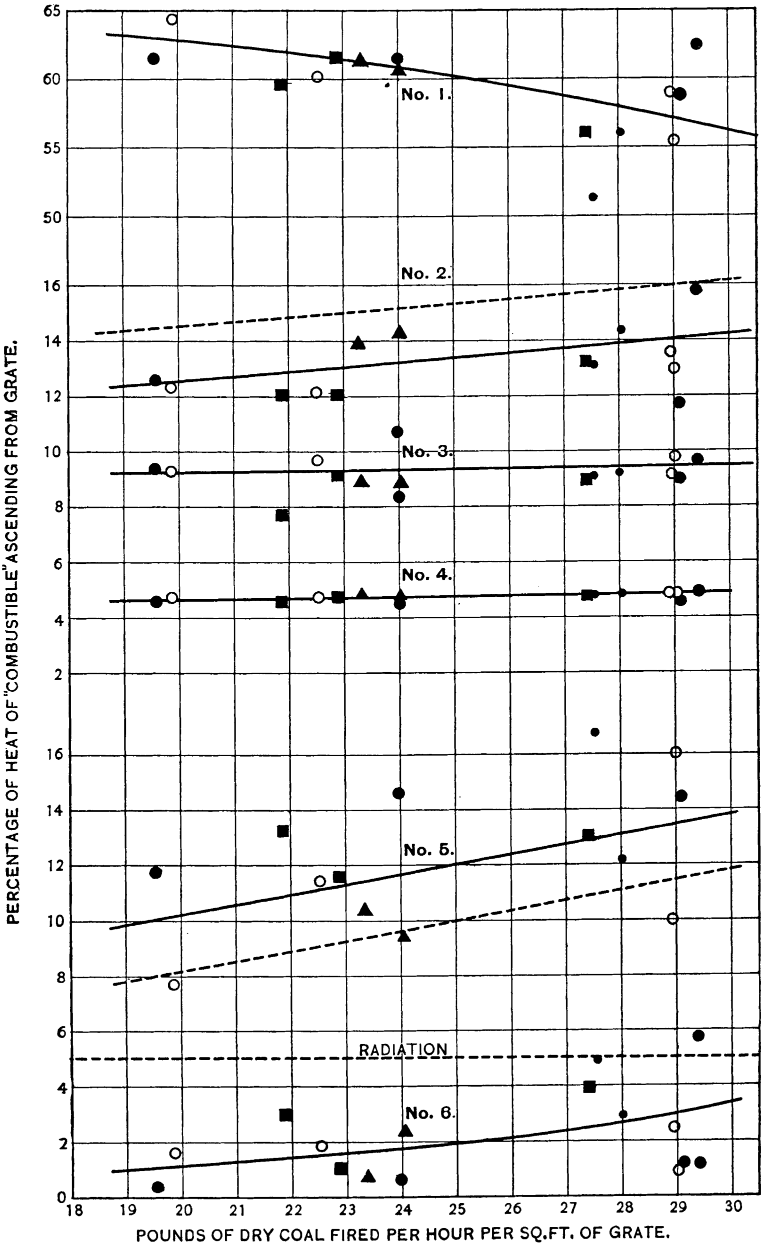

FIGURE 5.—Curves showing relations of rates of combustion to: 1, Heat absorbed by boiler; 2, heat lost in dry chimney gases; 3, heat lost in moisture in coal; 4, heat lost in moisture formed by the burning of hydrogen of coal; 5, heat unaccounted for; 6, heat lost in unburned CO in the flue gases.

Figure 5 shows the variation in the distribution of heat as the rate of combustion increases. Each item of the heat distribution is expressed in percentage of the total heat of combustible ascending from the grate. The amount of combustible thus consumed (column 23 of Table 3) is equal to the total combustible of coal as fired minus the amount of combustible in the refuse. The following equation shows the method of computing this factor (code item 30.1):

$$\left\{\begin{array}{c}\text{Com-}\\\text{bustible}\\\text{ascending}\\\text{from grate}\\\text{(pounds)}\end{array}\right\} = \left\{\begin{array}{c}\text{Total}\\\text{coal as}\\\text{fired}\\\text{(pounds)}\end{array}\right\} \frac{100-\left\{\begin{array}{c}\text{Moisture}\\\text{in coal}\\\text{(per cent)}\end{array}\right\}-\left\{\begin{array}{c}\text{Ash in}\\\text{coal}\\\text{(per cent)}\end{array}\right\}}{100} - \left\{\begin{array}{c}\text{Total}\\\text{refuse}\\\text{(pounds)}\end{array}\right\} \frac{\left\{\begin{array}{c}\text{Com-}\\\text{bustible}\\\text{in refuse}\\\text{(per cent)}\end{array}\right\}}{100}$$

The curves of figure 5 represent the items of the heat balance (columns 78–88, Table 3) plotted on the rates of combustion as abscissas. The ordinates to be used with each curve are directly at the left.

Curve 1 shows the relation of the rate of combustion to the amount of heat absorbed by the boiler which constitutes item 1 of the heat balance (column 78, Table 3), stated in percentage form as item 72.1 (column 67) in Table 3. In the code of the American Society of Mechanical Engineers for conducting steaming tests this item is designated "boiler efficiency," but strictly speaking it is the combined efficiency of the boiler and furnace exclusive of the grate.

The curve shows that in general this efficiency drops from about 63 to 57 per cent as the rate of combustion increases from 19 to 29 pounds of dry coal per square foot of grate per hour. This drop of about 6 per cent in efficiency is perhaps mostly due to less complete combustion of the gaseous combustible in the combustion space of the furnace. This statement is supported by the showing of curves 5 and 6. Curve 6 shows the heat loss caused by carbon monoxide (CO) leaving the furnace unburned. The indication is that as the rate of combustion increases from 19 to 29 pounds, the loss in CO increases from 1 to 3 per cent. When CO leaves the furnace unburned there is a very strong probability that traces of other combustible gases, such as H_2, CH_4, C_2H_4, and C_2H_2 are escaping unburned; also that small quantities of tar vapors and perhaps some solid carbon in the form of fine soot are passing unconsumed out of the furnace and causing further losses. Although each of these combustibles may escape in amounts so small that it is very difficult or impossible to measure them, there are probably so many of them that the total heat loss due to their leaving the furnace unburned may be much higher than the loss due to CO. This loss due to the unconsumed hydrogen and carbon and their various combinations appears in item 6 of the heat balance (columns 87 and 88, Table 3), which item is platted as curve 5 of figure 5. This item is called the unaccounted-for heat loss, and includes, besides the loss mentioned as due to incomplete combustion, also the loss due to radiation, as well as all the errors of observation, of sampling of coal and ash, and of chemical analysis. These errors are not likely to vary with the rate of combustion. Radiation varies with temperature only and not with the rate of making steam; therefore, the radiation loss decreases rather than increases with the rate of combustion. We may reasonably infer that if the unaccounted-for loss increases with the rate of combustion, the increase is due to the unconsumed tar vapors and gases as suggested above. On examining curve 5 it is seen that on the average the unaccounted-for loss rises from 10 to 13.5, or 3.5 per cent, as the rate of combustion increases from 19 to 29 pounds. This 3.5 per cent loss plus the 2 per cent increase in loss due to CO may perhaps account for 5.5 per cent of the total drop of 6 per cent in the efficiency accompanying the increased rate of combustion. These losses amounting to 5.5 per cent are caused by incomplete combustion and should be charged against the furnace.

Curve 2, figure 5, represents item 4 in the heat balance (columns 79 and 80, Table 3) and shows the relation of the rates of combustion to the heat carried away in dry chimney gases. The curve indicates that this loss increases from 12.5 to 14, or 1.5 per cent, as the rate of combustion increases from 19 to 29 pounds. This increase of heat carried away in dry chimney gases is caused by the rise of the temperature of the chimney gases; in other words, it is due to less complete absorption of the heat by the boiler from the gases. The increase in this loss is therefore directly chargeable to the boiler.

Curve 3 represents item 2 of the heat balance (columns 81 and 82, Table 3) and shows the relation of the rates of combustion to the heat carried away in moisture in coal. The symbols fall very closely along the line of the curve, showing that there was very little variation of this loss on different tests. Very little variation is due to the rate of combustion; the curve shows that the loss in the moisture in coal increases only about 0.25 per cent, while the rate of combustion ranges from 19 to 29 pounds.

Curve 4 represents item 3 of the heat balance (columns 83 and 84, Table 3) and shows the heat loss in moisture formed by burning the hydrogen of the coal. It has been platted rather to complete the graphical heat balance of this figure than to show any relation to other items. All the symbols of this item fall very closely along the curve, showing that this loss is about the same for all tests and very nearly the same for all rates of combustion.

It has been stated on page 15 that the recorded flue-gas temperature was probably 50° F. lower than the actual temperature. Assuming the correctness of this estimate of variation from the actual, the heat loss in dry chimney gases should be recorded 2 per cent higher and the unaccounted-for loss 2 per cent lower. Were the flue-gas temperature 50° F. higher, curve 2 of figure 5 should be shifted to the position of the dotted line above it and curve 5 to the position of the dotted line below it, but the relative position of the symbols along the curves would not be changed. The unaccounted-for loss would then run from 8 to 11.5 per cent, which is probably what it actually was.

It has been pointed out that for the investigated increase of the rate of combustion the heat loss in CO has increased 2 per cent and the unaccounted-for loss has increased 3.5; the probability has also been pointed out that the increase in the unaccounted-for loss was due to unconsumed combustible gases and tar vapors. Assuming the radiation loss to be 5 per cent and constant for all rates of combustion, by subtracting this 5 per cent from the unaccounted-for loss we have a remainder showing the loss due to unconsumed hydrogen and hydrocarbons to be represented by the corrected flue-gas temperature curve. This remainder is 3 per cent at the 19-pound rate of combustion and 6.5 per cent at the 29-pound rate of combustion. The increase is about the same as is shown by the CO curve. It should be stated here that CO in the flue gases should be considered as an indication of other losses due to incomplete combustion.

Steaming tests made by the Geological Survey with other coals have shown the same relation between the CO loss and the unaccounted-for loss, indicating that these two losses rise and fall together and that the variable part of the unaccounted-for loss is the loss due to incomplete combustion.

The showing of figure 5 may be summed up as follows: As the rates of combustion increase from 19 to 29 pounds the efficiency drops from 63 to 57 per cent, a drop of 6 per cent. About 5 per cent of this drop can be accounted for by incomplete combustion as shown by curves 5 and 6, and 1 per cent by incomplete absorption of heat by the boiler. In other words, of the total drop in efficiency about 5 per cent is probably due to lower furnace efficiency and 1 per cent to lower true boiler efficiency.

EFFECT OF MOISTURE IN COAL.

The coals burned during the tests reported in this bulletin contained very nearly the same percentage of moisture, so that the effect of moisture in coal on the economy of the operation of the steam-generating apparatus can not be deduced from the results of these tests. It is known that the presence of a small percentage of moisture may help the combustion enough to neutralize its tendency to reduce, by its high latent and specific heat, the temperature of the products of combustion; but if the moisture exceeds certain limits the reduction in temperature outweighs the advantages in combustion which may possibly be gained by its presence, and the economic efficiency of operation of a steam plant is lowered with every increase of moisture in the coal. Just what percentage of moisture in coal is beneficial in burning the coal under a boiler is at the present state of knowledge on this subject impossible to say. It undoubtedly varies with different coals. The treatment of this subject in this report relates only to the cooling effect of the moisture in coal on the products of combustion.

Heat flows of its own accord only from hot bodies to cold bodies; therefore only that portion of the heat in the products of combustion which is above the temperature of the water in the boiler can be absorbed by the water. That portion of the heat in the products of combustion which is below the temperature of the water in the boiler is not available for making steam. It follows that such condition of coal and such methods of burning it as will evolve the maximum amount of the heat in coal at a temperature above that of steam and a minimum of heat below that temperature will give the best results under a steam boiler. The harmful effect of excessive moisture in coal on steam-boiler operation is due to the fact that a large part of the heat held by the moisture is below the temperature of the water in the boiler and hence is not available for making steam. This can be illustrated by a specific example.

Suppose a boiler operates under a pressure corresponding to steam temperature of 350° F. (about 135 pounds, absolute), that the temperature of the product of combustion is 2,000° F., and that the temperature of the atmosphere is 70° F. Under these conditions 1 pound of moisture in the products of combustion contains heat units below the temperature of the water in the boiler (and hence not available for absorption by the boiler), as follows: Below the boiling point (212°–70°), 142 B. t. u.; latent heat of steam, 965 B. t. u.; superheating steam to 350° F. (350°–212°) 0.48, 66 B. t. u.—making a total of 1,173 B. t. u. The heat units in this pound of moisture above the temperature of the water in the boiler (and hence available for absorption) are (2,000°–350°) 0.48=792 B. t. u.

These figures show that the larger part of the heat in the moisture is not available for making steam. In fact, the moisture in coal and the moisture formed by burning the hydrogen of coal are equivalent to a small boiler placed in the furnace and making steam equal in weight to the moisture passing out of the furnace, thus absorbing that amount of heat before the main boiler gets a chance to absorb it.

In coals having high moisture content, such as the lignite used during the tests reported in this bulletin, the heat required to evaporate the moisture is taken from the highest temperature of the products of combustion, thereby reducing the heat available for absorption by the boiler and thus reducing the useful effect of the coal. This is shown in figure 6, illustrating the results of test 4, in burning coal with varying supplies of air. The coal used during test 4 contained 44.26 per cent of moisture. Calculations were made on the basis of 1 pound of combustible; moisture formed by the burning of hydrogen was added to the moisture in coal. Specific heat of water was taken as 1; latent heat of steam as 965; specific heat of steam as 0.48, constant at all temperatures; and specific heat of the gaseous products of combustion as 0.24, constant at all temperatures. The heat value of 1 pound of combustible, determined by calorimeter, was 11,567. The same calculations were made for coal with the moisture reduced to 20 per cent and for coal chemically dry. In all computations it was assumed that the combustible was completely burned, a condition which in practice would be difficult to obtain, especially with the low supply of air. The curves end at a point where the air supply is 10 pounds, which is near the theoretical minimum air supply with sufficient oxygen for complete combustion.

Curves 1, 2, and 3 should be studied in connection with the scales at the left and at the bottom of the figure. They show what theoretically maximum temperatures can be obtained with each air supply. Curve 3 gives the temperatures for coal having 44.26 per cent moisture; curve 2 gives the temperature for the coal with the moisture reduced to 20 per cent; curve 1 gives the temperature for the coal containing no moisture at all. Each of these curves shows that the temperature rises rapidly as the air supply is reduced. In practice this rise would not be so rapid, because as the air supply is reduced the combustion would be less complete and only part of the heat in the coal would be liberated; the temperature of the products of combustion would consequently be more or less lower than that indicated by the curves in the figure, the completeness of combustion depending on the fitness of the furnace to burn this kind of coal and on its manipulation. The three curves collectively show that for each 20 per cent reduction in moisture the temperature of the products of combustion with the same supply of air rises from 200° to 500° F.

Curves 4, 5, and 6 of figure 6 should be studied in connection with the upper scale at the right and the scale at the bottom of the figure. These curves show how much of the heat is above temperature 350° F., when 1 pound of combustible is burned with varying air supply, indicating the amount of heat available for a boiler operating under a water temperature of 350° F. Curve 6 shows this relation for the coal containing 44.26 per cent moisture; curve 5 for coal with the moisture reduced to 20 per cent, and curve 4 for coal with no moisture. The amount of gain in the available heat when the moisture is reduced is shown by curves 7 and 8, which together with curve 9 should be studied in connection with the lower scale at the right and the scale at the bottom of the figure. Curve 8 shows the higher percentage of the total heat of the combustible which is made available for the boiler by reducing the moisture from 44 to 20 per cent. Curve 7 shows how much more heat could be made available with the coal chemically dry.

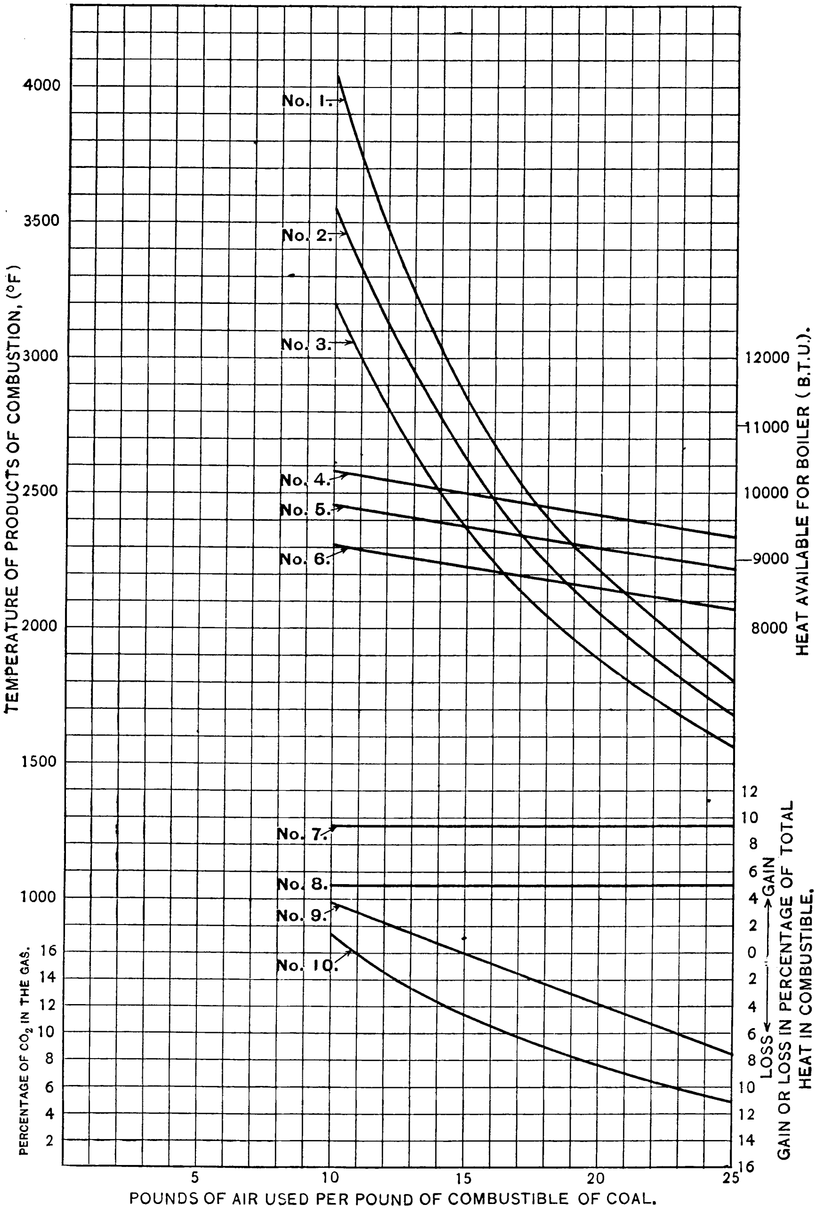

FIGURE 6.—Curves showing relation of the temperature of the products of combustion to the weight of air used to burn 1 pound of combustible; 1, for lignite chemically dry; 2, for lignite containing 20 per cent moisture; 3, for lignite containing 44 per cent moisture. Heat available for boiler in burning 1 pound of combustible of lignite: Curve 4, with moisture previously driven off; curve 5, with moisture reduced to 20 per cent; curve 6, with 44 per cent moisture. Curve 7 shows gain of conditions of curve 4 over conditions of curve 6. Curve 8 shows gain of conditions of curve 5 over conditions of curve 6. Curve 9 shows gain or loss when less or more than 15 pounds of air is used to burn 1 pound of combustible. Curve 10 shows percentage of CO_2 in the flue gases under varying air supply.

The curves show that by driving off 24 per cent of the moisture before burning the coal 5 per cent more of the total heat of combustible could be made available to the boiler, and that if the moisture were entirely driven off before burning the coal the heat available for the boiler would be increased by 9.5 per cent.

All the tests reported in this bulletin were run with about 15 pounds of air per pound of combustible. Curve 9 indicates how much more heat could be made available if the air supply were reduced below 15 pounds, provided the completeness of combustion would not be lowered The curve also indicates the decrease in the heat available if the air supply were increased beyond 15 pounds. The curve passes through zero point at the air supply equal to 15 pounds; increase in heat available for boiler is shown above the zero line, decrease in available heat below the line. It is shown that by decreasing the air supply to almost the theoretical minimum only about 3.5 per cent more heat could be made available for the boiler. It is doubtful whether in practice anything could be gained by reducing the air supply much below 15 pounds of air, because more heat would probably be lost by the incomplete combustion resulting from an insufficient supply of oxygen.

Curve 10 should be studied in connection with the lower scale at the left and the scale at the bottom of the figure. The curve shows the approximate percentage of CO_2 in the flue gases under varying air supply Thus when 15 pounds of air per pound of combustible are used the flue-gas analysis will show about 11 per cent of CO_2.

Figure 7 shows the effect of moisture in coal on the temperature of the products of combustion, the heat available for boiler, and the heat not available for boiler, when coal is burned with a constant supply of 15 pounds of air per pound of combustible, assuming that all the combustible burns perfectly.

Curve 1, to which the scales at the right and bottom of the figure apply, shows the relation of the percentage of heat available for the boiler to the percentage of moisture in coal. Thus, when the moisture in coal is 44 per cent, only 76 per cent of the total heat of coal can possibly be made available for the boiler; at 0 moisture the available heat rises to 86.5 per cent.

Curve 2, to which the scales at the left and bottom of the figure apply, shows the relation of the temperature of the products of combustion to the percentage of moisture in coal. The indication is that as the moisture decreases from 44 per cent to 0 the temperature of the products of combustion rises from 2,350° to 2,850° F.

Curves 3, 4, and 5 should be interpreted by the scale at the right. Curve 3 gives the total percentage of heat in the products of combustion unavailable for the boiler; that is, the heat which is below the temperature of the water in the boiler. Curve 5 gives the percentage of unavailable heat which is in the dry gaseous product of

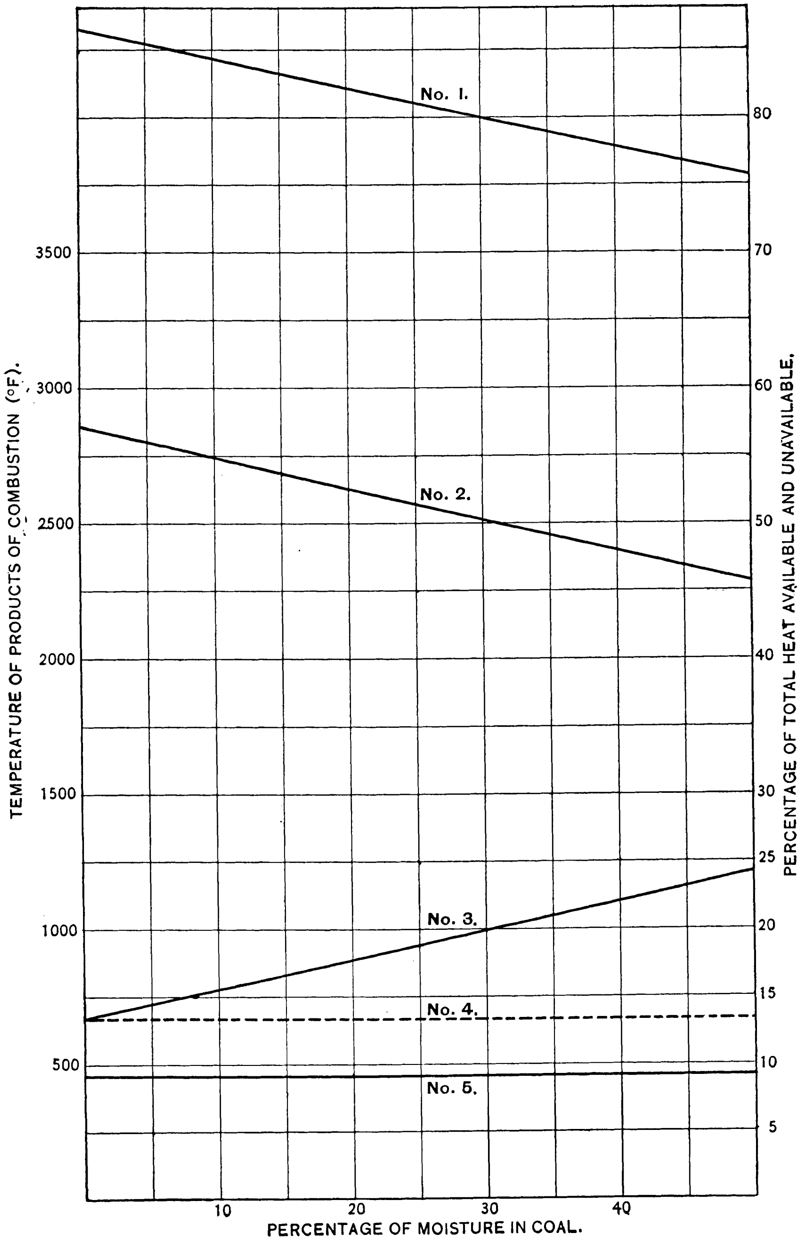

FIGURE 7.—Curves showing effect of moisture when 15 pounds of air are used to burn 1 pound of combustible: 1, on the percentage of heat available for boiler; 2, on temperature of products of combustion; 3, on the percentage of heat unavailable for boiler; 4, on the percentage of heat unavailable (curve 3) less that held by the free moisture in coal; 5, on the percentage of heat that is unavailable and is contained in dry gases. The difference between the ordinates of curves 4 and 5 gives the unavailable heat held in the moisture formed by the burning of the hydrogen of coal.

combustion. As the computation for figure 7 is made for a constant 15-pound supply of air, the percentage of heat unavailable in the gases is constant for all moistures. The difference between the ordinates of curves 5 and 4 gives the unavailable heat held in the moisture formed by the burning of the hydrogen of coal. The difference between the ordinates of curves 4 and 3 gives the unavailable heat held by the free moisture in coal. It is apparent from the figure that at the high-moisture end much more unavailable heat inheres in the combined moistures than in the dry products of combustion.

Table 4 gives the calculated values of heat available and unavailable for the boiler when burning the coal of test 4 with four different supplies of air and also four different moisture contents. The amount of heat is expressed in percentage of the total heat in the coal. Heat above 350° F. is taken as available whether in dry gases or in moisture; the unavailable is the heat below this temperature. The unavailable heat is separated into two parts, the unavailable heat in dry gases and that in the moisture, the latter being the sum of the moisture in coal and the moisture formed by burning the hydrogen of the coal. In the table each vertical column gives the percentages of heat for the same moisture in coal, but with different air supply. The last column under the heading "no moisture," shows that the unavailable heat in moisture is 4.4 per cent, which is the heat in the moisture formed by the burning of the hydrogen of coal; this moisture can not be avoided under any circumstances. The table shows clearly that so far as unavailable heat is concerned 44 per cent of moisture in coal, in addition to the moisture formed by burning hydrogen, is more harmful than 20 pounds of dry gas; also that more heat is made available in using 15 pounds of air per pound of combustible when moisture is reduced to 20 per cent, than in using the theoretical minimum supply of air when the moisture is kept at 44 per cent.

TABLE 4.—*Calculated values of heat in coal*[a] *available and unavailable for boiler under varying conditions of air supply and moisture.*

Weight of air used to burn 1 pound of combustible (pounds).	Moisture in coal (per cent).											
	44			20			10			No moisture.		
	Heat available for boiler.	Unavailable heat in— Dry gases.	Unavailable heat in— Moisture.	Heat available for boiler.	Unavailable heat in— Dry gases.	Unavailable heat in— Moisture.	Heat available for boiler.	Unavailable heat in— Gases.	Unavailable heat in— Moisture.	Heat available for boiler.	Unavailable heat in— Gases.	Unavailable heat in— Moisture.
10	79.9	6.3	13.8	85.0	6.3	8.7	87.1	6.3	6.6	89.3	6.3	4.4
15	77.0	9.2	13.8	82.1	9.2	8.7	84.2	9.2	6.6	86.4	9.2	4.4
20	74.1	12.1	13.8	79.2	12.1	8.7	81.3	12.1	6.6	83.5	12.1	4.4
25	71.2	15.0	13.8	76.3	15.0	8.7	78.4	15.0	6.6	80.6	15.0	4.4

[a] The amount of heat is expressed as a percentage of the total heat in the coal.

On test 4 the coal was burned with approximately 15 pounds of air per pound of combustible, and it contained 44.26 per cent of moisture. Table 4 shows that if all the combustible was burned perfectly only 77 per cent of the total heat in the coal could possibly be made available for the boiler. The gas analysis and the heat balance show, however, that the combustible was not burned perfectly and that about 5 or 6 per cent of the heat in coal was not developed in the furnace. This loss through incomplete combustion reduces the heat available to boiler to about 71 or 72 per cent. Furthermore, part of the heat developed in the furnace was radiated away through the walls and especially through the numerous cast-iron doors in the furnace and boiler setting. Probably a fair estimate of this loss by radiation is about 3 per cent. Deducting this loss from the amount of heat available leaves only about 69 per cent of the total heat in the coal which is really available for the boiler. No boiler ever built absorbs all the heat that is available for absorption; that is, no boiler ever reduces the temperature of the furnace gases to the temperature of the steam in the boiler. In the case of the boiler under consideration, the gases left the heating surface from 200° to 300° F. higher than the temperature of the steam in the boiler. Assuming that the true boiler efficiency of this particular boiler was 90 per cent, which estimate is rather high, the heat actually absorbed by the boiler is reduced to $69 \times 0.90 = 62.1$ per cent. Further loss of heat after being absorbed occurs by radiation from the boiler proper through the heads of the drum and through the thin brick covering on top of the steam drum. If this loss is assumed to be 2 per cent the heat carried away in steam would be reduced to 60 per cent of the heat in the coal. This is about the average actually obtained during the present series of tests.

Even if the incompleteness of combustion were reduced to, say, 2 per cent, which would be considered an unusually good result, the corresponding figures would be as follows: Heat available as generated in furnace, $77 - 2 = 75$ per cent; heat actually available after radiation loss from furnace, $75 - 3 = 72$ per cent; heat absorbed by boiler, $72 \times 0.90 = 64.8$ per cent; heat carried away in steam, $64.8 - 2 = 63$ (about) per cent.

Even should the air supply be reduced to nearly its theoretical minimum, the efficiency could not be raised very much. Thus, supposing it were possible to burn the coal with 10 pounds of air per pound of combustible, and estimating the loss through incomplete combustion at only 2 per cent, the corresponding CO_2 content of the flue gases would be about 17 per cent. For these conditions the next efficiency would be: Calculated maximum available heat (Table 4), 79.9 per cent; heat actually made available in furnace, $79.9 - 2 = 77.9$ per cent; heat actually available for boiler after radiation loss, $77.9 - 3 = 74.9$ per cent; heat absorbed by boiler, $74.9 \times 0.90 = 67.4$ per cent; heat carried away in steam, $67.4 - 2 = 65.4$ per cent.

These calculations are only approximate, but they show what can be expected from this coal when used for steaming purposes.

The above calculated figures expressing the heat carried away in steam should be compared with the results actually obtained and given in column 68 (72.1) of Table 3. The tabulated figures include the incomplete combustion in the furnace but do not include the combustible lost through the grate. The amount of loss through the grate depends on how often and how much the grates are shaken, and may amount to several per cent. Upon comparison of the calculated results with those of Table 3, it must be admitted that the results obtained during the tests herein reported are very good indeed; in fact they are as good as those obtained in many plants using the best of coal.

COMPOSITION OF FLUE GAS.

COMPARISON OF SAMPLES.

Table 5 shows the chemical composition of flue gas, the samples of which were collected at two different places in the boiler setting. The left-hand half of the table gives the composition of gas collected through the regular flue-gas sampler (described on p. 10) which was located in the uptake. The right-hand half of the table gives the composition of gases collected through a single one-fourth-inch pipe inserted through a hole in the lowest middle door in the rear of the boiler setting. The end of this single sampling pipe extended into the stream of the gases at the turn from the second to the third nest of boiler tubes. The object of taking gas samples in this position was to get samples that would be comparable with samples taken by the engineers of the plant in tests made the previous year, during which the same boiler was used.

TABLE 5.—*Comparison of composition of flue gas sampled in two different positions.*

No. of test.	Sampler in the uptake.					Sampler at middle door in rear of boiler.				
	Time of collecting sample.	Constituent gases (per cent).				Time of collecting sample.	Constituent gases (per cent).			
		CO_2.	O_2.	CO.	N_2.		CO_2.	O_2.	CO.	N_2.
11	3.15- 3.45...	11.4	8.2	0	80.4	3.30- 3.31...	13.6	6.0	0	80.4
	4.15- 4.45...	10.8	8.4	.3	80.8	4.28- 4.29...	17.8	.8	1.2	80.2
	5.00- 5.20...	9.8	9.6	0	80.6	5.15- 5.16...	13.8	5.6	0	80.6
12	8.30- 8.50...	10.6	8.0	1	80.4	8.40- 9.00...	15.6	3.2	0	81.2
	9.30-10.00...	12	6.6	.8	80.6	9.40- 9.55...	16.8	.6	1.6	81.0
	10.30-11.00...	12.2	5.2	2.2	80.4	10.50-11.00...	15.4	.2	3.4	81.0
	2.00- 2.30...	11.6	7.2	0	81.2	2.00- 2.30...	17	1.2	0	81.8
	3.00- 3.30...	12.4	6.2	0	81.4	3.00- 3.30...	17.6	.4	0	82.0
	4.05- 4.25...	12.6	6.0	.2	81.2	4.05- 4.25...	17.8	.6	.2	81.4
14	11.05-11.30...	11.4	7.8	0	80.8	11.05-11.30...	15.6	3.0	0	81.4
	1.00- 1.20...	10.2	9.4	0	80.4	1.00- 1.20...	14.8	4.6	0	80.6
	2.00- 2.25...	12.8	6.6	.2	80.4	2.05- 2.30...	17.4	1.0	1.0	80.6
	4.00- 4.30...	12.8	6.0	.8	80.4	4.05- 4.30...	17.4	.6	1.6	80.4
	7.30- 8.00...	10.2	9.0	.2	80.6	7.30- 8.00...	16.0	2.8	.4	80.8

The table shows that the sample collected through the single pipe ran 2 to 6 per cent higher in CO_2 and 2 to 6 per cent lower in O_2

than the sample collected through the regular sampler placed in the uptake. The CO content is also higher in the right-hand half of the table than in the left. There are two causes for the difference in composition of the two samples.

(1) Air leaks into the setting and increases the percentage of O_2, decreasing CO_2 by nearly the same amount. The leakage is particularly large in the last part of the gas passage on account of the numerous accessory doors and the preheating coils. There are also small but numerous openings around all metal objects which are bricked into the wall of the setting, because of the difference of contraction and expansion of metal and brick wall in response to thermal changes, and the contraction of the wall due to the drying mortar. This leakage is especially large in the last part of the gas passage because of the pressure drops from the outside air into the setting; or, in other words, because "the suction draft" is here larger than in any other part of the boiler setting.

(2) The second cause of the difference in gas composition is that the single-tube sampler drew the sample only from the central stream of gases, which was particularly high in CO_2. The sample thus taken did not represent the average gas composition of the entire cross section of the gas passage. Undoubtedly if the gas sample taken in the same cross section had been taken near the walls, it would have shown that the percentage of CO_2 at that place is even lower than the one taken in the uptake. On account of the construction and location of the sampler in the uptake the sample taken with it represented very nearly the average gas composition of that particular cross section. As the gas analysis was to be used in the computation of the heat carried up the stack, the sample should be taken just as the gases leave the heating plates of the boiler and air preheaters. Therefore the sampler was properly placed as it was. On the whole, the gas composition near the stack is good, except that occasionally, perhaps, the CO runs too high for good economy.

GAS ANALYSIS AS A HELP IN OPERATING.

The semigas-producer furnace with which these tests were made is rather delicate in its operation. Sometimes the least change of the air supply through the bridge wall or the air pressure in the ash pit, or even the condition of the fuel bed may result in high CO in the flue gases, indicating incompleteness of combustion. On a dry, clear day this incompleteness of combustion might be detected by a careful observer in the brownish color of the smoke at the top of the stack. On a damp, cloudy day, however, the moisture in the chimney gases condenses at the top or even in the stack; the fog or mist thus formed changes the color of the smoke and conceals the conditions within the furnace. The best method of learning the furnace conditions from time to time is to take a sample of gas and analyze it. The air supply through the bridge wall and the pressure in the ash pit may be regulated as need is shown by the analysis.

The function of the fuel bed is to generate the combustible gas; the function of the space above and beyond the bridge wall opening is to burn this combustible gas after air has been added. Now, if the gas analysis shows that a considerable quantity of CO escapes unburned, it is because too much gas is generated in the fuel bed for the amount of air supplied through the bridge wall. The remedy is either to increase the air supply by increasing the pressure in the duct bringing the air to the bridge wall openings or to reduce the rate of gas generation in the fuel bed by reducing the pressure in the ash pit; or both methods may be used together. Again, if the gas analysis shows high O_2 and no CO, too much air is used to burn the gases, the result being that the temperature of the products of combustion is low and less heat is available for the boiler. The remedy is either to reduce the air supply by decreasing the pressure in the air duct to the bridge wall or to generate more gas by increasing the pressure in the ash pit. Under varying loads the two pressures also have to be varied in order that the rate of heat generation in the furnace may correspond to the boiler's demand for steam.

It is impossible to determine in advance for a given capacity or rate of making steam the pressures required in the air duct to the bridge wall and in the ash pit to secure the best results, because the resistance of the fuel bed varies in accordance with the amount of ash and clinker accumulated therein. With low resistance to the passage of air through the fuel bed lower pressure in the ash pit will generate gas at the same rate as higher air pressure when the resistance of the fuel bed is high.

The resistance of the fuel bed will also vary with the size of the coal fired; smaller sizes of coal offer higher resistance to the passage of air than is offered by large uniform sizes.[a]

FORMATION OF CLINKER IN THE FUEL BED.

The ash of the coal fused at a comparatively low temperature, so that clinker was easily formed in the fuel bed. In selecting this furnace to burn this particular coal it was hoped that the solid combustible of the coal could be changed into gaseous combustible at low fuel-bed temperature, so as not to fuse the ash, and that the gas could then be burned in the combustion space at high temperature. But solid fuel to be gasified must be heated. Within certain limits the richness of the gas depends on the temperature—the higher the temperature the richer the gas.[b]

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[a] See Ray, W. T., and Kreisinger, Henry, Significance of drafts in steam boiler practice, Bull. U. S. Geol. Survey No. 367.

[b] See Clement, J. K., Adams, L. H., and Haskins, C. H., Essential factors in the formation of producer gas, Bull. 7, Bureau of Mines. See also Temperature differences in fuel bed, by J. K. Clement and H. A. Grine, in Bull. U. S. Geol. Survey No. 393, pp. 15–26.

Even the moderate temperature at which this furnace is operated is sufficient to fuse the ash and form clinker. Generally the clinker begins to form along the walls of the furnace where enough air passes along the wall to burn the fuel completely instead of only to gasify it, thus developing a temperature sufficiently high to fuse the ash. From the walls the clinker grows toward the center of the grate until the grate is entirely covered with a layer of clinkers. Shaking the grate usually helps but little; the pieces of clinker are large enough to extend over two or three grate bars, and when the bars are shaken the clinker simply rides on top of the bars and is seldom caught between them and made to fall into the ash pit. When starting to form the clinker is usually fused to the wall and therefore can not be shaken through the grate. When the grate is shaken there is always danger of shaking too much burning coal into the ash pit. The coal lies in very small pieces between and on top of the pieces of clinker, and is easily sifted through the grate into the ash pit, where it burns and heats the grate and the fuel bed above, thus helping to form more clinker. Apparently the best way to rid the fuel bed of clinkers would be to provide doors in the front of the furnace low enough so that the clinker could be easily removed by a hook or a hoe. This process of removing clinker if such doors were provided would keep the boiler out of service for only fifteen to twenty minutes during each cleaning at intervals of twelve to eighteen hours. The doors during these tests were too high above the grate and it was very difficult to remove any clinker through them. The side door, although not so high above the grate as the front fire doors, was unhandy on account of the small space available for handling the fire tools between the boilers.

CONCLUSIONS.

The combination of boiler and furnace setting described gives good results with the North Dakota lignite. Steam can be made with a fuel efficiency of 55 to 58 per cent of the heat in the coal, and no difficulty is experienced in obtaining the full capacity of the boiler. The authors are of the opinion that equally good or perhaps even better results can be obtained with mechanical stokers.

These results compare very favorably with the results obtained in the average plant using a good grade of bituminous coal when the heat available to the boiler is considered.

Little, if any, advantage is gained by crushing the coal by hand instead of in a power crusher.

To reduce the moisture in the coal by weathering seems to improve the economy, but these tests are not sufficient in number to determine definitely the condition of the fuel and the time required for weathering to insure the best results.

The steam blower for the ash pit is inefficient, and there is no gain in supplying superheated steam to it. A considerable saving in steam and equally good results could probably be obtained by substituting for the steam blower a fan such as is commonly used for forced draft.

PUBLICATIONS ON FUEL TESTING.

The following publications of the United States Geological Survey and the Bureau of Mines, except those to which a price is affixed, can be obtained free by applying to the Director of the Bureau of Mines, Washington, D. C. The priced publications can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C:

UNITED STATES GEOLOGICAL SURVEY.

BULLETIN 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, in St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp. 10 cents.

PROFESSIONAL PAPER 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. In three parts. 1492 pp. $1.50.

BULLETIN 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp. 20 cents.

BULLETIN 316. Contributions to economic geology, 1906, part 2, by M. R. Campbell and others. 1907. 543 pp. 70 cents.

BULLETIN 323. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 1907. 49 pp. 10 cents.

BULLETIN 325. A study of four hundred steaming tests, made at the fuel-testing plant, St. Louis, Mo., 1904-1906, by L. P. Breckenridge. 1907. 196 pp. 10 cents.

BULLETIN 332. Report of the United States fuel-testing plant at St. Louis, Mo., January 1, 1906, to June 30, 1907; J. A. Holmes, in charge. 1908. 299 pp. 25c.

BULLETIN 334. The burning of coal without smoke in boiler plants; a preliminary report, by D. T. Randall. 1908. 26 pp. 5 cents. (See Bulletin 373.)

BULLETIN 336. Washing and coking tests of coal and cupola tests of coke, by Richard Moldenke, A. W. Belden, and G. R. Delamater. 1908. 76 pp. 10 cents.

BULLETIN 339. The purchase of coal under government and commercial specifications on the basis of its heating value, with analyses of coal delivered under government contracts, by D. T. Randall. 1908. 127 pp. 5 cents. (See Bulletin 378.)

BULLETIN 343. Binders for coal briquets, by J. E. Mills. 1908. 56 pp.

BULLETIN 362. Mine sampling and chemical analyses of coals tested at the United States fuel-testing plant, Norfolk, Va., in 1907, by J. S. Burrows. 1908. 23 pp. 5 cents.

BULLETIN 363. Comparative tests of run-of-mine and briquetted coal on locomotives, including torpedo-boat tests and some foreign specifications for briquetted fuel, by W. F. M. Goss. 1908. 57 pp.

BULLETIN 366. Tests of coal and briquets as fuel for house-heating boilers, by D. T. Randall. 1908. 44 pp.

BULLETIN 367. Significance of drafts in steam-boiler practice, by W. T. Ray and Henry Kreisinger. 1909. 61 pp.

BULLETIN 368. Washing and coking tests of coal at Denver, Colo., by A. W. Belden, G. R. Delamater, and J. W. Groves. 1909. 54 pp.

BULLETIN 373. The smokeless combustion of coal in boiler plants, by T. D. Randall and H. W. Weeks. 1909. 188 pp. 20c.

BULLETIN 378. Results of purchasing coal under government specifications, by J. S. Burrows; Burning the small sizes of anthracite for heat and power purposes, by D. T. Randall. 1909. 44 pp. 10c.

BULLETIN 385. Briquetting tests at Norfolk, Va., by C. L. Wright. 1909. 41 pp.

BULLETIN 392. Commercial deductions from comparisons of gasoline and alcohol tests on internal-combustion engines, by R. M. Strong. 1909. 38 pp.

BULLETIN 393. Incidental problems in gas-producer tests, by R. H. Fernald, C. D. Smith, J. K. Clement, and H. A. Grine. 1909. 29 pp.

BULLETIN 402. The utilization of fuel in locomotive practice, by W. F. M. Goss. 1909. 28 pp.

BULLETIN 403. Comparative tests of run-of-mine and briquetted coal on the torpedo boat *Biddle*, by W. T. Ray and Henry Kreisinger. 1909. 49 pp.

BULLETIN 412. Comparative tests of run-of-mine and briquetted coal on a locomotive boiler, by W. T. Ray and Henry Kreisinger. 1909. 32 pp.

BULLETIN 416. Recent development of the producer-gas power plant in the United States, by R. H. Fernald. 1909. 82 pp.

BULLETIN 428. The purchase of coal by the Government under specifications, with analyses of coal delivered for the fiscal year 1908–9, by George S. Pope. 1910. 82 pp.

BUREAU OF MINES.

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

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

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