# A STUDY OF THE EFFECTS OF FIRING DIFFERENT SIZES OF COAL IN NO. 6 BOILER

by

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# TABLE OF CONTENTS

V. The Investigation

XI. Appendices

## List of Plates and Tables

## III. FOREWORD

The Virginia Polytechnic Institute is located in Blacksburg, in the Montgomery County of Virginia. It is situated in the scenic Alleghany Mountains at 2100 feet above see level. The Institute maintains its own electrical systems for the college and supplies the town with electricity. The power plant serves not only with its facilities but more in the practical study of their experiments.

To meet the ever increasing demand of electricity and heating requirements, the Institute acquired an additional steam generating unit, which was placed in service in 1949. This unit is known as the No. 6 Boiler and is equipped with a continuous front-ash discharge spreader stoker. It has a maximum capacity at 250 psi with 100 degree superheat of 60,000 lbs. of steam per hour burning bitumious coal, and 45,000 lbs. of steam per hour with semi-anthracite culm. From geographical considerations the burning of semi-anthracite culm would be favorable since Blacksburg is located where semi-anthracite deposits are prevalent.

With this existing unit which has an average use factor of 83.16 per cent for the past three years (1), it was considered of interest to conduct a preliminary investigation to determine the feasibility of burning different closely sized coals.

Several persons have contributed in some way that without which this thesis could never have been performed. The author has taken this privilege to express his deep appreciation to the following members of the faculty. The Advisory Committee comprising of Professor H . S. Miles, Jr.,

Associate Professor H. L. Wood, in the Mechanical Engineering Department, and Assistant Professor C. Shelton, Jr., in the Mining Department, for their valuable criticism, worthy suggestions and guidance.

C. H. Long, Associate Professor in Mechanical Engineering Department for his unselfish support and encouragement.

C. F. deBusk, Utility Engineer and the Power Plant personnel for their willingness to cooperate in the performance of this investigation.

## IV. REVIEW OF LITERATURE

The ever increasing emphasis on efficiency and economy towards utilization of lower grades of coal led to the development of the continuous front-ash discharge spreader stoker.

The fundamentals of a spreader stoker feeder unit comprises a reciprocating feeder plate to feed and regulate the rate of fuel supply in conjunction with a rotor having two rows of blades which project the feed into the furnace and distribute it over the corresponding grate area. Lateral distribution is achieved by having the feeders in line, while longitudinally, the distribution is varied by control of rotor speed or by adjustment of the still plate setting. Coal is spilled over the rotor and comes in contact with the blades for less than a quarter of a revolution. Withdrawal of the spill plates gives a high, long, trajectory and vice versa. The adjustment being very sensitive. The fuel bed is kept level by maintaining the proper adjustment of rotor speed and proper position of the spilling plate.

A section through a continuous front-ash discharge spreader stoker showing the setting of the feeder in relation to the grate which travels from the rear to the front of the furnace, where ash is discharged, is shown in figure 1. (2) The grate speed is variable and regulated to maintain the required fuel bed depths at the front end.

Spreader stokers use the combined principles of suspension burning and non-agitated type of fuel bed. The coal particles are introduced into the furnace at some distance above the grate, and at least some of it falls on the grate, but not all of it. The small particles of coal in suspension

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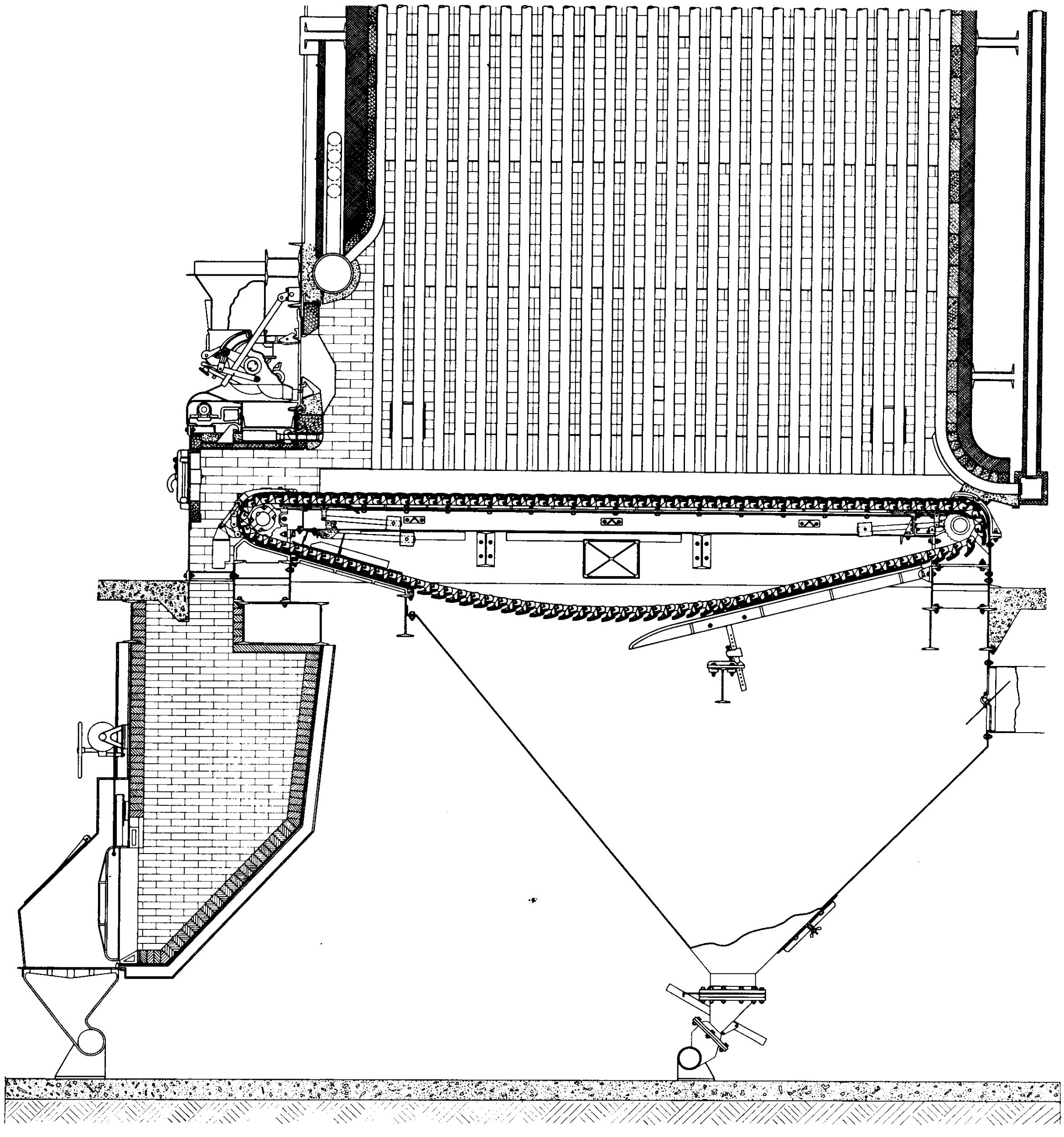

# DETROIT ROTOGRATE STOKER

FIG. 1 - A SECTION OF A CONTINUOUS FRONT ASH DISCHARGE SPREADER STOKER INSTALLATION

are heated rapidly when exposed to the intense heat of the furnace. These particles soften and swell into multicellular bubbles of coke, known as "cenospheres". Cenospheres are new-born cinders. This swelling action along with the driving-off of the volatile portion of the coal particles causes a substantial reduction in its specific density. This phenomenon has been investigated by Sinnatt (3), who found that particles of bituminous coal increase in volume up to forty times shortly after entering a furnace at 1100 degree F or hotter. With the average density of smaller saw particles equal to 1.5 the density of the cenospheres reduces to a value of 0.12 to 0.15 and possibly even lower. The sudden decrease in density of a coal particle causes it to remain bouyant in the gas stream, and is carried out of the furnace into the boiler passes, where combustion ceases before the carbon is entirely consumed. As found evident under the microscope, Kaiser (4) reports that whole cenospheres and fragments of cenospheres constitute a substantial proportion of boiler dust or carryover.

During firing, some large coal particles reach the grate. With the ingredients of ash diseminated throughout the structure of coal in varying degree of dispersion, the swelling of coal particles during cenosphere formation further subdivides and separates the ash into minute bits of specks. As the cenospheres burn, numerous minute bits of ash are released. Part of the ash that is released in the fuel bed is loose and powdery. The density of the ash likewise may be lowered to a point where the ash is picked up by the high velicity air and gas stream to be carried away. Practically all of the combustible in the flue dust comes from particles which remain in suspension and never reach the grate, while the non-combustible or pure ash in the flue dust actually comes from the fuel bed after the coal particles have been fired. (4)

Another type of ash consists of layers that remain fairly coeherent after the combustible portion is burned away. Such pieces remain on the grate. An additional portion of the ash sinters as it is released and forms agglomerates or clinkers, which are too dense and too heavy to float in the rising gases. (4)

In spreader stoker firing, only a portion of the total combustion process occurs in the traveling, but non-agitated bed. Since coal is projected into the furnace in a trajectory path due to the impact of the blades mounted on the revolving rotors, a wide range of sizes must be used to have a uniform distribution of fuel in the grate. If the coal particles are too large, they can not be completely consumed during the burning down period. In certain types of coals there is that tendency to enclose the unburned carbon in the shell of ash. Such losses could be minimized by lowering the maximum size of coal. (5)

Considerable range of sizes is necessary for satisfactory distribution of coal in the fuel bed. With fuels such as closely sized, double-screened bituminous coal, there is a tendency for much of the fuel to fall on one portion of the grate. If the size consist is well distributed between coarse and fine, the burning rate and ash bed are practically uniform over the entire grate surface. There should be very few pieces that require more than one minute to burn. The stoker, however, will burn fuel ranging from slack, all through 1/8 or 1/4 inch screen, to 1-1/4 inch or 1-1/2 inch nut and slack. (5) In coal having normal breakage characteristics 3/4 inch to zero or even 1/2 inch to zero will give excellent results. A minimum of 25 per cent over 1/4 inch is required to ensure a fully active fuel bed on the grate. A maximum of 50 per cent under 1/8 inch keeps suspension burning to reasonable proportions with coals of friability. (6) Bainbridge of the Detroit Stoker Company (7) recommends that most desirable sizes as 1-1/4 inch over zero, or 3/4 inch over zero with about 50 per cent fines.

The grate is protected by the residual coarse ash from combustion. It is generally accepted that if there is a 3 inch ash layer at the front discharge end of the grate, the protection is adequate.

The ash bed also diminishes the actual upward gas velocities above the fuel bed and reduces proportionately the carrying power of the furnace gases. An upward velocity exceeding the terminal velocity of the coal or ash particle will lift the particle in space and correspondingly increase the flue dust in the gases. (9)

To emphasize the effect of coal sizing, de Lorenzi (5) obtained a set of curves from several tests at different rates of combustion with several tests at different rates of combustion with several different sized fuels. These curves show that the per cent fuel burned in suspension increases as the top size of coal is reduced for the same combustion rate, and that at combustion rates between 20 and 30 lbs. per square feet per hour, the per cent fuel leaving the furnace in all the sizes of the fuel test is at a minimum. This can indicate that the carrying power of the furnace gases, or the vertical gas velocities above the fuel bed were minimum. When the burning rate is increased in firing 1-1/2 inch top size coal, the quantity of flue dust leaving the furnace does not increase appreciably as with the smaller coals. De Lorenzi also states that the combustible matter in the carryover varies from 20 to 60 per cent, and that is is almost directly proportional to the burning rate. By returning these fines to the furnace, approximately 50 per cent of their heat content may be recovered.

Holton and Engdahl (8) conducted 47 tests on Wickes 60,000 lbs. per hour, four-drum bent tube boiler fired by Detroit RotoGrate Continuous ash discharge spreader stoker consisting of 3 feeders. They found that the use of overfire jets reduces the carbon loss and dust emission fron the furnace without reinjection. The reinjection of cinder from the boiler hoppers decreased the carbon loss 2.3 percentage points while increasing the dust loading 20 per cent, and 4.1 percentage points while increasing dust loading by 40 per cent. Returning all the collected cinders to the furnace gave a further decrease in carbon loss of 2.1 to 2.8 percentage points at the expense of an increase in dust loading of 125 to 155 per cent. Holton and Engdahl further concluded, that the use of coal containing a small percentage of minus 1/8 inch material resulted in lower values of carbon loss and dust loading at the furnace outlet than were found with the finer coal, and that this decrease was not so great at either the boiler outlet or the stack.

Similar comprehensive studies were made by J. I. Case Company (9) and found that the gravity system of flyash return completely eliminates carbon loss from the flue dust carryover of the spreader stoker, and that boiler units equipped with gravity flyash return system operate with total carbon loss of less than 0.2 per cent in boiler efficiency heat balance.

De Lorenzi (5) states that in general, with the use of cinder recovery equipment and other favorable conditions carbon loss can be reduced to an average of 2 to 3 per cent, and without cinder recovery and under unfavorable firing conditions it may be as high as 12 per cent.

The adpatability of the spreader stoker to variations in fuel characteristics is an indication of its ability to meet extreme changes in fuel quality. Minor adjustments to distributor speed and coal and air controls enable the furnace to respond quickly to wide variation in coal characteristics and sizing. (5) Because of the very thin, active fuel bed, the spreader stoker is therefore very responsive to changes in fuel and air supply. An increase or decrease of fuel supply with constant air flow or vice versa will produce a marked change of carbon dioxide in the flue in a matter of a few seconds. (6) Efficient operation, therefore, demands that not only should fuel and air supply be varied simultaneously, but they should be varied by correct corresponding increments. For this reason automatic control is strongly recommended, or alternatively there should be a manually operated master control which will ensure that, by operating one control, the air and fuel are varied so that a predetermine relationship is maintained between them. (6)

# V. THE INVESTIGATION

## A. Object of Investigation

The object of this investigation was to study the effect of firing three different coal sizes; through 3/16 inch over zero, through 1/4 inch over 3/16 inch, and 1 inch over 1/4 inch, in Virginia Polytechnic Institute Heating and Power Plant Boiler No. 6 equipped with a continuous front ash discharge spreader stoker.

The effect of different coal sizes was studied with reference to the comparative potential heat losses, the amounts of flue dust carryover, and the ability of the spreader stoker feeder to distribute these sizes of coal on the grate.

## B. The No. 6 Boiler

The latest supplement to the steam generating capacity of the Virginia Polytechnic Institute Heating and Power Plant is provided by a two-drum, bent tube boiler designed by the Edge Moor Iron Works of Edge Moor, Delaware. The steam generating unit was placed in service in 1949. And, for the past three years, the Boiler No. 6 has an average use factor of 83.16 per cent (1)

This unit was designed to burn bituminous coal or semi-anthracite culm. It was designed for maximum actual evaporation of 60,000 lbs. per hour, with normal operating pressure of 250 psi with 100 degree superheat and feed water temperature at 215 degrees F. The steam drum is 54 inches in diameter and has a length of 15 feet. The mud drum is 36 inches in diameter and 14 feet and 6 inches long. This unit is encased in steel plates with walkways at the upper drum level for proper operation and maintenance. The instruments are panel-mounted in the front of the unit at the firing aisle.

The total water heating surface is 7,155 square feet, which consists of the boiler with 6,035 square feet and water walls equivalent to 1,120 square feet.

The superheater which furnishes the 100 degrees superheat has an area of 475 square feet.

An Edge Moor steam washer is installed in the steam drum to wash and dry the steam before it enters the superheater.

The air preheater contains 3030 square feet of heating surface. This was designed so that the gases of combustion will pass through the bottom on the inside of the tubes and the air is admitted at the top and passes along and around the tubes.

The furnace has a width of 11 feet and 6-1/4 inches. The mud drum is 6 feet from the floor, and the steam drum is 21 feet from the center line of the mud drum. The front and the side walls are water cooled. The rear wall is included in the boiler and composed of bare and armoured tubes.

The coal firing equipment consists of 3 units of Detroit Roto-Grate spreader stokers with a continuous front ash discharge traveling grate. The effective grate area is 116.9 square feet with the effective length of 11 feet. Integral with these units are the tuyeres provided to admit air into the furnace over the fire and under the coal stream. This air is supplied by an auxiliary air fan in the basement.

The forced draft fan is double inlet type driven by directly coupled electric motor. Capacity is 20,800 cfm of 100 degrees F. against a static pressure of 5.4 inches of water, 27.8 bhp at 1160 rpm. The output of the fan is controlled by the position of the radial vanes in the inlet sides.

The induced draft fan is a double inlet type and driven by an electric motor through a hydraulic coupling. Capacity of the fan is 36,000 cfm of flue gas at 425 degrees F. against a static pressure of 6 inches of water. It requires 61.5 bhp at 1145 rpm. This fan is located at the base of a 35 foot steel stack which has a diameter at the top of approximately 5 feet.

The dust collector was supplied by Prat-Daniel Corporation of the Thermix tubular dust collector type, designed to handle 83,000 lbs. of flue gas per hour at 500 degrees F.

The Boiler No. 6 is automatically controlled by Hays combustion control system. The superheater pressure actuates the primary element of the master control which in turn relays the regulation to the stoker feeders and output of the forced draft fan. The furnace draft is controlled by the induced draft fan speed. The outlet damper is manually adjusted if used.

The unit is equipped with a cinder return fan designed by Buffalo Forge, operating at a speed of 4380 rpm with 15 hp electric motor.

Refuse from the ash pit as well as flue dust from the collectors are disposed of by a steam pneumatic ash handling system. Refuse are delivered outside the building, to a tile storage bin, conditioned, and ready for disposal. Before entering the silo, the ash conveying air is cleaned by passing through a cyclone separator.

## C. Preparation of the Coal

The fuel selected to be used was in the classification of bituminous coal. This was suitable since the Boiler No. 6 was primarily designed to be efficiently operated with bituminous coal as shown in the manufacturer's performance test as shown in the Appendix.

The coal sizes investigated were below the recommended coal size for spreader stoker firing. In other words, the spreader stoker feeder was forced beyond its normal rating of coal size of through 1-1/4 inch over zero.

The sizes of coal selected to be used was within the available screening table in the power plant premises. This screening table has four standard round hole steel screens, with sizes of 1/4 inch, 3/16 inch, 1/8 inch and 1/16 inch. The effective lengths are 7 feet 10 inches, 7 feet 6 inches, 7 feet 2 inches, and 6 feet 11 inches, respectively. The width of all the screens was 1 foot - 11 inches. These screens were on top of one another and 1 inch apart. Also 1 inch above the 1/4 inch screen is a steel bar which will only allow passage of coal 1 inch in thickness. The series of screens are supported in movable straps and are tilted at approximately 20 degrees. The flow of coal was initiated by an electrical vibrator installed below the series of screens.

The original coal size that was separated was 1-1/4 inch over zero. In the process of screening, 16 size consist tests were done during a good weather to insure fairly good separation. The size consist of the coal size 1-1/4 inches over zero was taken from the average of these 16 screening tests, which is as follows:

## Table 1

### Size Consist of 1-1/4 inch over zero Coal

| Size Range | Per Cent by weight |
|---|---|
| Over 1 inch | 5.4 |
| Through 1 inch and over 1/4 inch | 48.26 |
| Through 1/4 inch and over 3/16 inch | 15.00 |
| Through 3/16 and over 1/8 inch | 10.33 |
| Through 1/8 inch and over 1/16 inch | 11.90 |
| Through 1/16 inch and over zero | 9.17 |
| Total | 100.00 |

The coal size over 1 inch were discarded by hand picking the material above the 1/4 inch screen. This material did not pass below the steel bar.

Before the test, the available fuel was approximately twenty tons, and due to the limited time and labor involved, it was decided that the sizes to be fired were as follows:

(1) Through 1 inch and over 1/4 inch

(2) Through 1/4 inch and over 3/16 inch

(3) Through 3/16 inch and over zero

These were the sizes that were fired in the Boiler No. 6 used in this investigation.

## D. Boiler Test Procedures

All these boiler tests were made under practical conditions of power plant operation, with more emphasis in the determination of boiler heat losses.

The Power Test Codes of the American Society of Mechanical Engineers was used as a basic reference in these test procedures.

With complete freedom in the choice of steam load, 25,000 lbs. of steam per hour was selected to increase the length of the test considering the quantity of fuel available. Based on the manufacturer's performance test, an efficiency of 84.86 per cent is obtained at 30,000 lbs. of steam per hour, burning bituminous coal of size range from 1-1/4 inch over zero, with the heating value of 13,700 Btu per pound. The expected efficiencies in these tests were all below this value.

With the load of 30,000 lbs. of steam per hour, the performance test burning bituminous coal indicated 13.5 per cent carbon dioxide. This was the maximum per cent of carbon dioxide that was to be expected in normal firing. The best value of per cent carbon dioxide obtained during the stabilization period in the first test was maintained. The second test was run approximately one per cent lower than the first test. The third test was run between the values of the first and second test.

During the stabilization period, minor adjustments were made on the spreader stoker feeder plate, the fuel feed and air controls. The per cent carbon dioxide and carbon monoxide was used as an immediate reference to indicate the effectiveness of combustion. Visual observation of the fuel bed in the front was made to estimate the carbon lost. Fuel bed thickness was primarily regulated by varying the grate speed and by adjusting the fuel feed and stoker feeder plate. With coal sizes 1 inch over 1/4 inch and through 1/4 inch over 3/16 inch, the fuel bed depths were regulated to approximately 3 to 4 inches in the front. With the size through 3/16 inch over zero, the fuel bed depth was kept to approximately 5 to 6 inches in the front. Each test was not started until the fuel on the grate was replaced by the test fuel.

The air to fuel ratio, and the grate speed was fixed before each test and was primarily maintained by the automatic control system during each test.

In the preparation before the test, the thermometer wells were cleaned and mercury was placed in them, to provide necessary immersion depths of the glass thermometers. The pressure gage in the main steam line was calibrated as it was to be used as a reference gage. The Orsat apparatus was cleaned and solutions renewed. It was tested for leaks and zeroed before use.

Mercury-in-glass thermometers were checked by comparison with several others in the temperature of boiling water at atmospheric pressure.

To prevent mixing the test coals with other coals and foreign materials, the coal bunker was cleaned before each test.

Immediately before the start of each test, the refuse was removed from the ashpit and the flue dust rejected from the dust collectors. The coal in the hopper was leveled, and the weight of the coal in the weigh larry was recorded.

When preliminary readings of the instruments indicated fairly stable boiler operating conditions the test was started. Initial readings were taken, and water level in the boiler was marked in the gage glass, and recorded as zero. Integrator reading of the steam flowmeter was immediately recorded at the start and all readings necessary to calculate the heat balance were taken every 15 minutes.

The duration of each test was primarily limited by the quantity of fuel, but whenever possible the test was conducted for 5 hours.

Refuse and flue dust from the dust collectors were pulled out and weighed every half hour. This was done as fast as possible so as to reduce the leakage of air into the furnace. No reinjection of cinders was done in all of these tests.

Flue gas analysis were taken every 15 minutes during each of the tests. The rate of continuous blowdown was taken at the same interval.

No measurement of feedwater was performed.

Samples of the fuel were taken by cutting a cross section of the coal in the spout of the weigh larry about one inch or two inches depending on the size of coal, by means of two parallel plates for each load. Samples were also taken by scoops in six strategic points in the coal hopper, as similar to ASTM recommended sampling method in the surface of a railroad car. These samples were placed in air-tight containers, air-dried, quartered, and crushed for proximate analysis. The American Standard Method of Analysis was closely followed through the ASTM specification D 271-48 (Standard Methods of Laboratory Sampling and Analysis of Coal and Coke).

Ash and Flue dust samples were taken and analyzed for combustibles as in the determination of ash, the loss of weight being recorded as per cent combustible in the flue dust or refuse.

## E. Data and Results

Since all of the coal fired was in the same classification but of different sizes, the evaluated analysis of "moisture and ash free" coal, shows fairly constant percentages of volatile matter and fixed carbon. These values of volatile matter ranges from 36.11 to 35.97 per cent.

To insure accurate results in the determination of the proximate analysis, three samples of each size was taken and analyzed. The average values of the proximate is shown in Table 2.

The observed performance of the three tests are shown in Table 3, 4 and 5. These are the average values of readings taken every fifteen minutes during the duration of each test.

The steam load fluctuated as much as 1500 pounds per hour in the first test and 1000 pounds per hour in the other two tests as indicated by the steam flowmeter from the average values given in the tables.

The values of the per cent carbon dioxide fluctuated to ± 1 per cent of the average value, and the per cent carbon monoxide to a± 0.2 per cent of the average value as shown in the tables of observed performances.

## Table 2

### Fuel Analysis

| Test No. | I | II | III |
|---|---|---|---|
| Size of Coal | -3/16" x 0 | -1/4" x +3/16" | 1" x +1/4" |
| Air Drying Loss | 4.81% | 2.26% | 2.25% |
| Proximate Analysis of "air-dried" Coal | | | |
| Moisture | 0.51% | 0.59% | 0.43% |
| Volatile Matter | 31.82 | 32.46 | 32.55 |
| Ash | 11.37 | 9.03 | 9.17 |
| Fixed Carbon | 56.30 | 57.92 | 57.85 |
| Calculated Analysis of "as-received" Coal | | | |
| Moisture | 5.30 | 2.84% | 2.67% |
| Volatile Matter | 30.29 | 31.73 | 31.82 |
| Ash | 10.82 | 8.82 | 8.96 |
| Fixed Carbon | 53.59 | 56.61 | 56.55 |
| Calculated Analysis of "dry" Coal | | | |
| Volatile Matter | 32.00% | 32.60% | 32.68% |
| Ash | 11.42 | 9.07 | 9.20 |
| Fixed Carbon | 56.58 | 58.33 | 58.12 |
| Calculated Analysis of "moisture and ash free" Coal | | | |
| Volatile Matter | 36.11% | 35.97% | 36.01% |
| Fixed Carbon | 63.89 | 64.03 | 63.99 |
| Per cent Combustible in Refuse | | | |
| | 20.15% | 9.71% | 8.72% |
| Per cent Combustible in Flue Dust | | | |
| Rear Hopper | 54.38% | 46.28% | 52.26% |
| Top Hopper | 27.01 | 23.9 | 26.04 |

Reference:

Standard Methods of Laboratory Sampling and Analysis of
Coal and Coke, ASTM Specification D 271-48

## Table 3

## Observed Performances

## Test 1

| | |
|---|---|
| Date Performed | September 4, 1956 |
| Type of Coal | Bituminous coal |
| Size of Coal | Under 3/16" x 0 |

Size Consist of Coal

| Size Range | Per cent by weight | Cumulative percentage |
|---|---|---|
| Through 1/16" over 0 | 29.2 | 29.2 |
| Through 1/8" over 1/16" | 37.9 | 67.1 |
| Through 3/16" over 1/8" | 32.9 | 100.0 |

| | |
|---|---|
| Duration of test | 4 hours |
| Average Observations: | |
| Weight of coal fired, lbs. per hour | 2,910 |
| Steam generated, lbs. per hour | 24,500 |
| Boiler drum pressure, psig | 263 |
| Superheater | |
| Pressure, psig | 257 |
| Steam inlet temperature, deg. F. | 400.5 |
| Steam outlet temperature, deg. F. | 506.5 |
| Main Steam Line | |
| Pressure, psig | 230.7 |
| Temperature, deg. F. | 483 |
| Feedwater heater | |
| Pressure, psig | 5.2 |
| Feedwater temperature, deg. F. | 226.8 |

| | |
|---|---|
| Flue gas temperatures | |
| Air heater inlet, deg. F. | 462 |
| Air heater, outlet, deg. F. | 380 |
| Air temperatures | |
| Air in the windbox, deg. F. | 234 |
| Forced draft Fan inlet | |
| Dry bulb temperature, deg. F. | 83.3 |
| Wet bulb temperature, deg. F. | 71.5 |
| Draft, inches of water | |
| Air into the heater | 0.34 |
| Windbox | 0.16 |
| Last pass | -0.12 |
| Gas out of the heater | -1.11 |
| Induced draft fan | -2.64 |
| Flue gas Analysis by Orsat apparatus per cent by volume | |
| Carbon dioxide | 8.56 |
| Oxygen | 9.58 |
| Carbon monoxide | 0.31 |
| Nitrogen | 81.55 |
| Temperature of the coal, deg. F. | 80.1 |
| Boiler room temperature, deg. F. | 83.3 |
| Barometric pressure, inches of Hg. | 28.24 |
| Weight of flue dust collected during the test | |
| Collected from the bottom hoppers, lbs. | 686.5 |
| Collected from the top hoppers, lbs. | 246.0 |
| Weight of refuse collected during the test, lbs. | 1005.0 |

### Table 4

### Observed Performances

### Test 2

| | |
|---|---|
| Date performed | September 5, 1956 |
| Type of coal | Bituminous coal |
| Size of coal | Through 1/4" over 3/16" |
| Duration of test | 3.167 hours |
| Average observations: | |
| Weight of coal fired, lbs. per hour | 2,555 |
| Steam generated, lbs. per hour | 24,650 |
| Boiler drum pressure, psig | 262.5 |
| Superheater | |
| Pressure, psig | 256.5 |
| Steam inlet temperature, deg. F. | 400 |
| Steam outlet temperature, deg. F. | 496.5 |
| Main steam line | |
| Pressure, psig | 230.2 |
| Temperature, deg. F. | 475 |
| Feedwater heater | |
| Pressure, psig | 4.52 |
| Feedwater temperature, deg. F. | 225 |
| Flue gas temperature | |
| Air heater inlet, deg. F. | 462.5 |
| Air heater outlet, deg. F. | 381.5 |
| Air temperatures | |
| Air in the windbox, deg. F. | 234.8 |
| Forced Draft fan inlet | |
| Dry bulb temperature, deg. F. | 80.7 |
| Wet bulb temperature, deg. F. | 70.5 |

| | |
|---|---|
| Boiler room temperature, deg. F. | 81.2 |
| Temperature of coal, deg. F. | 78.2 |
| Draft, inches of water | |
| Air into heater | 0.38 |
| Windbox | 0.18 |
| Furnace | -0.13 |
| Last pass | -0.60 |
| Gas out of the heater | -1.18 |
| Induced draft fan | -2.98 |
| Flue gas analysis by Orsat apparatus percent by volume | |
| Carbon dioxide | 7.53 |
| Oxygen | 11.03 |
| Carbon monoxide | 0.41 |
| Nitrogen (100 - $CO_2$ - CO - $O_2$) | 81.03 |
| Barometric pressure, inches of Hg. | 28.236 |
| Weight of flue dust collected during the test | |
| Collected from the bottom hoppers, lbs. | 247.75 |
| Collected from the top hoppers, lbs. | 299.75 |
| Weight of refuse collected during the test, lbs. | 367.0 |

## Table 5

### Observed Performances

### Test 3

| | |
|---|---|
| Date performed | September 6, 1956 |
| Type of coal | Bituminous coal |
| Size of coal | 1 inch over 1/4" |
| Duration of test | 5 hours |
| Average observations: | |
| Weight of coal fired, lbs. per hour | 2,266 |
| Steam generated, lbs. per hour | 21,200 |
| Boiler drum pressure, psig | 263.4 |
| Superheater | |
| Pressure, psig | 258 |
| Steam inlet temperature, deg. F. | 400 |
| Steam outlet temperature, deg. F. | 490 |
| Main steam line | |
| Pressure, psig | 234.5 |
| Temperature, deg. F. | 465.4 |
| Feedwater heater | |
| Pressure, psig | 2.48 |
| Feedwater temperature, deg. F. | 218.6 |
| Flue gas temperature | |
| Air heater inlet, deg. F. | 438.2 |
| Air heater outlet, deg. F. | 381.3 |
| Air temperatures | |
| Air in the windbox, deg. F. | 253.5 |
| Forced draft fan inlet | |
| Dry bulb temperature, deg. F. | 77.75 |
| Wet bulb temperature, deg. F. | 70.05 |

| | |
|---|---|
| Boiler room temperature, deg. F. | 81.8 |
| Temperature of coal, deg. F. | 78.67 |
| Draft, inches of water | |
| Air into heater | 0.325 |
| Windbox | 0.198 |
| Furnace | -0.126 |
| Last pass | -0.441 |
| Gas out of the heater | -0.838 |
| Induced draft fan | -2.065 |
| Flue gas analysis by Orsat apparatus per cent by volume | |
| Carbon dioxide | 8.37 |
| Oxygen | 9.35 |
| Carbon monoxide | 0.13 |
| Nitrogen (100 - $CO_2$ - $O_2$ - CO) | 81.65 |
| Barometric pressure, inches of Hg. | 28.14 |
| Weight of flue dust collected during the test | |
| Collected from the bottom hoppers, lbs. | 185.5 |
| Collected from the top hoppers, lbs. | 186.5 |
| Weight of refuse collected during the test, lbs. | 657 |

## THE HEAT BALANCE

Classic among heat power problems in the evaluation of the boiler heat balance. Its main object is to determine the thermal efficiency and distribution of heat losses of the steam generating unit.

In this investigation, it is important in evaluation the relative magnitude of the thermal losses in the unit.

The indirect method was preferred in determining the efficiency involving heat losses, since the direct method is limited by the use of feed water meters which will not give reliable measurement of imput, and accounting the coal in the grate and hoppers.

As regards to accuracy, Doxey (11) estimated with suitable and well maintained instruments and careful observations, including calculation, compares the two methods.

Direct Method ± 1.9 per cent to ± 2.3 per cent
Indirect Method ± 1.2 per cent to ± 1.8 per cent

With the indirect method, the limits of error increase as $CO_2$ fall and the figures above will correspond to 10 to 12 per cent and 7 to 9 per cent.

Therefore, given in each case, suitable and well maintained instruments and careful observations, indirect method is likely to be rather more accurate than the direct method. The indirect method is also preferred by boiler manufacturers in determining the thermal efficiency in the performance test for accuracy and economy.

The American Boiler and Affiliated Industries, Standards Committee has prepared and recommended a standard for estimating the radiation loss. This recommendation is shown in graphical form in most engineering references.

Further, the recommended standard for unaccountable loss is 1.5 per cent. In the performance test of the manufacturer of No. 6 Boiler as shown in Appendix A, the radiation loss is 1.7 per cent at a load of 30,000 lbs. of steam per hour. This values will be used in this calculation.

The high heating value, carbon and hydrogen content was determined by Evans Empirical Relations (12). These values were also compared with formulas given by M arks (13) and the heating value and carbon content approaches Mark's specified accuracy, but the hydrogen content shows to be larger within Mark's limits. The heat values recommended by the two authors was approximately the same with the value given in Power's Data Sheet (14). The value calculated from Evan's Empirical Relations were used in this computations.

From the Bulletin of the Bureau of Mines (15), of the typical ultimate analysis of coals in the United States, for coals from Virginia and West Virginia, the weight of oxygen and sulfur per pound of combustible does not vary very much. These values for oxygen ranges from 8.3 to 2.7 per cent and for sulfur 1.5 to 0.7 per cent. It would not be far off to consider the average values for oxygen and sulfur. From this the error would be considered in the plus and minus side, rather than the extremes. Without the average values of oxygen and sulfur, the weight of air would always be greater to about 0.20 lbs. per lb. of coal fired. Actually, this does not enter into this calculations except in the determination of the per cent excess air.

The amount of air supplied for combustion was determined by reduction from the analysis of exit gases. The per cent carbon dioxide of the exit gases was used as the indices of excess air supplied for combustion. On the other hand, the excess air was also calculated from the oxygen content of the flue gases which indicated much lower values than determined from the per cent $O_2$, but it shows approximately the same variations. This could be probably caused by the leakage in opening the ashpit during the test. And from the equation in determining the amount of excess air with oxygen, the per cent CO is too much involved and requires greater accuracy in its determination. The values determined by the per cent carbon dioxide was used in this calculation of heat balance.

In general, a certain amount of flue dust escapes in the stack even in the best arrangements for its collection.

In each of the test, the ash in the ash pit and the ash deposited in the collectors, were added and compared with the amount of ash determined by the proximate analysis of as fired coal. In Test 1, the total ash that was collected in the ash pit and collectors was in excess of the ash determined by the analysis. While in Test 2 and 3, a deficiency in the ash balance of 0.18 and 1.68 per cent of coal fired was noted. If, in these two tests, the deficiency was accounted as flue dust that escaped through the stack with a carbon content of flue dust collected in the top hoppers, this would amount to 0.101 and 1.06 lbs. of flue dust per 1000 lbs. of gas. The efficiency of the top collectors would be 94.2 per cent as compared with 42.2 per cent in Test 3, with 122 per cent and 110 per cent excess air, at approximately the same amount of flue dust entering the top collectors. This would indicate that these deficiencies could not be accounted as flue dust that escapes through the stack.

Preliminary to each test, a stabilization period was run to about an hour mostly fluatuating high amounts of excess air due to the process of adjustments. Very negligible amounts, if any, could have been picked up or was deposited in the collectors by the gases during each test. There was no reinjection of flue dust in all these tests.

These excess and deficiencies in the ash balance could only be attributed to the amount of refuse in the grate at the beginning and at the end of each test. This can be shown by the quantity of refuse taken 30 minutes after the beginning and 30 minutes before the end of each test. The amount of refuse collected was:

| Test | 1 | 2 | 3 |
|---|---|---|---|
| Weight of refuse collected in the last 30 minutes of the test | 48 lbs. | 69 lbs. | 92 lbs. |
| Weight of refuse collected in the first 30 minutes of the test | 118 lbs. | 57 lbs. | 68 lbs. |
| Difference in weight | -70 lbs. | 12 lbs. | 24 lbs. |

The difference indicates a close relation to the excess and deficiencies in the ash balance and the ash analysis.

In compensating these excess and deficiencies, it will be assumed that the flue dust that escapes through the stack will come within the limits of accuracy of the calculation. And with high amounts of excess air, the top collectors will be very efficient that the amount of flue dust that escapes will be negligible since the performance of mechanical collectors shows that the efficiency increases with gas flow.

The corrected amounts of refuse will correspond to the amount of unburned carbon of -0.24, 0.02 and 0.17 per cent of coal fired correspondingly, over the actual amounts in the refuse. The corrected values for each test will be used in all the calculations.

From these tests, the amount of flue dust that escapes through the stack can not be determined accurately unless special equipment in determining the amounts of flue dust coming in or out the collectors is used.

## Table 6

## Heat Balance

Test 1

| | | |
|---|---|---|
| Size of coal fired | | through 3/16 inch over zero |
| Heating value of coal as fired, Btu per lb. | | 12,860 |
| | Btu per lb | Per cent |
| Loss due to dry flue gas | 1328 | 10.32 |
| Loss due to unburned carbon | 774 | 6.02 |
| Loss due to hydrogen in the fuel | 473.5 | 3.68 |
| Loss due to incomplete combustion | 225 | 1.75 |
| Loss due to moisture in the fuel | 62.5 | 0.48 |
| Loss due to moisture in the air | 35.4 | 0.27 |
| Loss due to blowdown | 7.4 | 0.07 |
| Loss due to radiation | 219 | 1.7 |
| Unaccountable loss | 192 | 1.5 |
| Total losses | 3316.8 | 25.79 |
| Efficiency by difference | | 74.21 |

## Table 6

## Heat Balance

**Test 2**

| | | |
|---|---|---|
| Size of coal fired | through 1/4 inch over 3/16 inch | |
| Heating value of coal as fired, Btu per lb. | | 13,545 |

| | Btu per lb | Per cent |
|---|---|---|
| Loss due to dry flue gas | 1620 | 12.10 |
| Loss due to unburned carbon | 391 | 2.89 |
| Loss due to hydrogen in the fuel | 497 | 3.67 |
| Loss due to incomplete combustion | 366.5 | 2.70 |
| Loss due to moisture in the fuel | 34.8 | 0.25 |
| Loss due to moisture in the air | 43.2 | 0.32 |
| Loss due to blowdown | 6.0 | 0.05 |
| Loss due to radiation | 230 | 1.7 |
| Unaccountable loss | 203 | 1.5 |
| Total losses | 3391.5 | 25.18 |
| Efficiency by difference | | 74.21 |

### Table 6

### Heat Balance

Test 3

| | | |
|---|---|---|
| Size of coal fired | | 1 inch over 1/4 inch |
| Heating value of coal as fired, Btu per lb. | | 13,550 |
| | Btu per lb | Per cent |
| Loss due to dry flue gas | 1558 | 11.50 |
| Loss due to unburned carbon | 276 | 2.04 |
| Loss due to hydrogen in the fuel | 498 | 3.68 |
| Loss due to incomplete combustion | 109.5 | 0.81 |
| Loss due to moisture in the fuel | 31.6 | 0.23 |
| Loss due to moisture in the air | 40.7 | 0.30 |
| Loss due to blowdown | 14.6 | 0.11 |
| Loss due to radiation | 230 | 1.7 |
| Unaccountable loss | 203 | 1.5 |
| Total losses | 2961.4 | 21.87 |
| Efficiency by difference | | 78.13 |

## VI. DISCUSSION

The major variable heat losses in these tests will constitute the loss due to dry flue gas, loss due to unburned carbon, loss due to incomplete combustion, and loss due to moisture in the air and fuel.

### Dry Flue Gas Loss

Losses due to the heat in the dry flue gases assumes a major importance in heat balance work. No other heat loss is so large and readily subject to control in boiler operation. However well the excess air may be controlled, sensible heat will still be lost in the flue gases, which, apart from the excess oxygen, consist mainly of nitrogen, carbon dioxide and carbon monoxide which carries off considerable heat. The extent of this flue gas loss depends not only upon the amount of excess air used but also upon the efficiency of the boiler proper as a medium for extracting heat from the gases transfering it to the water or steam in the boiler.

The design conditions of the Boiler No. 6 in its manufacturer's performance guarantee called for, the dry flue gas losses ranges approximately 7 to 10 per cent, equivalent to 959 to 1370 Btu per pound of bituminous coal or heating value of 13,700 Btu per pound. The flue gas exit temperature was to be 345 to 424 degrees F. at load ranges of 30,000 to 60,000 lbs. of steam per hour. The per cent $CO_2$ was to be kept at 13.5 per cent with the amount of excess air at approximately 40 per cent.

In the three tests, using the three different sizes of coal the heat loss due to dry flue gas ranges from 1320 to 1640 Btu per pound of coal fired, with flue gas exit temperatures at approximately 380 degrees F. with excess air from 92 to 122 per cent. These tests were performed far from the best values of excess air to obtain the adverse effect in the flue dust carryover. To possibly operate in the economical range the amount of excess air should be kept to a minimum where there will be efficient combustion of the fuel, with minimum potential heat loss as unburned carbon and incomplete combustion of gases. In other words, there will be always a best value of excess air for a given type or size of coal for economical operation in a given boiler.

### Unburned Carbon Loss

In these particular tests, where the spreader stoker was forced beyond its normal rating of coal size 1-1/4 inch to zero, the flue dust becomes an important factor. From the heat balance, the unburned carbon in the flue dust, which is shown in figure UB-1, constituted 65.8 to 83 per cent of the total unburned carbon in the fuel.

By analysis as shown in Table 2, the unburned carbon in the flue dust collected in the top and bottom hoppers ranges from 23.9 to 27.01 and 46.28 to 54.38 per cent of flue dust collected in the respective hoppers. From these variations the total amount of unburned carbon will largely depend on the amount of flue dust deposited in the hoppers of the flue dust collectors.

In Test 1, the size of coal fired was all through 3/16 inch to zero. The size consist which was evaluated from Table, was as follows:

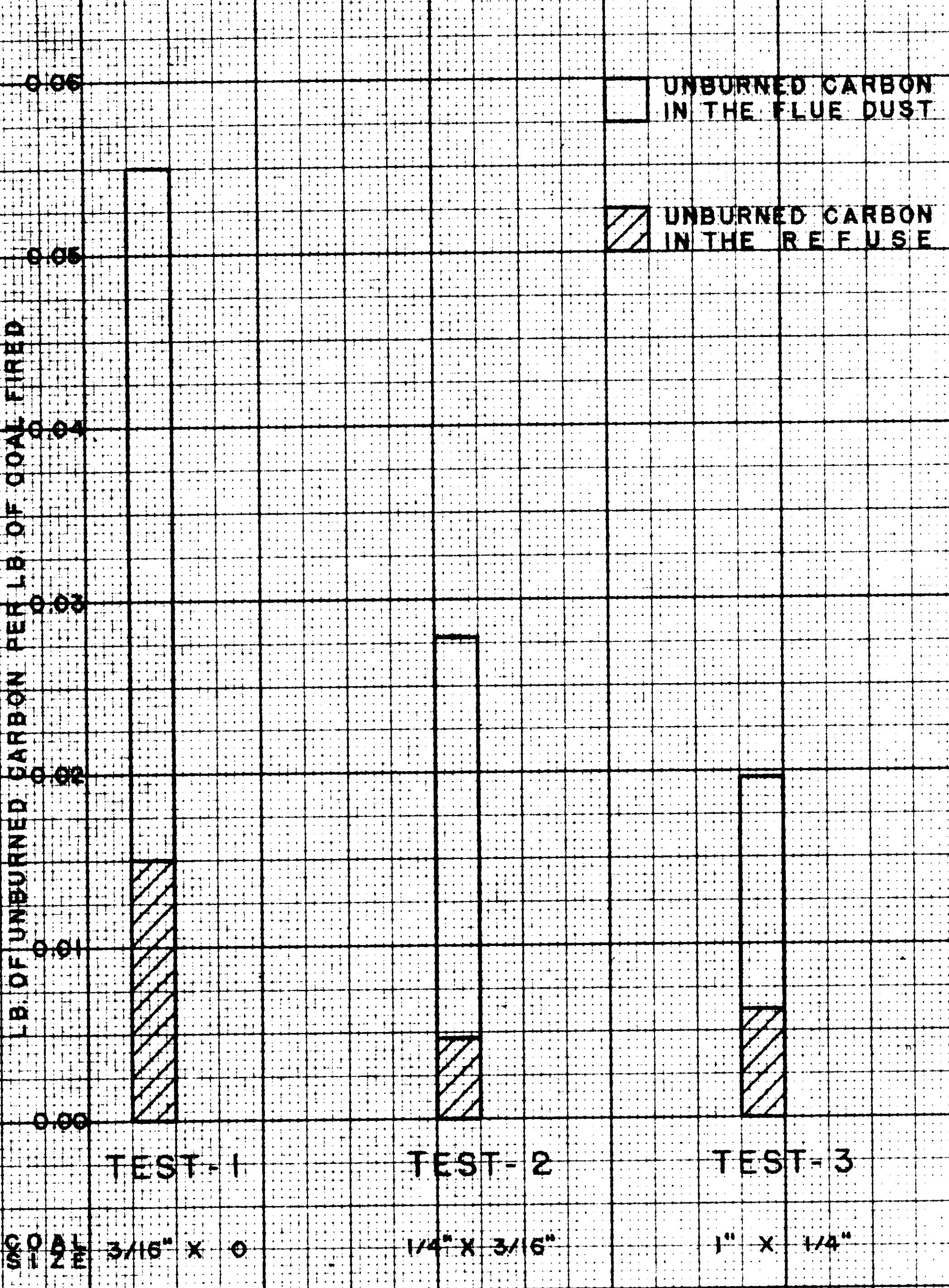

FIG. UB-I UNBURNED CARBON

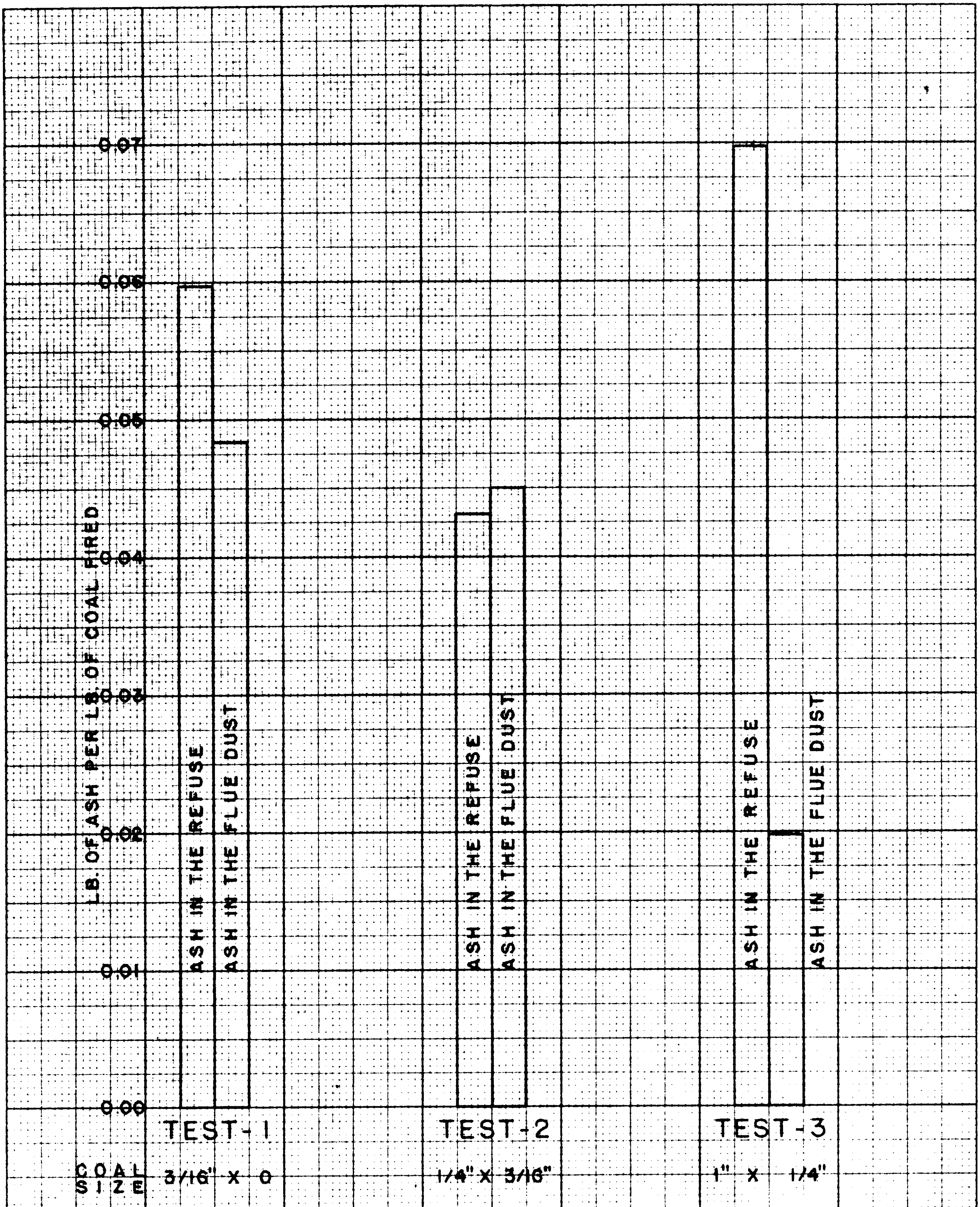
LB. OF ASH PER LB. OF COAL FIRED
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
ASH IN THE REFUSE
ASH IN THE FLUE DUST
ASH IN THE REFUSE
ASH IN THE FLUE DUST
ASH IN THE REFUSE
ASH IN THE FLUE DUST
TEST-1
TEST-2
TEST-3
COAL SIZE
3/16" X 0
1/4" X 3/16"
1" X 1/4"

FIG. UB-2 ASH

| Size range | Per cent by weight | Cumulative percentage |
|---|---|---|
| Through 1/16" to zero | 29.2 | 29.2 |
| Through 1/8" to over 1/16" | 37.9 | 67.1 |
| Through 3/16" to over 1/8" | 32.9 | 100.0 |

The amount of ash in the coal ash fired was 10.82 per cent. The amount of ash deposited in the collectors was approximately 44.75 per cent as shown in the figure UB-2, at the specified excess air. Although it can not be shown in Test 1, that the amount of ash, consequently flue dust, collected in the hoppers could increase with increasing amounts of excess air, Test 2 and 3 as shown in Figure FD-1, indicates that the ash collected in the hoppers increases with the amount of excess air, even at the size range of through 1/4 inch over 3/16 inch and 1 inch over 1/4 inch, where there was very few coal particles below the size of 3/16 inch. In Test 1, the amount of flue dust collected will depend mainly in the amount of operating excess air. And, with the size of coal through 3/16 inch over zero, there would always be an amount of flue dust carryover with the lowest amount of excess air to support combustion. The flue dust carryover would be inherent in this size range of the coal.

In Test 2 and 3, where the sizes of coal fired were through 1/4 inch over 3/16 inch and 1 inch over 1/4 inch, considerable amount of ash was deposited in the flue dust collectors as graphically represented in figure UB-2. In Test 2, where the lower size limit of the coal was 3/16 inch, the ash deposited in the collectors was approximately 51 per cent compared with Test 3 where the lower size limit was 1/4 inch, the ash collected was 22 per cent, with reduced amount of excess air.

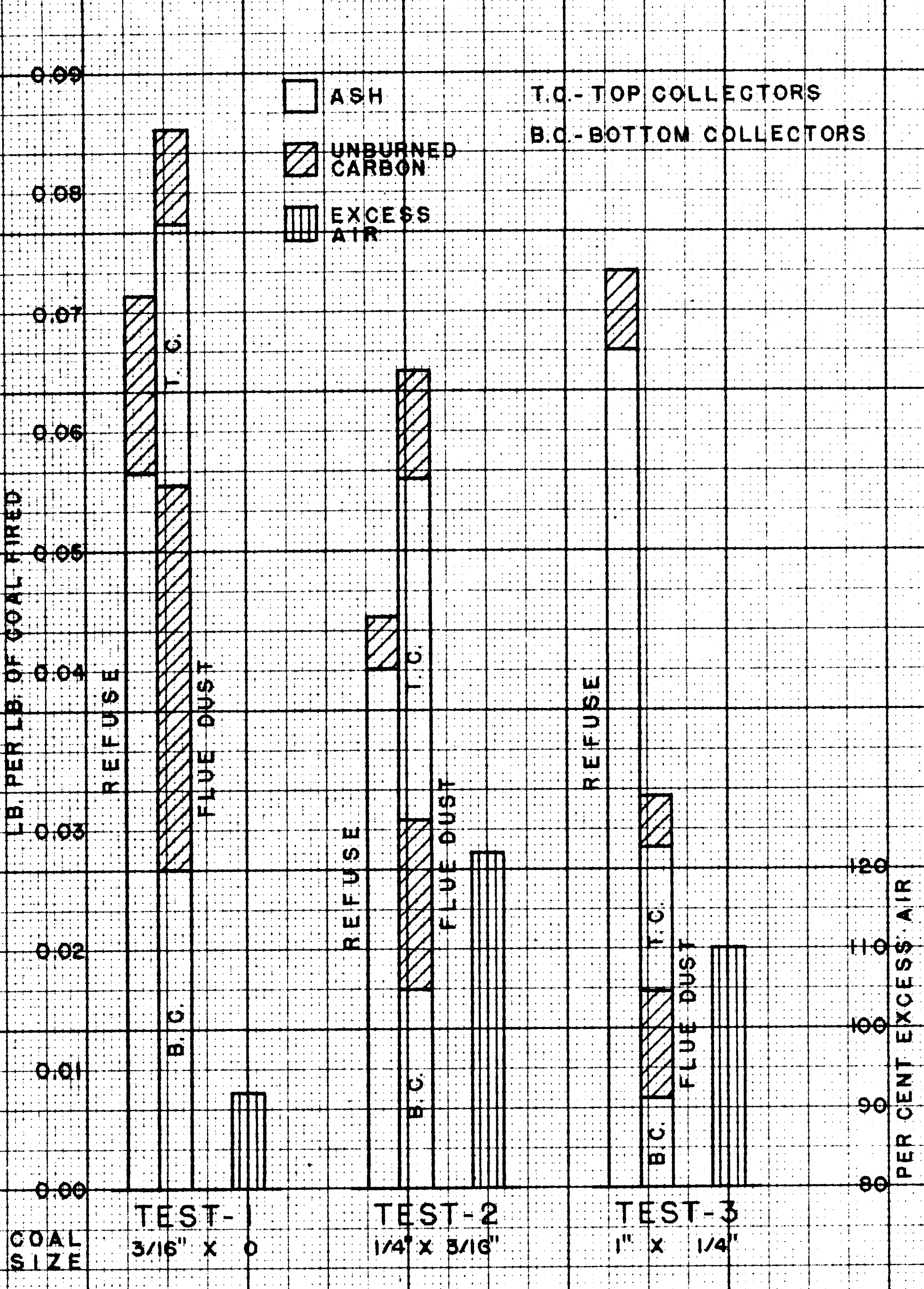

FIG. FD-1 REFUSE AND FLUE DUST

The possible sources of the ash, consequently flue dust, deposited in the collectors could possibly be the coal sizes below the lower limits of the size range of the coal fired. This raw coal particles would be the result due to the inefficiency of screening or separation. Since the coal was not washed or cleaned, smaller coal particles were attached to the surfaces of the larger pieces of coal, even at low moisture content. In these cases, below 3 per cent. In the process of transporting or conveying the coal to the grate, a certain amount of coal below 3/16 inch could develop through breakage and crushing between pieces of coal. From these two factors, it would not probably account the ash deposited in the collector in Test 2 as shown in figure UB-2, which consist of approximately 51 per cent of the total ash. This would lead to the grate as the source of the ash, deposited in the collectors carried by the gases due to the high amount of excess air. From the investigation of Kaiser (4), it was found that a substantial portion of the boiler dust constitutes the whole or fragments of cenospheres or new-born cinders, and some part of the ash that was released in the fuel bed was loose and powdery. This would make up the aggregate amount deposited in the collectors.

In any size of coal fired in the boiler, the amount of flue dust carryover would be affected by the operating excess air and the flue dust carryover would be affected by the operating excess air and the flue dust carryover will increase with increasing amount of excess air. But, the flue dust carryover can be reduced to a considerable amount with double-screened coal, as shown in Test 2 and 3 compared with Test 1, where it is shown graphically in FD-1. With double screened coal, the flue dust and consequently the unburned carbon will be reduced considerably when operating in the best values of excess air to support the combustion of the coal.

Unburned Carbon in the Refuse

In Test 1, by analysis, the unburned carbon was 20.15 per cent of the refuse. This could be attributed to the uneven distribution of the coal on the grate at the given amount of excess air and size of coal. The unburned carbon loss could be possibly reduced by proper setting of the stoker feeder spilling plate. In this operation this feeder plate was permanently set for normal operation of coal size 1-1/4 inch to zero, and adjustments were made by the hand wheel, which could not possibly satisfy for sizes of under 3/16 inch to zero. At this condition, a certain amount of coal was constantly dumped in front of the grate, and falls in the ash pit in the burning state, which contributed to a high carbon loss in the refuse.

With the three stoker feeders in No. 6 Boiler, the coal distribution in the grate would possibly improve when the setting of the feeder spilling plates would be in such a way that, the two feeders will distribute coal in the back of the grate and one feeder would supply in the front of the grate.

In Test 2, where the coal size fired was through 1/4 inch over 3/16 inch, the unburned carbon in the refuse was 9.71 per cent as shown in the fuel analysis in Table 2. At the high amount of excess air supplied, this value appears to be high. This would result from the uneven distribution of coal on the grate with the improper setting of the feeder spilling plate. This adjustment could be changed to give a much better distribution in this size range of coal similar to Test 1.

These changes in the setting of the spilling plate could not be made during this investigation due to the limited quantity of the prepared fuel and possibly would interupt the operation of the boiler.

In Test 3, with coal size ranging from 1 to over 1/4 inch, there was a suitably even distribution of coal in the grate. Lowering the top size of coal in this case would be effective in reducing the unburned carbon in the refuse. From the inspection of the biggest particles of the refuse, it shows that the inside part of these particles contains or is relatively raw coal or unburned carbon.

### Loss Due to Incomplete Combustion

When carbon monoxide is formed, the loss which this would indicate is not limited to the partial combustion of carbon, but it is related to the serious losses that are involved through the escape of hydrocarbon gases of some heating value.

In Test 1 and 2, the high amount of CO could result from the uneven distribution of coal in the grate, and consequently stratification of gases will occur. At these high amounts of excess air, turbulence could be considered as ineffective.

### Loss Due to Moisture in the Fuel

The heat loss due to the moisture in the fuel is comparatively smaller than the operating losses. With all the flue gas exit temperature almost constant in all these tests, this loss primarily depends on the content of the fuel. With all the coal having almost the same degree of exposure in the atmosphere during its preparation, the moisture content of the coal will vary with its sizes, and the moisture content of the coal will increase as the size is smaller or finer, as found in the proximate analysis of the fuel.

## Operating Efficiencies

The efficiency obtainable in these tests will be largely governed by the heat losses due to dry flue gases, unburned carbon and incomplete combustion of the gases. The heat loss due to unburned carbon will be primarily a source of potential heat loss due to the size of the fuel and the characteristic firing of the spreader stoker. With finer sizes of coal as in Test 1, this loss could be reduced by the reinjection of flue dust in the furnace.

The heat balance shows, the advantage of double screened coal even with considerably higher sensible heat losses in the flue gases. With Test 2, where the coal size fired was through 1/4 inch over 3/16 inch, the increase in efficiency was 0.61 per cent, and with Test 3, where coal size fired was 1 inch over 1/4 inch the increase in efficiency was 3.92 per cent.

## VII. CONCLUSIONS

The sensible heat losses in the flue gases was exceeding the best economical operating ranges of the Boiler No. 6. This was done to study the adverse effect on the flue dust carryover in the furnace.

The flue dust carryover in firing double-screened coal in sizes through 1/4 inch over 3/16 inch and 1 inch over 1/4 inch was considerably less than with the coal in the size of through 3/16 over zero. The flue dust carryover is inherent in the coal size of through 3/16 inch over zero.

The potential heat losses in the coal size through 3/16 inch over zero will be greater than the double-screened coals, with the same operating conditions.

With the operating characterisites of the spreader stoker, the coal size through 3/16 inch over zero would be difficult to maintain an even distribution of coal on the grate. As with the operating conditions in Test 1 and 2, the distribution could be improved with the proper setting of the feeder spilling plate, but would not compare to the possibilities of advantages of firing double-screened coal with a wider range of coal size as in the case of Test 3.

## VIII. RECOMMENDATIONS

If studies are to be made in the future as to the different coal sizes to be fired in the Boiler No. 6, a much better screening and crushing equipment should be available to have a greater output and efficiency.

The best amount of excess air for efficient combustion in firing different sizes of double-screened coal in Boiler No. 6 should be investigated to compare their economical advantages with the cost of double-screened coals.

A study should be made where spilling plates of the three stoker feeders of the No. 6 Boiler are set to different positions with coal sizes through 3/16 inch over zero and through 1/4 inch over 3/16 inch, to effect more even distribution of coal on the grate.

An investigation should be made with different designs of the rotor blades in each of the stoker feeders to give an even distribution of coal on the grate in firing coal sizes through 3/16 inch over zero and through 1/4 inch to over 3/16 inch.

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# APPENDIX A

Manufacturer's Performance Data *

Kind of Fuel - Bituminous Coal

Proximate Analysis

| | |
|---|---|
| Moisture | 3.3 per cent |
| Volatile Matter | 34.1 |
| Fixed Carbon | 54.9 |
| Ash | 7.7 |

Ultimate Analysis

| | |
|---|---|
| Carbon | 77.1 |
| Oxygen | 7.7 |
| Hydrogen | 5.4 |
| Nitrogen | 1.5 |
| Sulfur | 0.6 |
| Ash | 7.7 |

| | |
|---|---|
| Ash Softening Temperature | 2,400 deg. F. |
| High Heating Value | 13,740 Btu per lb. |

| | |
|---|---|
| Capacity, lbs. of steam per hour | 30,000 |
| Steam pressure at superheater outlet, psi | 250 |
| Boiler drum pressure, psi | 251.3 |
| Temperature of steam at superheat outlet, deg. F. | 490 |
| Temperature of feedwater, deg. F. | 215 |
| Temperature of flue gas leaving the boiler, deg. F. | 482 |
| Temperature of flue gas leaving the furnace, deg. F. | 1920 |
| Temperature of flue gas leaving the air heater, deg. F. | 345 |
| Temperature of the air entering the air heater, deg. F. | 80 |
| Temperature of the air leaving the air heater, deg. F. | 269 |
| | |
| Per Cent $CO_2$ in the furnace | 14.5 |
| Per cent $CO_2$ in the Boiler Exit | 14 |
| Per cent $CO_2$ in the Air Heater Exit | 13.5 |
| | |
| Furnace Draft loss, inches of water | 0.15 |
| Boiler and Superheater draft loss | 0.18 |
| Air heater draft loss | 0.15 |
| Dust collector draft loss | 0.57 |
| Flues - draft loss | 1.18 |

* From V. P. I. Heating and Power Plant Records

| | |
|---|---|
| Air resistance - stoker and windbox | 0.70 |
| Air resistance - air heater to windbox | 0.25 |
| Air resistance - air heater | 0.19 |

| | |
|---|---|
| Flue gas leaving the Boiler, lbs. per hour | 39,300 |
| Flue gas leaving the Air Heater, lbs. per hour | 40,700 |
| Air entering the Air Heater, lbs. per hour | 30,800 |
| Air required for combustion, lbs. per hour | 36,200 |

| | |
|---|---|
| Fuel burned, lbs. per hour | 2,810 |

| | |
|---|---|
| Heat liberation in the furnace, Btu/cu Ft/hr | 13,800 |

Heat Balance

| | |
|---|---|
| Loss due to dry flue gas | 6.9 per cent |
| Loss due to hydrogen and moisture in the fuel | 4.18 |
| Loss due moisture in the air | 0.16 |
| Loss due Unburned Carbon | 0.70 |
| Loss due to Radiation | 1.70 |
| Unaccountable loss | 1.50 |
| Total | 15.14 |
| Efficiency | 84.86 |

# APPENDIX B

## HEAT BALANCE CALCULATIONS

### 1. Calculated Ultimate Analysis from the Proximate Analysis of Coal

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Proximate analysis of coal "moisture and ash free" | | | |
| Per cent volatile matter (V) | 36.11 | 35.97 | 36.01 |
| Per cent fixed carbon (FC) | 63.89 | 64.03 | 63.99 |
| 100 - per cent moisture (M) - per cent ash (A) | 83.88 | 88.34 | 88.37 |
| (a) Calculations from Evans Emprirical Relations (12) | | | |
| High heating value = 18,750 -9,440 V | | | |
| Btu per lb of combustible | 15,340 | 15,355 | 15,350 |
| Average heating value | | | |
| Btu per lb of combustible | 15,348 | 15,348 | 15,348 |
| Average heating value (1 - M - A) | | | |
| Btu per lb of coal as fired | 12,860 | 13,545 | 13,550 |
| Total carbon (C) in the coal = 1.095 - 0.663 V | | | |
| lb per lb of combustible | 0.856 | 0.856 | 0.856 |
| Total carbon (C) = (1.095 - 0.633 V) (L - M - A) | | | |
| lb per lb of coal as fired | 0.717 | 0.756 | 0.756 |
| Hydrogen (H) in the coal = 0.0457 + 0.0206 V | | | |
| lb per lb of combustible | 0.0531 | 0.0531 | 0.0531 |
| Hydrogen = )0.0457 + 0.0206) (1 - M - A) | | | |
| lb per lb of coal as fired | 0.0445 | 0.0468 | 0.0468 |

(b) Calculation from Mark's equations (13)

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Volatile carbon = $0.9 (V - 14)$ for bituminous and semi-bituminous coal, accurate to ± 2 per cent by weight | 19.9 | 19.77 | 19.8 |
| Fixed carbon, per cent of combustible | 63.89 | 64.03 | 63.99 |
| Total carbon, per cent of combustible | 83.79 | 83.80 | 83.79 |
| Total carbon x $(1 - m - A)$ per cent of coal as fired | 70.3 | 74.0 | 74.0 |
| Hydrogen (H) in the coal = $V ((7.35/V + 10) - 0.013)$ accurate to ± 0.02 per cent by weight of combustible | 5.72 | 5.70 | 5.70 |
| $H = V ((7.35/V + 10) - 0.013) (1 - M - A)$ per cent by weight of coal as fired | 4.79 | 5.03 | 5.03 |
| Nitrogen (N) in the coal = $2.10 - 0.012 V$ for bituminous and semi-bituminous coals accurate to ± 0.5 per cent by weight of combustible | 1.667 | 1.668 | 1.668 |
| Nitrogen = $(2.10 - 0.012 V) (1 - M - A)$ per cent of coal as fired | 1.398 | 1.471 | 1.472 |

**Remarks:**

The fixed carbon may contain several tenths of hydrogen and oxygen, 0.4 to 1 per cent of nitrogen and 0.5 per cent of sulphus that was in the coal.

## (e) Comparison of Heating values

Approximate ultimate analysis from Evans Empirical Relations, assuming averagevalues of oxygen and sulphur as compiled from the Bulletin of the Bureau of Mines (15), lb per lb of combustible.

High heating value of coal = $14{,}544\ C + 62{,}028(H - O/8) + 4050\ S$ Btu per lb of combustible
$C = 0.856$; $H = 0.053$; $O = 0.049$; and $S = 0.0098$ lb per lb of combustible

High heating value of coal = 15,389 Btu per lb of combustible.

High heating value of coal = $18{,}750 - 9{,}440\ V = 15{,}348$ Btu per lb of combustible

Approximate ultimate analysis from Mark's equations, assuming average values of oxygen and sulphur as compiled from the Bulletin of the Bureau of Mines (15), lb per lb of combustible.

Carbon = 0.838; Hydrogen = 0.057; Oxygen = 0.049; Sulphur = 0.0098

High heating value of coal = $14{,}544\ C + 62{,}028(H - O/8) + 4050\ S$ Btu per lb of combustible
= 15,330 Btu per lb of combustible

From Power Data Sheet (14) of December 1956, the heating value of coal from this curve was 15,200 Btu per pound of combustible.

## 2. Ash Balance

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Total weight of coal fired during each test, lbs. | 11,640 | 8,020 | 11,330 |
| **Ash in the refuse** | | | |
| Total weight of refuse during each test, lbs. | 1,005 | 367 | 657 |
| Refuse, per cent of coal fired | 8.63 | 4.58 | 5.8 |
| Per cent ash in the refuse, 100 per cent combustible in the refuse | 79.84 | 90.28 | 91.28 |
| Ash in the refuse, per cent of coal fired | 6.89 | 4.145 | 5.3 |
| **Ash in the refuse** | | | |
| Total weight of flue dust collected during each test, lbs. | 346 | 299.75 | 186.5 |
| Top hoppers | | | |
| Bottom hoppers | 686.5 | 247.75 | 185.5 |
| Flue dust, per cent of coal fired | | | |
| Top hoppers | 2.97 | 3.74 | 1.65 |
| Bottom hoppers | 5.89 | 3.09 | 1.63 |
| Ash, per cent of flue dust, 100 - per cent combustible in the flue dust | | | |
| Top hoppers | 72.99 | 76.1 | 73.96 |
| Bottom hoppers | 45.62 | 53.72 | 47.74 |
| Ash in flue dust, per cent of coal fired | | | |
| Top hoppers | 2.16 | 2.84 | 1.215 |
| Bottom hoppers | 2.68 | 1.66 | 0.766 |
| Total ash, per cent of coal fired | 11.73 | 8.645 | 7.281 |
| Ash, per cent of coal as fired, by analysis | 10.82 | 8.82 | 8.96 |
| Difference | 0.91 | -0.18 | -1.68 |

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Corrected amount of refuse | | | |
| Ash in the refuse, per cent of coal fired | 6.89 | 4.145 | 5.3 |
| Difference in the Balance, per cent of coal fired | -0.91 | 0.18 | 1.68 |
| Corrected ash in the refuse, per cent of coal fired | 5.98 | 4.325 | 6.98 |
| Corrected amount of refuse, per cent of coal fired | 7.48 | 4.78 | 7.65 |
| 3. Unburned Carbon | | | |
| Unburned carbon in the refuse | | | |
| Corrected amount of refuse, per cent of coal fired | 7.48 | 4.78 | 7.65 |
| Unburned carbon, per cent of refuse, by analysis | 20.15 | 9.71 | 8.72 |
| Unburned carbon in the refuse, per cent of coal as fired | 1.5 | 0.465 | 0.67 |
| Unburned carbon in the flue dust | | | |
| Flue dust, per cent of coal fired | | | |
| Top hoppers | 2.97 | 3.74 | 1.65 |
| Bottom hoppers | 5.87 | 3.09 | 1.63 |
| Unburned carbon, per cent of flue dust, by analysis | | | |
| Top hoppers | 27.01 | 23.9 | 26.04 |
| Bottom hoppers | 54.38 | 46.28 | 52.26 |
| Unburned carbon in the flue dust, per cent of coal fired | | | |
| Top hoppers | 0.80 | 0.89 | 0.436 |
| Bottom hoppers | 3.20 | 1.43 | 0.860 |
| Unburned carbon in the refuse and flue dust, per cent of coal as fired | 5.50 | 2.785 | 1.96 |

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| 4. Carbon Burned | | | |
| Carbon in the coal, per cent of coal fired, from Evans Empirical Relations | 71.7 | 75.6 | 75.6 |
| Unburned carbon in the refuse and flue dust, per cent of coal as fired | 5.5 | 2.785 | 1.96 |
| Carbon burned, per cent of coal as fired | 66.2 | 72.82 | 73.64 |
| 5. Weight of Air Theoretically required for combustion | | | |
| Weight of carbon per lb of combustible, from Evans Empirical Relations | 0.856 | 0.856 | 0.856 |
| Weight of hydrogen per lb of combustible, from Evans Empirical Relations | 0.0531 | 0.0531 | 0.0531 |
| Weight of oxygen per lb of combustible, average value compiled from Bulletin of Bureau of Mines | 0.049 | 0.049 | 0.049 |
| Weight of sulphur per lb of combustible, average value compiled from Bulletin of Bureau of Mines | 0.0098 | 0.0098 | 0.0098 |
| Weight of theoretical air per lb of combustible $= 11.53\ C + 34.34\ (H_2 - O_2/8) + 4.29\ S$ | 11.529 | 11.529 | 11.529 |
| 6. Weight of Dry Flue Gas per lb of Coal Fired | | | |
| Flue gas analysis, per cent by volume, average observations | | | |

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Carbon dioxide | 8.56 | 7.53 | 8.37 |
| Oxygen | 9.58 | 11.03 | 9.35 |
| Carbon Monoxide | 0.31 | 0.41 | 0.13 |
| Nitrogen = $100 - CO_2 - O_2 - CO$ | 81.55 | 81.03 | 81.65 |
| Weight of carbon burned, lb per lb of coal as fired | 0.662 | 0.728 | 0.736 |
| Weight of dry gas per pound of coal fired, lbs $\frac{11\,CO_2 + 8\,O_2 + 7(N_2 + CO)}{3\,(CO_2 + CO)}$ (Carbon burned) | 18.55 | 22.65 | 21.35 |
| If sulphur taken to account which is 0.0098 lb per combustible x (1 - M - A) | 0.0082 | 0.0086 | 0.0086 |
| Equivalent carbon burned = carbon burned + 0.425 S | 0.6655 | 0.7317 | 0.7397 |
| Weight of dry gas per lb of coal as fied | 18.63 | 22.72 | 21.42 |
| 7. Weight of air supplied per lb of coal as fired | | | |
| $(3.04\,N_2/CO_2 + CO)$ (carbon burned) | 18.55 | 22.65 | 21.35 |
| 8. Per cent Excess air | | | |
| Weight of air theoretically required for combustion, lb per lb of coal fired | 9.67 | 10.18 | 10.18 |
| Per cent excess air = $(W_a/Wt - 1)$ (100. | 92 | 122 | 110 |
| Per cent excess air = $(O_2 - CO/2) / 0.264\,N_2 - (O_2 - CO/2))$ | 78.8 | 102 | 83.2 |

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| 9. Loss due to dry flue gas | | | |
| Weight of dry flue gas per lb of coal fired (Wg) | 18.63 | 22.7 | 21.35 |
| Mean specific heat at constant pressure, (Cp) Btu per lb per deg. F. | 0.24 | 0.24 | 0.24 |
| Temperature of air supplied (Ta), degrees F. average observations | 83.3 | 80.7 | 77.75 |
| Exit flue gas temperature (Tg), degrees F. average observations | 380 | 381.5 | 381.3 |
| Temperature difference | 296.7 | 300.8 | 302.55 |
| Loss due to dry flue gas per lb of coal as fired = (Wg) (Cp) (Tg - Ta) Btu per lb | 1328 | 1640 | 1558 |
| 10. Loss due to Unburned Carbon | | | |
| Unburned carbon in the refuse and flue dust, lb per lb of coal fired | 0.055 | 0.0278 | 0.0196 |
| Loss due to unburned carbon = 14,093 x unburned carbon, Btu per lb of coal as fired | 774.0 | 391 | 276 |
| 11. Loss due to Hydrogen in the Coal | | | |
| Weight of hydrogen in the coal per lb of coal fired, from Evans Empirical Relations | 0.0445 | 0.0468 | 0.0468 |

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Flue gas exit temperature (Tg), degrees F. | 380 | 381.5 | 381.3 |
| Temperature of the air (Ta), degrees F. | 80.1 | 72.2 | 78.8 |
| Loss due to hydrogen in the fuel = $9H_2$(1089 + 0.46 Tg - Ta) Btu per lb of coal fired | 473.5 | 497 | 498 |
| 12. Loss due to incomplete combustion | | | |
| From the flue gas analysis, average observations | | | |
| carbon dioxide | 8.56 | 7.53 | 8.37 |
| carbon monoxide | 0.31 | 0.41 | 0.13 |
| Carbon dioxide + carbon monoxide | 8.87 | 7.94 | 8.5 |
| Carbon burned, lb per lb of coal fired | 0.662 | 0.728 | 0.736 |
| Loss due to incomplete combustion = (carbon burned) ($CO/CO_2$ - CO) (9,746) Btu per lb of coal fired | 225 | 366.5 | 109.5 |
| 13. Loss due to moisture in the fuel | | | |
| Per cent moisture in the fuel as fired (Wm) | 5.30 | 2.94 | 2.67 |
| Flue gas exit temperature (Tg), degrees F. | 380 | 381.5 | 381.3 |
| Temperature of the fuel (Tf), degrees F. | 80.1 | 72.2 | 78.8 |
| Loss due to moisture in the fuel = (Wm) (1089 + 0.46 Tg - Ta) Btu per lb of coal as fired | 62.5 | 34.8 | 31.62 |

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| 14. Loss due to moisture in the air | | | |
| Weight of dry air supplied per pound of coal fired (Ws) | 18.55 | 22.65 | 21.35 |
| Dry bulb temperature of air, degrees F. | 83.3 | 80.7 | 77.75 |
| Wet bulb temperature, degrees F. | 71.5 | 70.5 | 70.05 |
| Weight of water vapor per lb of dry air, (Wa) from the psychrometric chart, lbs. | 0.014 | 0.0138 | 0.0137 |
| Loss due to moisture in the air = 0.46 ($T_g$ - $T_a$)($W_v$)($W_a$) Btu per lb of coal fired | 35.4 | 43.2 | 40.7 |
| 15. Loss due to blowdown | | | |
| Weight of blowdown per lb of coal fired, lbs (Wbd) | 0.0306 | 0.0247 | 0.602 |
| Enthalpy of saturated water at boiler drum pressure, Btu per lb of water ($h_{f1}$) | 281 | 280.6 | 281.0 |
| Enthalpy of saturated water at make-up water temperature of 70 degrees F. Btu per lb ($h_{f2}$) | 38.04 | 38.04 | 38.04 |
| Loss due to blowdown = Wbd ($h_{f1}$ - $h_{f2}$) Btu per pound of coal asfired | 7.43 | 5.97 | 14.6 |