AN INVESTIGATION OF THE EFFECT OF THE FUEL BED DEPTH ON THE PERFORMANCE OF BOILER NO. 6

by

Kingston F. Peng

and

Fu-Jen Tou

Thesis submitted to the Graduate Faculty of the

Virginia Polytechnic Institute

in candidacy for the degree of

MASTER OF SCIENCE

in

Power and Fuel Engineering

APPROVED:

Director of Graduate Studies

Dean of Engineering

APPROVED:

Head of Department

Chairman of Advisory Committee

June 1, 1951

Blacksburg, Virginia

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I

INTRODUCTION

In 1949, a new Edge Moor boiler, Boiler No. 6, was put into operation in the Virginia Polytechnic Institute Heating and Power Plant. The boiler was designed to burn Virginia semi-anthracite culm coal having an ash content of 19.6 percent. At the present time, the Merrimac Mine located five miles from the plant supplies a large amount of culm for the plant, which has an ash content as high as 24 percent. Early operating experience with the boiler showed that the use of Merrimac culm alone presented big problems in coal handling, ash disposal, unsatisfactory combustion, and inability to maintain load above 45,000 pounds of steam per hour. Later a mixture of Merrimac culm and bituminous coal was burned in this unit in an effort to overcome these difficulties. The results were favorable.

In the spring of 1950, Messrs. O. Coplon, G. R. Cottingham, and J. D. Murphy made an extensive investigation to select the most economical mixture of Merrimac culm and bituminous coal for the boiler. Their selection was based on boiler tests as well as the costs of operation and coals used. They concluded that*: (1) the 4-1 mixture of Merrimac culm

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*Coplon, O., Cottingham, G. R., and Murphy, J. D., Determination of Mixture of Merrimac Culm and Bituminous Coal for No. 6 Boiler, Thesis, V. P. I., 1950.

and bituminous coal was proved to be the most economical mixture in their first series of tests; and (2) the 6-1 mixture was proved to be more economocial than the 4-1 mixture in their second series of tests. The 4-1 mixture is defined as the mixture in which four scoops of Merrimac culm are mixed with one scoop of bituminous coal, and the 6-1 mixture as the mixture in which six scoops of Merrimac culm are mixed with one scoop of bituminous coal.

Their tests were based on a constant load of 45,000 pounds of steam per hour. Because of the high percentage of Merrimac culm in the 6-1 mixture and increased ash handling when the coal is wet and load is above 45,000 pounds of steam per hour, it was decided to burn the 4-1 mixture in Boiler No. 6. Furthermore, with such a wide range of mixture to be tested and the time limitation for their investigation, it was possible for them to test each mixture at only one set of operating conditions. Since there are many factors affecting the operation of a boiler, the conditions they picked may not be optimum and the results may not be representative for each mixture. Therefore, the authors feel that further investigation of the 4-1 mixture would be desirable.

It is the authors' intention to investigate the effect of the fuel bed depth on the performance of Boiler No. 6 by burning the 4-1 mixture at a load of 50,000 pounds of steam per hour. The reason for picking 50,000 pounds of steam per hour as the test load is that it represents the average load carried by No. 6 Boiler during the winter season.

II

THE REVIEW OF LITERATURE

Boiler No. 6 is equipped with a Detroit Rotograte stoker having a forward moving grate which discharges refuse continuously over the front end of the grate into the ash pit. The coal is thrown out from the coal hoppers into the furnace by the revolving paddles at the front. The fine particles are partly burned in suspension, and the larger particles are consumed on the grate. Therefore, the Rotograte stoker uses the combined principles of suspension and grate burning. The main advantages of these principles are the ability to burn satisfactorily a wide range of coals and quicker response to load variation than any other stoker. The best performance is obtained with coal of good quality and uniform size. This method of firing, however, was developed primarily to burn those lower grades of non-clinkering coals which have high ash contents and low ash-fusion temperatures.

Most of the combustion process occurs on the grate. The fuel bed of the stoker consists of a relatively thin, level layer of coal on top of a uniform layer of ash. The fuel bed is non-agitated but intensively active. Under proper operating conditions, there is never more than a few minutes' supply of coal on the grate. This thin layer of coal lies on a cooled ash bed, and as a result of these conditions even though the ash fusion temperature may be low, few or no clinkers are formed. Furthermore, this protective layer of ash, together with uniform air flow through all portions of the grate, keeps the grate to within 50 degrees F of the air supply temperature.

Fuel burned efficiently on a grate depends on a number of factors which are so interconnected that sometimes they cannot be separated from one another. The fuel physical characteristics, composition and size of furnace, method of firing, general operating conditions of boiler and its equipment exert a marked influence on the boiler economy and efficiency. As to the method of firing, maintaining the proper depth of fuel bed is one of the variables of great importance.

In general, the best combustion results are obtained with a fuel bed that has the lowest possible resistance to air flow which will permit the air and fuel to combine completely and leave a small proportion of excess oxygen remaining in the products of combustion. Low resistance to air flow fundamentally means low air velocity which in turn minimizes the amount of fuel and ash blown upward into the furnace. Low resistance should produce a fairly uniform condition over the entire stoker.

The resistance of the fuel bed to the air flow through it is a function of at least three factors: (1) the thickness of the fuel bed; (2) the proportion of coke to green coal; and (3) the amount and characteristics of ash present. Considering the three factors, we find that it is necessary to correlate all three in order to produce suitable resistance.

As most of the oxygen from the primary air is consumed in the first four inches of fuel bed measured from the grate, it is not necessary with the ordinary rates of combustion to run a fuel bed thicker than four to six inches. The rate of gasification of coal depends on the amount of air that can be passed through the fuel bed. The thicker the fuel bed, the higher is its resistance to the flow of air through it, and the less air can be passed through with a given available draft. A thick fuel bed, therefore, reduces the rate of combustion and thus reduces the capacity of the boiler.

A thick fuel bed is further undesirable because it increases the tendency of the coal to form troublesome clinkers. On the other hand, a thin fuel bed gives less resistance for air to pass through. But, when the boiler is carrying a high load, a thin fuel bed causes difficulty in maintaining constant pressure and requires close attention to prevent holes being burned in spots.

A test* to determine the effect of the depth of fuel bed on the efficiency of a boiler has been conducted on a 350-horsepower Stirling Boiler equipped with a chain grate stoker at the power plant of the Armour Institute of Technology of Chicago. The fuel bed thickness was varied from two to seven inches. The result showed that 4.25 inches of fuel bed gave the highest boiler efficiency.

For a given furnace and boiler, quality and size of coal, and intensity of draft, a certain depth of fuel bed will give maximum efficiency. On account of the number of considerations upon which the proper thickness depends, it can be determined only by actual test.

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*Gebhart, F. G., Steam Power Plant Engineering, New York: John Wiley and Sons, Inc., 1917, p. 93.

III

THE INVESTIGATION

(1) Object of Investigation

The object of this investigation is to study the effect of the depth of fuel bed on the performance of Boiler No. 6 at a load of 50,000 pounds of steam per hour by using the 4-1 mixture of Merrimac culm and bituminous coal, and to determine the optimum depth of fuel bed at these conditions.

(2) Proposed Method of Procedure

Boiler tests will be conducted with three different depths of fuel bed at a load of 50,000 pounds of steam per hour by using the 4-1 mixture of Merrimac culm and bituminous coal. The three depths of fuel bed shall be 2-3/4, 4 and 5½ inches. For each fuel bed depth, two boiler tests will be run in order to obtain a check of the results. The other operating factors for the boiler will be held as constant as possible throughout the entire investigation.

The boiler tests will, whenever possible, conform to the A.S.M.E. Power Test Code for Stationary Steam-Generating Units. The duration of each test shall be five hours. Although the Power Test Code recommends the duration of test should be at least twenty-four hours or not less than ten hours for stoker fired units, the authors feel justified to reduce the duration of test to five hours with the Rotograte stoker. The reasons are that the coal burns either in suspension or within a short time after it falls on the bed, and the weight of coal in the furnace does not vary to any great extent from the start to the end of a test. Also the facilities of the plant demanded short tests.

In addition to the boiler tests, a coal sample for each boiler test will be collected to determine the proximate analysis. From the proximate analysis, Evans' Empirical Relations will be applied to determine the higher heating value of coal, and total carbon and hydrogen in coal. For each boiler test, a refuse sample will be collected. A combustible analysis will be run on each refuse sample to determine the percentage of combustible in refuse.

From the test data, the boiler efficiency and heat losses will be determined.

The results of this investigation should serve as an operating guide for the power plant when the 4-1 mixture is used and the load is around 50,000 pounds of steam per hour.

(3) Apparatus

The equipment used in this investigation consisted of the following:

Steam Generator: The steam generator was designed and erected by Edge Moor Iron Works. It is a cross-drum bent-tube boiler having two drums. Its specification and dimensions of various parts are as follows:

1. Maximum evaporation .... 60,000 Lb of steam per hour
2. Operating pressure .... 250 psig
3. Total temperature .... 506 deg. F.
4. Heating surface:
    - Boiler .... 6034 sq. ft.
    - Water walls .... 1120 sq. ft.
    - Superheater .... 475 sq. ft.
    - Air preheater .... 3030 sq. ft.

5. Diameter of top drum .... 54 inches
6. Length of top drum .... 15 feet
7. Diameter of bottom drum .... 36 inches
8. Length of bottom drum .... 14.6 feet
9. Tubes:

Boiler	592 tubes	2 in. dia.	12 BWG
Water walls ..	46 tubes	3.25 in. dia. .	10 BWG
Superheater ..	26 tubes ...	1.875 in. dia. .	9 BWG

<u>Stoker:</u> The stoker is a Detroit Rotograte Stoker manufactured by the Detroit Stoker Company. It is equipped with three hoppers with a coal feed and rotor assembly for each hopper. It has a forward moving grate which discharges the refuse continuously over the front end of the grate into the ashpit. The following are its physical dimensions:

1. Width .... 10 ft. 7½ in.
2. Length .... 12 ft. 8 in.
3. Effective grate surface .... 116.9 sq. ft.
4. Effective length .... 11 ft.

<u>Dust Collector:</u> The dust collector is Thermix tubular type manufactured by the Pratt-Daniel Corporation. It was designed to handle 83,000 pounds of flue gas per hour at 500 deg. F.

<u>Forced Draft Fan:</u> The forced draft fan was manufactured by W. H. Sturtevant, B. F. Sturtevant Company Division. It delivers 20,800 cubic feet of air per minute at sea level, and is driven by a 30-horsepower Westinghouse Induction Motor.

<u>Induced Draft Fan:</u> The induced draft fan was manufactured by Pratt-Daniel Corporation. It is driven by a 75-horsepower motor through an American Blower hydraulic coupling. The capacity of the fan is 36,000 cubic feet per minute at 425 deg. F.

<u>Cinder Return Fan:</u> The cinder return fan was manufactured by the Buffalo Forge Company. It is driven by a 15-horsepower General Electric Motor.

Auxiliary Air Fan: The auxiliary air fan was manufactured by the Clarage Fan Company. It is driven by a 2-horsepower General Electric Motor.

Ash System: The plant is equipped with a vacuum type ash system, which was designed and installed by the United Conveyor Corporation. The vacuum is maintained by means of a steam jet. The ash system will draw the ash from the ash pit after the ashes are pulled from the ash hopper, from the dust collector hoppers, and also from the downspouts of the dust collector as desired.

Boiler Feed Water Pump: The boiler feed water pump is a multi-stage centrifugal pump and is driven by a 50-horsepower Westinghouse Induction Motor. Its capacity is 100 gallons per minute.

Auxiliary Boiler Feed Water Pump: The auxiliary boiler feed water pump is a multi-stage centrifugal pump manufactured by American Marsh Pumps, Inc., and is driven by a steam turbine manufactured by Whiton Machine Company. Its capacity is 135 gallons per minute.

Combustion Control: The boiler is equipped with and controlled by a Hays Combustion Control system. The master control is governed by the steam pressure. The master control actuates the forced draft fan control, then in turn acts on the coal feed control. The induced draft fan is actuated by the furnace draft. The fan changes its speed thus holding the furnace draft to the required setting. The damper is set on this installation and is not changed except for changes in fuel type or extreme changes in firing conditions.

Miscellaneous Equipment: Pressure gages, thermometers, Orsat apparatus, platform scales, weigh larry, steam flow meter, blow down meter, automatic recorders for temperature and pressure, draft gages.

(4) Procedure

In order to investigate the effect of the depth of fuel bed on the performance of Boiler No. 6 by using the 4-1 mixture of Merrimac culm and bituminous coal, and to obtain test results as an operating guide, boiler tests were run under conditions similar to everyday plant operation. However, some variables were held as constant as possible in order to obtain comparative results on different depths of fuel bed. Throughout the entire investigation, the variables held constant were the test load, the duration of test, the firing method, the method of mixing the coals, and the methods of sampling coal and refuse.

These tests conformed to the A.S.M.E. Power Test Code for Stationary Steam Generating Units whenever possible. Two five-hour tests were run with the 4-1 mixture for each depth of fuel bed at a load of 50,000 pounds of steam per hour. The duration of test was cut short for the reasons previously stated in the Proposed Method of Procedure. The depths of fuel bed were 2-3/4, 4 and 5 ½ inches, measured under the front arch of the stoker.

Before starting the test, the overhead storage bins were emptied and then filled with the 4-1 mixture of Merrimac culm and bituminous coal to be tested. A payloader having a twenty cubic foot scoop was employed to mix the coals. Four scoops of Merrimac culm and one scoop of bituminous coal were first unloaded on the ground near the screw conveyor. Then the whole mass of the coals was pushed through the grate to the screw conveyor and was delivered to the storage bins by the coal handling system.

The test fuel was burned in the furnace for about two hours before the actual start of the boiler test, in order to allow the furnace and fuel bed to reach the required, stable operating conditions. The load was adjusted to 50,000 pounds of steam per hour by regulating the load on one of the plant's steam turbo-generators and by varying the amount of steam bled to the low pressure line. The instantaneous load was showed by a pointer on the Cochrane steam flow meter, and the total steam flow was obtained by getting the difference in the integrator readings at the beginning and at the end of each test. This meter was calibrated to give the correct reading at a pressure of 250 psig and total temperature of 506 degrees F. For conditions other than those for which the meter was calibrated, a correction factor was applied to the reading to give the correct amount of steam flow. The correction factor was the ratio of the specific volume of steam at calibrated conditions to the specific volume of steam at the average pressure and temperature of each test.

The per cent of CO_2, as noted on the CO_2 recorder, was kept within the range of 10 to 12 per cent by adjusting the fuel feed control. The fuel bed was held at the desired thickness as constant as possible by adjusting the grate speed. The flyash was returned to the furnace for reburning. The furnace combustion was closely watched to be sure that a sufficient amount of fuel was burned at the back end of the grate. The speed of the revolving paddles was adjusted in order that the fuel would be thrown to the back end of the grate in case unsatisfactory combustion was noticed.

Before each test, the Orsat apparatus was checked and its solutions were renewed, the soot was removed from the tubes by the soot blowers, the boiler was blown down, the flyash was removed from the down-spouts, and the ash pit was cleaned.

At the beginning and the end of each test, the furnace hoppers were filled, the integrator reading was taken, the blow-down flow meter was read, and the boiler drum water level was checked and marked. During each test, the majority of the meter and gage readings were taken at fifteen minute intervals except those noted on the data sheets.

Each time the furnace hoppers were filled, a coal sample was collected and kept in air-tight jars. The sample for each test was then prepared for the proximate analysis. The methods of sampling, preparation, and the proximate analysis were those of the A.S.T.M. Standards on Coal and Coke.

The ash sample was collected from the ash pit whenever the ashes were pulled. The sample was then prepared for the combustible analysis. By using the result from the combustible analysis, the amount of refuse was calculated. The method of calculation is shown in the sample calculations.

Before and after this investigation, the pressure gages were calibrated by using a dead weight tester. The thermometers were calibrated against a resistance thermocouple. Corrections were applied to all readings before calculating the results.

(5) COMPOSITE RESULT SHEET

Test No.	1	2	3	4	5	6
Date of test, 1951	Feb.16	Feb.16	Feb.27	Feb.27	Mar.6	Mar.9
Duration of test, hours	5	5	5	5	5	5
Depth of fuel bed, inches	5½	4	4	5½	2 3/4	2 3/4
Fuel used; Mixture of Merrimac culm and bituminous coal at the ratio of	4:1	4:1	4:1	4:1	4:1	4:1
Coal as fired						
Moisture, per cent	5.7	5.8	6.3	6.8	6.0	7.0
Volatile matter, per cent	14.3	13.7	12.0	13.8	12.2	12.9
Ash content, per cent	19.2	19.6	24.8	24.4	30.6	22.6
Fixed carbon, per cent	60.8	60.9	56.9	55.0	51.2	57.5
Higher heating value, Btu per lb	11,730	11,720	10,840	10,820	9,960	11,190
Carbon, per cent	68.4	62.8	62.5	61.5	56.9	63.5
Hydrogen, per cent	3.11	4.95	3.34	3.43	3.75	3.50
Refuse analysis						
Combustible, per cent	32.3	32.2	32.9	30.0	27.0	32.2
Coal burned, lb. per hour	6,451	6,112	7,276	8,143	8,125	7,045
Steam generated, lb. per hour	48,220	47,172	49,100	48,650	48,700	50,000
Evaporation, lb. steam/lb. of coal	7.45	7.73	6.75	6.53	5.98	7.10
Weight of refuse, lb. per hour	1,990	1,772	3,698	2,600	3,560	2,044
Blowdown, lb. per hour	1,544	1,475	633	598	1,505	1,405
Temperatures, degree Fahrenheit						
Dry-bulb	62.1	61.9	81.1	78.3	76.8	72.2
Wet-bulb	47.0	49.8	57.9	53.1	59.2	51.4
Fuel	74.4	71.8	80.6	81.9	75.5	78.1
Gas to air heater	620	615	582	580	585	598
Gas from air heater	432.5	435	436.6	437.5	435	441
Air to air heater	68.5	66.4	84.3	82.7	78.0	70.7
Air from air heater	318	322	326	329	324	325
Feedwater	227.5	223.0	229.3	225.0	228.7	224.4
Superheater inlet	401	402	400	400	403	404
Superheater outlet	514	505	516	518	516	516

(5) COMPOSITE RESULT SHEET

(Continued)

Test No.	1	2	3	4	5	6
Pressures, psig						
Steam drum	260	261	259	258	257.5	263
Superheater outlet	248.5	250	248	247.5	247.6	252
Barometric pressure, in. Hg.	28.48	28.32	27.96	27.96	28.14	28.24
Draft gage readings, in. of water						
Air in air heater	3.45	2.56	3.03	2.62	3.26	2.81
Windbox	1.84	1.22	1.74	1.48	1.72	1.51
Furnace	-0.27	-0.23	-0.16	-0.22	-0.23	-0.27
Last Pass	-1.50	-1.30	-1.42	-1.41	-1.50	-1.47
Air heater outlet	-3.00	-2.33	-2.63	-2.55	-2.85	-2.76
Induced draft fan	-6.00	-4.85	-5.07	-4.88	-5.56	-5.39
Analysis of flue gas, per cent in volume						
CO_2	10.63	12.00	9.50	10.26	10.70	10.25
O_2	7.30	6.77	9.27	8.77	8.14	8.48
CO	0.07	0.05	0.08	0.06	0.02	0
N_2	82.06	81.18	81.15	80.90	81.14	81.27
Excess air, per cent	51.0	65.5	70.0	69.0	61.3	65.5
Heat Balance, per cent						
Heat absorbed by unit	68.10	69.90	66.80	65.15	64.50	68.40
Loss due to dry flue gas	10.52	8.52	10.39	10.72	9.16	10.18
Loss due to moisture in coal	0.58	0.61	0.70	0.76	0.73	0.76
Loss due to water from combustion of H_2	2.90	3.34	3.34	3.44	4.12	3.42
Loss due to moisture in air	0.07	0.08	0.09	0.05	0.12	0.06
Loss due to carbon monoxide	0.34	0.40	0.40	0.30	0.01	0
Loss due to carbon in refuse	11.35	11.61	16.42	13.87	16.55	12.15
Loss due to blowdown	0.38	0.41	0.15	0.14	0.34	0.36
Loss due to radiation	1.14	1.14	1.14	1.14	1.14	1.14
Unaccounted-for losses	3.41	3.99	0.47	4.43	3.43	3.53
Total	100.0	100.0	100.0	100.0	100.0	100.0
Boiler efficiency, per cent	68.10	69.90	66.80	65.15	64.50	68.40

(6) Curves

Fig. 1: The curve on this figure shows the boiler efficiency against the fuel bed depth. The boiler efficiency at each fuel bed depth has been converted to 23.53 per cent of the ash content in the coal mixture, which is the average ash content of the coal mixture for the six boiler tests. The reason for this conversion is explained in the Discussion of Results, and the method of calculation is shown in Appendix (3).

Fig. 2: The curves plotted on this figure show heat losses at various fuel bed depths.

Fig. 3 and 4: The curves plotted on these figures illustrate the test results at various fuel bed depths.

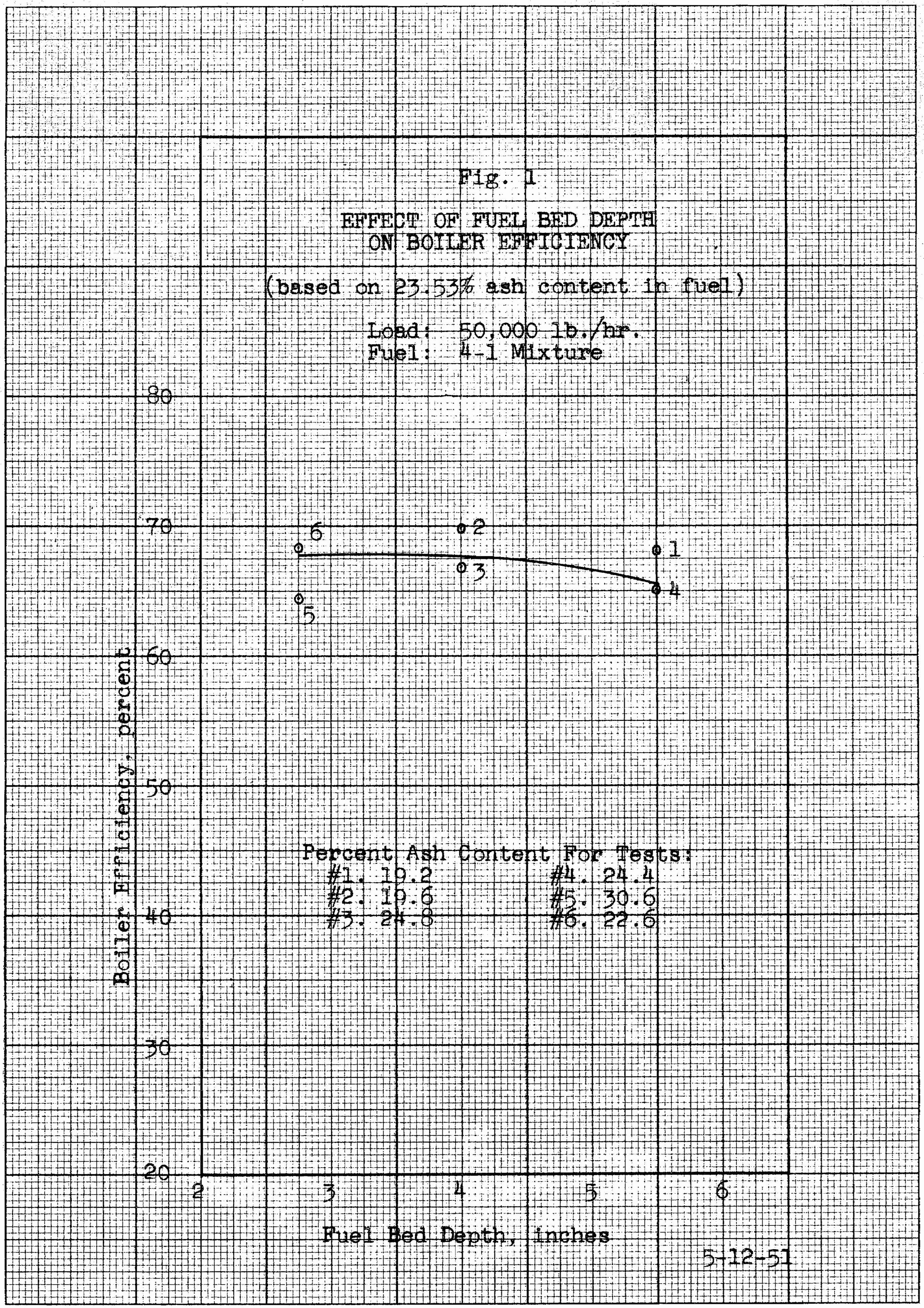
Fig. 1
EFFECT OF FUEL BED DEPTH
ON BOILER EFFICIENCY
(based on 23.53% ash content in fuel)
Load: 50,000 lb./hr.
Fuel: 4-1 Mixture
Boiler Efficiency, percent
80
70
60
50
40
30
20
6
2
1
3
4
5
Percent Ash Content For Tests:
#1. 19.2
#2. 19.6
#3. 24.8
#4. 24.4
#5. 30.6
#6. 22.6
2
3
4
5
6
Fuel Bed Depth, inches
5-12-51

Fig. 2

HEAT LOSSES AT VARIOUS FUEL BED DEPTHS

Load: 50,000 lb./hr.
Fuel: 4-1 Mixture

Legend:
⊙ heat loss due to carbon in refuse
▲ heat loss due to dry flue gas

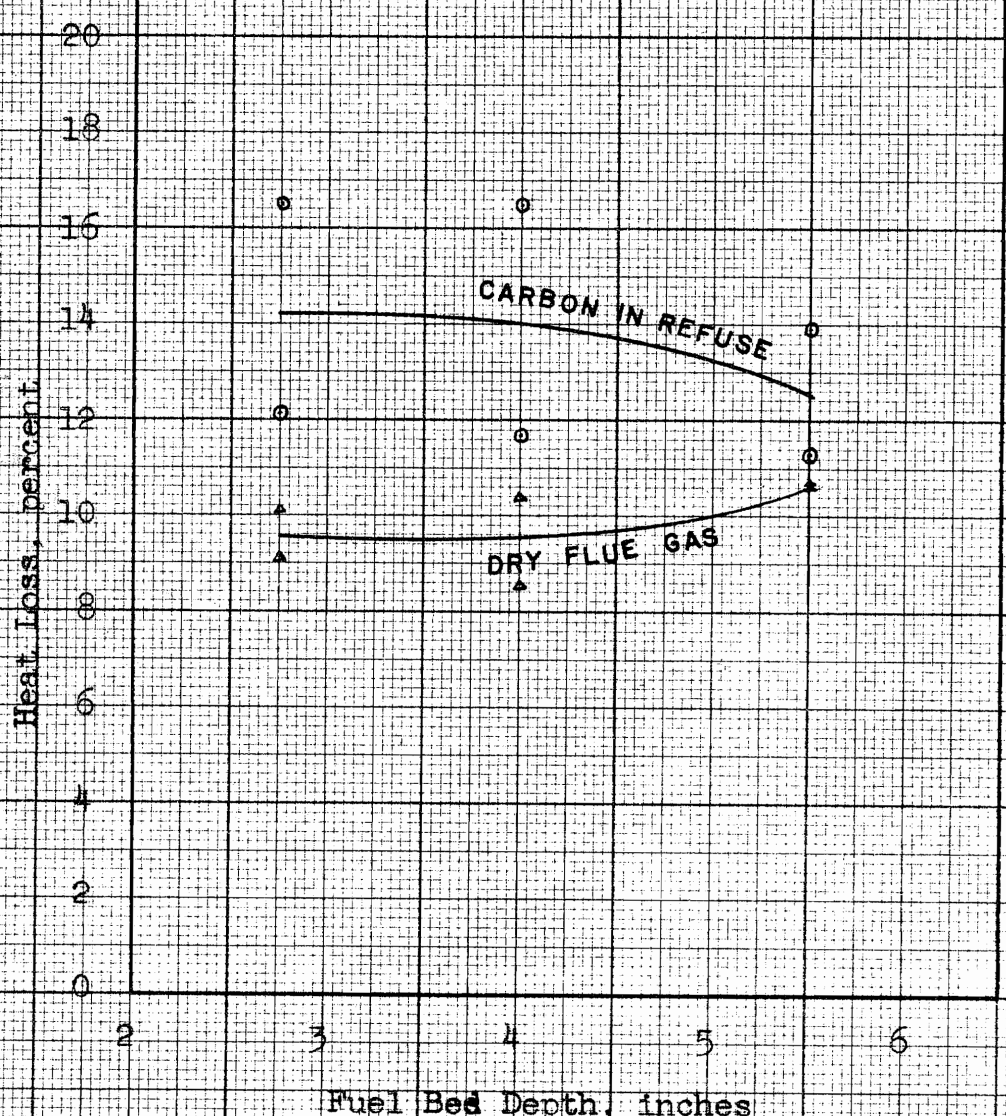

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Fig. 3

TEST RESULTS AT VARIOUS FUEL BED DEPTHS

Load: 50,000 lb./hr.
Fuel: 4-1 Mixture

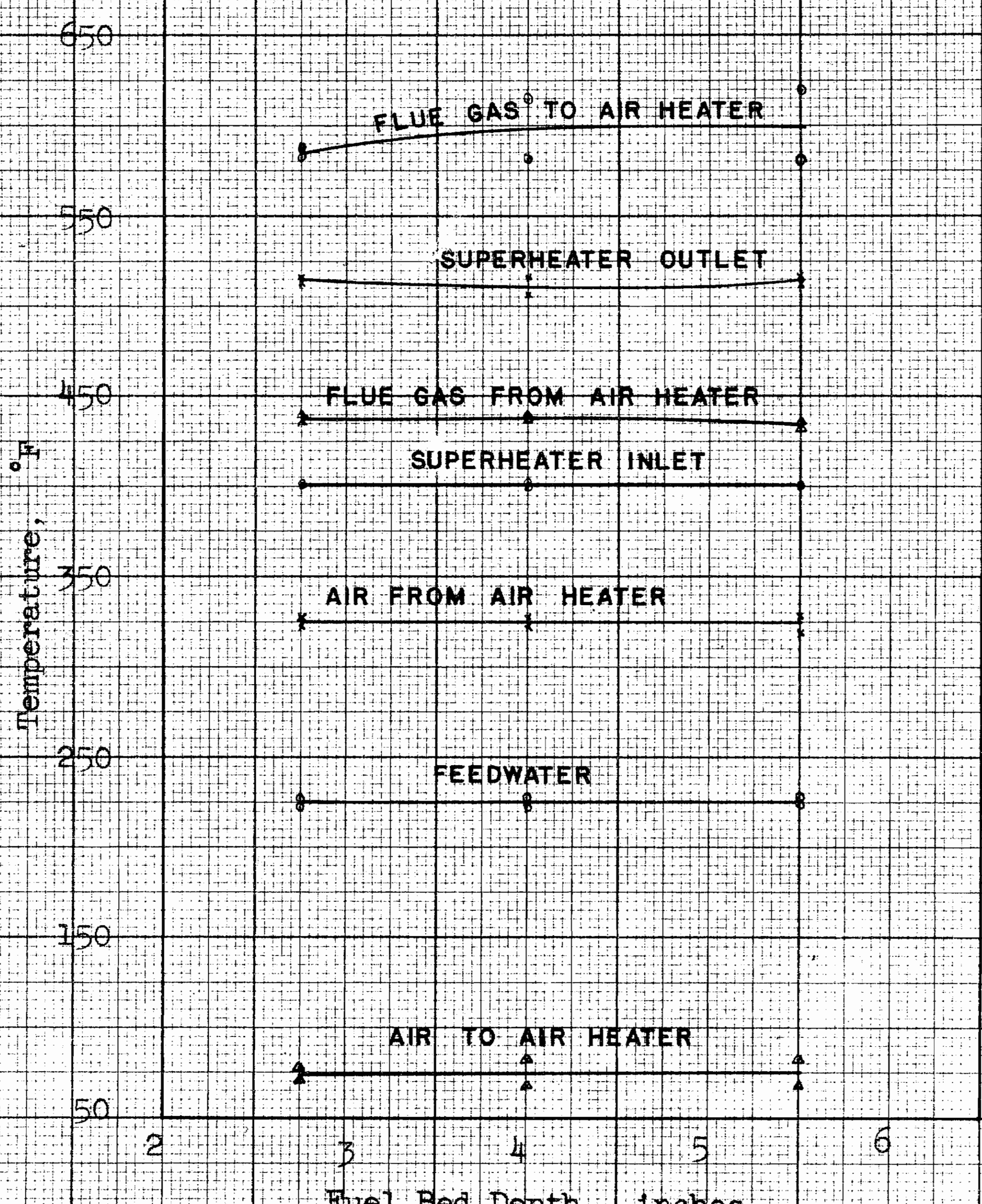

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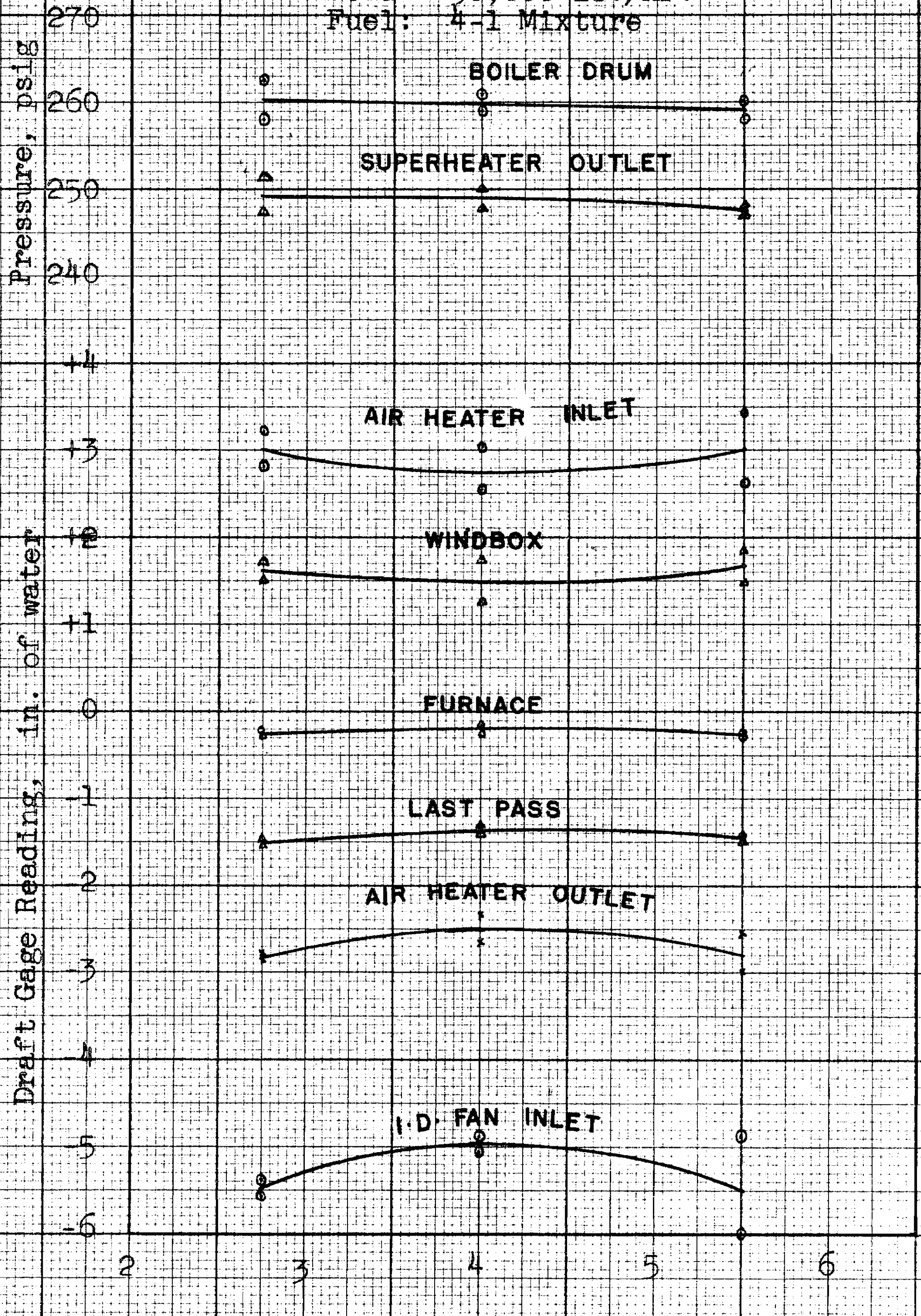
Fig. 4

TEST RESULTS AT VARIOUS FUEL BED DEPTHS

Load: 50,000 lb./hr.
Fuel: 4-1 Mixture



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IV

DISCUSSION OF RESULTS

The maximum fuel bed depth that can be obtained in Boiler No. 6 is limited by the distance between the grate and the front arch of the stoker. This distance was designed to be seven inches. But it was detrimental to the stoker as the fuel bed was increased above 5½ inches. When the depth of the fuel bed was high, clinkers were formed. Because of such a narrow space between the fuel bed and the front arch, the clinker formed at a fuel bed above 5½ inches had the tendency to stick on the front arch. The refractory on the front arch was likely to be damaged. On the other hand, the fuel bed could not be lower than 2-3/4 inches at the load of 50,000 pounds of steam per hour, because of the difficulty in maintaining the pressure at 250 psig. Therefore, the boiler tests were run at 2-3/4, 4, and 5½ inches fuel bed depth.

The proximate analyses of the coal mixture for the six boiler tests showed that the ash content was in the range of 19.2 to 30.6 per cent. With such a wide range of ash content, it was not justified to compare the boiler efficiencies at various depths of fuel bed. As stated in Fuels and Combustion Handbook*, for each one per cent increase in ash content, the

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*Johnson, A. J. and Auth, G. H., Fuels and Combustion Handbook, 1st Edition, New York: McGraw-Hill Book Company, Inc., 1951, p. 40.

boiler efficiency decreases about one third of one per cent or greater in cases where the loss of carbon in refuse is not carefully controlled, and where the coal is of such poor quality that appreciably greater draft is required to maintain the load. The test results of this investigation agreed with these reference values. Therefore, in order to obtain a true comparison of the effect of the fuel bed depth on the boiler efficiency, the curve in Figure 1, showing the boiler efficiency against the fuel bed depth, has been drawn for the boiler efficiencies based on the ash content of 23.53 per cent. This percentage ash content is the average ash content of the coal mixture for the six boiler tests.

The curve in Figure 1 illustrates that the boiler efficiency remains approximately constant between 2-3/4 and 4 inches of the fuel bed depth, and decreases as the fuel bed depth is increased above 4 inches.

In performing the boiler tests at a 2-3/4 inches fuel bed depth, close attention was necessary to keep the pressure at 250 psig. This was due to the fact that the amount of the fuel on the bed was considerably less and the quality of the coal mixture was not uniform. In case the quality of the coal mixture was poor, the boiler pressure would drop. Since the fuel bed was thin, there was comparatively low resistance to the flow of air through the fuel bed. Under this condition, the mixing of air and fuel was more complete, and as a result, the combustion in the furnace was better. Because the grate speed was so high less time was available for the fuel to burn on the grate. This resulted in a large amount of the carbon being lost in the refuse. As shown in Figure 2, the heat loss due to carbon in the refuse was the highest loss at this depth among the three depths of fuel bed tested.

During the boiler tests at a 4 inches fuel bed depth, it was relatively easy to hold the boiler pressure at 250 psig, since the grate speed was lower than that at the 2-3/4 inches fuel bed depth, and the time for the fuel to burn on the grate was longer, the heat loss due to carbon in the refuse was reduced appreciably as shown by the curve in Figure 2.

For the boiler tests at a 5½ inches fuel bed depth, the grate speed was low and the fuel had more time to burn on the grate. The test results showed that the heat loss due to carbon in the refuse was the lowest loss at this depth among the three fuel bed depths tested. When the fuel bed was thick, it was difficult for air to flow through it. Under this condition, the temperature of the fuel bed was high. Because of this high temperature in the fuel bed, clinkers were formed. In general, the combustion in the furnace was poor at this fuel bed depth.

The size of the bituminous coal used in the coal mixture was larger than that of the Merrimac culm. Consequently, the size of the coal particles in the mixture was not uuiform. After being thrown out of the coal hoppers by the revolving paddles, the large lumps of bituminous coal fell near the front end of the grate. There was little time for them to burn on the grate. The result was that the loss of carbon in the refuse was generally high. The combustible analyses of the refuse from the six boiler tests showed that the percentage of carbon in the refuse was in the range of 27 to 32.9 per cent. These large losses could be lowered if the bituminous coal were crushed to a uniform size as Merrimac culm.

Another effect of the non-uniform size of the coal mixture was the size segregation. When the coal mixture was dumped from the coal handling system to the storage bins, and from the weigh larry to the coal hoppers, the large lumps of the bituminous coal had a tendency to separate themselves from the rest of the fine coal. As the coal mixture burned in the furnace, there was a large amount of the bituminous coal at one time and a small amount at the other. Because of this intermittent change of the coals fed into the furnace, the combustion was greatly affected. For this reason, close attention was necessary to adjust the fuel feed in order to hold the boiler at desirable conditions.

V

SUMMARY

In attempting to use the 4-1 mixture for Boiler No. 6 in the Virginia Polytechnic Institute Heating and Power Plant, the problem of maintaining proper depth of fuel bed had arisen. This problem seemed to warrant an investigation, which was subsequently made.

The fuel bed depth that will give the best results for a boiler depends on many factors, and it is best determined by boiler tests. Therefore, the authors decided to investigate the effect of the fuel bed depth on the boiler performance and to determine the optimum fuel bed depth, when the 4-1 mixture was used and the load was 50,000 pounds of steam per hour.

This investigation consisted of the collection and evaluation of data obtained from the boiler tests at various fuel bed depths. During the boiler tests, some of the variables were held as constant as possible in order to obtain comparative results. The fuel bed depths tested were 2-3/4, 4, and 5½ inches. The optimum depth of fuel bed is that fuel bed which would give the highest boiler efficiency and good boiler control.

The results of the tests showed that the boiler efficiency remained approximately constant between 2-3/4 and 4 inches of the fuel bed depths and decreased as the fuel bed depth was increased above 4 inches. But, at 2-3/4 inches of the fuel bed, close attention was necessary to control the

boiler, whenever the load swung, or there was a change of the quality of fuel fed into the furnace. The authors, therefore, conclude that Boiler No. 6 should have a fuel bed depth between 3 and 4 inches deep when the 4-1 mixture is used and the load is about 50,000 pounds of steam per hour.

VI

RECOMMENDATIONS

It is recommended that:

(1) The fuel bed depth be maintained between 3 and 4 inches for Boiler No. 6 when the 4-1 mixture is used and the load is about 50,000 pounds of steam per hour.

(2) Bituminous coal used in the 4-1 mixture for Boiler No. 6 be crushed to as uniform a size as Merrimac culm.

(3) Investigations be made to determine the fuel bed depth to be maintained in Boiler No. 6 at loads other than 50,000 pounds of steam per hour when the 4-1 mixture is used.

(4) A higher percentage of bituminous coal be used in the coal mixture for Boiler No. 6 in case the coals are very wet and the load is about 50,000 pounds of steam per hour.

VII

ACKNOWLEDGMENTS

It is difficult to reflect in words the measure of indebtedness that the authors feel to Prof. C. H. Long, Prof. R. F. Glazebrook, Jr., and Mr. L. A. Padis, of the Mechanical Engineering Department, whose helpful suggestions and constructive criticism have made this thesis possible.

Sincere appreciation is extended to Prof. J. B. Jones, Head of the Mechanical Engineering Department, for his aid in the organization of our thesis. Gratitude goes to Mr. C. F. DeBusk, Utility Engineer of Virginia Polytechnic Institute, who has given many helpful suggestions and has made the arrangement for the boiler tests; to Prof. F. M. Morris, of the Mining Engineering Department, who has given helpful suggestions in connection with the coal sampling and the coal analysis; to Prof. F. H. Fish, of the Chemistry Department, who has given helpful suggestions in preparing the solutions for the Orsat apparatus; to Mr. O. Coplon, instructor in Mechanical Engineering, who has made many suggestions.

Our indebtedness is extended to all graduate students in Power and Fuel Engineering for their cooperation and encouragement throughout this investigation; to the plant personnel for their cooperation during the boiler tests.

For valuable assistance in typewriting this thesis, grateful acknowledgment is expressed to Mrs. R. M. Bottoms.

VIII

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IX

VITA

Kingston Fu Peng was born on October 15, 1918, in Hsianying, Hunan, China. He was reared and educated in Changsha, Hunan, from his childhood.

After his graduation from the National Hunan University with a B.S. degree in Mechanical Engineering, he worked as a junior engineer in locomotive design about six months before he went to the Chinese Air Force to take candidate officer's training.

Commissioned as a second lieutenant early in 1943 after completion of the training, he was then assigned as an aircraft armament and gunnery instructor for a period of one year and half. While on staff duty in the CAF Headquarters in Chungking, the war-time capitol of the Republic of China, he was transferred to the United States to command a group of Chinese air cadets who were to receive their training in this country in 1945.

In 1947, he was assigned to Washington, D. C., as a procurement officer and aircraft inspector. This duty enabled him to travel extensively in the United States and Canada.

Later in 1949, after seven years of service, he was honorably discharged from the Air Force of the Republic of China with the rank of captain.

He came to the Virginia Polytechnic Institute to pursue graduate study in Mechanical Engineering in January, 1950. Later in September, he received a Power and Fuel Engineering Fellowship. At present he is a candidate for the degree of Master of Science in Power and Fuel Engineering.

Pu-Jen Tou was born in Kunming, Yunnan, China, on March 8, 1922. He attended various public schools in Kunming and graduated from Kunhua Technic High School in June, 1940. After graduation, he was employed by the National 21st Arsenal of China.

After passing the examination conducted by the Yunnan Provincial Government in 1943, he was awarded a four-year scholarship for studying in the United States of America.

On August 2, 1945, he landed at New York City after one month of travel. He took his under-graduate studies in Mechanical Engineering at Cornell University. In June, 1949, he received the degree of Bachelor of Mechanical Engineering from Cornell University.

In September, 1949, he entered the Virginia Polytechnic Institute for graduate studies. During the next year, he received a research fellowship in Power and Fuel Engineering from the Virginia Polytechnic Institute. At present he is a candidate for the degree of Master of Science in Power and Fuel Engineering.

X

APPENDICES

TEST NO. 1 SUMMARY OF DATA

Depth of Fuel Bed:	5½ inches
Test Coal Mixture:	4:1
Test Load:	50,000 lb. steam per hour
Duration of Test:	5 hours

Proximate Analysis:	Air-dry	As Fired	Combustible
Moisture	0.45	5.7	
Volatile Matter	15.50	14.3	18.9
Ash Content	20.25	19.2	
Fixed Carbon	63.80	60.8	81.1
Air-dry Loss	5.23		

Carbon and Hydrogen:	As Fired
Carbon	0.6840
Hydrogen	0.0311

Higher Heating Value: 11,730 Btu per lb. As Fired

Refuse:	Per Cent Refuse	Carbon in Refuse
	28.35	32.3

Average Orsat Analysis:	CO_2	O_2	CO	N_2
	10.63	7.3	0.07	82.00

Average Data: Item	Corrected Reading
Boiler Drum Pressure, psig	260
Superheater Outlet Pressure, psig	248.5
Barimetric Pressure, in. Hg.	28.48
Feedwater Temperature, °F	227.5
Superheater Outlet Temperature, °F	514.0
Dry-bulb Temperature, °F	62.1
Wet-bulb Temperature, °F	47.0
Flue Gas Temperature from Air Heater, °F	442.8
Fuel Temperature, °F	74.4
Weight of Coal, lbs.	32,373
Steam Generated, lbs.	241,100
Evaporation, lbs. of steam/lb. of coal	7.45
Blowdown, lbs.	7,720

TEST NO. 1 DATA SHEET

2-16-51

	TEMPERATURES (°F)										
TIME	DRY BULB	WET BULB	FUEL	GAS TO HEATER (RECORDER)	GAS FROM HEATER (RECORDER)	AIR TO HEATER (RECORDER)	AIR FROM HEATER (RECORDER)	AIR FROM HEATER (THERMO.)	FEEDWATER (RECORDER)	INLET SUPERHEATER (THERMO.)	OUTLET SUPERHEATER (THERMO.)
6:30	64	48	80	619	440	69	338	320	225	402	511
6:45	63	48		619	440	70	330	315	225	398	518
7:00	63	48	81	625	450	70	340	320	225	401	515
7:15	63	48		626	450	69	340	322	226	400	515
7:30	63	48	75	623	450	69	340	321	226	401	517
7:45	63	48		620	450	68	334	320	223	402	518
8:00	62	47	74	620	448	69	342	320	226	402	516
8:15	63	48		621	449	69	340	318	227	402	518
8:30	62	47	74	622	449	69	332	318	230	402	518
8:45	62	47		622	450	68	338	321	230	401	516
9:00	62	47	74	620	443	69	336	318	230	402	516
9:15	62	47		620	440	69	336	315	230	402	516
9:30	61	46	74	620	440	69	334	315	230	402	510
9:45	61	46		620	440	69	324	315	230	402	510
10:00	59	46	73	620	445	69	340	320	230	402	513
10:15	60	46		620	445	69	340	321	230	402	510
10:30	59	46	72	620	440	69	340	320	230	402	512
10:45	61	47		620	440	68	340	318	225	401	512
11:00	60	46	70	620	440	65	340	318	225	401	510
11:15	59	46		620	438	65	330	318	227	401	510
11:30	60	46	72	618	440	65	336	318	230	401	510
Ave.	62.1	47	74.4	620	442.8	68.5	337	318	227.5	401	514

TEST NO. 1 DATA SHEET

2-16-51

TIME	PRESSURE									ORSAT			
	BAROMETER IN. HG.	DRUM PRESS. PSIG	S. H. PRESS. PSIG	AIR IN HEATER IN. H_2O	WINDBOX IN. H_2O	FURNACE IN. H_2O	LAST PASS IN. H_2O	OUTLET AIR HEATER IN. H_2O	I. D. FAN IN. H_2O	CO_2	O_2	CO	N_2
6:30	28.47	265	258	3.2	1.7	-0.23	-1.5	-3	-5.8	11.2	6.7	0.1	81.0
6:45		260	250	4.0	2.2	-0.21	-1.4	-3	-6	—	—	—	—
7:00		265	254	3.5	1.9	-0.12	-1.5	-3	-6	11.8	6.3	0.1	80.8
7:15		265	253	3.5	1.9	-0.31	-1.5	-3	-6	10.4	8.0	0.2	81.4
7:30	28.48	263	253	3.5	1.9	-0.35	-1.5	-3	-6	8.2	7.8	0	84.0
7:45		265	253	3.3	1.7	-0.45	-1.5	-3	-6	10.6	8.0	0.2	81.2
8:00		262	254	4.0	2.2	-0.30	-1.5	-3	-6	10.6	7.6	0.2	81.6
8:15		264	252	4.0	2.1	-0.26	-1.5	-3	-6	8.8	9.7	0.1	81.4
8:30	28.48	264	255	4.1	2.1	-0.22	-1.5	-3	-6	9.8	7.8	0	82.4
8:45		265	255	3.5	1.8	-0.33	-1.5	-3	-6	—	—	—	—
9:00		265	255	3.4	1.8	-0.27	-1.5	-3	-6	9.8	8.0	0.1	82.1
9:15		265	255	3.6	2.0	-0.24	-1.5	-3	-6	9.4	6.8	0.1	83.7
9:30	28.48	265	255	3.2	1.7	-0.30	-1.5	-3	-5.9	15.2	6.8	0.1	77.9
9:45		265	256	3.6	1.9	-0.13	-1.5	-3	-5.9	9	8.6	0	82.4
10:00		266	255	3.1	1.7	-0.30	-1.5	-3	-5.9	10.8	7.3	0.1	81.6
10:15		266	259	3.0	1.6	-0.30	-1.5	-3	-5.8	11.1	7.5	0	81.4
10:30	28.48	266	254	3.4	1.8	-0.23	-1.5	-3	-6	11.0	7.2	0	81.8
10:45		264	254	3.2	1.7	-0.29	-1.5	-3	-6	11.3	7.2	0.1	81.4
11:00		265	255	3.3	1.8	-0.30	-1.5	-3	-6	11	6.9	0	82.1
11:15		265	255	3.0	1.6	-0.23	-1.5	-3	-6	—	—	—	—
11:30	28.48	267	257	3.0	1.7	-0.28	-1.5	-3	-6	11.3	7.1	0	81.9
Ave.	28.48	265	254.5	3.45	1.84	-0.27	-1.5	-3	-6	10.63	7.30	0.07	82.00

TEST NO. 2 SUMMARY OF DATA

Depth of Fuel Bed:	4 inches
Test Coal Mixture:	4:1
Test Load:	50,000 lb. steam per hour
Duration of Test:	5 hours

Proximate Analysis:	Air-dry	As Fired	Combustible
Moisture	0.56	5.8	
Volatile Matter	14.68	13.7	18.4
Ash Content	20.67	19.6	
Fixed Carbon	64.09	60.9	81.6
Air-dry Loss	5.30		

Carbon and Hydrogen:	As Fired
Carbon	0.6280
Hydrogen	0.0495

Higher Heating Value: 11,720 Btu per lb. As Fired

Refuse:	Per Cent Refuse	Carbon in Refuse
	28.9	32.2

Average Orsat Analysis:	CO_2	O_2	CO	N_2
	12.0	6.77	0.05	81.18

Average Data: Item	Corrected Reading
Boiler Drum Pressure, psig	261.0
Superheater Outlet Pressure, psig	250.0
Barimetric Pressure, in. Hg.	28.32
Feedwater Temperature, °F	233.0
Superheater Outlet Temperature, °F	505.0
Dry-bulb Temperature, °F	61.9
Wet-bulb Temperature, °F	49.8
Flue Gas Temperature from Air Heater, °F	425.0
Fuel Temperature, °F	71.8
Weight of Coal, lbs.	30,518
Steam Generated, lbs.	235,648
Evaporation, lbs. of steam/lb. of coal	7.73
Blowdown, lbs.	7,385

TEST NO. 2 DATA SHEET

2-16-51

TIME	TEMPERATURES (°F)										
	DRY BULB	WET BULB	FUEL	GAS TO HEATER (RECORDER)	GAS FROM HEATER (RECORDER)	AIR TO HEATER (RECORDER)	AIR FROM HEATER (THERMO.)	AIR FROM HEATER (RECORDER)	FEEDWATER (RECORDER)	INLET SUPERHEATER (THERMO.)	OUTLET SUPERHEATER (THERMO.)
4:30	59	47	73	665	437	65	344	327	234	402	501
4:45	60	47		650	435	65	348	328	231	402	502
5:00	60	47	71	680	439	65	340	320	230	402	502
5:15	61	48		650	435	65	338	320	231	402	506
5:30	59	47	70	650	437	65	340	319	232	402	506
5:45	60	48		650	435	65	342	320	235	402	506
6:00	63	50	73	655	435	65	336	320	235	402	504
6:15	63	50		655	438	65	348	326	233	402	504
6:30	60	48	74	655	438	65	338	322	232	402	507
6:45	60	48		655	434	65	340	322	232	402	509
7:00	60	48	72	652	438	65	340	320	235	402	509
7:15	62	50		650	435	65	340	320	232	402	506
7:30	65	52	70	650	438	68	338	320	232	402	508
7:45	64	51		650	440	68	340	322	233	402	505
8:00	65	51	68	635	440	68	340	330	232	402	508
8:15	64	53		630	435	68	340	325	234	402	504
8:30	61	52	72	630	430	68	338	320	235	402	504
8:45	61	51		628	425	68	338	320	235	402	504
9:00	64	54	73	628	430	68	338	320	236	402	502
9:15	62	54		615	435	68	338	320	236	402	505
9:30	63	54	73	615	435	68	340	320	235	402	509
Ave.	61.9	49.8	71.8	645	435	66.4	340	322	233	402	505

TEST NO. 2 DATA SHEET

2-16-51

TIME	PRESSURE									ORSAT			
	BAROMETER IN. HG.	DRUM PRESS. PSIG	S. H. PRESS. PSIG	AIR IN HEATER IN. H_2O	WINDBOX IN. H_2O	FURNACE IN. H_2O	LAST PASS IN. H_2O	OUTLET AIR HEATER IN. H_2O	I. D. FAN IN. H_2O	CO_2	O_2	CO	N_2
4:30	28.32	268	255	2.2	1.2	-0.22	-1.2	-2.2	-4.2	12.2	6.9	0.2	80.7
4:45		270	260	2.0	1.0	-0.22	-1.1	-2.1	-4.0	13.6	5.2	0.3	80.9
5:00		265	255	2.7	1.4	-0.25	-0.9	-2.9	-5.5	11.8	7.4	0	80.8
5:15		266	255	2.8	1.3	-0.17	-1.5	-1.8	-3.7	9.4	8.1	0.1	82.4
5:30	28.32	263	254	2.5	1.7	-0.23	-1.0	-3.0	-6.0	11.4	7.0	0	81.6
5:45		266	257	2.2	1.3	-0.23	-1.2	-2.0	-4.0	13.0	5.8	0	81.2
6:00		267	258	2.3	1.1	-0.35	-1.3	-2.4	-4.5	12.0	7.0	0	81.0
6:15		265	255	2.5	1.3	-0.24	-1.2	-2.3	-4.5	12.4	6.6	0	81.0
6:30	28.32	265	255	2.3	1.3	-0.25	-1.3	-2.4	-4.7	12.4	6.6	0	81.0
6:45		266	257	2.7	1.2	-0.20	-1.3	-2.3	-4.5	11.0	7.1	0.1	81.8
7:00		265	255	2.5	1.4	-0.20	-1.4	-2.6	-5.0	11.7	7.4	0	80.9
7:15		265	255	2.3	1.2	-0.26	-1.5	-2.5	-4.8	12.5	7.0	0	80.5
7:30	28.32	265	255	2.7	1.4	-0.24	-1.5	-2.7	-5.0	11.3	6.4	0.1	81.2
7:45		265	255	2.8	1.4	-0.18	-1.5	-2.7	-5.2	12.2	7.8	0.1	79.9
8:00		265	258	2.2	1.1	-0.30	-1.3	-2.7	-5.0	11.9	7.4	0	80.7
8:15		266	258	2.2	1.1	-0.28	-1.2	-2.3	-4.3	11.7	7.3	0	81.0
8:30	28.32	265	256	2.5	1.4	-0.20	-1.5	-2.1	-4.2	13.1	5.9	0	81.0
8:45		268	258	2.1	1.1	-0.23	-1.5	-1.7	-3.0	12.9	5.4	0.1	80.7
9:00		265	257	2.2	1.1	-0.15	-1.5	-3.0	-5.5	12.0	6.3	0	81.7
9:15		266	258	2.2	1.1	-0.30	-1.2	-2.7	-5.0	11.6	6.7	0	81.7
9:30	28.32	262	253	3.0	1.1	-0.17	-1.3	-2.7	-5.0	11.2	7.0	0	81.8
Ave.	28.32	266	256	2.56	1.22	-0.23	-1.3	-2.33	-4.85	12.0	6.77	0.05	81.18

TEST NO. 3 SUMMARY OF DATA

Depth of Fuel Bed: 4 inches
Test Coal Mixture: 4:1
Test Load: 50,000 lb. steam per hour
Duration of Test: 5 hours

Proximate Analysis:	Air-dry	As Fired	Combustible
Moisture	1.73	6.3	
Volatile Matter	12.60	12.0	17.4
Ash Content	26.00	24.8	
Fixed Carbon	59.67	56.9	82.6
Air-dry Loss	4.66		

Carbon and Hydrogen:	As Fired
Carbon	0.6250
Hydrogen	0.0344

Higher Heating Value: 10,840 Btu per lb. As Fired

Refuse:	Per Cent Refuse	Carbon in Refuse
	36.0	32.9

Average Orsat Analysis:	CO_2	O_2	CO	N_2
	9.50	9.27	0.08	81.15

Average Data: Item	Corrected Reading
Boiler Drum Pressure, psig	259.0
Superheater Outlet Pressure, psig	248.0
Barimetric Pressure, in. Hg.	27.95
Feedwater Temperature, °F	229.3
Superheater Outlet Temperature, °F	516.0
Dry-bulb Temperature, °F	81.1
Wet-bulb Temperature, °F	57.9
Flue Gas Temperature from Air Heater, °F	436.6
Fuel Temperature, °F	80.6
Weight of Coal, lbs.	36,378
Steam Generated, lbs.	245,500
Evaporation, lbs. of steam/lb. of coal	6.75
Blowdown, lbs.	3,176

TEST NO. 3 DATA SHEET

2-27-51

TIME	TEMPERATURES (°F)										
	DRY BULB	WET BULB	FUEL	GAS TO HEATER (RECORDER)	GAS FROM HEATER (RECORDER)	AIR TO HEATER (RECORDER)	AIR FROM HEATER (THERMO.)	AIR FROM HEATER (RECORDER)	FEEDWATER (RECORDER)	INLET SUPERHEATER (THERMO.)	OUTLET SUPERHEATER (THERMO.)
10:15	77	61	80	580	435	80	338	320	230	400	516
10:30	80	58		583	435	81	334	320	230	400	516
10:45	80	58	81	580	430	83	340	320	230	400	513
11:00	82	64		580	430	85	338	315	230	400	516
11:15	81	59	80	580	431	85	340	320	231	400	512
11:30	81	59		585	433	85	346	322	231	401	514
11:45	81	58	82	583	435	87	344	322	230	400	510
12:00	82	59		590	445	85	342	330	230	400	519
12:15	82	59	81	580	440	86	346	332	230	401	513
12:30	84	59		578	432	87	344	329	230	400	518
12:45	84	59	80	580	435	80	342	329	230	400	516
1:00	84	59		584	436	87	342	330	230	399	518
1:15	83	58	80	580	435	88	340	329	230	400	516
1:30	83	58		582	440	88	340	329	230	399	517
1:45	83	57	80	587	440	88	340	325	230	398	516
2:00	82	57		585	440	86	342	329	230	400	520
2:15	82	58	81	578	437	86	342	330	230	400	516
2:30	79	54		583	440	86	344	329	230	400	516
2:45	78	54	82	580	440	83	342	328	230	400	518
3:00	78	54		578	440	83	344	332	226	400	520
3:15	79	54	80	580	440	83	342	330	226	400	512
Ave.	81.1	57.9	80.6	582	436.6	84.3	342	326	229.3	400	516

TEST NO. 3 DATA SHEET

2-27-51

TIME	PRESSURE									ORSAT			
	BAROMETER IN. HG.	DRUM PRESS. PSIG	S. H. PRESS. PSIG	AIR IN HEATER IN. H_2O	WINDBOX IN. H_2O	FURNACE IN. H_2O	LAST PASS IN. H_2O	OUTLET AIR HEATER IN. H_2O	I. D. FAN IN. H_2O	CO_2	O_2	CO	N2
10:15	27.96	260	251	3.4	2.2	-0.1	-1.5	-3.0	-5.7	9.7	9.9	0	81.2
10:30		263	253	3.3	1.8	-0.22	-1.5	-3.0	-4.7	9.2	9.6	0.2	81.0
10:45		261	251	3.2	1.9	-0.05	-1.2	-2.2	-4.5	9.0	9.8	0	81.2
11:00		262	251	3.4	2.0	-0.15	-1.5	-2.7	-5.3	8.3	10.9	0	80.8
11:15	27.96	265	251	3.0	1.8	-0.18	-1.5	-2.6	-4.6	8.6	10.6	0	80.8
11:30		265	255	2.9	1.7	-0.15	-1.4	-2.4	-4.1	10.2	9.0	0.2	80.6
11:45		265	255	2.8	1.6	-0.24	-1.3	-2.1	-6.0	9.2	10.4	0.2	80.2
12:00		263	252	3.4	2.2	-0.14	-1.5	-3.0	-5.0	8.7	10.5	0	80.8
12:15	27.95	265	255	2.6	1.5	-0.22	-1.5	-2.6	-4.5	10.2	8.4	0.3	81.1
12:30		265	255	2.7	1.6	-0.02	-1.3	-2.3	-4.5	10.4	8.4	0.1	81.1
12:45		266	255	2.7	1.5	-0.13	-1.3	-2.4	-4.5	9.4	10.1	0.1	80.4
1:00		265	255	2.7	1.6	-0.09	-1.2	-2.3	-4.8	11.6	7.8	0	80.6
1:15	27.94	265	255	2.6	1.5	-0.20	-1.4	-2.3	-5.4	10.1	9.7	0	80.2
1:30		264	252	3.1	1.7	-0.28	-1.5	-2.8	-5.9	9.6	10.2	0	80.2
1:45		260	250	3.6	2.0	-0.18	-1.5	-3.0	-5.6	9.0	10.4	0	80.6
2:00		265	255	3.2	1.8	-0.20	-1.5	-2.9	-4.6	—	—	—	—
2:15	27.94	265	255	2.8	1.7	-0.10	-1.3	-2.3	-5.7	10.2	9.3	0	80.5
2:30		265	255	3.3	1.9	-0.10	-1.5	-3.0	-5.3	9.0	10.4	0.2	80.4
2:45		264	253	3.0	1.8	-0.11	-1.5	-2.9	-4.9	8.8	10.8	0.3	80.1
3:00		265	255	2.6	1.5	-0.15	-1.6	-2.5	-5.6	9.3	9.9	0	80.8
3:15	27.94	265	255	2.6	1.4	-0.32	-1.5	-3.0	-5.0	—	—	—	—
Ave.	27.95	264	253.7	3.03	1.74	-0.16	-1.42	-2.63	-5.07	9.50	9.27	0.08	81.15

TEST NO. 4 SUMMARY OF DATA

Depth of Fuel Bed:	$5\frac{1}{2}$ inches
TEst Coal Mixture:	4:1
Test Load:	50,000 lb. steam per hour
Duration of Test:	5 hours

Proximate Analysis:	Air-dry	As Fired	Combustible
Moisture	2.60	6.8	
Volatile Matter	14.30	13.8	20.0
Ash Content	24.50	24.4	
Fixed Carbon	58.60	55.0	80.0
Air-dry Loss	4.29		

Carbon and Hydrogen:	As Fired
Carbon	0.6150
Hydrogen	0.0343

Higher Heating Value: 10,820 Btu per lb. As Fired

Refuse:	Per Cent Refuse	Carbon in Refuse
	34.85	30.0

Average Orsat Analysis:	CO_2	O_2	CO	N_2
	10.26	8.77	0.06	80.91

Average Data: Item	Corrected Reading
Boiler Drum Pressure, psig	258.0
Superheater Outlet Pressure, psig	247.5
Barimetric Pressure, in. Hg.	27.96
Feedwater Temperature, °F	225.0
Superheater Outlet Temperature, °F	518.0
Dry-bulb Temperature, °F	78.3
Wet-bulb Temperature, °F	53.1
Flue Gas Temperature from Air Heater, °F	437.5
Fuel Temperature, °F	81.9
Weight of Coal. lbs.	40,715
Steam Generated, lbs.	243,250
Evaporation, lbs. of steam/lb. of coal	6.53
Blowdown, lbs.	2,990

TEST NO. 4 DATA SHEET

2-27-51

	TEMPERATURE (°F)										
TIME	DRY BULB	WET BULB	FUEL	GAS TO HEATER (RECORDER)	GAS FROM HEATER (RECORDER)	AIR TO HEATER (RECORDER)	AIR FROM HEATER (RECORDER)	AIR FROM HEATER (THERMO.)	FEEDWATER (RECORDER)	INLET SUPERHEATER (THERMO.)	OUTLET SUPERHEATER (THERMO.)
4:15	79	54	81	585	445	84	330	342	226	400	524
4:30	78	53		585	442	84	330	340	225	400	522
4:45	79	54	79	580	440	85	329	338	225	400	521
5:00	82	56		580	439	87	330	334	225	400	518
5:15	80	55	80	575	435	87	330	336	226	400	508
5:30	79	53		575	430	85	328	334	225	400	505
5:45	78	53	81	580	440	85	328	334	225	399	514
6:00	77	52		582	442	85	328	332	225	399	513
6:15	78	53	82	580	438	82	330	336	225	400	517
6:30	82	56		580	440	85	330	334	225	400	511
6:45	79	53	84	570	430	85	320	334	225	400	506
7:00	77	82		590	445	82	330	330	225	400	518
7:15	76	52	83	580	440	82	332	332	225	400	517
7:30	77	52		576	435	80	330	334	225	400	517
7:45	76	51	81	580	440	80	330	334	225	400	510
8:00	79	53		582	435	80	330	332	225	400	510
8:15	81	56	82	575	435	82	330	334	225	400	511
8:30	79	53		580	435	80	330	334	225	400	512
8:45	76	52	83	572	430	80	330	320	225	400	509
9:00	75	51		575	433	80	329	336	225	400	510
9:15	74	51	82	575	432	80	328	334	225	400	514
Ave.	78.3	53.1	81.9	580	437.5	82.7	329	334	225	400	516

TEST NO. 4 DATA SHEET

2-27-51

TIME	PRESSURE									ORSAT			
	BAROMETER IN. HG.	DRUM PRESS. PSIG	S. H. PRESS. PSIG	AIR IN HEATER IN. H_2O	WINDBOX IN. H_2O	FURNACE IN. H_2O	LAST PASS IN. H_2O	OUTLET AIR HEATER IN. H_2O	I. D. FAN IN. H_2O	CO_2	O_2	CO	N_2
4:15	27.94	265	255	3.0	1.7	-0.30	-1.5	-2.9	-5.6	8.1	11.3	0.2	80.4
4:30		265	255	3.0	1.7	-0.24	-1.5	-2.8	-5.3	6.2	13.3	0	80.5
4:45		260	250	3.0	1.8	-0.15	-1.5	-3.0	-5.8	10.6	9.0	0.1	80.3
5:00		263	253	2.9	1.7	-0.17	-1.4	-2.5	-4.9	11.6	7.4	0	81.0
5:15	27.94	263	252	2.5	1.2	-0.19	-1.3	-2.3	-4.5	11.2	7.3	0.1	81.4
5:30		265	251	2.3	1.5	-0.05	-1.1	-2.2	-4.1	10.9	8.5	0.1	80.5
5:45		260	250	3.0	1.6	-0.30	-1.5	-3.0	-6.0	8.0	11.4	0	80.6
6:00		260	250	3.0	1.7	-0.31	-1.5	-3.0	-5.8	—	—	—	—
6:15	27.96	264	252	2.7	1.5	-0.20	-1.4	-2.4	-4.6	—	—	—	—
6:30		260	250	2.8	1.6	-0.23	-1.5	-3.0	-5.5	8.9	11.0	0	80.1
6:45		268	258	2.5	1.5	-0.10	-1.6	-1.2	-2.0	13.6	5.3	0	81.1
7:00		262	252	3.0	1.7	-0.30	-1.5	-3.0	-6.0	12.3	6.4	0.1	81.2
7:15	27.96	265	255	2.6	1.5	-0.32	-1.5	-2.7	-5.2	9.2	9.6	0	81.2
7:30		265	255	2.4	1.5	-0.23	-1.3	-2.4	-4.5	10.2	8.8	0	81.0
7:45		264	255	2.5	1.4	-0.40	-1.5	-3.0	-6.0	10.9	7.8	0	81.3
8:00		260	252	2.3	1.3	-0.26	-1.4	-2.5	-4.7	8.9	9.6	0.2	81.3
8:15	27.99	262	253	2.4	1.3	-0.23	-1.4	-2.5	-4.7	10.8	7.9	0.1	81.2
8:30		265	255	2.4	1.3	-0.11	-1.2	-2.2	-4.2	12.4	6.1	0.2	81.3
8:45		266	255	2.2	1.3	-0.12	-1.2	-2.3	-4.1	11.0	7.7	0.1	81.2
9:00		262	255	2.3	1.2	-0.24	-1.4	-2.4	-4.5	11.0	8.2	0	80.8
9:15	27.99	265	252	2.3	1.2	-0.18	-1.3	-2.5	-4.4	9.2	10.0	0	80.8
Ave.	27.96	263	252	2.62	1.48	-0.22	-1.41	-2.55	-4.88	10.26	8.77	0.06	80.91

TEST NO. 5 SUMMARY OF DATA

Depth of Fuel Bed:	2-3/4 inches
Test Coal Mixture:	4:1
Test Load:	50,000 lb. steam per hour
Duration of Test:	5 hours

Proximate Analysis:	Air-dry	As Fired	Combustible
Moisture	1.55	6.0	
Volatile Matter	14.30	12.2	19.2
Ash Content	32.06	30.6	
Fixed Carbon	52.09	51.2	80.8
Air-dry Loss	4.50		

Carbon and Hydrogen:	As Fired
Carbon	0.5690
Hydrogen:	0.0375

Higher Heating Value: 9,960 Btu per lb. As Fired

Refuse:	Per Cent Refuse	Carbon in Refuse
	41.92	27.0

Average Orsat Analysis:	CO_2	O_2	CO	N_2
	10.70	8.14	0.02	81.14

Average Data: Item	Corrected Reading
Boiler Drum Pressure, psig	257.5
Superheater Outlet Pressure, psig	247.6
Barimetric Pressure, in. Hg.	28.14
Feedwater Temperature, °F	228.7
Superheater Outlet Temperature, °F	516.0
Dry-bulb Temperature, °F	76.8
Wet-bulb Temperature, °F	59.2
Flue Gas Temperature from Air Heater, °F	436.0
Fuel Temperature, °F	75.5
Weight of Coal, lbs.	40,625
Steam Generated, lbs.	243,500
Evaporation, lbs. of steam/lb. of coal	5.98
Blowdown, lbs.	7,525

TEST NO. 5 DATA SHEET

3-6-51

	TEMPERATURE (°F)										
TIME	DRY BULB	WET BULB	FUEL	GAS TO HEATER (RECORDER)	GAS FROM HEATER (RECORDER)	AIR TO HEATER (RECORDER)	AIR FROM HEATER (THERMO.)	AIR FROM HEATER (RECORDER)	FEEDWATER (RECORDER)	INLET SUPERHEATER (RECORDER)	OUTLET SUPERHEATER (RECORDER)
3:15	79	61	79	580	430	80	324	320	236	402	524
3:30	79	61		570	425	80	328	315	236	396	519
3:45	79	60	78	575	430	80	336	318	230	400	512
4:00	78	60		590	435	80	330	320	226	386	500
4:15	77	60	78	580	430	80	328	320	226	400	514
4:30	79	60		585	435	80	328	325	230	403	514
4:45	79	60	78	585	438	80	340	328	227	402	515
5:00	80	61		585	435	80	340	325	227	401	513
5:15	79	60	78	585	438	80	345	326	227	402	514
5:30	78	59		590	440	80	340	325	227	403	517
5:45	78	59	78	590	440	80	346	328	228	403	518
6:00	77	59		590	440	80	346	330	230	404	519
6:15	77	59	74	590	435	79	340	325	226	404	520
6:30	76	59		590	440	78	345	332	226	404	519
6:45	75	58	73	588	435	75	345	330	230	404	520
7:00	74	58		588	435	75	345	325	230	404	520
7:15	73	58	73	580	428	73	345	320	230	403	518
7:30	73	57		580	425	72	346	320	230	402	519
7:45	73	57	71	590	435	72	335	320	230	404	512
8:00	74	58		590	440	72	350	328	226	403	515
8:15	75	58	71	590	432	72	340	325	225	404	515
Ave.	76.8	59.2	75.5	585	436	78	338.5	324	228.7	403	516

TEST NO. 5 DATA SHEET

3-6-51

	PRESSURE									ORSAT			
TIME	BAROMETER IN. HG.	DRUM PRESS. PSIG	S. H. PRESS. PSIG	AIR IN HEATER IN. H_2O	WINDBOX IN. H_2O	FURNACE IN. H_2O	LAST PASS IN. H_2O	OUTLET AIR HEATER IN H_2O	I. D. FAN IN. H_2O	CO_2	O_2	CO	N_2
3:15	28.15	260	249	3.6	2.0	-0.20	-1.5	-2.9	-5.6	9.2	9.6	0.1	81.1
3:30		245	235	3.7	2.1	-0.16	-1.5	-2.7	-5.3	9.8	8.8	0	81.4
3:45		253	245	3.7	2.1	-0.26	-1.5	-3.0	-5.7	10.4	7.6	0	82.0
4:00		253	250	3.7	2.1	-0.23	-1.5	-3.0	-5.8	8.0	10.0	0	82.0
4:15	28.15	267	256	3.3	1.6	-0.13	-1.5	-2.5	-4.5	11.3	7.3	0.1	81.3
4:30		266	256	3.1	1.7	-0.17	-1.4	-2.6	-5.5	11.9	7.1	0	81.0
4:45		266	256	3.0	1.5	-0.36	-1.5	-2.8	-5.5	12.6	6.4	0.1	80.9
5:00		265	255	3.0	1.7	-0.15	-1.5	-3.0	-5.8	11.4	7.8	0	80.8
5:15	28.14	262	250	3.5	1.9	-0.20	-1.5	-3.0	-6.0	11.2	7.0	0	81.8
5:30		265	246	3.7	1.9	-0.25	-1.5	-3.0	-6.0	8.8	9.2	0.1	81.9
5:45		265	255	3.8	1.9	-0.22	-1.5	-3.0	-6.0	8.8	9.7	0	81.5
6:00		267	258	2.7	1.4	-0.32	-1.5	-2.8	-5.5	12.2	7.2	0	80.6
6:15	28.14	266	256	3.5	1.9	-0.15	-1.5	-3.0	-6.0	—	—	—	—
6:30		268	258	3.2	1.6	-0.17	-1.5	-3.0	-6.0	11.8	7.6	0	80.6
6:45		268	258	2.5	1.3	-0.32	-1.5	-3.0	-6.0	10.1	8.6	0	81.3
7:00		265	255	3.0	1.5	-0.32	-1.5	-3.0	-6.0	11.3	8.1	0	80.6
7:15	28.14	265	256	3.0	1.6	-0.17	-1.4	-2.5	-4.9	11.9	7.1	0	81.0
7:30		267	258	2.8	1.4	-0.30	-1.4	-2.4	-4.5	11.1	7.8	0	81.1
7:45		264	255	3.8	2.0	-0.20	-1.5	-3.0	-6.0	9.6	8.9	0	81.5
8:00		266	256	3.5	1.7	-0.33	-1.5	-2.8	-5.2	9.8	8.6	0	81.6
8:15	28.14	266	257	2.8	1.4	-0.27	-1.5	-2.7	-5.1	10.2	8.4	0	81.4
Ave.	28.14	263	253.3	3.26	1.72	-0.23	-1.5	-2.85	-5.56	10.7	8.14	0.02	81.14

TEST NO. 6 SUMMARY OF DATA

Depth of Fuel Bed:	2-3/4 inches
Test Coal Mixture:	4:1
Test Load:	50,000 lb. steam per hour
Duration of Test:	5 hours

Proximate Analysis:	Air-dry	As Fired	Combustible
Moisture	0.80	7.01	
Volatile Matter	13.70	12.9	18.3
Ash Content	24.10	22.6	
Fixed Carbon	61.40	57.5	81.7
Air-dry Loss	6.25		

Carbon and Hydrogen:	As Fired
Carbon	0.6350
Hydrogen	0.0350

Higher Heating Value: 11,190 Btu per lb. As Fired

Refuse:	Per Cent Refuse	Carbon in Refuse
	33.3	32.2

Average Orsat Analysis:	CO_2	O_2	CO	N_2
	10.25	8.48	0	81.27

Average Data: Item	Corrected Reading
Boiler Drum Pressure, psig	263.0
Superheater Outlet Pressure, psig	252.0
Barimetric Pressure, in. Hg.	28.24
Feedwater Temperature, °F	224.4
Superheater Outlet Temperature, °F	516.0
Dry-bulb Temperature, °F	72.2
Wet-bulb Temperature, °F	51.4
Flue Gas Temperature from Air Heater, °F	441.0
Fuel Temperature, °F	78.1
Weight of Coal, lbs.	35,225
Steam Generated, lbs.	250,000
Evaporation, lbs. of steam/lb. of coal	7.10
Blowdown, lbs.	7,025

TEST NO. 6 DATA SHEET

3-9-51

	TEMPERATURES (°F)										
TIME	DRY BULB	WET BULB	FUEL	GAS TO HEATER (RECORDER)	GAS FROM HEATER (RECORDER)	AIR TO HEATER (RECORDER)	AIR FROM HEATER (THERMO.)	AIR FROM HEATER (RECORDER)	FEEDWATER (RECORDER)	INLET SUPERHEATER (THERMO.)	OUTLET SUPERHEATER (THERMO.)
6:30	78	53	74	600	445	77	348	330	225	402	517
6:45	72	50		600	450	72	354	333	222	404	518
7:00	71	50	74	600	450	70	352	330	222	404	517
7:15	74	52		600	443	73	348	325	222	404	515
7:30	74	51	74	600	443	73	350	328	222	403	514
7:45	73	51		600	441	73	346	328	223	404	510
8:00	74	52	75	600	445	73	350	325	223	403	518
8:15	70	49		604	450	70	350	325	225	404	516
8:30	75	53	75	600	440	70	340	325	225	404	516
8:45	72	52		600	440	70	338	325	225	404	510
9:00	75	54	80	600	440	70	342	320	225	404	512
9:15	74	53		600	440	70	344	320	225	404	510
9:30	66	48	84	605	450	67	350	325	225	404	520
9:45	70	50		605	450	67	348	330	226	404	524
10:00	73	52	80	600	440	70	348	325	226	404	519
10:15	72	52		590	435	70	344	325	226	405	520
10:30	72	52	82	600	450	70	352	330	226	406	516
10:45	72	52		605	445	70	382	320	225	406	517
11:00	70	52	80	600	440	70	342	320	225	404	517
11:15	70	51		590	435	70	342	320	225	404	510
11:30	69	51	82	580	425	67	336	320	225	404	512
Ave.	72.2	51.4	78.1	598	441	70.7	346.5	325	224.4	404.5	516

TEST NO. 6 DATA SHEET

3-9-51

	PRESSURE									ORSAT			
TIME	BAROMETER IN. HG.	DRUM PRESS. PSIG	S. H. PRESS. PSIG	AIR IN HEATER IN. H_2O	WINDBOX IN. H_2O	FURNACE IN. H_2O	LAST PASS IN. H_2O	OUTLET AIR HEATER IN. H_2O	I. D. FAN IN. H_2O	CO_2	O_2	CO	N_2
6:30	28.24	269	259	2.8	1.5	-0.32	-1.5	-2.9	-5.5	10.0	8.8	0	81.2
6:45		269	260	2.4	1.5	-0.22	-1.5	-2.9	-5.9	9.8	8.7	0	81.5
7:00		269	260	3.3	1.7	-0.26	-1.5	-3.0	-6.0	10.1	9.1	0	80.8
7:15		266	257	3.1	1.7	-0.25	-1.5	-2.9	-5.6	10.2	8.6	0	81.2
7:30	28.24	266	257	2.9	1.5	-0.26	-1.5	-2.7	-5.2	10.2	8.6	0	81.2
7:45		266	259	3.3	1.7	-0.25	-1.5	-3.0	-5.8	9.8	8.2	0	82.0
8:00		266	256	3.7	1.8	-0.50	-1.5	-2.9	-5.7	10.0	9.0	0	81.0
8:15		269	257	2.7	1.3	-0.32	-1.5	-3.0	-5.7	9.7	9.1	0	81.2
8:30	28.24	270	259	2.8	1.5	-0.31	-1.5	-2.8	-5.2	10.5	8.5	0	81.0
8:45		270	260	2.7	1.4	-0.23	-1.5	-2.5	-4.9	10.0	8.5	0	81.5
9:00		265	256	3.2	1.6	-0.27	-1.5	-3.0	-4.9	9.8	9.1	0	80.1
9:15		267	259	3.0	1.5	-0.25	-1.5	-2.8	-5.4	9.3	8.7	0	81.0
9:30	28.24	268	256	3.0	1.6	-0.25	-1.5	-2.5	-6.0	9.7	9.2	0	81.1
9:45		268	257	3.2	1.4	-0.38	-1.5	-3.0	-6.0	9.5	9.3	0	81.2
10:00		269	259	2.9	1.5	-0.18	-1.3	-2.8	-4.6	9.7	9.1	0	81.2
10:15		270	260	2.4	1.3	-0.20	-1.4	-3.0	-4.3	9.4	8.2	0	81.4
10:30	28.24	270	260	3.1	1.6	-0.17	-1.5	-3.0	-6.0	9.9	8.7	0	81.4
10:45		269	260	3.0	1.4	-0.30	-1.5	-2.5	-4.8	10.0	8.8	0	81.2
11:00		265	255	2.5	1.8	-0.23	-1.5	-2.3	-4.8	—	—	—	—
11:15		267	257	2.5	1.2	-0.25	-1.5	-2.6	-6.0	12.0	6.5	0	81.5
11:30	28.24	270	260	2.1	1.1	-0.17	-1.1	-1.9	-3.6	14.0	4.1	0	81.9
Ave.	28.24	268	258	2.87	1.51	-0.27	-1.47	-2.76	-5.39	10.25	8.48	0	81.27

APPENDIX (2)

SAMPLE CALCULATIONS

The methods of calculation shown below are used for all tests. The values used here are taken from boiler test No. 1 for the purpose of demonstration.

(A) Determination of higher heating value, carbon and hydrogen in the test coal.

(1) Fuel analysis, per cent:

Items	Air-dry	As Fired	Combustible
Moisture	0.5	5.7	
Volatile Matter	15.5	14.3	18.9
Ash	20.2	19.2	
Fixed Carbon	63.8	60.8	81.1
Air-dry Loss	5.2		

(2) Conversion of proximate analysis from air-dry basis to as fired basis:

$$M_{af} = M_{ad} \times \frac{100-L}{100} + L$$

$$= 0.5 \times \frac{100 - 5.2}{100} + 5.2 = 5.7\%$$

$$V_{af} = V_{ad} \times \frac{100 - L}{100}$$

$$= 15.5 \times \frac{100 - 5.2}{100} = 14.3\%$$

$$A_{af} = A_{ad} \times \frac{100 - L}{100}$$

$$= 20.2 \times \frac{100 - 5.2}{100} = 19.2\%$$

$$FC_{af} = 100 - (M_{af} + V_{af} + A_{af})$$

$$= 100 - (5.7 + 14.3 + 19.2) = 60.8\%$$

Where: M_{af} = moisture in as fired basis, per cent

M_{ad} = moisture in air-dry basis, per cent

V_{af} = volatile matter in as fired basis, per cent

V_{ad} = volatile matter in air-dry basis, per cent

A_{af} = ash in as fired basis, per cent

A_{ad} = ash in air-dry basis, per cent

FC_{af} = fixed carbon in as fired basis, per cent

FC_{ad} = fixed carbon in air-dry basis, per cent

L = air-dry loss, per cent

(3) Conversion of proximate analysis from as fired basis to combustible basis:

$$V_c = \frac{V_{af}}{V_{af} + FC_{af}} \times 100$$

$$= \frac{14.3}{14.3 + 60.8} \times 100 = 18.9\%$$

$$FC_c = \frac{FC_{af}}{V_{af} + FC_{af}} \times 100$$

$$= \frac{60.8}{14.3 + 60.8} \times 100 = 81.1\%$$

Where: V_c = volatile matter in combustible basis, per cent

V_{af} = volatile matter in as fired basis, per cent

FC_c = fixed carbon in combustible basis, per cent

FC_{af} = fixed carbon in as fired basis, per cent

(4) Determination of higher heating value, carbon and hydrogen of the test coal from the proximate analysis to the combustible basis by using F. C. Evans' Imperical Relations*:

HHV_c = 16,160 - 2,250V_c (V_c is between 16 - 36%)

HHV_c = 16,160 - 2,250 x 0.189 = 15.635 Btu/lb.

C_c = 0.943 - 0.242V_c (V_c is between 0 - 36%)

C_c = 0.943 - 0.242 x 0.189 = 0.897

H_c = 0.0457 + 0.0206V_c (V_c is 16% and up)

H_c = 0.0457 + 0.0206 x 0.189 = 0.0414

Where: HHV_c = higher heating value in combustible basis, Btu/lb.

C_c = fraction of carbon in combustible basis

H_c = fraction of hydrogen in combustible basis

V_c = fraction of volatile matter in combustible basis

(5) Conversion of higher heating value, carbon and hydrogen of test coal from the combustible basis to the as fired basis:

$$HHV_{af} = HHV_c \left(\frac{100 - M_{af} - A_{af}}{100}\right)$$

$$= 15,635 \left(\frac{100 - 5.7 - 19.2}{100}\right) = 11,730 \text{ Btu/lb.}$$

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*Barnard, W. N., Ellenwood, F. O., and Hirshfeld, C. F., Heat-Power Engineering, Third Edition, New York: John Wiley and Sons, 1930, Volume II, Table XXX, p. 325.

$$C_{af} = C_c \left(\frac{100 - M_{af} - A_{af}}{100}\right)$$

$$= 0.897 \left(\frac{100 - 5.7 - 19.2}{100}\right) = 0.684$$

$$H_{af} = H_c \left(\frac{100 - M_{af} - A_{af}}{100}\right)$$

$$= 0.0414 \left(\frac{100 - 5.7 - 19.2}{100}\right) = 0.0311$$

Where: HHV_c, C_c, H_c = as specified in (4)

HHV_{af} = higher heating value in as fired basis, Btu/lb

C_{af} = fraction of carbon in as fired basis

H_{af} = fraction of hydrogen in as fired basis

M_{af} = moisture in as fired basis, per cent

A_{af} = ash in as fired basis, per cent

(B) Determination of per cent refuse.

The per cent of refuse is calculated by dividing the per cent of ash in coal from the proximate analysis by the per cent of ash in refuse from the combustible analysis of the refuse in the ash pit.

$$\%R = \frac{A_{af}}{A_r} \times 100$$

$$= \frac{19.2}{67.7} \times 100 = 28.35\%$$

Where: $\%R$ = per cent of refuse

A_{af} = ash in as fired basis, per cent

A_r = ash in refuse from the combustible analysis of refuse, per cent

The above method of computing the per cent of refuse has been proved to be accurate to within one per cent of actual weighing of refuse from the ash pit, refuse from cyclone separator, and calculated weight of refuse leaving the stack.*

(C) Heat Balance.

(1) Average Orsat analysis, per cent by volume

CO_2	10.63
CO	0.01
O_2	7.30
N_2	82.06

(2) Average experimental data:

Item	Uncorrected Value	Corrected Value
Superheater outlet temperature, °F	514	514
Superheater inlet temperature, °F	401	401
Temperature of fuel, °F	74.4	74.4
Flue gas outlet temperature, °F	432.5	432.5
Dry-bulb temperature, °F	62.1	62.1
Wet-bulb temperature, °F	47.0	47.0
Feed-water temperature, °F	227.5	227.5
Boiler drum pressure, psig	265	260
Superheater pressure, psig	253.5	248.5

*Coplon, O., Cottingham, G. R., and Murphy, J. D., Determination of Mixture of Merrimac Culm and Bituminous Coal for No. 6 Boiler, Thesis Virginia Polytechnic Institute, 1950, p.43-45.

Barometric pressure, in. Hg.	28.48	28.48
Weight of coal, lbs.	32,430	32,373
Steam generated, lbs.	266,200	241,100
Evaporation, lbs. steam/lb. coal	---	7.45
Carbon in refuse, per cent	---	32.3
Refuse, per cent of coal burned	---	28.35
Blowdown, lbs.	7720	7720

(3) Correction factor for steam flow:

$$C_f = \frac{V_c}{V} = \frac{2.037}{2.094} = 0.974$$

Where: C_f = correction factor

V_c = specific volume of steam at 250 psig and 100° F superheat, cu.ft./lb

V = specific volume of steam at 248.5 psig and 514° F, cu.ft./lb

(4) Corrected weight of steam flow:

W_s = (weight of steam flow) x C_f

= 247,650 x 0.974

= 241,100 lbs.

Where: W_s = corrected weight of steam flow, lbs.

C_f = correction factor for steam flow

(5) Corrected weight of coal burned:

W_f = (weight of coal) x C_f

= 32430 x 0.996

= 32,373 lbs.

Where: W_f = corrected weight of coal burned, lbs.

C_f = correction factor which was obtained from the calibration of the weigh larry.

(6) Evaporation:

$$W_{nf} = \frac{W_s}{W_f} = \frac{241,100}{32,373} = 7.45 \text{ lbs steam/lb coal}$$

Where: W_{nf} = evaporation, lbs steam/lb coal

W_s = weight of steam, lbs

W_f = weight of coal burned, lbs

(7) Heat balance:

(a) Heat absorbed by water and steam in unit:

$$E = W_{nf}\,(h_1 - h_f)$$

$$= 7.45(1270.2 - 195.5)$$

$$= 8,000 \text{ Btu/lb}$$

Where: E = heat absorbed, Btu/lb

W_{nf} = evaporation, lbs steam/lb coal

h_1 = enthalpy of steam at superheater outlet, Btu/lb

h_f = enthalpy of feedwater entering boiler drum, Btu/lb

(b) Heat loss due to moisture in coal:

$$L_M = M_{af}(1089 + 0.46t_g - t_f)$$

$$= 0.056\,(1089 + 0.46 \times 432.5 - 74.4)$$

$$= 67 \text{ Btu/lb}$$

Where: L_M = heat loss due to moisture in coal, Btu/lb.

M_{af} = moisture in coal, lb/lb coal

t_g = temperature of flue gas leaving last heating surface, °F

t_f = temperature of fuel, °F

(c) Heat loss due to water from combustion of hydrogen in fuel:

$$L_H = 9W_H\,(1089 + 0.46t_g - t_f)$$

$$= 9 \times 0.0311\,(1089 + 0.46 \times 432.5 - 74.4)$$

$$= 340 \text{ Btu/lb}$$

Where: L_H = heat loss due to water from combustion of available hydrogen in fuel, Btu/lb

W_H = weight of hydrogen in fuel, lb/lb coal

t_g = temperature of flue gas leaving, °F

t_f = temperature of fuel, °F

(d) Heat loss due to moisture in air:

(i) fraction of carbon burned in fuel:

$$C_b = C_{af} - (\%R)\,(C_r)$$

$$= 0.684 - (0.2835)\,(0.323)$$

$$= 0.592 \text{ lb/lb coal}$$

Where: C_b = fraction of carbon burned, lb/lb coal

C_{af} = fraction of carbon in fuel, lb/lb coal

$\%R$ = per cent of refuse

C_r = carbon in refuse, per cent

(ii) weight of dry air supplied:

$$W_A = \frac{28N_2}{(.768)\,(12)\,(CO_2 + CO)}\,C_b$$

$$= \frac{28 \times 0.8206}{(.768)\ (12)\ (.1063 + .0001)} \times 0.592$$

$= 13.89$ lb/lb coal

Where: W_A = weight of dry air supplied per pound of coal burned

N_2, CO_2, and CO are respectively fraction by volume nitrogen, carbon dioxide and carbon monoxide in dry flue gas

C_b = weight of carbon burned in fuel

(iii) heat loss due to moisture in air:

$$L_{MA} = 0.46\ M_A\ W_A\ (t_g - t_a)$$

$$= 0.46 \times \frac{23.6}{7000} \times 13.89\ (432.5 - 62.1)$$

$= 7.95$ Btu/lb

Where: L_{MA} = heat loss due to moisture in air, Btu/lb

M_A = moisture in dry air at dry-bulb temperature 62.1°F and wet-bulb temperature 47°F, lb/lb dry-air

W_A = weight of dry-air supplied, lb/lb coal

t_g = temperature of flue gas leaving, °F

t_a = temperature of air entering, °F

(e) Heat loss due to dry flue gas:

(i) weight of dry flue gas:

$$W_g = \frac{44CO_2 + 28CO + 32\ O_2 + \ 28N_2}{12\ (CO_2 + CO)}\ C_b$$

$$= \frac{(44)(0.1063)+(28)(0.0001)+(32)(0.073)+(28)(0.8206)}{12\ (0.1063 + \ 0.0001)} \times 0.592$$

$= 13.90$ lb/lb coal

Where: W_g = weight of dry flue gas per pound of coal burned

CO_2, CO, O_2 and N_2 are respectively the per cent by volume of carbon dioxide, carbon monoxide, oxygen and nitrogen in dry flue gas.

C_b = fraction of carbon burned

(ii) heat loss due to dry flue gas:

$$L_g = 0.24\ W_g\ (t_g - t_a)$$

$$= 0.24 \times 13.9\ (432.5 - 62.1)$$

$$= 1235 \text{ Btu/lb coal}$$

Where: L_b = heat loss due to dry flue gas, Btu/lb

W_g = weight of dry flue gas per pound of coal burned

t_g = temperature of flue gas leaving, °F

t_a = temperature of air entering, °F

(f) Heat loss due to carbon monoxide:

$$L_{CO} = \frac{CO}{CO + CO_2} \times C_b \times 10{,}160$$

$$= \frac{0.0007}{0.0007 + 0.1063} \times 0.592 \times 10{,}160$$

$$= 39.5 \text{ Btu/lb coal}$$

Where: L_{CO} = heat loss due to carbon monoxide, Btu/lb

CO_2 and CO are respectively the per cent by volume of carbon dioxide and carbon monoxide in dry flue gas

C_b = fraction of carbon burned

(g) Heat loss due to carbon in refuse:

$$L_{cr} = W_r \times 14600$$

$$= 0.0913 \times 14{,}600$$

$$= 1332 \text{ Btu/lb coal}$$

Where: L_{cr} = heat loss due to carbon in refuse, Btu/lb

W_r = weight of carbon in refuse per pound of coal burned

$= (\%R)\ (C_r)$

(h) Heat loss due to blowdown:

$$L_b = W_b(h_s - h_f)$$

$$= \frac{7720}{32,373}\ (383.00 - 195.5)$$

$$= 44.3 \text{ Btu/ lb coal}$$

Where: L_b = heat loss due to blowdown, Btu/lb

W_b = weight of blowdown per pound of coal burned

h_s = enthalpy of saturated water at boiler drum pressure, Btu/lb

h_f = enthalpy of feedwater entering boiler drum, Btu/lb

(i) Heat loss due to radiation:

$$L_{ra} = (\text{per cent of radiation loss})\ (\text{HHV})$$

$$= (0.0114)\ (11,730)$$

$$= 134 \text{ Btu/lb}$$

Where: L_{ra} = heat loss due to radiation, Btu/lb

Note: Per cent of radiation loss was obtained from Plate 3, A.S.M.E. Power Test Code On Stationary Steam-Generating Units, 1946.

(j) Unaccounted-for losses:

$$L_u = (\text{HHV}) - (\text{Summation of items (a) through (i)})$$

$$= (11,730)-(8,000+67+340+7.95+1235+5.65+1332+44.3+134)$$

$$= 463.8 \text{ Btu/lb}$$

Where: L_u = unaccounted-for losses, Btu/lb

(k) Boiler efficiency:

$$\text{Boiler efficiency} = \frac{\text{heat absorbed}}{\text{HHV}}$$

$$= \frac{8,000}{11,730}$$

$$= 68.1\%$$

(D) Excess air.

$$x = \frac{(O_2 - 0.5\ CO) \times 100}{0.264\ N_2 - (O_2 - 0.5\ CO)}$$

$$= \frac{(7.30 - 0.5 \times 0.01) \times 100}{0.264 \times 82.06 - (7.30 - 0.5 \times 0.01)}$$

$$= 51.0\%$$

Where: x = excess air, per cent

O_2, CO and N_2 are respectively per cent by volume of oxygen, carbon monoxide and nitrogen in dry flue gas

APPENDIX (3)

METHOD TO CALCULATE BOILER EFFICIENCY BASED ON AVERAGE ASH CONTENT

This method of calculation is based on the consideration that the decrease in boiler efficiency is directly proportional to the increase in ash content in coal. The sample calculation shown here is for the fuel bed depth of $5\frac{1}{2}$ inches.

(A) Average ash content of test mixture:

$$\text{Average ash content} = \frac{19.2 + 19.6 + 24.4 + 24.8 + 30.6 + 22.6}{6} = 23.53\%$$

(B) Boiler efficiency at average ash content of 23.53% for $5\frac{1}{2}$ inch fuel bed depth:

Difference in ash content = 24.4 - 19.2 = 5.2%

Difference in boiler efficiency = 68.1 - 65.15 = 2.95%

Hence each per cent of ash content decreases $\frac{2.95}{5.2}$ or 0.567% of boiler efficiency

$$E = E_b - 0.567\,(23.53 - A_b)$$
$$= 68.1 - 0.567\,(23.53 - 19.2)$$
$$= 65.53\%$$

Where: E = calculated boiler efficiency at average ash content of 23.53% in coal, per cent

E_b = boiler efficiency from actual test at ash content 19.2% per cent

A_b = per cent of ash content in coal corresponding to boiler efficiency, E_b

(C) Boiler efficiencies at average ash content of 23.53% for 4 in. and 2-3/4 in. fuel bed depths are 67.56% and 67.95% respectively.

ABSTRACT

In attempting to use the 4-1 mixture of Merrimac culm and bituminous coal for boiler No. 6 in the Virginia Polytechnic Institute Heating and Power Plant, the problem of maintaining a proper depth of fuel bed had arisen. This problem seemed to warrant an investigation, which was subsequently made.

The fuel bed depth that will give the best results for a boiler depends on many factors, and it is best determined by boiler tests. Therefore, the authors decided to investigate the effect of the fuel bed depth on the performance of Boiler No.6 and to determine the optimum fuel bed depth, when the 4-1 mixture was used and the load was 50,000 pounds of steam per hour.

This investigation consisted of the collection and evaluation of data obtained from the boiler tests at various fuel bed depths. During the boiler tests, some of the variables were held as constant as possible in order to obtain comparative results. The fuel bed depths tested were 2-3/4, 4, and 5-1/2 inches. The optimum depth of fuel bed is that fuel bed which would give the highest boiler efficiency and good boiler control.

The results of the tests showed that the boiler efficiency remained approximately constant between 2-3/4 and 4 inches of the fuel bed depths and decreased as the fuel bed depth was increased above 4 inches. But, at 2-3/4 inches of the fuel bed,

close attention was necessary to control the boiler, whenever the load swung, or there was a change of the quality of fuel fed into the furnace. The authors, therefore, conclude that Boiler No.6 should have a fuel bed depth between 3 and 4 inches deep when the 4-1 mixture is used and the load is about 50,000 pounds of steam per hour.