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SUBJECT : COMBUSTION TESTS ON SOUTH AFRICAN ANTHRACITE AND COAL.

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COMBUSTION TESTS ON SOUTH AFRICAN ANTHRACITE AND COALS.

by

DR. F. W. QUASS.

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COMBUSTION TESTS ON SOUTH AFRICAN ANTHRACITE AND COAL.

(Condensed Report)

Anthracite ?

ABSTRACT AND SUMMARY:

In order to establish the relative suitability for steam raising purposes of South African anthracite, firing tests were carried out in an experimental furnace on a number of nut size coals and an anthracite. The selection of the fuels was based largely on the volatile matter content which ranged from 8.0 per cent (anthracite) to 34.7 per cent.

The experimental furnace was fired by hand (overfeed stoking) every 10 minutes. Forced draught was applied in most of the tests, the primary air being delivered under the grate by an electrically driven fan. At least one test was conducted on every coal, however, using only the natural draught of the chimney.

During the firing tests measurements were made of the pressure under and over the fuel bed and of the temperature in the chimney. Samples were taken of the gases rising from the fuel bed.

The clinker formed on the grate was recovered after the combustion tests and subjected to shatter tests in order to assess its relative hardness.

From the point of view of the potential steam-raising qualities of anthracite, it was found that:

1. Anthracite has a slower combustion rate than coal for the same primary air rate owing to its smaller volatile matter and greater fixed carbon contents. The anthracite requires ? approximately 6 pounds of primary air per pound of fuel, whereas the coals require 4-5 pounds of primary air per pound of fuel, the quantity required decreasing with increase in volatile matter content.

2. The gas rising from the fuel bed of anthracite contains an equal percentage of combustible components, is richer in CO, ? poorer in H_2, CH_4, illuminants and smoke and its composition is less variable than the gases rising from the fuel beds of the coals.

3. In spite of its high ash fusion temperature the anthracite has a high and uniform bed resistance and allows limited quantities of air to be drawn through the bed by natural draught. This characteristic of the anthracite may probably be attributed to its tendency, when heated suddenly, to decrepitate into small cubes, which pack closely in the bed.

4. The anthracite forms less and softer clinker than the coals at all combustion rates.

5. Assuming the heat liberated by the anthracite to be unity, the ratio of the heat liberated per unit of grate area per unit of time under different conditions by the anthracite to that delivered by the coals under similar conditions can be seen from the figures in the following table:-

Average Heat Ratio with

Fuel	Equal Rate of Primary Air	Equal Rate of Total Air		Natural Draught
		No Excess Air	50% Excess Secondary Air.	
N.A.Anthracite	1.0	1.0	1.0	1.0
Mooifontein	1.1	1.05	1.05	0.95
Tshoba	1.2	1.1	1.1	1.85
Wolvekrans Middlings	1.25	1.2	1.2	1.75
Wolvekrans Whole Coal	1.35	1.3	1.2	1.7
Bankfontein	1.35	1.1	1.05	1.9
Bellevue	1.4	1.1	1.0	1.5
Waterpan	1.4	1.3	1.2	1.85
Wolvekrans Float	1.4	1.3	1.25	-

6. In view of its tendency to decrepitate on the bed, it is considered that anthracite is unsuitable for high draught conditions and for fire-tube furnaces.

Consequently, it is concluded that anthracite would compare favourably with normal industrial coals as a steam-raising fuel under forced draught conditions where medium to low steaming rates are required. With natural draught its performance would only be equal to that of low grade coals. ?

The following information was also derived from the experiments:-

1. Two formulae have been established with which it is possible to calculate the combustion rate of a fuel from its proximate analysis and the available primary air rate of a furnace:

   Formula 1: $100y_1 + 2.3x_1 = 176$,
   where y_1 is the primary air requirement in cf/sq.ft./min. per lb. of fuel/sq.ft./hour, and x_1 is the percentage volatile matter of the fuel on a dry, ash-free basis.

   Formula 2: $100y_2 + 8.5x_1 = 660$,
   where y_2 represents the primary air requirement in lbs.air/lb. of fuel, and x_1 is the percentage volatile matter of the fuel on a dry, ash-free basis.

2. The significance that must be attached to the ash fusion temperature of a coal is great, since this factor is a measure of its relative bed resistance and natural draught and also the quantity and hardness of the clinker formed in the bed. ? An ash fusion temperature of $1400^{\circ}C$ was found to be a limiting or critical temperature in many respects.

3. ? The complete and effective combustion of the gaseous products rising from the fuel beds of coking coals would be difficult to control since great variations occur in the composition of these gases.

4. At least twice as much air must be passed over a fire as is delivered under it for all fuels in order to achieve complete combustion.

INTRODUCTION:

There are, in Natal, very large deposits of low volatile, anthracitic and semi-anthracitic coals, which are generally believed to be unsuitable for steam-raising purposes. Of the total of 3,000 million tons of proved and estimated coal reserves in Natal, Wybergh(1) in 1925 placed approximately 25 per cent or 750 million tons in the semi-anthracitic (volatile matter from 10 to 16 per cent) and anthracitic (volatile matter under 10 per cent) classes. In a later survey of the coal reserves of the Vryheid Coalfield only in 1940, Blignaut, Furter and Vogel(2) estimated the reserves of anthracitic and semi-anthracitic coals in the Vryheid district to be 281 million tons, whereas the figure for the estimated reserves of all bituminous coals (volatile matter over 16 per cent) were only 149 million tons. Extensive drilling in Natal during the past 20 years has indicated that the ratio of bituminous to anthracitic plus semi-anthracitic coal in the other coalfields of Natal is also much smaller than estimated by Wybergh.

In South Africa, at the present time, coking coals of which the reserves are very limited, are being used as steam coals. If the enormous reserves of low volatile coals could be used for steam-raising purposes, the problem of the conservation of the coking coal deposits would be more readily solved.

Wybergh(1) states "that in every colliery in Natal the workings are bounded in one direction or another by coal which is considered to be too low in volatiles to work (i.e. coal having a volatile matter content of less than 16 per cent)."

The general attitude towards the use of anthracite for steam-raising purposes may be indicated by the following quotations from Steart(3) : "The Natal anthracites are altered bituminous coals, having become anthracitic by loss of a proportion of volatile matter, including valuable heat-producing hydrocarbons. It appears, therefore, that these coals, which have been rendered anthracitic by igneous action, must be poorer than the original bituminous coals containing their full proportion of volatile matter. It can hardly be seriously contended, therefore, that a coal seam which has been partly burned or consumed, is richer than before, or that its calorific value has been thereby increased ......the anthracitic types of Natal coal have not been successfully used for steam-raising purposes ..... the speed of combustion is too slow, even under the influence of forced draught, to give good results."

The non-existence of available data on controlled combustion tests carried out on South African anthracites has unfortunately only strengthened this prejudice against the use of these coal types. This is borne out by the very limited market the anthracitic coals have in South Africa. Out of a total of over 5 million tons of coal mined in Natal in 1944, less than 50,000 tons of anthracite were produced, i.e. less than 1 per cent of the total Natal coal production.

During the past few years, however, a number of Natal coals with volatile matter contents varying from 11 to 15 per cent have been used as steam coal overseas, in ships, by the South African Railways' locomotives and in local industries. The performance of these semi-anthracites appears to have been satisfactory and it would seem that the percentage volatile matter demanded has decreased considerably from the original "unsuitability" limit of 16 per cent.

The greatest difference between the South African and the highly recommended Welsh anthracites is the higher ash contents of the former. This is not necessarily a disadvantage since too low an ash content may cause damage to the fire bars.(4)

It has also been stated that during the combustion of South African anthracites a layer of ash forms on the surface of the lumps thereby preventing or retarding further combustion of the residual "carbon". This fact is held to be responsible for the slow burning characteristics of the South African anthracites.

Steart's(3) description of coals rendered anthracitic by igneous action as having been "partly burned or consumed" may require modification. It has been suggested that these anthracites have not lost a portion of their combustible matter owing to igneous action. The anthracites, for example, in the Mount Ngwibi range, Vryheid district, have similar ash contents as the nearby bituminous coals where the seams are unaffected and it may therefore be assumed that although the anthracites are altered bituminous coals, they have not lost a significant proportion of their original carbon content. It is possible that the volatile matter underwent a process of thermal decomposition (pyrolysis), but that the products were retained in the coal, yielding the "anthracite" as it is mined today.

If a means of utilising the anthracite could be found then the reserves of semi-anthracite could probably be used for the same purpose. Many collieries in Natal, nearing the end of their estimated "life" owing to the complete extraction of all bituminous coal, may continue mining for a further period should an adequate market be found for the anthracitic types of coal still available in situ.

In order to test the contention regarding the unsuitability of South African anthracites for steam-raising purposes and to compare the combustion characteristics of the low volatile coals with high volatile coals, it was decided to conduct a series of combustion tests on a number of coals varying from low to high volatile matter contents.

THE OBJECTS OF THE INVESTIGATION.

(a) To determine the suitability of South African anthracite for steam-raising purposes.

(b) To obtain and compare the combustion rates of typical South African coals and anthracite.

(c) To determine and compare the composition of the products of primary combustion of anthracite and coal, i.e. of the gases rising from the fuel beds.

(d) To study and compare the resistance to forced and natural draught of the fuel beds of coals and anthracite.

(e) To determine and compare the size composition and hardness of the clinker obtained from the coals and the anthracite.

A. REVIEW OF THE LITERATURE ON THE USES OF ANTHRACITE.

Anthracite can be successfully gasified in Pintsch generators, pressure or suction gas, plants or gas-producers and yields approximately 200,000 cubic feet of gas per ton of anthracite.(5,6,7,8,9,12)

In the building industry, anthracite is used for brick- and lime-burning and for cement-making. Low grade anthracite duff has been used for these purposes. (9,10,11)

For the manufacture of coke, anthracite is added to the coal to improve the coke, to reduce stresses on the oven walls and to increase output.(12,13)

In the iron industry anthracite has been successfully used both in place of coke or mixed with coke. Owing to its greater density more anthracite than coke can be charged into a cupola. The comsumption of anthracite is less than that of coke and the superheating greater. (5,10,12,14,15)

For domestic heating in cookers, stoves and stokers, generally on the "slow-combustion" principle, anthracite has found general application. (9,20,21,31,34,35,36,37). Household briquettes are also made from anthracite, mixed with other coals, or alone, by the use of a binder or by impact.(9,18)

Anthracite alone or mixed with coal, is advocated for pulverised fuel burners.(4,7,9,22,23,24,31,38) For this purpose a clean fuel is required so that the milling plant does not suffer unduly.(4)

As an industrial steam-raising fuel anthracite is used in hand- or automatically-fired furnaces,(9,20,21,22,25,26,27,28) and it has on water-tube boilers proved to be most successful.(22) For screw- or worm-feed stokers, a special grate with side- and dead-plates is used.(20,21,26,27) For burning small sizes of anthracite, the chain-grate stoker has no pier. (27) Anthracite may be mixed with coal or fed underneath a layer of coal on a chain-grate stoker.(4,20,22,26,27,28,29,32) Anthracite requires forced draught through the fuel bed (9,10,29,30,31) but very little or no secondary air (20,21,22,26) It burns with a short, practically invisible flame, forms very little smoke and requires a smaller combustion space than coal.(26,27,30) Anthracites have high bed resistances, ignition temperatures, and ash fusion temperatures(25,31) but low hydrogen contents and the flue-gases therefore contain less moisture. (32) The fuel-bed when firing anthracite should be kept thin, it may be readily banked and it requires very little attention (21,22,27,29,30). The limiting combustion rate of anthracite is about 25 pounds per square foot per hour and a CO_2 percentage of 14-15 in the flue gases can be obtained.(22) However, a combustion rate of 60 pounds per square foot per hour has been obtained with CO_2 in the flue-gases of 16-18 per cent.(21)

Further uses of anthracite are in the production of calcium-carbide(9), granular carbon for resistance furnaces(16,17) and electrodes (5) and as a filtering material for water(37).

THE COALS AND THE ANTHRACITE USED IN THE FIRING TESTS.

In Table 1 the details of size, proximate analysis, and swelling numbers, calorific values and ash fusion temperatures of the coals and the anthracite are given.

With the exception of the Wolvekrans Float (ash 7.0 per cent) and the Mooifontein (ash 22.3 per cent) coals, the ash contents of the coals and the anthracite vary from 11 to 17 per cent. This represents the normal range for industrial coals in South Africa.

The volatile matter contents vary from 8.0 to 34.7 per cent, the calorific values from 10.75 to 14.05 Evaporative Units (lbs.steam F.& A./lb.fuel) and the ash fusion temperatures from 1190°C to +1500°C.

APPARATUS:

Experimental Stack: The stack (see Figure 1 at back of report,) consisted of a vertical shaft 18 by 18 inches square internally by 20 feet high, (of which 18 feet are above grate level) constructed of fire-bricks. Between these and the supporting brick structure was a 2 inch cavity filled in with vermiculite, except for the bottom 2 feet, where a concrete filling was used.

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A heavy metal plate, 18 by 18 inches with a 16 by 16 inches opening, was placed on the grate bars. The small slots between this plate and the furnace walls were sealed off with fire-cement. This effectively prevented channelling of the primary air along the circumference of the grate, but it immobilised the grate.

The primary air was admitted into an air-tight ash pit under the grate by an electrically driven fan. The air was metered by means of an orifice meter.

Gas Sampling Apparatus: The system employed for sampling the gas is shown in Figure 2 (see back of report,) During natural draught tests the "cone" gas sampler was used (see Figure 3, at back of report,) with the cone resting on the fire bed and (as the firing door could not be left open in these tests) the tube from the cone passing through the observation hole in the door.

With forced draught tests, the water-cooled sampler was employed (see Figure 4, at back of report,) The firing door was kept open. During sampling, the copper tube openings of the sampler were situated approximately ½ inch from the surface of the bed.

EXPERIMENTAL.

A firing test in the experimental stack may conveniently be subdivided into the following phases:

(a) The development of the fuel bed.
(b) The actual combustion test.
(c) The quenching of the bed in order to determine the amount of cinders and unburnt carbon on the fuel bed, or
(d) The burning out of the fire to obtain clinker.

TABLE 1.

General Details of the Coals and the Anthracite. – Bituminous coals & Semi-anthracite ?

Sample No.	Fuel	District	Province	Seam	Method of Preparation	Size of Coal	% Ash	% H_2O	% V.M.	% F.C.	C.V. (lbs/lb)	Sw. No.	Ash Fusion Temp.
M261	Natal Ammonium Anthracite	Vryheid	Natal	Gus	Run-of-mine nuts	$-1\frac{1}{2}+5/8$	11.4	1.7	8.0	78.9	13.8	P	+1500°C
N19	Tshoba	Vryheid	Natal	Alfred	Run-of-mine nuts	$-1+\frac{1}{2}$	17.0	1.2	16.7	65.1	12.85	1	1460
N289	Wolvekrans Middlings	Witbank	Transvaal	No.2	Run-of-mine. nuts IF 1.35-1.55	$-1+\frac{1}{2}$	14.1	2.1	22.3	61.5	12.55	F	+1500
N328	Wolvekrans Whole coal	Witbank	Transvaal	No.2	Run-of-mine nuts	$-1+\frac{1}{2}$	12.7	2.3	27.2	57.8	12.85	1	1490
N288	Wolvekrans Float	Witbank	Transvaal	No.2	Run-of-mine nuts. Float 1.35	$-1+\frac{1}{2}$	7.0	2.0	30.9	60.1	14.05	$3\frac{1}{2}$	1410
M266	Waterpan	Witbank	Transvaal	No.2	Washed nuts	$-1+\frac{1}{2}$	12.5	2.1	27.4	58.0	12.75	1	1390
N163	Mooifontein	Ermelo	Transvaal	B	Run-of-mine nuts	$-1\frac{1}{2}+5/8$	22.3	2.9	22.6	52.2	10.75	F	1190
N362	Bankfontein	Breyten	Transvaal	C	Run-of-mine nuts	$-1\frac{1}{2}+\frac{1}{2}$	13.2	2.9	30.2	53.7	12.4	$1\frac{1}{2}$	1350
N348	Bellevue	Ermelo	Transvaal	C	Run-of-mine nuts	$-1\frac{1}{2}+\frac{1}{2}$	11.2	3.0	34.7	51.1	12.4	F	1260

Owing to the formation of a bed of clinker on the grate, a shaking or rocking grate could not be incorporated in the experimental stack. It was therefore necessary to obtain a live fuel bed on the fixed grate prior to the commencement and leave a similar one on completion of the actual combustion test.

The following was the procedure adopted during a test: A fire was started on the grate by igniting 25-50 pounds of coal with 10-20 pounds of charcoal. A fire bed 4-8 inches was developed by burning 75-150 pounds of coal in 1½-2 hours. The rate of stoking was determined during this stage of the test by fixing the primary air rate at the value required and feeding the coal uniformly at 10 minute intervals at approximately the same rate as it was burnt away.

The actual combustion test was then started and the following information was recorded at regular intervals (i) water gauge readings under and over the bed (ii) the total depth of the bed (iii) the temperature in the stack as measured by a thermocouple 10½ feet above the bed. At least two series of 10 gas samples each were taken. For each series a gas sample was obtained for every minute of the interval during two successive stokings. The actual combustion test required from 1 to 6 hours depending on the rate of combustion. Since no ash was removed from the grate, the fire bed built up and when it attained a thickness of 12 inches, the actual combustion test was stopped. The final procedure was varied according to what further data was required.

In determining the rate of combustion of a coal, the fire was immediately quenched with water and the stack allowed to cool overnight. The residue on the grate was removed from the stack, dried and weighed. This weight represented the cinders (ash plus unburnt carbon) remaining from the total weight of coal used for the test. The cinders were crushed and quartered and a -60 mesh laboratory sample prepared on which an ash determination was made.

For determining the nature of the clinker formed, the fire was allowed to burn out without reducing the primary air supply. After the stack had been allowed to cool, the clinker was removed, its size determined by screening and a shatter test carried out on the + 3/8 inch material to determine its hardness. The figure of 3/8 inch was chosen since this was the width of the grate openings.

DEFINITIONS, CALCULATIONS AND COMPUTATIONS.

The following are explanatory comments on some of the terms used in this report, together with methods of determination or calculation.

Depth of Fuel Bed. This was measured from the grate level to the top surface of the fuel bed. The thickness of the bed increases with time. (Kreisinger, Ovitz and Augustine (39) describe the fuel bed to be only the layer of incandescent and freshly-fired fuel and do not include the layers of ash and clinker lying on the grate. The lack of suitable apparatus prevented the study of the travel of the "live" fuel bed during these tests.

Cinders. The unburnt carbon, ash and clinker in the fuel bed constitute the cinders. The percentage cinders may be determined from the weight of cinders obtained or it may be calculated from the ash contents of the coal used and the weight of cinders recovered:

Let the calculated percentage cinders be x,
the ash content of coal used be a per cent.
and the ash content of cinders recovered be b per cent.
Now 100 parts cinders contain b parts ash.
Thus x parts cinders contain $\frac{x}{100} \times b$ parts ash.

But 100 parts coal give x parts cinders containing a parts of ash.

$$\text{Thus} \quad a = \frac{x}{100} \times b$$

$$\text{and} \quad x = \frac{a \times 100}{b}$$

Therefore calculated percentage cinders =

$$\frac{\text{Ash content of coal} \times 100}{\text{Ash content of cinders}} \quad \ldots\ldots\ldots(\text{Eq. } 1)$$

In this report the calculated percentage cinders values were always used to determine the percentage unburnt carbon, since the weight of cinders recovered is usually incorrect owing to loss of material (fly-ash and fly-cinders) through the stack. In boiler testing the percentage cinders is generally calculated.

Unburnt Carbon. This is the difference between the percentage of cinders and the ash content of a coal. It is obtained from the calculated percentage cinders as follows:

$$\begin{aligned} & \text{Percentage Unburnt Carbon} \\ = \; & \text{Percentage Calculated Cinders} - \text{Percentage Ash in Coal} \\ = \; & x - a \\ = \; & \frac{a \times 100}{b} - a \\ = \; & \frac{a(100-b)}{b} \quad \ldots\ldots\ldots\ldots(\text{Eq. } 2) \end{aligned}$$

For the purpose of calculating the combustion rates of the fuels it was assumed that 1 pound of Unburnt Carbon was equivalent to 1 pound of fuel.

Combustion Rate. The combustion rate of a fuel is expressed as the weight of fuel in pounds combusted on the grate per square foot of grate area per hour.

Primary Air Rate. This is expressed as the volume of air in cubic feet passing through one square foot of grate area per minute. (c.f./sq.ft./min.)

Air Requirements. The air requirements of a fuel, whether primary, secondary or total air, are the weight in pounds of air required to combust one pound of fuel (lbs.air/lb.fuel) or are expressed as the volume in cubic feet of air required per square foot of grate area per minute to burn one pound of fuel per square foot of grate area per hour (c.f./sq.ft./min per lb.fuel/sq.ft./hour).

In Pretoria 16 cubic feet of air weigh approximately 1 pound.

Excess Air. This is the quantity of air in excess of the amount theoretically required for complete combustion. It is expressed as a percentage of the total air required for combustion and is calculated as follows:

$$\text{Percentage Excess Air} = \frac{O_2 - \frac{1}{2}CO}{21/79 \times N_2 - (O_2 - \frac{1}{2}CO)} \times 100 \quad \ldots\text{(Eq.3)}$$

where $O_2 - \frac{1}{2}CO$ represents O_2 in excess of that required for combustion,

$N_2 \times 21/79$ represents total O_2 in air used

and $N_2 \times 21/79 - (O_2 - \frac{1}{2}CO)$ represents the O_2 necessary for combustion. (40)

A negative percentage excess air denotes the percentage further air required to complete combustion.

Excess Secondary Air. Excess air is added over the fire, i.e. together with the secondary air. In this report the term Percentage Excess Secondary Air denotes the percentage of secondary air in excess of the volume of secondary air theoretically required for combustion.

Theoretical Primary Air Requirements of Pure Carbon.

When 1 pound of pure carbon burns to CO it requires 5.75 pounds or 92 cubic feet of air.

Assuming the pure carbon to be mixed with pure or "highly-volatile" volatile matter, which would be immediately driven off on the grate and would not combust, the primary air requirements of such mixtures are given below:

Composition of Fuel	Primary Air Requirements	
	lbs.air/lb.fuel	c.f./sq.ft/min per lb/sq.ft/hr.
100% Carbon + 0% V.M.	5.75	1.55
90 " 10 "	5.17	1.40
80 " 20 "	4.59	1.24
70 " 30 "	4.03	1.09
60 " 40 "	3.45	0.93
50 " 50 "	2.88	0.78

Natural Draught. This is the natural suction of the chimney. The volume of air passing through the bed was not obtained by direct measurement and had to be calculated from the primary air requirements of a fuel (available from forced draught experiments) and the combustion rate of the fuel with natural draught:

Natural Draught in c.f./sq.ft./min.
= Combustion rate with natural draught X primary air requirements X 16 (c.f.) X 1/60 mins.
= lbs.fuel/sq.ft./hr. X lbs.air/lb.fuel X $\frac{16}{60}$ ....(Eq. 4.)

Resistance of Fuel Bed. This is the difference in pressure in cms. water gauge under and over the fuel bed. The pressure over the bed was always negative, i.e. suction, due to the suction of the chimney. The pressure under the bed was positive with forced draught and negative (very small, practically negligible values) with natural draught.

Ash Plus Clinker. The residue remaining on the grate when the fire bed was allowed to burn out consisted of Removable Ash (unfused ash and fused particles smaller than 3/8 inch) and Clinker (fused ash larger than 3/8 inch).

Shatter Test on Clinker. The + 3/8 inch Clinker was screened out of the bed residue, and dropped five times from a height of six feet in a standard coke shatter apparatus. The -3/8 inch material formed on shattering was taken as a measure of the relative hardness of the clinker.

RESULTS OBTAINED AND DISCUSSION.

A. The Combustion Rates of the Fuels.

(i) The Composition of the Cinders removed from the Grate.

In Table 2 a comparison is made between the values obtained for the determined and calculated percentage cinders for tests on the anthracite and the coals.

The determined values for the percentage cinders are greater than the calculated results for low primary air rates (33 c.f./sq.ft./min. and under), but for the higher air rates (53 c.f./sq.ft./min. and over) the figures for the calculated percentage cinders become greater than those determined. There are very few exceptions to this rule.

The above facts can be attributed to the formation and the composition of fly-ash and fly-cinders. With the higher rates of primary air supply a greater proportion of the heavier ash is blown out of the chimney, leaving a smaller proportion of heavier ash to lighter carbon on the grate. This causes the ash content of the residual cinders to be too small, hence the calculated percentage cinders is greater than the determined value. With the lower rates of air supply the reverse is the case and the ash content of the cinders removed from the grate is therefore too great making the calculated percentage cinders too small.

The Mooifontein coal showed a tendency to channel in the bed at the higher air rates. The force of the air through these channels is great and it probably causes much fly-ash to be carried out of the chimney. The greatest differences between calculated and determined cinders figures are found with this coal.

The differences between the determined and calculated values are never great, even for high values of unburnt carbon.

The figures for the percentage unburnt carbon given in Table 2, are, with very few exceptions, less than 10 per cent.

The procedure adopted in boiler testing of calculating the unburnt carbon from the ash content of a representative sample of the cinders would appear to be sufficiently accurate for all practical purposes.

(ii) The Reproducibility of the Results Obtained.

The accuracy of the combustion rate determination can be studied from the results of repeat tests given in Table 3.

From a single test the combustion rate of a fuel can be determined to the nearest 2 lbs./sq.ft./hour. The possible error for the average of duplicate experiments is approximately 1 lb./sq.ft./hour.

TABLE 2.

Comparison of Determined and Calculated Percentage Cinders at Various Air Speeds.

Fuel	% Ash (a)	Test No.	c.f./ sq.ft/ min.	% Ash in Cinders	% Cinders Deter. (b)	% Cinders Calc. (c)	% Cinders Diff. (c-b)	% Unburnt Carbon (c-a)
N.A.Anthracite	11.4	F2	*14	33.5	40.3	34.1	-6.2	22.7
		K2	*16	70.0	17.9	16.3	-1.6	4.9
		A2	33	56.8	22.3	20.1	-2.2	8.7
		A1	53	60.6	16.8	18.8	+2.0	7.4
		B1	53	55.9	18.7	20.4	+1.7	9.0
		P1	67	55.7	17.9	20.5	+2.6	9.1
Tshoba	17.0	H2	*25	88.9	21.0	19.1	-1.9	2.1
		Z1	33	75.7	22.7	22.5	-0.2	5.5
		G1	53	74.3	22.3	22.9	+0.6	5.9
		T1	67	82.1	20.0	20.7	+0.7	3.7
		V1	80	70.8	23.3	24.0	+0.7	7.0
Mooifontein	22.3	G2	*12	60.9	37.6	37.0	-0.6	14.7
		P2	33	67.1	33.8	33.2	-0.6	10.9
		I1	53	73.8	22.9	30.2	+7.3	7.9
		U1	67	78.4	22.2	28.5	+6.3	6.3
		Y1	93	84.9	21.8	26.3	+4.5	4.0
Waterpan	12.5	D2	*20	61.5	25.1	20.3	-4.8	7.8
		E2	*22	77.3	22.1	16.2	-5.9	3.7
		C2	33	71.7	21.2	17.4	-3.8	4.9
		E1	53	76.9	13.3	16.3	+3.0	3.8
		R1	67	82.7	13.6	15.1	+1.5	2.6
		X1	93	85.2	15.0	14.7	-0.3	2.2
Bellevue	11.2	D3	*18	64.2	19.9	17.4	-2.5	6.3
		C3	33	55.3	22.3	20.1	-2.2	8.9
Bankfontein	13.2	J3	*21	73.5	18.9	18.0	-0.9	4.8
		I3	33	56.8	21.3	23.2	+1.9	10.0
Wolvekrans Whole coal.	12.7	V2	*20	82.9	18.1	15.3	-2.8	2.6
		U2	33	60.7	20.7	20.9	+0.2	8.2
Wolvekrans Middlings	14.1	R2	*22	76.0	21.8	18.6	-3.2	4.5
		O2	33	77.4	20.6	18.2	-2.4	4.1

* Obtained by Natural Draught.

T A B L E 3.

REPRODUCIBILITY OF COMBUSTION RATE RESULTS.

Fuel	Test No.	Duration	Primary Air c.f./sq.ft/min.	Total weight of Fuel used	Weight Cinders	% Ash in Cinders	Calc. % Cinders	Calc. % Unburnt C.	Weight fuel for combustion test	Nett Weight fuel combusted	Combustion Rate. lbs/sq.ft/hr.
N.A. Anthracite	A_1	210 mins.	53	446 lbs.	75 lbs.	60.6	18.8	7.4	289	268	34.0
	B_1	210	53	444	83	55.9	20.4	9.0	285	259	32.9
	C_1	210	53	450	-	-	*19.6	*8.2	292	268	34.0
	D_1	210	53	449	-	-	*19.6	*8.2	291	267	33.9
	L_1	100	53	256	-	-	*19.6	*8.2	142	130	34.7
Waterpan	D_2	150	⌿20	219	55	61.5	20.3	7.8	114	106	18.8
	E_2	240	⌿22	303	67	77.3	16.2	3.7	192	185	20.6
	I_2	300	⌿20	289	-	-	**16.2	**3.7	231	222	19.7
N.A. Anthracite	F_2	300	⌿14	231	93	33.5	34.1	22.7	129	100	8.9
	K_2	310	⌿16	229	41	70.0	16.3	4.9	125	119	10.2
	S_2	390	⌿16	211	-	-	⌿⌿16.3	⌿⌿4.9	158	150	10.3

* Average of Tests A_1 and B_1

** Assumed from Test E_2

⌿ Obtained by Natural Draught.

⌿⌿ Assumed from Test K_2

TABLE 4.

The Combustion Rates of the Fuels at Different Primary Air Rates.

Fuel	% V.M. (d.a.f.)	% F.C. (d.a.f.)	No. of Test	P.A. Rate c.f./sq.ft/min.	C. Rate lbs./sq.ft/hr.	P.A. Requirements lbs. air/lb. fuel
N.A. Anthracite	9.2	90.8	3	*15	10	5.63
			2	33	21	5.89
			5	53	34	5.84
			2	67	43	5.85
			1	93	57	6.12
			1	133	71	6.87
Tshoba	20.4	79.6	1	* 25	20	4.68
			1	33	26	4.76
			3	53	43	4.62
			1	67	54	4.66
			1	80	64	4.68
			1	133	80	6.23
Wolvekrans Middlings	26.6	73.4	1	* 22	19	4.34
			1	33	29	4.27
			2	53	46	4.32
Mooifontein	30.2	69.8	2	* 12	12	3.75
			2	33	30	4.13
			4	53	49	4.06
			1	67	65	3.89
			1	93	87	4.02
			1	133	129	3.87
Wolvekrans Whole coal	32.0	68.0	1	* 20	18	4.17
			1	33	30	4.13
			1	53	49	4.06
Waterpan	32.1	67.9	2	* 20	20	3.75
			2	33	31	4.00
			3	53	50	3.99
			2	67	64	3.93
			1	93	85	4.11
			1	133	109	4.58
Wolvekrans Float	34.0	66.0	1	53	51	3.90
Bankfontein	36.0	64.0	1	* 21	21	3.75
			1	33	31	4.00
			1	53	52	3.82
Bellevue	40.5	59.5	1	* 18	17	3.97
			1	33	31	4.00
			1	53	53	3.75

* Obtained by Natural Draught.

(iii) The Combustion Rates of a Number of South African Coals and an Anthracite.

In Table 4 the average combustion rates at various rates of primary air supply of eight coals and one anthracite are given.

From the figures tabulated in Table 4 the following statements may be made:

(a) The rate of combustion, expressed in pounds of fuel burnt per square foot of grate area per hour increases with increase in primary air supply.

(b) The amount of primary air required for the combustion of a fixed weight of a fuel expressed in pounds of air per pound of fuel remains constant for the different rates of combustion. (The exceptions to this rule, notably at the very high forced air rate of 133 c.f./sq.ft/min. are due to irregularities in the bed, which will be referred to in later chapters).

(c) The combustion rates of the coals and the anthracite at a given rate of primary air increase with increasing volatile matter (dry, ash-free) contents and decrease with increasing fixed carbon (dry, ash-free) contents.

(d) The primary air requirements of fuels decrease with increasing volatile matter (dry, ash-free) and decreasing fixed carbon (dry, ash-free) contents of fuels.

The last conclusion is clearly illustrated in Table 5, in which the average primary air requirements, excluding the values for the forced draught rate of 133 c.f./sq.ft/min. are listed.

TABLE 5.

Average Primary Air Requirements of the Fuels.

Fuel	% V.M. (d.a.f)	% F.C. (d.a.f)	Primary Air Requirements	
			lbs.air/lb.fuel	cf/sq.ft/min.per lb/sq.ft/hr.
N.A.Anthracite	9.2	90.8	5.87	1.57
Tshoba	20.4	79.6	4.68	1.25
W.Middlings	26.6	73.4	4.31	1.15
Mooifontein	30.2	69.8	3.95	1.05
W.Whole Coal	32.0	68.0	4.12	1.10
Waterpan	32.1	67.9	3.96	1.06
W.Float	34.0	66.0	3.90	1.04
Bankfontein	36.0	64.0	3.86	1.03
Bellevue	40.5	59.5	3.91	1.04

The Natal Ammonium Anthracite has the lowest rate of combustion at all rates of primary air supply. The fuels having low volatile matter (dry, ash-free) contents (less than 30%) show considerable differences in combustion rates for equal primary air rates. For the coals containing more than 30 per cent volatile matter (dry, ash-free basis) the differences are not significant and lie within the experimental error.

In Graph 1 the rate of air supply is plotted against the combustion rate for three of the coals and the anthracite.

With the use of Graph 1 it is possible to assess the approximate combustion rate of a coal or anthracite from its volatile matter (dry, ash-free) content and the available primary air.

It is evident that the greater the volatile matter content of a coal, the greater will be the rate of firing for the same rate of primary air supply. When the coal is fed onto the bed, the volatile matter is driven off, leaving only the fixed carbon as combustible material on the grate. However, for two coals having the same volatile matter contents, but different ash contents, the coal having the higher ash content will have the least fixed carbon on the grate and will therefore burn faster for the same rate of air supply and also require a faster rate of stoking. It is therefore necessary to bear in mind the ash contents of the coals and the anthracite when their combustion rates are compared.

In Graph 2 the combustion rates of the coals and the anthracite at different primary air rates are plotted against the volatile matter (dry, ash-free) and fixed carbon (dry, ash-free) contents.

Graph 2 can also be used to estimate the approximate combustion rate of a fuel if the available primary air and the proximate analysis of the fuel are known.

(iv) The Combustion Rate of the Fixed Carbon of the Fuels.

In Table 6 the combustion rates of the fixed carbon contents of the coals and the anthracite are given. These values are calculated as follows:

$$\text{Combustion rate of fixed carbon} = \text{Combustion rate of fuel} \times \frac{\text{Percentage fixed carbon}}{100} \qquad \text{.........(Eq. 5.)}$$

The same quantity of fixed carbon is burnt for all fuels at the same rate of primary air supply.

The theoretical combustion rates of pure carbon at the different rates of primary air supply are also shown in Table 6. The values are higher than for the fixed carbon contents of the coals and the anthracite. With the natural fuels small quantities of CO_2 are found in the gas rising from the fuel bed (see later chapter on "Gas Analyses") and partial combustion of the volatile matter probably takes place. These factors will tend to give lower combustion rates for the fixed carbon of these fuels.

It may be of interest to note that for the same primary air rate the pure carbon has a calculated combustion rate equal to that of the N.A.Anthracite (whole coal).

The average values for the combustion rates of the fixed carbon of the coals and the anthracite are plotted against the primary air rates in Graph 3, together with the combustion rates of pure carbon at similar air rates.

The higher rates of air supply give combustion rate values which are probably less accurate than for the lower air rates. The greater the primary air rate, the greater becomes the difference between the average combustion rate of the fixed carbon and that of the pure carbon.

(v) Deduction of Combustion Rate Formulae.

In Graph 4 the primary air requirements of the fuels as given in Table 5 are plotted against the volatile matter (dry, ash-free) and fixed carbon (dry, ash-free) contents.

TABLE 6.

The Combustion Rates of the Fuels and their Fixed Carbon Contents (lbs/sq.ft/hr) at Various Primary Air Rates

Fuel	% F.C.	33 cf/sq.ft/min.		53 cf/sq.ft/min.		67 cf/sq.ft/min.		80 cf/sq.ft/min		93 cf/sq.ft/min.	
		Fuel	Fixed C.	Fuel	Fixed C.	Fuel	Fixed C.	Fuel	Fixed C.	Fuel	Fixed C.
N.A.Anthracite	78.9	21	16.6	34	26.8	43	33.9	-	-	57	45.0
Tshoba	65.1	26	16.9	43	27.9	54	35.1	64	41.7	-	-
W.Middlings	61.5	29	17.8	46	28.3	-	-	-	-	-	-
Woolfontein	52.2	30	15.7	49	25.6	65	33.9	-	-	87	45.4
W.Whole Coal	57.8	30	17.3	49	28.3	-	-	-	-	-	-
Waterpan	58.0	31	18.0	50	29.0	64	37.1	-	-	85	49.3
W. Float	60.1	-	-	51	30.6	-	-	-	-	-	-
Bankfontein	53.7	31	16.7	52	28.0	-	-	-	-	-	-
Bellevue	51.1	31	15.8	53	27.1	-	-	-	-	-	-
Limits			16-18		25½-30½		34-37		-		45-49
Average			17		28		35½		42		47
Pure Carbon	100	21	21	34	34	43	43	51½	51½	60	60

The primary air requirements of mixtures of pure carbon and "pure" volatile matter are also given in Graph 4. For the coals having volatile matter (dry, ash-free) contents between 20 (Tshoba) and 35 (Wolvekrans Float and Bankfontein) per cent the curve approaches the artificial fuel line closely.

For practical purposes the line for the natural fuels may be considered to be straight for fuels having volatile matter (dry, ash-free) contents between 5 and 35 per cent. This is given as the dotted line in Graph 4 and includes the anthracitic and semi-anthracitic ranges.

From the dotted line in Graph 4 the following equations can be deduced:

(i) $100y_1 + 2.3x_1 = 175$ ...... Formula 1.

where y_1 represents the primary air requirements in c.f./sq.ft/min. per lb.fuel combustion/sq.ft/hour, and x_1 represents the volatile matter (dry, ash-free) content of the fuel.

(ii) $100y_2 + 8.5x_1 = 660$ ...... Formula 2.

where y_2 represents the primary air requirements in lbs.air/lb.fuel,
and x_1 represents the volatile matter (dry, ash-free) content of the fuel.

From these equations it is possible to calculate the primary air requirements for coals, semi-anthracites and anthracites, having volatile matter (dry, ash-free) contents between 5 and 35 per cent. If the available supply of primary air is also known, the rate and amount of fuel burnt on the grate of a furnace can also be calculated.

(vi) Conclusions re Combustion Rate Tests of Fuels.

(a) For all practical purposes the percentage of cinders may be calculated from the ash content of a representative sample of cinders recovered from the grate.

(b) The percentage of unburnt carbon left in the fuel bed was usually found to be less than 10 per cent.

(c) The combustion rate of a fuel may be determined to the nearest 2 lbs/sq.ft/hour by a single test. The possible error for duplicate experiments is of the order of 1 lb./sq.ft/hour.

(d) The combustion rates of the fuels vary from 10 to 129 lbs./sq.ft/hour for different primary air rates.

(e) The combustion rate of a fuel increases with increasing primary air supply.

(f) The quantity of primary air required per pound of fuel remains constant for different primary air rates.

(g) The combustion rates increase and the primary air requirements decrease with increasing volatile matter contents (dry, ash-free basis) of the fuels.

(h) The combustion rates of the fixed carbon contents of the fuels are equal for equal rates of primary air supply.

(i) For coals having more than 30 per cent volatile matter on a dry, ash-free basis, the differences in combustion rates at equal primary air rates due to increasing volatile matter contents are small.

B. THE COMPOSITION OF THE GAS RISING FROM THE FUEL BEDS.

(i) Reproducibility of Results.

The area of the grate and therefore of the surface of the bed was 1^1 by $1\frac{1}{2} = 2\frac{1}{4}$ square feet. The area covered by the water-cooled sampler was $\frac{1}{2}$ by $\frac{1}{2} = \frac{1}{4}$ square feet. The cone sampler covered approximately 1/5 square foot. The gas samplers therefore covered only 1/9 - 1/10 of the total surface of the fuel bed. Since it was impossible to stoke the surface of the bed absolutely even it was necessary to ascertain the reliability of the gas samples.

In Table 7 the average gas composition of every series (i.e. the average analysis of 10 samples taken every minute during a combustion interval) obtained for all the fuels with a primary air rate of 53 cf/sq.ft/min. is tabulated.

The duplicate results of the CO_2 and CO percentages show close agreement generally, whereas the H_2 and CH_4 values vary considerably. The CO figures, though of greater magnitude than the H_2 results, give considerably smaller variations than the H_2 figures.

It was found that while the thickness of the freshly stoked green coal underlying the sampler did not materially affect the CO and CO_2 contents of the gas, it had a decided influence on the H_2 and CH_4 figures. The CO and CO_2 are mainly derived from the incandescent portion of the fuel bed, which remains approximately constant in thickness and composition. The H_2 and CH_4 on the other hand issue mainly from the comparatively thinner layer of green coal, the thickness of which will directly influence the H_2 and CH_4 contents of the gas.

The coking Wolvekrans Float coal shows the greatest variations for all constituents of the gas rising from the fuel bed. Tshoba coal, which displayed decided "caking" on the surface of the fuel bed, has the second greatest variations for CO and CO_2 values. The effective combustion of these variable gaseous products over the fire would therefore be more difficult in the case of the coking (and caking) coals. This conclusion is supported by Evans (41) who has stated "that the coking properties of coals add to the difficulty of ensuring the controlled air supply, which is essential to efficient combustion." Haslam (4) has also stated "that the caking qualities influence the burning qualities of a coal." The N.A. Anthracite possessing no caking properties whatsoever, displayed generally the smallest variations in gas composition for all tests. No general correlation exists however between the magnitude of the variations of the CO_2 and CO values and the swelling number of the fuels.

Every effort was always made to achieve even and uniform firing of the whole bed. In view of the large number of gas samples taken, the average analyses may be regarded as representing very closely the composition of the gases rising from the fire bed of the different fuels.

(ii) Changes in the Gas Composition during the Combustion Interval.

In Tables 8A-I the average composition of the gas samples taken during every minute of the combustion interval for all the fuels are given.

The following general conclusions may be drawn:

(a) The CO and CO_2 values tend to remain unchanged over the whole period between stokings (thus over the whole combustion test period).

T A B L E 7.

Maximum Variations of the Average Gas Composition per Series of all Tests with a Primary Air Rate of 53 c.f./sq.ft/min. for all the Fuels Tested.

Fuel	Sw. No.	Gas	First Test				Second Test		Total Average	Variations	
			1 Series	2 Series	3 Series	4 Series	1 Series	2 Series		Maximum	From Average
N.A.Anthracite	P	CO_2	0.6	0.6	0.3	-	-	-	0.4	0.3	0.2
		O_2	0.2	0.3	0.3	-	-	-	0.3	0.1	0.1
		CO	32.9	31.7	32.7	-	-	-	32.4	1.2	0.7
		*CH_4	0.8	1.2	1.0	-	-	-	1.0	0.4	0.2
		H_2	5.4	9.5	7.6	-	-	-	7.5	4.1	2.1
		N_2	60.1	57.0	58.1	-	-	-	58.4	3.1	1.7
Mooifontein	F	CO_2	2.2	2.3	2.8	-	-	-	2.4	0.6	0.4
		O_2	0.2	0.4	0.3	-	-	-	0.3	0.2	0.1
		CO	30.9	30.5	29.5	-	-	-	30.3	1.4	0.8
		*CH_4	2.1	1.3	1.9	-	-	-	1.8	0.8	0.5
		H_2	11.1	7.5	9.1	-	-	-	9.2	3.6	1.9
		N_2	53.5	58.0	56.4	-	-	-	56.0	4.5	2.5
W.Middlings	F	CO_2	2.1	2.7	4.3	-	2.1	1.6	2.5	2.7	1.8
		O_2	0.5	1.6	0.2	-	0.3	0.9	0.7	1.4	0.9
		CO	29.6	27.1	26.5	-	27.6	28.6	27.9	3.1	1.7
		*CH_4	1.3	0.9	0.6	-	2.8	2.4	2.0	2.2	1.1
		H_2	8.3	4.9	3.8	-	13.6	12.2	9.3	9.8	5.5
		N_2	58.2	62.8	64.6	-	53.6	54.3	57.6	11.0	5.2
Bellevue	F	CO_2	3.7	3.5	-	-	-	-	3.6	0.2	0.1
		O_2	0.2	0.5	-	-	-	-	0.3	0.3	0.3
		CO	25.3	23.4	-	-	-	-	24.4	1.9	1.0
		*CH_4	6.6	6.1	-	-	-	-	6.4	0.5	0.3
		H_2	15.5	15.1	-	-	-	-	15.3	0.4	0.2
		N_2	48.7	51.4	-	-	-	-	50.0	2.7	1.4
Tshoba	1	CO_2	4.7	2.9	3.3	-	1.4	1.2	2.4	3.5	2.3
		O_2	0.4	0.3	0.5	-	0.7	0.5	0.5	0.4	0.2
		CO	23.6	28.0	26.1	-	29.1	29.0	27.5	5.5	3.9
		*CH_4	1.6	1.4	1.9	-	1.6	2.2	2.0	0.8	0.6
		H_2	9.1	6.8	10.4	-	10.8	12.8	10.3	6.0	3.5
		N_2	60.6	60.6	57.8	-	56.4	54.3	57.3	6.3	3.3

TABLE 7 (continued)

Fuel	Sw. No.	Gas	First Test				Second Test		Total Average	Variations	
			1 Series	2 Series	3 Series	4 Series	1 Series	2 Series		Maximum	From Average
Waterpan	1	CO_2	3.4	4.6	4.2	-	-	-	4.1	1.2	0.7
		O_2	0.2	0.0	1.1	-	-	-	0.4	1.1	0.7
		CO	26.5	24.5	23.6	-	-	-	24.9	2.9	1.6
		*CH_4	3.4	2.6	3.7	-	-	-	3.2	1.1	0.6
		H_2	12.8	9.0	14.6	-	-	-	12.1	5.6	3.1
		N_2	53.7	59.3	52.8	-	-	-	55.3	6.5	4.0
W.Whole Coal	1	CO_2	2.2	1.2	-	-	-	-	1.7	1.0	0.5
		O_2	0.8	0.5	-	-	-	-	0.6	0.3	0.2
		CO	28.4	28.2	-	-	-	-	28.3	0.2	0.1
		*CH_4	1.4	2.1	-	-	-	-	1.7	0.7	0.4
		H_2	11.6	13.7	-	-	-	-	12.7	2.1	1.1
		N_2	55.6	54.3	-	-	-	-	55.0	1.3	0.7
Bankfontein	1½	CO_2	4.1	4.0	-	-	-	-	4.1	0.1	0.1
		O_2	0.3	0.2	-	-	-	-	0.2	0.1	0.1
		CO	25.5	25.5	-	-	-	-	25.5	0.0	0.0
		*CH_4	3.1	3.1	-	-	-	-	3.1	0.0	0.0
		H_2	11.5	12.9	-	-	-	-	12.2	1.4	0.7
		N_2	55.5	54.3	-	-	-	-	54.9	1.2	0.6
W. Float	3½	CO_2	3.3	1.5	6.1	1.6	-	-	3.2	4.6	2.9
		O_2	0.7	0.2	0.9	0.6	-	-	0.6	0.7	0.4
		CO	22.6	29.7	18.5	26.5	-	-	24.3	11.2	5.8
		*CH_4	5.4	2.2	1.7	4.6	-	-	4.1	3.7	2.4
		H_2	20.8	9.7	7.9	17.1	-	-	13.6	12.9	7.2
		N_2	47.2	56.7	64.9	49.6	-	-	54.2	17.7	10.7

* Includes Illuminants.

T A B L E 8A.

Changes in Gas Composition with Time after Stoking:- N.A. Anthracite.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
*15 cf/sq.ft/min 3 tests:6 series	CO_2	3.1	3.1	3.1	3.3	3.5	3.3	3.4	3.3	3.5	3.5	3.3
	O_2	0.5	0.3	0.3	0.3	0.2	0.4	0.4	0.3	0.2	0.2	0.3
	CO	27.9	28.4	27.8	27.2	26.2	26.6	26.5	26.6	26.9	26.8	27.2
	CH_4	1.2	1.2	1.6	1.5	1.5	1.6	1.5	1.3	1.2	0.9	1.3
	H_2	6.8	7.2	7.8	9.6	9.9	10.9	11.3	10.4	10.0	9.5	9.3
	Ill.	0.2	0.1	0.3	0.1	0.2	0.0	0.3	0.3	0.2	0.4	0.2
	N_2	60.3	59.7	59.1	58.0	58.5	57.2	56.6	57.8	58.0	58.7	58.4
33 cf/sq.ft/min. 2 tests: 5 series	CO_2	0.9	1.1	1.1	1.1	1.1	1.2	1.3	1.4	1.4	1.7	1.2
	O_2	0.0	0.2	0.1	0.1	0.2	0.2	0.2	0.5	0.2	0.2	0.2
	CO	31.8	31.9	31.5	31.4	31.7	31.2	31.7	31.9	31.9	31.6	31.7
	/CH_4	1.1	0.9	1.1	1.0	1.1	1.0	0.8	0.7	0.7	0.7	0.9
	H_2	7.4	7.5	7.2	8.1	7.5	7.3	6.5	5.5	4.5	4.2	6.6
	N_2	58.8	58.4	59.0	58.3	58.4	59.1	59.5	60.0	61.3	61.6	59.4
53 cf"sq.ft/min 1 test: 3 series	CO_2	0.5	0.3	0.4	0.4	0.5	0.5	0.3	0.4	0.3	0.3	0.4
	O_2	0.3	0.2	0.1	0.2	0.4	0.2	0.2	0.3	0.2	0.4	0.3
	CO	31.6	31.5	31.3	31.4	32.0	32.5	32.6	33.2	34.0	34.3	32.4
	/CH_4	1.4	1.4	1.5	1.0	0.9	0.8	1.0	0.7	0.5	0.4	1.0
	H_2	10.0	10.1	10.0	10.1	9.7	7.9	6.0	4.5	3.7	3.1	7.5
	N_2	56.2	56.5	56.7	56.9	56.5	58.1	59.9	60.9	61.3	61.5	58.4
67 cf/sq.ft/min. 2 tests: 3 series	CO_2	0.3	0.2	0.1	0.3	0.2	0.2	0.3	0.2	0.1	0.2	0.2
	O_2	0.3	0.4	0.5	1.2	0.3	0.3	0.2	1.2	0.5	1.1	0.6
	CO	30.8	31.3	32.2	32.8	32.9	34.7	33.7	34.1	34.8	34.1	33.1
	/CH_4	1.5	1.6	1.2	1.1	0.5	0.6	0.3	0.6	0.3	0.5	0.9
	H_2	10.3	10.0	8.6	7.8	7.3	4.2	2.9	1.3	1.6	1.3	5.5
	N_2	56.8	56.5	57.4	56.8	58.8	60.0	62.6	62.6	62.7	62.8	59.7

93/....

TABLE 8A, contd.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
93 cf/sq.ft/min. 1 test: 2 series	CO_2	0.3	0.2	0.3	0.3	0.2	0.0	0.2	0.2	0.1	0.1	0.2
	O_2	0.2	0.2	0.9	0.2	0.1	0.3	1.0	0.9	0.4	0.6	0.5
	CO	29.8	30.1	30.2	30.6	31.6	32.9	32.8	33.4	33.3	33.1	31.8
	CH_4	1.7	1.8	1.5	1.5	1.1	0.9	0.7	0.7	0.8	0.7	1.1
	H_2	13.5	13.5	12.4	10.9	8.8	5.8	5.1	3.4	2.9	2.7	7.9
	ill.	0.4	0.3	0.2	0.2	0.3	0.2	0.1	0.2	0.1	0.2	0.2
	N_2	54.1	53.9	54.5	56.3	57.9	59.9	59.9	61.2	62.4	62.6	58.3
133 cf/sq.ft/min. 1 test: 2 series	CO_2	0.2	0.2	0.0	0.2	0.2	0.1	0.1	0.3	0.8	0.6	0.3
	O_2	0.4	0.8	0.3	0.2	0.4	0.3	0.1	0.8	0.1	0.1	0.3
	CO	31.1	30.3	31.1	31.5	31.3	31.7	32.8	32.8	32.8	32.5	31.8
	CH_4	1.8	1.5	1.5	1.3	1.3	1.2	1.1	0.8	1.1	0.9	1.2
	H_2	10.9	11.8	11.0	8.9	9.6	7.4	6.8	5.4	2.5	2.8	7.6
	ill.	0.3	0.1	0.1	0.1	0.4	0.2	0.1	0.2	0.3	0.1	0.2
	N_2	55.3	55.3	56.0	57.8	56.8	59.1	59.0	59.7	62.4	63.0	58.6

* Obtained by Natural Draught.

≠ Includes illuminants.

T A B L E 8B.

Changes in Gas Composition with Time after Stoking:- Tshoba.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
*25 cf/sq.ft/min.	CO$_2$	6.6	6.9	6.1	6.3	5.2	6.9	7.2	6.9	7.0	8.5	6.7
1 test: 3 series	O$_2$	1.7	0.2	0.3	0.1	0.1	0.3	0.1	0.3	0.5	0.1	0.4
	CO	17.5	19.2	19.7	19.5	20.3	19.7	20.9	21.5	20.6	17.8	19.8
	+CH$_4$	3.0	4.0	3.9	2.7	1.8	0.9	0.8	0.7	0.4	0.7	1.9
	H$_2$	8.2	14.0	17.9	15.3	17.0	10.5	4.2	3.3	2.1	1.6	9.1
	N$_2$	63.0	55.7	52.1	56.1	55.6	61.7	66.8	67.3	69.4	71.3	62.1
33 cf/sq.ft/min.	CO$_2$	1.6	1.3	1.4	1.5	1.6	-	2.2	2.3	-	2.4	1.7
1 test: 3 series	O$_2$	0.3	0.2	0.2	0.3	0.2	-	1.2	0.7	-	0.3	0.5
	CO	30.1	29.9	30.0	30.2	30.5	-	29.4	29.3	-	30.3	30.1
	+CH$_4$	2.5	2.6	1.9	1.9	1.4	-	1.5	1.3	-	0.9	1.7
	H$_2$	8.1	9.8	10.0	8.6	8.6	-	7.8	7.7	-	4.6	7.8
	N$_2$	57.4	56.2	56.5	57.5	57.7	-	57.9	58.7	-	61.5	58.2
53 cf/sq.ft/min	CO$_2$	2.4	2.5	2.6	2.3	2.2	2.0	2.1	2.1	2.6	3.0	2.4
2 tests: 5 series	O$_2$	0.5	0.5	0.6	0.8	0.4	0.6	0.2	0.5	0.4	0.4	0.5
	CO	27.1	26.6	26.5	26.7	27.4	28.2	28.7	30.0	28.0	28.1	27.5
	CH$_4$	2.5	2.4	2.1	2.1	2.0	1.6	1.6	0.9	1.1	0.9	1.8
	H$_2$	9.3	11.2	12.9	12.4	12.1	11.7	10.2	7.2	8.0	5.8	10.3
	ill.	0.1	0.1	0.4	0.4	0.2	0.1	0.2	0.2	0.4	0.1	0.2
	N$_2$	58.1	56.7	54.9	55.3	55.7	55.8	57.0	59.1	59.5	61.7	57.3
67 cf/sq.ft/min	CO$_2$	2.1	1.5	1.4	1.5	1.4	1.5	1.9	1.7	1.5	1.5	1.6
2 tests: 5 series	O$_2$	0.6	0.3	0.7	0.5	0.5	1.0	1.5	1.1	0.9	0.5	0.7
	CO	28.1	28.7	29.2	29.5	30.2	29.6	29.3	30.6	32.0	31.4	29.9
	+CH$_4$	2.8	2.9	2.0	2.3	1.9	1.9	1.4	1.7	1.2	1.0	1.9
	H$_2$	8.1	10.4	9.9	9.8	9.0	8.1	5.9	4.9	4.5	3.5	7.4
	N$_2$	58.3	56.2	56.8	56.2	57.0	57.9	60.0	60.0	59.9	62.1	58.5

TABLE 8B., contd.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
80 cf/sq.ft/min. 1 test: 2 series	CO_2	-	1.4	1.4	1.2	1.3	1.4	0.6	0.5	0.3	0.6	0.9
	O_2	-	0.1	0.0	1.0	0.1	0.3	0.3	0.1	0.2	0.4	0.3
	CO	-	29.9	30.2	28.9	30.9	30.9	31.4	32.6	33.6	33.5	31.2
	⌿CH_4	-	2.0	2.1	1.7	1.8	1.7	1.1	1.2	0.7	0.6	1.5
	H_2	-	10.9	11.6	10.1	10.7	11.0	9.4	6.7	4.5	3.4	8.8
	N_2	-	55.7	54.7	57.1	55.2	54.9	57.2	58.9	60.7	61.5	57.3
133 cf/sq.ft/min 1 test: 2 series	CO_2	3.5	2.5	1.7	1.0	0.7	1.8	3.3	4.4	5.8	6.7	3.2
	O_2	0.0	0.2	0.2	0.4	0.9	0.1	0.0	0.2	0.1	0.0	0.2
	CO	25.5	28.4	30.1	31.6	31.9	30.7	28.8	26.3	24.7	23.4	28.1
	CH_4	2.8	2.1	2.5	1.7	1.3	1.6	1.2	1.1	1.1	0.7	1.6
	H_2	9.2	7.7	7.0	7.2	4.7	4.2	3.0	3.5	2.4	2.2	5.2
	ill.	0.3	0.3	0.4	0.5	0.5	0.3	0.2	0.3	0.3	0.1	0.3
	N_2	58.7	58.8	58.1	57.6	60.0	61.3	63.5	64.2	65.6	66.9	61.4

* Obtained by Natural Draught.

⌿ Includes illuminants.

T A B L E 8C.

Change in Gas Composition with Time after Stoking:- Mooifontein

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
*12 cf/sq.ft/min. 2 tests: 4 series	CO_2	2.4	2.9	3.3	3.2	3.6	3.4	2.9	3.0	2.8	2.4	3.0
	O_2	0.5	0.2	0.3	0.2	0.3	0.1	0.1	0.2	0.1	0.5	0.3
	CO	29.5	29.8	29.6	29.0	29.7	29.4	29.1	28.5	29.0	28.9	29.1
	CH_4	1.5	1.7	2.4	2.4	2.5	2.2	2.1	1.8	1.6	1.1	1.9
	H_2	5.0	5.3	6.0	7.5	7.0	9.0	9.9	10.5	10.5	9.9	8.3
	ill.	0.1	0.4	0.7	0.6	0.4	0.5	0.6	0.5	0.2	0.2	0.4
	N_2	61.0	59.7	57.7	57.1	56.5	55.4	55.3	55.5	55.8	57.0	57.0
33 cf/sq.ft/min. 2 tests: 4 series	CO_2	1.7	1.7	1.1	2.0	2.3	2.1	1.4	1.7	2.0	2.0	1.9
	O_2	0.2	0.2	0.5	0.3	0.2	0.2	0.3	0.3	0.1	0.2	0.3
	CO	31.0	29.9	30.1	30.7	30.4	30.9	31.4	31.5	30.6	30.5	30.6
	CH_4	1.4	1.6	1.2	1.7	1.8	1.8	1.6	1.5	1.4	1.2	1.5
	H_2	6.3	6.6	7.6	8.3	8.2	8.7	8.3	7.8	8.2	7.7	7.8
	ill.	0.5	0.4	0.6	0.4	0.5	0.6	0.4	0.4	0.2	0.3	0.4
	N_2	58.9	59.6	58.9	56.6	56.6	55.7	56.6	56.8	57.5	58.1	57.5
53 cf/sq.ft/min. 1 test: 3 series	CO_2	3.0	3.1	3.1	2.8	2.7	2.7	1.6	1.7	1.8	1.8	2.4
	O_2	0.4	0.2	0.2	0.2	0.5	0.3	0.6	0.2	0.3	0.3	0.3
	CO	30.4	29.8	29.7	28.5	29.9	30.0	30.2	30.9	31.1	31.5	30.2
	+CH_4	2.0	2.7	2.6	2.2	1.7	2.0	1.4	1.2	0.7	0.8	1.7
	H_2	8.0	9.6	10.5	10.9	11.1	10.8	10.3	9.7	7.0	4.8	9.2
	N_2	56.2	54.6	53.9	55.4	54.1	54.2	55.9	56.3	59.1	60.8	56.2
67 cf/sq.ft/min. 1 test: 2 series	CO_2	5.4	5.6	5.7	5.7	6.1	6.6	7.9	10.2	11.3	13.3	7.8
	O_2	0.8	0.2	0.2	0.2	0.2	0.2	0.8	0.4	0.3	0.1	0.4
	CO	22.2	24.9	24.9	24.5	24.1	23.4	20.5	17.3	14.7	12.3	20.9
	+CH_4	3.0	2.8	2.4	1.6	1.2	0.9	0.7	0.7	0.9	0.9	1.5
	H_2	7.8	8.5	8.6	7.9	6.2	4.3	2.2	1.0	1.2	0.5	4.8
	N_2	60.8	58.0	58.2	60.1	62.2	64.6	67.9	70.4	71.6	72.9	64.6

TABLE 8C, contd.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
93 cf/sq.ft/min. 1 test: 2 series	CO_2	7.8	7.3	6.8	6.9	7.8	7.9	9.0	10.7	9.8	12.7	8.7
	O_2	0.1	0.2	0.2	0.1	0.3	0.2	0.1	0.1	0.1	0.1	0.1
	CO	21.5	21.5	22.8	22.9	22.3	21.9	20.0	16.9	17.9	12.6	20.1
	⁄CH_4	3.3	2.4	1.7	1.2	1.0	0.7	0.7	0.8	0.7	1.4	1.4
	H_2	10.3	11.5	8.6	5.1	3.8	2.6	1.3	0.9	0.6	0.2	4.5
	N_2	57.0	57.1	59.9	63.8	64.8	66.7	68.9	70.6	70.9	73.0	65.2
133 cf/sq.ft/min. 1 test: 1 series	CO_2	8.4	6.7	7.2	7.6	7.2	8.0	8.8	11.0	12.6	15.8	9.3
	O_2	0.3	0.0	0.7	0.4	0.0	0.4	0.2	0.3	0.6	0.2	0.3
	CO	21.0	23.0	21.8	19.6	21.0	20.8	18.9	15.9	13.6	7.0	18.3
	CH_4	3.3	3.7	3.6	2.1	3.1	1.6	1.4	1.0	1.0	0.5	2.1
	H_2	10.4	13.9	13.5	18.3	10.7	7.7	3.7	1.5	0.8	1.1	8.2
	ill.	0.5	0.7	0.5	0.4	0.4	0.6	0.5	0.3	0.0	0.4	0.4
	N_2	56.1	52.0	52.7	51.6	57.6	60.9	66.5	70.0	71.4	75.0	61.4

* Obtained by Natural Draught

⁄ Includes illuminants.

T A B L E 8D.

Change in Gas Composition with Time after Stoking: Waterpan.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
*20 cf/sq.ft/min. 2 tests: 4 series	CO$_2$	5.3	5.9	5.2	5.6	6.0	5.8	5.8	5.8	5.5	5.5	5.6
	O$_2$	1.0	0.0	0.2	0.0	0.3	0.0	0.2	0.0	0.2	0.0	0.2
	CO	24.1	23.7	24.2	23.4	22.2	23.5	23.1	21.8	22.0	21.4	23.1
	+CH$_4$	2.6	3.4	3.0	2.5	3.0	2.9	2.1	1.5	1.3	0.8	2.3
	H$_2$	6.5	9.7	10.3	9.9	8.5	8.0	7.1	6.7	6.4	6.4	8.0
	N$_2$	60.5	57.3	57.1	58.6	60.0	59.8	61.7	64.2	64.6	65.9	60.8
33 cf/sq.ft/min. 2 tests: 4 series	CO$_2$	3.6	2.7	2.9	2.6	2.5	2.4	2.7	3.1	3.8	3.9	3.0
	O$_2$	0.2	0.1	0.1	0.0	0.3	0.0	0.2	0.3	0.2	0.1	0.2
	CO	27.6	28.1	28.6	28.7	29.3	29.4	27.8	28.5	29.0	27.5	28.5
	+CH$_4$	2.8	2.9	2.7	2.3	2.0	1.9	1.1	0.9	1.1	1.0	1.9
	H$_2$	7.3	11.2	11.4	10.2	8.8	7.0	4.9	3.1	2.1	1.6	6.8
	N$_2$	58.5	55.0	54.3	56.2	57.1	59.3	63.3	64.1	63.8	65.9	59.6
53 cf/sq.ft/min. 1 test:3 series	CO$_2$	4.6	4.7	4.0	3.5	3.6	3.5	3.9	3.8	4.2	4.7	4.1
	O$_2$	0.3	0.2	0.2	1.1	0.2	1.9	1.1	0.1	0.1	0.3	0.4
	CO	24.0	23.8	24.7	24.5	24.3	24.1	25.2	26.2	26.9	24.7	24.9
	+CH$_4$	3.7	3.5	4.4	4.2	4.3	4.1	2.7	2.1	1.8	1.3	3.2
	H$_2$	10.2	14.6	15.4	14.6	14.6	15.9	13.0	9.7	8.3	4.9	12.1
	N$_2$	57.2	53.2	51.3	52.1	53.0	51.5	54.1	58.1	58.7	64.1	55.3
67 cf/sq.ft/min. 2 tests:4 series	CO$_2$	2.8	1.6	1.6	1.3	1.7	1.2	1.8	2.3	2.2	2.2	1.8
	O$_2$	0.5	0.7	1.1	0.2	0.2	0.0	0.2	0.1	0.5	0.1	0.4
	CO	26.7	27.3	27.9	28.0	29.2	29.9	29.4	29.8	27.9	29.3	28.5
	+CH$_4$	2.4	2.7	2.4	2.2	2.5	1.9	2.1	1.6	2.0	1.1	2.1
	H$_2$	16.3	15.6	17.6	16.2	12.8	11.3	10.8	8.1	6.5	7.5	12.2
	N$_2$	51.3	52.1	49.4	52.1	53.6	55.7	55.7	58.1	60.9	59.8	55.0
93 cf/sq.ft/min. 1 test:2 series	CO$_2$	4.4	3.3	3.2	2.7	2.9	3.0	3.2	4.7	5.4	6.0	3.9
	O$_2$	0.5	0.2	0.2	0.4	0.2	0.6	0.3	0.6	0.7	0.3	0.4
	CO	26.6	26.5	27.3	29.5	28.6	29.0	28.6	26.9	26.4	24.5	27.4
	+CH$_4$	3.1	3.1	3.0	3.1	2.5	2.2	1.9	1.2	1.2	0.5	2.2
	H$_2$	9.7	12.7	12.3	8.4	8.1	7.5	6.2	5.9	6.0	4.7	8.1
	N$_2$	55.7	54.2	54.0	55.9	57.7	57.7	59.8	60.7	60.3	64.0	58.0

Table 8D, contd.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
133 cf/sq.ft/min. 1 test:2 series.	CO2	2.7	2.6	2.6	2.7	2.8	2.7	2.2	1.6	2.4	2.1	2.5
	O2	0.9	1.0	0.0	0.0	0.1	0.0	0.2	0.7	0.1	0.7	0.4
	CO	26.5	25.7	25.9	26.8	27.3	26.9	27.0	27.5	27.4	28.1	26.9
	CH4	4.3	4.6	4.6	3.7	3.4	3.5	3.8	3.5	3.9	3.5	3.9
	H2	10.1	13.0	15.7	15.3	14.6	16.6	15.1	14.4	13.9	10.6	14.0
	ill	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.3	0.5
	N2	55.0	52.5	50.6	50.9	51.3	49.8	51.2	51.8	51.9	54.7	51.8

* Obtained by Natural Draught.
/ Includes illuminants.

T A B L E 8E.

Change in Gas Composition with Time After Stoking: Wolvekrans Whole Coal.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
*20 cf/sq.ft/min. 1 test:2 series	CO2	8.0	7.3	6.1	6.5	7.2	6.9	7.6	8.0	8.2	8.4	7.3
	O2	0.9	0.4	0.7	0.3	0.6	0.3	0.4	0.6	0.5	0.3	0.5
	CO	16.1	18.5	19.7	20.7	21.2	21.5	21.2	19.8	19.3	18.1	19.6
	CH4	2.1	2.1	1.6	1.3	0.6	0.7	0.6	0.4	0.4	0.4	1.0
	H2	13.9	17.7	18.7	15.2	9.1	3.0	2.1	2.0	1.8	2.2	8.6
	ill.	1.1	1.2	0.4	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.4
	N2	57.9	52.8	55.6	55.8	61.0	67.4	68.0	69.0	69.6	70.4	62.6
33 cf/sq.ft/min. 1 test:2 series	CO2	2.7	2.7	2.6	-	2.7	2.9	3.3	3.1	-	3.5	3.0
	O2	1.8	1.6	1.5	-	0.2	0.8	0.4	0.5	-	0.6	0.9
	CO	26.0	25.2	25.8	-	27.6	27.4	27.2	27.8	-	27.9	27.0
	CH4	2.0	1.6	2.1	-	2.4	1.8	1.0	0.9	-	0.4	1.5
	H2	9.4	10.8	10.4	-	11.4	9.7	9.0	6.9	-	4.7	9.0
	ill.	0.7	0.2	0.3	-	0.4	0.2	0.2	0.1	-	0.1	0.3
	N2	57.4	57.9	57.3	-	55.3	57.2	58.9	60.7	-	62.8	58.3

Table 8E, contd.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
53 cf/sq.ft/min. 1 test:2 series	CO_2	2.4	2.3	2.1	2.1	1.7	1.6	1.5	1.2	1.5	0.6	1.7
	O_2	0.6	0.4	0.1	1.5	0.1	0.9	0.8	0.6	0.0	0.6	0.6
	CO	26.7	25.9	26.8	27.6	28.4	27.8	29.2	29.5	29.8	31.0	28.3
	CH_4	2.2	1.9	2.4	1.5	1.4	1.4	0.9	0.7	0.8	0.6	1.4
	H_2	12.3	15.8	14.8	15.0	14.8	13.3	11.4	11.4	9.7	8.4	12.7
	ill.	0.3	0.7	0.5	0.4	0.4	0.3	0.2	0.1	0.2	0.3	0.3
	N_2	55.5	53.0	53.3	51.9	53.2	54.7	56.0	56.5	58.0	58.5	55.0

* Obtained by Natural Draught.

T A B L E 8F

Changes in Gas Composition with Time After Stoking: Wolvekrans Float.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
53 cf/sq.ft/min. 1 test:4 series	CO_2	3.6	2.7	2.3	2.5	3.3	2.9	3.0	3.8	3.7	3.1	3.2
	O_2	1.1	1.8	0.5	0.3	0.3	0.4	0.2	0.5	0.6	0.5	0.8
	CO	23.9	23.4	25.8	26.0	24.3	25.0	23.8	23.0	23.7	23.0	24.3
	CH_4	3.8	3.2	3.7	4.0	3.3	3.5	3.5	3.5	3.4	3.2	3.5
	H_2	12.1	11.6	15.1	14.3	16.1	15.7	16.2	13.7	12.0	12.2	13.6
	ill.	0.7	0.7	0.7	0.8	0.6	0.6	0.5	0.5	0.6	0.4	0.6
	N_2	54.8	56.6	51.9	52.1	52.1	51.9	52.8	55.0	56.0	57.6	54.0

* Obtained by Natural Draught.

T A B L E 8G

Changes in Gas Composition with Time After Stoking: Wolvekrans Middlings.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
⁎22 cf/sq.ft/min 1 test:2 series	CO2	7.2	6.5	6.1	5.9	6.0	6.1	6.6	6.9	7.5	7.6	6.6
	O2	0.6	0.3	0.7	0.5	0.5	0.8	0.7	0.7	0.4	0.8	0.6
	CO	19.9	20.6	21.5	23.0	23.8	23.4	23.5	22.6	21.7	20.1	22.0
	CH4	1.4	1.5	1.3	0.7	0.3	0.2	0.3	0.3	0.5	0.4	0.7
	H2	11.9	15.0	13.9	6.0	3.5	1.6	1.4	1.6	1.5	1.6	5.8
	ill.	0.5	0.6	0.4	0.1	0.2	0.2	0.0	0.3	0.1	0.3	0.3
	N2	58.5	55.5	56.1	63.8	65.7	67.7	67.5	67.6	67.7	69.2	64.0
33 cf/sq.ft/min 1 test:3 series	CO2	2.1	2.1	2.2	2.3	2.4	2.3	1.9	2.0	2.0	2.0	2.1
	O2	0.5	0.2	0.5	1.3	0.3	0.5	0.3	0.6	0.2	0.6	0.5
	CO	28.5	28.6	28.7	28.3	29.1	29.0	29.7	29.9	30.2	30.1	29.2
	CH4	2.3	1.6	1.9	1.3	1.1	1.1	1.1	0.6	0.7	0.8	1.3
	H2	9.3	11.3	10.4	11.2	11.1	9.7	7.8	6.0	4.7	3.3	8.4
	ill.	0.2	0.1	0.0	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1
	N2	57.1	55.9	56.3	55.4	55.8	57.3	58.9	60.7	62.1	63.1	58.4
55 cf./sq.ft/min. 2 tests:5 series	CO2	2.8	2.9	2.3	2.4	2.2	2.1	2.2	2.5	2.5	2.7	2.5
	O2	0.6	0.5	1.1	1.2	0.8	0.8	0.6	0.4	0.9	0.6	0.7
	CO	27.8	27.5	27.2	26.6	27.8	27.3	28.5	28.9	28.6	29.0	27.9
	CH4	2.0	2.2	2.1	2.2	2.0	1.7	1.9	1.6	1.3	1.0	1.8
	H2	9.9	11.1	12.0	12.0	12.0	10.3	8.6	7.5	6.0	4.5	9.3
	ill.	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.2
	N2	56.7	55.5	55.1	55.4	55.0	57.5	57.9	58.9	60.5	61.9	57.6

⁎ Obtained by Natural Draught.

T A B L E 8H

Changes in Gas Composition with Time After Stoking:- Bankfontein.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
*21 cf/sq.ft/min. 1 test:2 series.	CO_2	12.4	10.6	12.7	12.2	11.1	10.3	11.3	10.2	9.8	9.6	11.1
	O_2	0.9	0.3	0.6	0.3	0.7	0.4	0.4	0.5	0.5	0.2	0.5
	CO	9.0	13.5	10.6	8.8	8.1	7.0	7.0	5.6	7.2	5.0	8.2
	CH_4	1.8	1.4	1.1	0.9	0.4	0.5	0.7	0.5	0.8	0.6	0.9
	H_2	5.9	7.0	2.3	1.2	0.9	1.1	0.9	0.8	0.7	1.1	2.2
	ill.	0.5	0.2	0.0	0.1	0.0	0.2	0.2	0.1	0.3	0.2	0.2
	N_2	69.5	67.0	72.7	76.5	78.8	80.5	79.7	82.3	80.7	83.3	70.9
33 cf/sq.ft/min. 1 test:1 series	CO_2	2.8	3.1	3.2	3.2	2.8	3.0	3.3	3.5	3.3	3.8	3.2
	O_2	0.6	0.3	0.0	2.2	2.0	0.2	0.0	0.3	0.0	0.0	0.6
	CO	29.4	26.8	28.2	23.5	24.6	27.1	27.0	26.6	27.4	26.8	26.7
	CH_4	3.0	3.6	4.2	4.7	4.7	4.4	4.0	3.9	4.2	4.0	4.1
	H_2	5.9	9.2	9.4	10.7	13.1	14.5	14.7	13.5	12.9	11.2	11.5
	ill.	0.4	0.4	0.8	0.4	0.6	0.8	0.7	0.6	0.7	0.2	0.6
	N_2	57.9	56.6	54.2	55.3	52.2	50.0	50.3	51.6	51.5	54.0	53.3
53 cf/sq.ft/min. 1 test:2 series	CO_2	4.2	-	3.8	3.9	3.7	3.7	3.4	-	4.6	5.4	4.1
	O_2	0.4	-	0.4	0.1	0.4	0.3	0.2	-	0.1	0.3	0.2
	CO	25.4	-	25.4	25.4	25.6	25.8	26.5	-	25.5	24.1	25.5
	/CH_4	3.1	-	4.1	4.3	4.3	3.6	2.8	-	1.5	0.9	3.1
	H_2	11.7	-	14.7	14.9	14.9	15.1	13.6	-	7.8	4.2	12.2
	N_2	55.2	-	51.6	51.4	51.3	51.5	53.5	-	60.5	65.1	54.9

* Obtained by Natural Draught.

/ Includes illumants.

T A B L E 8I

Changes in Gas Composition with Time After Stoking:- Bellevue.

Minutes after Stoking		1	2	3	4	5	6	7	8	9	10	Average
✱18 cf/sq.ft/min. 1 test:2 series	CO_2	2.7	3.1	3.3	3.1	2.9	3.0	2.6	3.0	3.0	2.5	2.9
	O_2	0.3	0.8	0.2	0.0	0.5	0.2	0.3	0.2	0.2	0.5	0.3
	CO	29.1	28.7	28.7	28.3	28.1	28.0	28.5	27.9	27.0	28.0	28.2
	CH_4	2.5	3.3	4.5	4.9	5.1	6.4	5.9	5.7	5.3	4.8	4.8
	H_2	6.1	7.8	7.5	9.8	10.5	12.5	13.0	15.0	16.2	15.6	11.4
	ill.	0.8	1.0	1.2	1.7	1.9	1.7	1.5	1.2	0.7	0.6	1.2
	N_2	58.5	55.3	54.6	52.2	51.0	48.2	48.2	47.0	47.6	48.0	51.2
33 cf/sq.ft/min. 1 test: 2 series	CO_2	1.4	1.7	1.7	1.2	-	1.3	-	1.1	1.5	1.0	1.4
	O_2	0.9	0.4	0.7	0.6	-	0.9	-	0.7	0.1	0.5	0.6
	CO	29.3	30.1	29.3	29.7	-	28.4	-	31.2	31.0	30.1	30.0
	/ CH_4	2.2	2.7	3.5	3.8	-	3.2	-	2.8	2.1	2.0	2.8
	H_2	9.3	9.1	9.2	9.8	-	9.2	-	9.0	9.2	9.0	9.3
	N_2	56.9	56.0	55.6	54.9	-	57.0	-	55.2	56.1	57.4	55.9
53 cf/sq.ft/min. 1 test:2 series	CO_2	3.1	4.8	4.1	4.2	4.0	-	4.0	4.4	-	3.9	3.6
	O_2	0.7	0.2	0.1	0.1	1.3	-	0.3	0.0	-	0.2	0.3
	CO	27.0	24.1	25.1	24.3	21.8	-	24.0	24.0	-	24.3	24.4
	CH_4	3.4	4.4	5.8	5.8	6.4	-	5.2	5.3	-	3.7	5.1
	H_2	7.1	11.5	14.1	19.1	17.9	-	18.8	16.6	-	14.6	15.3
	ill.	0.9	1.0	1.4	1.2	1.6	-	1.5	1.3	-	1.0	1.3
	N_2	57.2	54.0	49.4	45.3	47.0	-	46.2	48.4	-	52.3	50.0

✱ Obtained by Natural Draught.
/ Includes illuminants.

(b) The H_2 and CH_4 values are medium during the first few minutes (1-2 minutes) after stoking, then increase, reaching peak values halfway in the interval (5 minutes), and then decrease generally to lower values than are found just after stoking. Considerable quantities of H_2 and CH_4 are, however, still present even 10 minutes after stoking.

Breckenridge et al (42) reporting on the results obtained for similar tests, state "that the percentages of H_2 and CH_4 are low immediately after firing and gradually increase during the first three minutes after firing". Since they collected no gas samples after three minutes, a further comparison with the results given above is not possible.

Variations from the general observations given above in a few tests on the fuels are due to the following irregularities in the fuel beds:

(a) At the very high primary air rates blow-holes were formed through which free CO_2 unconverted to CO may escape. The Mooifontein coal was a notable example in this respect.

(b) With natural draught tests the beds were so thin that the escape of unconverted CO_2 was possible.

For a number of tests the percentage Illuminants (unsaturated hydrocarbons) were also determined and have also been listed in Tables 8A-I. A study of these results show that:

(a) The coals having the highest volatile matter contents tend to yield the greatest percentages of H_2, CH_4 and Illuminants in the gas.

(b) For the same coal the greater the H_2 content of the gas, the greater are the CH_4 and Illuminants values generally.

(c) In cases where the hydrogen contents of the gases are the same, the coals having the greatest volatile matter contents have the greatest CH_4 and Illuminants percentages in the gas.

(iii) The Average Composition of the Gas rising from the Fuel Beds at Different Combustion Rates.

In Table 9 the average composition of the gas rising from the fuel beds with the different rates of primary air are given.

The following general conclusions regarding the gas combustion can be drawn:

(a) For the same fuel the composition of the gas rising from the fuel bed is independent of the rate of combustion.

(b) The compositions of the gases rising from the fuel beds of the coals and the anthracite is dependent on their volatile matter contents.

(c) The coals having the highest volatile matter contents have the lowest CO and the highest H_2, CH_4 and Illuminants values in the gas. Bellevue coal is the outstanding example.

(d) The fuels with the lowest volatile matter contents have the highest percentages of CO and lowest H_2, CH_4 and Illuminants in the gas. In this respect N.A.Anthracite is prominent.

(e) The limiting values of the percentage combustibles in the gas for all tests vary from 35 to 45. The differences in the CO contents of the gases from the different fuels are approximately counter balanced by opposing difference in the H_2, CH_4 and Illuminants figures.

(f) The percentage excess air(40) in the gas for all tests varies from -35 to -51.

(g) The equivalent oxygen contents of the gases rising from the fuel beds lie between 16 and 19 per cent. The nitrogen contents of the gases should thus be 59-71 per cent, but the actual nitrogen contents found lie between 52 and 65 per cent.

The few exceptions to the above rules are generally associated with irregularities in the fuel beds, such as blow-holes and too thin beds, described in the previous section.

The average bed resistance increases with increasing rates of primary air supply. This increase has no effect on the composition, at different combustion rates, of the gas rising from the fuel bed of a coal or anthracite.

(iv) The Excess Oxygen Content of the Gas Rising from the Fuel Beds.

The figures given in Table 9 for the oxygen content of the gas rising from the fuel bed indicate that more oxygen than is available in the primary air takes part in the combustion reactions on the grate. The most feasible explanation of this finding would be the decomposition of the moisture in the coal and in the primary air into H_2 and O_2 by dissociation or interaction with the hot carbon in the fuel bed. The free O_2 presumably takes part in the primary combustion reactions, whereas the free H_2 passes mainly through the bed. The H_2 content of the gas rising from the fire bed should therefore be greater than that accounted for by the H_2 in the coal.

As a result of firing tests and other experiments with superheated steam and hot carbon, Breckenridge et al(41) deduced "that by far the greater part of the steam introduced under the grate ... or of the moisture in the coal ... is decomposed in the fuel bed. The fact should be kept in mind that the O_2 of the decomposed steam does not leave the fuel bed in its free state, but that it is combined with carbon, mostly in the form of CO, and therefore is not available for the combustion of the free hydrogen."

In order to test this hypothesis a number of theoretical calculations have been made from the available data. In Table 10 the weights of H_2 and O_2 theoretically available per hour from tests on two coals and the anthracite are compared with the weights of H_2 and O_2 actually present in the exit gases. The H_2 contents of tar-vapours were excluded and illuminants included under CH_4 to assess the available H_2 in the gas.

With high H_2 percentages in the exit gases, the weights of H_2 and O_2 in the exit gases are in excess of the weight theoretically available from the primary air and coal alone.

With low H_2 values for the exit gases, the weights of H_2 available in the coal and the moisture of the coal are approximately equal to the H_2 content of the exit gases. There is no general relationship in this instance between the excess O_2 in the exit gas and the O_2 available in the coal plus moisture of the coal.

It will be seen that for the tests giving high H_2 contents in the exit gases, the O_2 and H_2 resulting from the decomposition of an average moisture content of the primary air does not account for the O_2 and H_2 excess in the gases.

From these considerations it is concluded that total or partial decomposition of the moisture in the coal and/or the primary air took place during the combustion of the coals and the anthracite in the experimental stack.

TABLE 10

Comparison of H_2 and O_2 Available in the Fuels and Present in the Exit Gases.

Relative H_2 content of exit gas	High			Low		
Fuel	N.A. Anthracite	Waterpan	Bellevue	N.A. Anthracite	Waterpan	Bellevue
% Volatile Matter	8.0	27.4	34.7	8.0	27.4	34.7
Air Rate (cf/sq.ft/min.)	15	53	53	67	33	33
Combustion Rate (lbs/sq.ft/hour)	10	50	53	43	31	31
Total Available H_2 in fuel plus moisture of fuel (lbs/hr)	0.4	2.3	2.7	1.5	1.4	1.6
Total H_2 in exit gas (lbs/hr)	0.6	3.5	5.8	1.6	1.2	1.7
Excess H_2 in exit gas (lbs/hr)	0.2	1.2	3.1	0.1	-	0.1
Excess O_2 in exit gas (lbs/hr)	1.2	6.6	8.3	5.0	2.8	2.3
Available O_2 in fuel plus moisture of fuel (lbs/hr)	0.4	4.7	5.8	1.6	2.9	3.4
Excess O_2 in exit gas (lbs/hr)	0.8	1.9	2.5	3.4	-	-
Approximate O_2 in moisture of primary air assuming 0.0004 lbs.moisture/cf. (lbs/hr.)	0.3	1.1	1.1	1.4	0.7	0.7
Approximate H_2 in moisture of primary air assuming 0.0004 lbs.moisture/cf. (lbs/hr.)	0.04	0.14	0.14	0.18	0.09	0.09

(v) Details of Smoke Formation in the Experimental Stack.

Observations were made of the smoke issuing above the stack during the different tests. At the higher combustion rates, the smoke usually caught fire on contact with the atmosphere at the top of the stack. On opening the firing door for stoking or gas-sampling purposes, no smoke issued from the stack since a large excess of secondary air was then drawn in over the bed.

The following are the outstanding features noted:

(a) The N.A.Anthracite formed very small quantities of smoke,which burned readily, at practically all combustion rates, with barely visible pale pink flames. The smoke stained the steel cover of the stack white.

(b) The coals including the low volatile Tshoba, evolved large quantities of smoke at the medium to high combustion rates. The smoke from the high volatile coals appeared to be more difficult to ignite than that from the coals (and anthracite) with lower volatile matter contents. When ignited, the smoke from all the coals burned with an orange coloured flame. The smoke from the coals stained the steel cover of the stack black.

(c) No visible flames appeared above the stack when any of the coals or the anthracite were combusted with natural draught

(d) Generally large quantities of smoke (or flames) were emitted for about 5 minutes after stoking, the volume subsequently decreasing rapidly. These observations may be correlated with the decrease in the contents of H_2, CH_4 and Illuminants in the gas sampled over the fire.

(vi) The Temperatures measured in the Stack during Firing Tests.

The temperatures in the stack as measured by the thermocouple $10\frac{1}{2}$ feet above the grate were recorded regularly during the firing tests. These temperatures did not result from secondary combustion, but were probably mainly due to the radiant heat from the coal burning on the grate and the sensible heat of the gases flowing past the thermocouple. When the firing-door was opened, the stack tended to cool owing to excess air being drawn into the chimney.

It was noted that as the rate of combustion increased the temperatures generally increased for all the fuels. This can be seen from the following figures:

Combustion with natural draught - Temperature Range, 300-600°C.
" " 33 cf/sq.ft/min. - " " 500-600°C.
" " 53 " " " - " " 600-700°C.
" " 67 " " " - " " 700-900°C.
" " 93 " " " - " " 900-1100°C.

The duration of a test was, however, also an important factor: the longer a test, the higher generally were the temperatures recorded for the same combustion rate.

With the natural draught tests the greatest variations in stack temperatures were observed. Large temperature differences for different tests on N.A.Anthracite with natural draught did not appear to influence the rate of natural draught of the chimney or of the rate of combustion of the anthracite. Similar observations were made with the Waterpan coal.

(vii) Conclusions re Gas rising from Fuel Bed.

(a) The CO and CO2 contents of the gases rising from the fuel beds show little variation and remain unchanged during the combustion of a fuel.

(b) The H2 and CH4 contents of the exit gases vary considerably with varying thicknesses of freshly-stoked coal on top of the bed. The H2 and CH4 values increase during the first five minutes after stoking and then decrease rapidly during the second half of the combustion period. Similarly the greater portion of the smoke was observed to issue from the stack during the first half of the combustion period.

(c) The greater the volatile matter content of a fuel, the smaller is the CO and the greater are the H_2, CH4 and Illuminants contents of the gas rising from its fire bed. The percentage combustible gas in the exit gases of the fuels is similar and varies between 35 and 45 per cent.

(d) For the same fuel the composition of the gas rising from the fuel bed is independent of the primary air supply.

(e) The equivalent oxygen and hydrogen contents of the exit gas of a fuel are greater than the quantities of oxygen and hydrogen available in the fuel and primary air. Total or partial decomposition of the moisture content of the fuel and/or the primary air takes place in the fire bed.

(f) The temperatures of the stack increased with increasing rates of primary air supply and were approximately equal for all the fuels for equal primary air rates.

C. THE RESISTANCE OF THE FUEL BEDS.

(i) The Suction recorded above the Fuel Bed.

In Table 11 the figures showing the average suction in cms. W.G. over the fuel beds in all the tests are given.

The minimum values are generally 0.3 to 0.4 cms.W.G., the maximum values 0.4 to 0.5 cms. and the average suction 0.4 cms. The rate of primary air does not appear to influence the suction over the fuel beds.

(ii) Changes in the Resistance of the Fuel Beds during Combustion Tests.

Bed resistance measurements were made approximately every 30 minutes during the combustion tests. These values were found to be reproducible, except in the cases where blowholes were formed in the fuel bed. Such irregularities are particularly characteristic of the Mooifontein coal.

The average bed resistances every 30 minutes for all tests are given in Table 12, together with the depth of the fuel bed at the start and end of the combustion tests.

Two resistance forming types of the fuels investigated can be recognized:-

(a) Coals giving fuel beds of which the resistance increases with time and depth of bed, viz. Mooifontein, Bellevue and Bankfontein coals. These coals have the lowest ash fusion temperatures, viz. 1190°C, 1260°C and 1350°C respectively.

TABLE 11

Suction (cms.W.G.) Recorded above Fuel Beds.

Fuel	Air Rate	C. Rate	Suction Recorded		
	cf/sq.ft/min	lbs/sq.ft/hr.	Minimum	Maximum	Average
N.A. Anthracite	*15	10	0.37	0.38	0.38
	33	21	0.30	0.40	0.35
	53	34	0.30	0.40	0.35
	67	43	0.33	0.40	0.37
	93	47	0.40	0.50	0.45
	133	71	0.25	0.55	0.40
Tshoba	*25	20	0.35	0.40	0.38
	33	26	0.30	0.35	0.33
	53	43	0.40	0.40	0.40
	67	54	0.30	0.40	0.35
	80	64	0.35	0.40	0.38
	133	80	0.40	0.45	0.43
Wolvekrans Middlings	*22	19	0.30	0.40	0.35
	33	29	0.20	0.45	0.33
	53	46	0.38	0.45	0.42
Mooifontein	*12	12	0.33	0.35	0.34
	33	30	0.25	0.35	0.30
	53	49	0.35	0.40	0.38
	67	65	0.35	0.35	0.35
	93	87	0.35	0.40	0.38
	133	129	0.30	0.40	0.35
Wolvekrans Whole Coal	*20	18	0.30	0.35	0.33
	33	30	0.40	0.45	0.43
	53	49	0.35	0.50	0.43
Waterpan	*20	20	0.30	0.35	0.33
	33	31	0.35	0.38	0.37
	53	50	0.35	0.45	0.40
	67	64	0.30	0.35	0.33
	93	85	0.40	0.45	0.43
	133	109	0.35	0.50	0.43
Bankfontein	*21	21	0.30	0.40	0.35
	33	31	0.35	0.45	0.40
	53	52	0.30	0.45	0.38
Wolvekrans Float	53	51	0.45	0.45	0.45
Bellevue	*18	17	0.25	0.40	0.33
	33	31	0.30	0.40	0.35
	53	53	0.25	0.40	0.33

* Obtained by natural draught.

T A B L E 1 2

Changes in Average Resistances of fuel beds with time.

Fuel	cf/sq.ft/ min.	Resistance of Bed in Cms. W.G.							Average Resis- tance	Average Depth of bed (ins.)	
		0-30m	30-60m	60-90m	90-120m	120-150m	150-180m	180-210m		Start	End
Tshoba (Ash M.P:1460°C)	33	0.6	-	-	0.6	-	-	-	0.6	6	9
	53	1.3	1.1	1.2	-	1.0	-	-	1.1	7	11
	67	1.7	-	1.3	-	1.2	-	-	1.5	7	11
	80	2.6	2.2	-	-	-	-	-	2.5	7	9
	133	6.6	4.6	-	-	-	-	-	6.6	8	12
Waterpan (Ash M.P:1390°C)	33	0.9	-	0.8	0.8	0.9	-	-	0.9	7	10
	53	1.5	1.9	2.0	2.1	2.8	-	-	2.0	7	9
	67	2.3	-	2.3	-	2.3	-	-	2.3	8	11
	93	3.6	3.5	-	-	-	-	-	3.5	5	7
	133	7.2	6.5	-	-	-	-	-	6.9	10	12
N.A.Anthracite (Ash M.P:+1500°C)	33	1.4	1.6	1.8	-	1.5	-	1.3	1.5	5	10
	53	3.5	4.1	5.0	3.9	-	3.5	-	3.8	8	12
	67	4.9	-	5.1	4.9	4.6	-	-	4.9	8	11
	93	7.4	-	6.5	-	-	-	-	6.7	9	12
	133	12.9	10.2	-	-	-	-	-	10.6	9	12
Mooifontein (Ash M.P:1190°C)	33	1.4	-	3.1	3.6	-	-	-	2.5	6	10
	53	4.0	5.4	5.4	6.9	6.8	7.1	-	5.6	7	11
	67	4.1	-	4.8	5.3	-	-	-	4.8	6	10
	93	5.3	5.1	-	5.3	-	-	-	5.3	6	11
	133	8.6	8.1	-	-	-	-	-	8.3	7	11
Wolvekrans W.Coal (Ash M.P: 1490°C)	33	0.7	-	0.7	-	0.8	-	-	0.8	7	10
	53	1.4	-	1.7	1.5	-	-	-	1.5	7	10
Wolvekrans Float (Ash M.P: 1410°C)	53	1.6	1.7	-	1.9	-	1.7	-	1.9	6	9
Wolvekrans Middlings (Ash M.P:+1500°C)	33	0.6	-	0.6	-	0.7	-	-	0.7	5	10
	53	1.3	-	1.3	1.4	-	-	-	1.2	6	10
Bellevue (Ash M.P: 1260°C)	33	0.9	-	1.1	-	-	1.5	1.9	1.4	4	11
	53	1.4	1.6	-	2.6	-	3.6	-	2.5	4	10
Bankfontein (Ash M.P: 1350°C)	33	0.6	-	0.8	-	1.4	-	1.7	1.1	5	10
	53	1.4	-	1.8	-	2.3	-	-	1.8	6	10

(b) Fuels giving fuel beds having the same bed resistance throughout a test. The fuels, having ash fusion temperatures of 1390°C and over can be grouped here. Amongst these fuels are some, e.g. N.A.Anthracite, which consistently show an increase and then a decrease in the bed resistance with time at all rates of combustion and may possibly constitute a separate group.

These findings are clearly illustrated in Graph 5.

The average bed resistance for a fuel at a specific primary air rate is obtained from all the readings for all tests at this air rate. These values are given in Table 13, together with relevant analysis of the fuels.

The following conclusions may be drawn:

(a) The ash content of a fuel has no significant effect on its bed resistance, e.g. Tshoba coal with an ash content of 17 per cent has the lowest bed resistance.

(b) The coals having low ash fusion temperatures tend to have high bed resistances while the coals having high ash fusion temperatures show low bed resistances. The limiting ash fusion temperature between these two groups is approximately 1410°C.

(c) The N.A.Anthracite, on the other hand, has both a high ash fusion temperature and a high bed resistance.

(d) The bed resistance is characteristic of a fuel and increases with increasing primary air rates. This is graphically illustrated in Graph 6.

(iii) The Effect of the Resistance of the Fuel Bed on the Primary Air Rate obtained by Natural Draught.

In Table 13 the rates of primary air obtained by the natural draught of the stack are also included. The maximum difference between duplicate tests is 2 cf/sq.ft/min.

The results show that the amount of air drawn through the fuel beds by the chimney increases with decreasing bed resistance of the fuels as measured by forced draught tests. This is very significant. The N.A.Anthracite having the second highest bed resistance allows the second lowest amount of primary air to be sucked through the bed.

The primary air rates with natural draught vary from 25 cf/sq.ft/min with Tshoba coal to 12 cf/sq.ft/min with Mooifontein coal.

The correlation exists between the ash fusion temperatures of the coals and the primary air rate obtainable by natural draught. The Mooifontein and Bellevue coals have the lowest natural draught rates and ash fusion temperatures, the other coals have ash fusion temperatures of 1350°C or more and allow more air to be drawn through their fuel beds.

(iv) Conclusions re Resistance of Fuel Beds.

(a) The resistance of a fuel bed increases with increasing primary air rate.

(b) The coals having low ash fusion temperatures have high bed resistances which increase with increasing depth of fuel bed. These coals give the lowest natural draught air rates.

T A B L E 13

The Effect of the Bed Resistance on the Amount of Air Drawn by the Chimney Through the Beds by Natural Draught.

Rate of Air Supply cf/sq.ft/min.				33	53	67	80	93	133	Quantity of Air in cf/sq.ft/min. obtained by natural draught.			
Fuel	Size	% Ash	Ash M.P.	Average Resistance of Bed in cms.W.G.						Test 1	Test 2	Test 3	Test 4.
Tshoba	-1+½	17.0	1460	0.6	1.1	1.5	2.5	-	6.6	25	-	-	25
Waterpan	-1+½	12.5	1390	0.9	2.0	2.3	-	3.5	6.9	20	22	20	20
N.A.Anthracite	-1½+5/8	11.4	+1500	1.5	3.8	4.9	-	6.7	10.6	14	16	16	15
Mooifontein	-1½+5/8	22.3	1190	2.5	5.6	4.8	-	5.3	8.3	12	14	-	12
Wolvekrans Middlings	-1+½	14.1	+1500	0.7	1.2	-	-	-	-	22	-	-	22
Wolvekrans Float 1.35	-1+½	7.0	1410	-	1.9	-	-	-	-	-	-	-	-
Wolvekrans Whole coal	-1+½	12.7	1490	0.8	1.5	-	-	-	-	20	-	-	20
Bellevue	-1½+½	11.2	1260	1.4	2.5	-	-	-	-	18	-	-	18
Bankfontein	-1½+½	13.2	1350	1.1	1.8	-	-	-	-	21	-	-	21

(c) The coals with high ash fusion temperatures show low bed resistances which remain constant with increasing depth of fuel bed and gave the highest natural draught air rates.

(d) The anthracite with a high ash fusion temperature has a high bed resistance and has a very low natural draught air rate.

D. THE SIZE COMPOSITION AND HARDNESS OF THE CLINKER FORMED ON THE FUEL BEDS.

(i) Quantity of Ash plus Clinker recovered from Grate.

In Table 14 the quantity of ash plus clinker recovered from the fuel beds is compared with the theoretical amount obtainable, i.e. the actual ash content of the fuels.

For low primary air rates, 33 cf/sq.ft/min. or less, a greater weight of ash plus clinker is recovered from the grate than should result from the actual weight of the fuel combusted. The material probably contains unburnt carbon.

For the higher air rates, the weight of ash plus clinker is less than the theoretically available amount. Fly-ash and fly-cinders are probably carried out of the bed. This is especially evident in the case of the Mooifontein coal which formed channels in the bed. The air rate through these channels is high and would tend to carry much ash out of the stack.

A few minor exceptions to these general rules exist.

These findings agree very closely with those obtained on the amount of cinders recovered from the grate. The limiting rate of primary air (33 cf/sq.ft/min) is similar.

(ii) Reproducibility of Composition and Hardness Results.

The maximum variation for duplicate tests of the yield of -3/8 inch material (removable ash) in the fuel bed was found to be 2 per cent. The maximum difference between duplicate experiments of the -3/8 inch material formed on shattering the +3/8 inch clinker recovered from the bed was 5 per cent.

(iii) The Composition and Hardness of the Clinker formed at Different Combustion Rates.

The size compositions of the ash plus clinker formed on the bed at different combustion rates for a number of the fuels are given in Table 15.

The results indicate that the composition of the ash plus clinker formed on the bed is not affected to any great extent by the rate of combustion. Here again the few exceptions may be disregarded owing to distinct irregularities in the fuel bed during these tests.

In Table 16 the results of shatter tests on the +3/8 inch clinker obtained from the tests recorded in Table 15 are listed.

For the same fuel the hardness of the clinker, as measured by the percentage -3/8 inch material formed on shattering, is not greatly affected by the combustion rate.

Since the rate of combustion did not influence the quantity or the hardness of the clinker formed on the bed, comparative tests were carried out on all the fuels with a primary air rate of 53 cf/sq.ft/min.

The details of the size composition of the ash plus clinker recovered from these tests are given in Table 17.

TABLE 14

A Comparison of the Determined Ash plus Clinker Recovered with the Actual Ash Content of a Fuel.

Fuel	Test No.	cf/sq.ft/ min	Wht. fuel used (lbs)	% Ash in fuel (a)	% Ash plus clinker recovered. (b)	Difference (a-b)
N.A.Anthracite	S2	*16	211	11.4	13.6	-3.2
	L2	33	349		12.0	-0.6
	D1	53	449		10.2	+1.2
	Q1	67	426		10.1	+1.3
	X2	93	399		10.5	+0.9
	Y2	133	310		10.8	+0.6
Tshoba	H1	53	415	17.0	18.1	-1.1
	A3	133	338		16.0	+1.0
Mooifontein	E3	*14	247	22.3	24.3	-2.0
	F3	33	262		21.4	+0.9
	J1	53	504		19.4	+2.9
	K1	53	504		18.8	+3.5
	M1	53	502		18.1	+4.2
	G3	133	439		19.0	+3.3
Waterpan	I2(1)	*20	289	12.5	14.5	-2.0
	I2(2)	33	358		14.0	-1.5
	F1	53	562		10.6	+1.9
	S1	67	530		13.2	-0.7
	L2	133	387		12.7	-0.2
Bellevue	B3	53	479	11.2	11.0	+0.2
Bankfontein	N3	53	499	13.2	11.1	+3.1
W.Whole Coal	T2	53	378	12.7	12.9	-0.2
W. Middlings	N2	53	379	14.1	13.3	+0.8
W. Float	M2	53	562	7.0	6.7	+0.3

* Obtained by natural draught.

TABLE 15

Composition of Ash plus Clinker at different Rates of Air Supply.

Fuel	% Ash	Ash M.P.	Size	Rate of Air Supply (cf/sq.ft/min.)					
				N.Draught	33	53	67	93	133
N.A.Anthracite	11.4	+1500	%+1½	15	23	16	8	5	5
			+ 3/8	55	62	60	52	45	46
			- 3/8	45	38	40	48	55	54
Tshoba	17.0	1460	%+1½	-	-	9	-	-	7
			+ 3/8	-	-	69	-	-	57
			- 3/8	-	-	31	-	-	43
Waterpan	12.5	1390	%+1½	10	19	42	16	-	11
			+ 3/8	57	70	77	71	-	72
			- 3/8	43	30	23	29	-	28
Mooifontein	22.3	1190	%+1½	28	30	28	-	-	16
			+ 3/8	68	66	74	-	-	77
			- 3/8	32	34	26	-	-	23

TABLE 16

Hardness of Clinker (+3/8 inch Material): Size Analysis After Shatter Test

Fuel	% Ash	Ash M.P.	Size	Rate of P.air Supply (cf/sq.ft/min)					
				N.Draught	33	53	67	93	133
N.A.Anthracite	11.4	+1500	%+1½ remaining	5	14	4	4	0	0
			+ 3/8 remaining	68	71	64	64	68	68
			- 3/8 formed	32	29	36	36	32	32
Tshoba	17.0	1460	%+1½ remaining	-	-	4	-	-	2
			+ 3/8 remaining	-	-	78	-	-	77
			- 3/8 formed	-	-	22	-	-	23
Waterpan	12.5	1390	%+1½ remaining	2	13	40	17	-	6
			+ 3/8 remaining	72	87	89	89	-	83
			- 3/8 formed	28	13	11	11	-	17
Mooifontein	22.3	1190	%+1½ remaining	29	33	31	-	-	12
			+ 3/8 remaining	84	86	92	-	-	89
			- 3/8 formed	16	14	8	-	-	11

TABLE 17

Size Composition of Ash plus Clinker formed on the Fuel Beds with an Air Supply of 53 cf/sq.ft/min.

Fuel	% Ash	Ash M.P.	% +1½"	% +3/8"	% -3/8"
Wolvekrans Middlings	14.1	+1500	2	50	50
Wolvekrans Whole Coal	12.7	1490	7	56	44
N.A.Anthracite	11.4	+1500	16	60	40
Wolvekrans Float	7.0	1410	11	63	37
Tshoba	17.0	1460	9	69	31
Bankfontein	13.2	1350	28	72	28
Mooifontein	22.3	1190	28	74	26
Bellevue	11.2	1260	40	75	25
Waterpan	12.5	1390	42	77	23

The fuels show two classes of ash plus clinker material:

(a) The fuels with ash fusion temperatures of 1400°C and over give over 30 per cent of -3/8 inch removable ash and under 20 per sent of +1½ inch material on the grate.

(b) The coals with ash fusion temperatures of 1400°C and under yield under 30 per cent of -3/8 inch and 30-40 per cent +1½ inch material on the grate.

The hardness values of the +3/8 inch clinker obtained in these tests are given in Table 18.

TABLE 18

Hardness of Clinker (+3/8 inch material) of the Fuels with Air Supply of 53 cf/sq.ft/min: Size Analysis after Shatter Test.

Fuel	% Ash	Ash M.P.	% + 1½ Remaining	% + 3/8 Remaining	%-3/8 Formed
N.A.Anthracite	11.4	+1500	4	64	36
Wolvekrans Middlings	14.1	+1500	1	67	33
Wolvekrans W.Coal	12.7	1490	0	77	23
Tshoba	17.0	1460	4	78	22
Wolvekrans Float	7.0	1410	8	78	22
Waterpan	12.5	1390	40	89	11
Bellevue	11.2	1260	40	90	10
Bankfontein	13.2	1350	34	91	9
Mooifontein	22.3	1190	31	92	8

The shatter tests also indicate that two classes of clinker exist:

(a) Soft Clinker: This is obtained from the coals and the anthracite with ash fusion temperatures over 1400°C. It yields 20-40 per cent -3/8 inch material on shattering. Very few large lumps of +1½ inch material, usually less than 10 per cent, remain.

(b) Hard Clinker: This is formed from coals with ash fusion temperatures under 1400°C. It yields 10 per cent -3/8 inch and 30-40 per cent +1½ inch material on shattering.

In the group "Soft Clinker" the fuels with ash fusion temperatures of over 1500°C are included. These yield 30-40 per cent -3/8 inch material on shattering. It is evident from these results that the N.A. Anthracite forms very little and very soft clinker on the grate. The beneficial effect on Wolvekrans coal of cleaning by washing is also shown: the Wolvekrans Middlings has decided advantages over the Wolvekrans Whole Coal in this respect.

It would seem that 1400°C and +1500°C are limiting or critical ash fusion temperatures of the fuels. Nicholls and Selvig(43) have, with similar tests on American coals, concluded that "the quantity of larger clinker pieces decreases rapidly with increasing ash softening temperature* until 2600°F (1427°C) is reached, after which the rate of decrease is low ... Clinker formation does not increase materially until the softening temperature of the coal ash is below 2600°F (1427°C).

(iv) Conclusions re Size Composition and Hardness of Clinker.

(a) The size composition and hardness results are reproducible to 2 and 5 per cent of -3/8 inch material respectively.

(b) The size composition of the ash plus clinker and the hardness of the clinker formed on a fuel bed is independent of the rate of combustion.

(c) The percentage and hardness of the clinker formed in the bed increases with decreasing ash fusion temperature of the fuel.

E. GENERAL BURNING CHARACTERISTICS OF THE FUELS.

On quenching the fire, the bed usually had the following vertical section:

2 - 3 inch.	Cinders (on surface of bed)
2 - 3 "	Cinders and ash
3 - 5 "	Clinker and ash
½ - 1 "	Ash
Grate bars	

When the fire was allowed to burn out, the fuel bed had the following section:

1 inch	Ash (on surface of bed)
3 - 7 inch	Clinker and ash
½ - 1 "	Ash
Grate bars!	

With the exception of the Tshoba coal, the fuels with swelling numbers of 1½ and less showed no caking on the bed.

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* The "ash softening temperatures" as determined by Nicholls and Selvig are comparable to the "ash fusion temperatures" given in this report.

When "green" anthracite nuts were fired on to the bed, the lumps developed cracks and after a short period on the bed broke into smaller particles. This process of disintegration (decrepitation) continued until the fuel bed contained very much smaller sized, partially-combusted cubical particles. The cubes tended to "pack" closely and thereby caused a great resistance to air flow. With the higher primary air rates rapid decrepitation occurred and the smaller particles were blown out of the stack (fly-cinders). Tests were also carried out using anthracite rounds and similar decrepitation as with the nuts took place. The belief that on partial combustion of South African Anthracite an ash surface develops on the lumps, rendering further combustion impossible or slow, was shown by these observations to be untenable. At the same time it would appear that N.A.Anthracite is unsuitable, in view of its tendency to decrepitate, for high draught conditions, such as exist in locomotives and in most fire-tube furnaces.

Owing to its slow combustion rate, its mode of disintegration in the fuel bed and its uniform bed resistance, the N.A. Anthracite should be very suitable for furnaces which require banking and where medium to low uniform loads are required.

The Tshoba coal fuel bed tended to build up very rapidly owing to the "porosity" of its clinker layer, which contained numerous large holes and channels. This was probably a cause of the low bed resistance of the Tshoba coal. At very high primary air rates, the Tshoba coal tended to decrepitate when the lumps were incandescent.

It was observed that in the case of the coals the lumps formed ash layers on their outer surfaces. The ash was, however, light and feathery and on disturbing the bed flaked away from the coal particles very easily.

THEORETICAL DEDUCTIONS AND CALCULATIONS.

A. Volume of Secondary and Total Air Required.

(i) Method of Calculation of Secondary Air.

In Table 9 (see page 35) the following average analysis is given for the gas rising from the fuel bed of the N.A.Anthracite combusted with a primary air supply of 33 cf/sq.ft/min:

% CO_2	1.2
O_2	0.2
CO	31.7
* CH_4	0.9
H_2	6.6
N_2	59.4

* Includes illuminants.

The volume of the exit gas rising from the fuel bed per square foot of grate area per minute is calculated from the N_2 content of the primary air and that of the exit gas:

$$\frac{79}{59.4} \times 33 = 43.8 \text{ cf/sq.ft/min.}$$

The volume of each individual component of the exit gas can hence be calculated:

$$CO_2 = \frac{1.2}{100} \times 43.8 = 0.5 \text{ cf/sq.ft/min.}$$

$$O_2 = \frac{0.2}{100} \times 43.8 = 0.1 \quad "$$

$$CO = \frac{31.7}{100} \times 43.8 = 13.9 \quad "$$

$$CH_4 = \frac{0.9}{100} \times 43.8 = 0.4 \text{ cf/sq.ft/min.}$$

$$H_2 = \frac{6.6}{100} \times 43.8 = 2.9 \quad "$$

$$NN_2 = \frac{59.4}{100} \times 43.8 = 26.1 \quad "$$

$$\text{Total} = 43.9 \text{ cf/sq.ft/min.}$$

Each volume of CO, CH_4 and H_2 requires for combustion $\frac{1}{2}$, 2 and $\frac{1}{2}$ volumes of secondary O_2 respectively.

Thus 13.9	cf/sq.ft/min.	CO	require	6.95	cf/sq.ft/min.	O_2
0.4	"	CH_4	"	0.8	"	"
and 2.9	"	H_2	"	1.45	"	"
			Total	9.2	"	"

The volume of secondary air required is thus:

$$\frac{9.2}{21} \times 100 = 43.8 \text{ cf/sq.ft/min.}$$

The following ratios may therefore be calculated:

$$\text{(a)} \quad \frac{\text{Volume Exit Gas}}{\text{Volume Primary Air}} = \frac{43.9}{33} = 1.33$$

$$\text{(b)} \quad \frac{\text{Volume Secondary Air}}{\text{Volume Primary Air}} = \frac{43.8}{33} = 1.33$$

$$\text{(c)} \quad \frac{\text{Volume Secondary Air}}{\text{Volume Exit Gas}} = \frac{43.8}{43.9} = 1.00$$

The following considerations must be noted:

The N_2 and O_2 contents of the fuel may be neglected in these calculations, together with the O_2 required for the small quantities of CO_2 and undetermined steam formed. It has furthermore been indicated that the moisture of the coal and the primary air may be partially decomposed to H_2 and O_2. It is probable that these factors will to some extent neutralise one another.

(ii) Calculated Volumes of Secondary Air Required.

For the purpose of calculating the amount of secondary air required, a number of the tests giving high CO_2 and low CO, H_2 and CH_4 values have not been considered. These results are probably derived from abnormal conditions in the bed and do not represent the general average composition of the gas rising from the fuel bed.

The average ratios between the volumes of primary and secondary air and exit gas for the fuels are given in Table 19.

TABLE 19

Ratios of Primary Air, Exit Gases and Secondary Air Required.

Fuel	% V.M.	% F.C.	% V.M. (d.a.f)	Average Ratios of Exit gas / Primary Air	Secondary Air / Primary Air	Secondary Air / Exit Gas
N.A.Anthracite	8.0	78.9	9.2	1.35	1.4	1.0
Tshoba	16.7	65.1	20.4	1.4	1.5	1.1
Wolvekrans Middlings	22.3	61.5	26.6	1.4	1.5	1.1
Mooifontein	22.6	52.2	30.2	1.4	1.55	1.1
Wolvekrans W.Coal	27.2	57.8	32.0	1.4	1.65	1.15
Waterpan	27.4	58.0	32.1	1.4	1.7	1.2
Wolvekrans Float	30.9	60.1	34.0	1.5	1.9	1.3
Bankfontein	30.2	53.7	36.0	1.5	2.0	1.35
Bellevue	34.7	51.1	40.5	1.6	2.2	1.5

From Table 19 it will be seen that.

(a) The ratio $\frac{\text{Exit Gas}}{\text{Primary Air}}$ for the different fuels increases with increasing volatile matter content (from 1.35 for N.A.Anthracite to 1.6 for Bellevue coal.)

(b) The ratio $\frac{\text{Secondary Air}}{\text{Primary Air}}$ increases with increasing volatile matter content (from 1.4 for N.A.Anthracite to 2.2 for Bellevue coal).

(c) The ratio $\frac{\text{Secondary Air}}{\text{Exit Gas}}$ increases with increasing volatile matter content (from 1.0 for N.A.Anthracite to 1.5 for Bellevue coal.)

The correlation between the volatile matter contents of the fuels and the ratios $\frac{\text{Secondary Air}}{\text{Primary Air}}$ of their exit gases can also be studied from Table 19:

(a) For volatile matter contents of 8 to 23 per cent (9 to 30 per cent on dry, ash-free basis) the ratio varies only slightly from 1.4 to 1.55.

(b) For volatile matter contents of 23 to 35 per cent (30 to 41 per cent on dry, ash-free basis) the ratio increases more rapidly from 1.55 to 2.2

It has previously been shown that the combustion rate for the same primary air rate does not vary appreciably for fuels with over 30 per cent volatile matter (dry, ash-free basis) content (see Table 5, page 15). It is, however, now clear that greater volumes of secondary air are required for equal primary air rates for the coals with the higher volatile matter contents.

In Table 20 the combustion rates of the fuels with primary air rates of 33 and 53 cf/sq.ft/min. are compared with the $\frac{\text{Secondary Air}}{\text{Primary Air}}$ ratios.

TABLE 20.

Combustion Rates Compared to Ratio $\frac{\text{S.A.}}{\text{P.A.}}$

Fuel	% V.M. (d.a.f)	P.A. Rate cf/sq.ft/min	C.Rate lbs/sq.ft/hr.	Ratio $\frac{\text{S.A.}}{\text{P.A.}}$
N.A.Anthracite	9.2	33	21	1.4
Tshoba	20.4	"	26	1.5
Wolvekrans Middlings	26.6	"	29	1.5
Mooifontein	30.2	"	30	1.55
Wolvekrans Whole Coal	32.0	"	30	1.65
Waterpan	32.1	"	31	1.7
Wolvekrans Float	34.0	"	-	1.9
Bankfontein	36.0	"	31	2.0
Bellevue	40.5	"	31	2.2
N.A.Anthracite	9.2	53	34	1.4
Tshoba	20.4	"	43	1.5
Wolvekrans Middlings	26.6	"	46	1.5
Mooifontein	30.2	"	49	1.55
Wolvekrans Whole Coal	32.0	"	49	1.65
Waterpan	32.1	"	50	1.7
Wolvekrans Float	34.0	"	51	1.9
Bankfontein	36.0	"	52	2.0
Bellevue	40.5	"	53	2.2

It will be seen that with $\frac{\text{Secondary Air}}{\text{Primary Air}}$ ratios of 1.4 to 1.55, the rate of combustion increases rapidly, whereas with values from 1.55 to 2.2, the combustion rates show only a slight increase.

These facts are illustrated in Graph 7.

(iii) Ratio of Secondary to Primary Air when Excess Secondary Air is Allowed.

The average ratios $\frac{\text{Secondary Air}}{\text{Primary Air}}$ for the fuels when 0, 25 and 50 per cent of excess secondary air is supplied are given in Table 21

TABLE 21

Ratio of Secondary to Primary Air Required for Varying Quantities of Excess Secondary Air.

Fuel	% V.M.	% F.C.	% VM. (d.a.f.)	Ratio S.A. to P.A. required with 0% Excess	25% Excess	50% Excess
N.A.Anthracite	8.0	78.9	9.2	1.4	1.75	2.1
Tshoba	16.7	65.1	20.4	1.5	1.9	2.25
W.Middlings	22.3	61.5	26.6	1.5	1.9	2.25
Mooifontein	22.6	52.2	30.2	1.55	1.95	2.3
W.Whole Coal	27.2	57.8	32.0	1.65	2.05	2.5
Waterpan	27.4	58.0	32.1	1.7	2.1	2.55
Wolvekrans Float	30.9	60.1	34.0	1.9	2.4	2.85
Bankfontein	30.2	53.7	36.0	2.0	2.5	3.0
Bellevue	34.7	51.1	40.5	2.2	2.8	3.3

The influence of the volatile matter contents of the coals and the anthracite is even more marked in the $\frac{\text{Secondary Air}}{\text{Primary Air}}$ ratios when excess secondary air is considered.

(iv) The Secondary and Total Air Requirements of the Fuels.

From the primary air requirements of the fuels given in Table 5 and the $\frac{\text{Secondary Air}}{\text{Primary Air}}$ ratios shown in Table 20, the secondary and total air requirements (lbs.air/lb.fuel) can be calculated. The values are listed in Table 22.

The quantity of secondary air required decreases with volatile matter (dry, ash-free basis) contents from 9 to 30 per cent and then increases with volatile matter (dry, ash-free basis) contents from 30 to 40 per cent. The total air requirements behave similarly.

To combust 1 pound of coal $10-12\frac{1}{2}$ pounds of total air are required. For one pound of N.A.Anthracite 14 pounds of total air are needed. The anthracite requires more secondary air per pound of fuel than the coals, with the exception of Bellevue coal.

Since a definite excess of secondary air is always required for complete combustion - usually more than 25 per cent - it is evident that for the coals and the anthracite at least twice as much air must be passed over the fire as is delivered under it.

In Table 23 the rates of secondary and total air supply in cf/sq.ft/min. are shown for a primary air rate of 53 cf/sq.ft/min.

For the same rate of primary air supply the anthracite requires less secondary air than the coals, hence also less total air. For the same rate of primary air supply the rates of secondary and total air increase with increasing volatile matter (dry, ash-free basis) contents.

(v) Relationship between the Composition and Air Requirements of the Fuels.

It might be expected that the total air requirements of a fuel are dependent on the combustible content of the fuel. In Table 24 the values for total combustible material of the coals and

TABLE 22

Primary, Secondary and Total Air Requirements (lbs.air/lb.fuel) with Varying Percentages of Excess Secondary Air.

Fuel	% V.M. (d.a.f)	0% Excess Air				25% Excess Air				50% Excess Air			
		Ratio SA/PA	P.A.	S.A.	T.A.	Ratio SA/PA	P.A.	S.A.	T.A.	Ratio SA/PA	P.A.	S.A.	T.A.
N.A.Anthracite	9.2	1.4	5.9	8.2	14.1	1.75	5.9	10.3	16.2	2.1	5.9	12.4	18.3
Tshoba	20.4	1.5	4.7	7.0	11.7	1.9	4.7	8.9	13.6	2.25	4.7	10.6	15.3
Wolvekrans Middlings	26.6	1.5	4.3	6.5	10.8	1.9	4.3	8.2	12.5	2.25	4.3	9.7	14.0
Mooifontein	30.2	1.55	4.0	6.1	10.1	1.95	4.0	7.8	11.8	2.3	4.0	9.4	13.4
W.Whole Coal	32.0	1.65	4.1	6.8	10.9	2.05	4.1	8.4	12.5	2.5	4.1	10.2	14.3
Waterpan	32.1	1.7	4.0	6.7	10.7	2.1	4.0	8.4	12.4	2.55	4.0	10.2	14.2
Wolvekrans Float	34.0	1.9	3.9	7.4	11.3	2.4	3.9	9.4	13.3	2.85	3.9	11.1	15.0
Bankfontein	36.0	2.0	3.9	7.7	11.6	2.5	3.9	9.7	13.6	3.0	3.9	11.7	15.6
Bellevue	40.5	2.2	3.9	8.6	12.5	2.8	3.9	10.7	14.6	3.3	3.9	12.9	16.8

TABLE 23.

Rate of Secondary and Total Air Required for a Primary Air Rate of 53 cf/sq.ft/min.

Fuel	% V.M. (d.a.f)	P.A. cf/sq. ft/min.	S.A. cf/sq. ft/min.	T.A. cf/sq. ft/min.	S.A.Factor when N.A.A. = 1.00	T.A.Factor when N.A.A. = 1.00
N.A.Anthracite	9.2	53	73	126	1.00	1.00
Tshoba	20.4	53	80	133	1.08	1.06
W.Middlings	26.6	53	80	133	1.08	1.06
Mooifontein	30.2	53	80	133	1.08	1.06
W.Whole Coal	32.0	53	89	142	1.19	1.13
Waterpan	32.1	53	90	143	1.20	1.13
W.Float	34.0	53	101	154	1.35	1.22
Bankfontein	36.0	53	107	160	1.44	1.27
Bellevue	40.5	53	122	175	1.63	1.39

TABLE 24

Total Combustible of Fuels Compared with their Air Requirements. (lbs.air/lb.fuel)

Fuel	% V.M.	% F.C.	Total Combustible	Air Requirements (lbs.air/lb. fuel)		
			% V.M.+ %F.C.	P.A.	S.A.	T.A.
N.A.Anthracite	8.0	78.9	86.9	5.87	8.22	14.09
Tshoba	16.7	65.1	81.8	4.68	7.02	11.70
W.Middlings	22.3	61.5	83.8	4.31	6.47	10.78
Mooifontein	22.6	52.2	74.8	3.95	6.12	10.07
W.Whole Coal	27.2	57.8	85.0	4.12	6.80	10.92
Waterpan	27.4	58.0	85.4	3.96	6.73	10.69
W. Float	30.9	60.1	91.0	3.90	7.41	11.31
Bankfontein	30.2	53.7	83.9	3.86	7.72	11.60
Bellevue	34.7	51.1	85.8	3.91	8.59	12.50

the anthracite represented by the sum of the volatile matter and fixed carbon contents of the fuels are given.

It will be seen that no relationship exists between the volatile matter plus fixed carbon contents of a fuel and its total air requirements for combustion.

In Table 25 the ultimate analyses of the fuels and their air requirements in lbs.air/lb.fuel are given.

It appears that a correlation only exists between the H_2 (dry, ash-free basis) contents and C/H ratios of the fuels and their secondary and total air requirements, if the N.A.Anthracite is not included. Generally speaking, the coals require more secondary and total air for increasing H_2 (dry, ash-free basis) contents and decreasing C/H ratios, hence also increasing size of combustion spaces for increasing H_2 (d.a.f.) contents and decreasing C/H ratios.

TABLE 25

Ultimate Analyses of Fuels and Their Air Requirements (lbs.air/lb.fuel).

Fuel	% C	% H	% O	% C (d.a.f.)	% H (d.a.f.)	% V. (d.a.f.)	C/H Ratio	Air Requirements (lbs.air/lb.fuel)		
								P.A.	S.A.	T.A.
N.A.Anthracite	78.4	3.4	2.2	90.7	3.95	2.5	23.0	5.87	8.22	14.09
Tshoba	72.0	4.2	2.8	88.8	5.13	3.5	17.3	4.68	7.02	11.70
W. Middlings	70.3	3.8	7.5	84.2	4.53	9.0	18.6	4.31	6.47	10.78
Mooifontein	61.3	3.3	6.5	83.9	4.57	8.9	18.4	3.95	6.12	10.07
W. Whole Coal	70.7	4.1	7.1	84.2	4.90	8.5	17.2	4.12	6.80	10.92
Waterman	71.2	4.4	7.6	83.6	5.18	8.9	16.1	3.96	6.73	10.69
Wolvekrans Float	75.6	4.8	7.8	83.5	5.29	8.6	15.8	3.90	7.41	11.31
Bankfontein	68.3	4.4	8.4	81.9	5.31	10.1	15.4	3.86	7.72	11.60
Bellevue	68.9	4.7	8.9	81.4	5.59	10.5	14.6	3.91	8.59	12.50

Kreisinger et al(44) have found that for American coals the size of the combustion space required appeared to be directly proportional to the percentage O_2 (dry, ash-free basis) of the coals. This would not seem to be the case for South African coals.

(vi) Heat Liberated by the Fuels per Pound of Total Air.

If it were assumed that the total weight of air required to combust one pound of a fuel was proportional to the available heat in one pound of the fuel (hence to the calorific value of the fuel), then the total air requirements should be proportional to the calorific values of the fuels.

In Table 26 the heat liberated in Evaporative Units (lbs. steam F. and A.) liberated by one pound of total air from each fuel is shown.

TABLE 26

Comparison of Total Air (lbs.air/lb.fuel) and C.V. of the Fuels.

Fuel	C.V.: (A) E.V./lb.fuel	Total Air: (B) lbs.air/lb. fuel	Heat liberated per lb. air. Ratio A/B
N.A.Anthracite	13.8	14.1	0.98
Tshoba	12.85	11.7	1.10
Wolvekrans Middlings	12.55	10.8	1.16
Mooifontein	10.75	10.1	1.06
W. Whole Coal	12.85	10.9	1.18
Waterpan	12.75	10.7	1.19
Wolvekrans Float	14.05	11.3	1.24
Bankfontein	12.4	11.6	1.07
Bellevue	12.4	12.5	0.99

The fuels evolve different quantities of heat for the same total air supply. The Bellevue coal gives the least heat per pound of air for all the coals and this is equal to the heat liberated by the anthracite per pound of total air.

With the exception of the N.A.Anthracite and the Bellevue coal, the fuels generally evolve 1.1 to 1.2 E.Units per pound of total air. The Witbank coals are very similar in this respect and show the highest values.

B. THE HEAT EVOLVED BY THE FUELS WITH EQUAL PRIMARY AIR RATES.

The heat evolved by the fuels for the various primary air rates may be calculated from the combustion rate and calorific value of the fuels. For comparative purposes this is expressed as the Evaporative Units liberated by the fuel per square foot of grate area per minute. The results are tabulated in Table 27.

The N.A.Anthracite liberates the least heat per unit of grate area per unit of time for the same rate of primary air supply.

The coals with medium volatile matter contents (17 to 23 per cent) viz. Tshoba, Mooifontein and Wolvekrans Middlings give less heat for equal rates of primary air than the coals with higher volatile matter contents. The latter coals give similar quantities of heat for equal primary air supplies.

TABLE 27

Heat Evolved by the Fuels with Equal Primary Air Rates.

Fuel	% V.M.	Heat Evolved (E.U./sq.ft/min.)for P.Air Rates of: 33 cf/sq. ft./min.	53 cf/sq. ft./min.	67 cf/sq. ft./min.	93 cf/sq. ft./min.
N.A.Anthracite	8.0	4.8	7.8	9.9	13.1
Mooifontein	22.6	5.4	8.8	-	-
Tshoba	16.7	5.6	9.2	11.6	-
W. Middlings	22.3	6.1	9.6	-	-
W.Whole Coal	27.2	6.4	10.5	-	-
Bankfontein	30.2	6.4	10.7	-	-
Bellevue	34.7	6.4	11.0	-	-
Waterpan	27.4	6.6	10.6	13.6	18.1
W. Float	30.9	-	11.9	-	-

C. THE HEAT DEVELOPED BY THE FUELS WITH EQUAL TOTAL AIR SUPPLY.

(i) Without Excess Air.

The total quantities of air required to completely combust the N.A.Anthracite for primary air rates of 33, 53, 67 and 93 cf/sq. ft/min. are 77, 128, 156 and 228 cf/sq.ft/min respectively. Assuming these fixed total air rates, the relative quantities of heat evolved by the coals can be calculated. These results are tabulated in Table 28.

TABLE 28

Heat Developed by the Fuels for Equal Total Air Rates when no Excess Air is Supplied.

Fuel	% V.M.	Heat Evolved(E.U/sq.ft/min) for Total Air Rates of: 77 cf/sq. ft./min.	128 cf/sq. ft./min.	156 cf/sq. ft./min.	228 cf/sq. ft./min.
N.A.Anthracite	8.0	4.8	7.8	9.9	13.1
Mooifontein	22.6	5.0	8.3	-	-
Bellevue	34.7	5.6	7.7	-	-
Bankfontein	30.2	4.9	9.5	-	-
Tshoba	16.7	5.3	8.9	11.0	-
W. Middlings	22.3	5.9	9.3	-	-
W. Float	30.9	-	9.9	-	-
W.Whole Coal	27.2	6.3	9.7	-	-
Waterpan	27.4	6.5	9.4	11.8	18.2

It is evident from these figures that the differences in heat developed per square foot of grate area per minute between the N.A. Anthracite and the coals with the same total air supply are very much smaller than when equal primary air rates are considered. However, the anthracite liberates the least amount of heat under these conditions, then follow the Ermelo-Breyten and Natal coals generally and lastly the Witbank coals appear to develop the most heat with equal total air rates.

The order of the fuels is similar to that shown in Table 26 (page 56) where the heat in E.Units developed by one pound of total air is calculated.

(ii) With 50 Per Cent Excess Secondary Air.

The different rates of total air required for efficient combustion with 50 per cent excess air of the N.A.Anthracite for primary air rates of 33, 53, 67 and 93 cf/sq.ft/min. would be 99, 166, 201 and 296 cf/sq.ft/min. respectively. The heat units/sq.ft/min. developed by the coals assuming these total air rates and 50 per cent excess secondary air were calculated from the average ratios $\frac{\text{Secondary Air}}{\text{Primary Air}}$ given in Table 21. The results are shown in Table 29.

TABLE 29.

Heat Developed by the Fuels for Equal Total Air Rates when 50% Excess Secondary Air is Supplied.

Fuel	% V.M.	Heat Evolved (E.U/sq.ft/min.) for Total Air Rates of: 99 cf/sq. ft./min.	166 cf/sq. ft./min.	201 cf/sq. ft./min.	296 cf/sq. ft./min.
N.A.Anthracite	8.0	4.8	7.8	9.9	13.1
Mooifontein	22.6	4.9	8.3	-	-
Bellevue	34.7	4.5	8.1	-	-
Bankfontein	30.2	4.9	8.5	-	-
Tshoba	16.7	5.1	8.9	10.7	-
W. Middlings	22.3	5.5	9.3	-	-
W. Float	30.9	-	9.7	-	-
W. Whole Coal	27.2	5.5	9.3	-	-
Waterpan	27.4	5.6	9.4	11.6	16.1

The differences between heat developed by the anthracite and by the coals have generally been narrowed down by this comparison. The general order of the coals has not been altered, however.

D. THE HEAT DEVELOPED BY THE FUELS WITH NATURAL DRAUGHT.

In Table 30 the heat liberated by the fuels with natural draught expressed in Evaporative Units per square foot of grate area per minute is given.

TABLE 30.

Heat Liberated by the Fuels with Natural Draught.

Fuel	% V.M.	% Ash	Heat developed by Natural Draught in E.U./sq.ft/min.
N.A.Anthracite	8.0	11.4	2.3
Mooifontein	22.6	22.3	2.2
Bellevue	34.7	11.2	3.5
Bankfontein	30.2	13.2	4.3
Tshoba	16.7	17.0	4.3
W. Middlings	22.3	14.1	4.0
W. Float	30.9	7.0	-
W. Whole Coal	27.2	12.7	3.9
Waterpan	27.4	12.5	4.3

With the exception of the low calorific value and high ash Mooifontein coal, the coals develop more heat than the anthracite with natural draught. This is not only due to the slower burning characteristics but also to the very high bed resistance of the N.A.Anthracite.

An interesting feature indicated in Table 30 is that under natural draught conditions, the Wolvekrans Middlings coal will develop more heat than the Wolvekrans Whole Coal. This fact will be of great importance in determining whether the two-stage washing treatment of Witbank coal is advisable.

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The Director of the Fuel Research Institute, Dr. F.J. Tromp, initiated the research described in this report realising the necessity to investigate avenues for a greater utilization of anthracitic coal in South Africa.

The work was under his direction in the initial stages and he also designed the watercooled gas sampler which gave such excellent service.

Later Dr. L.A. Bushell directed the work and his interest and valuable advice in the experimental work and in the preparation of the report are greatly appreciated.

The experimental stack was designed and its construction supervised by Mr. G.W. van Doornum, the Institute's Engineer.

Practically all the members of the Institute's staff participated in some way or other in this research. Special mention may be made of the services rendered by Mr. S.D.Coetzee who showed great skill and perseverance with the analysis of the numerous gas samples.

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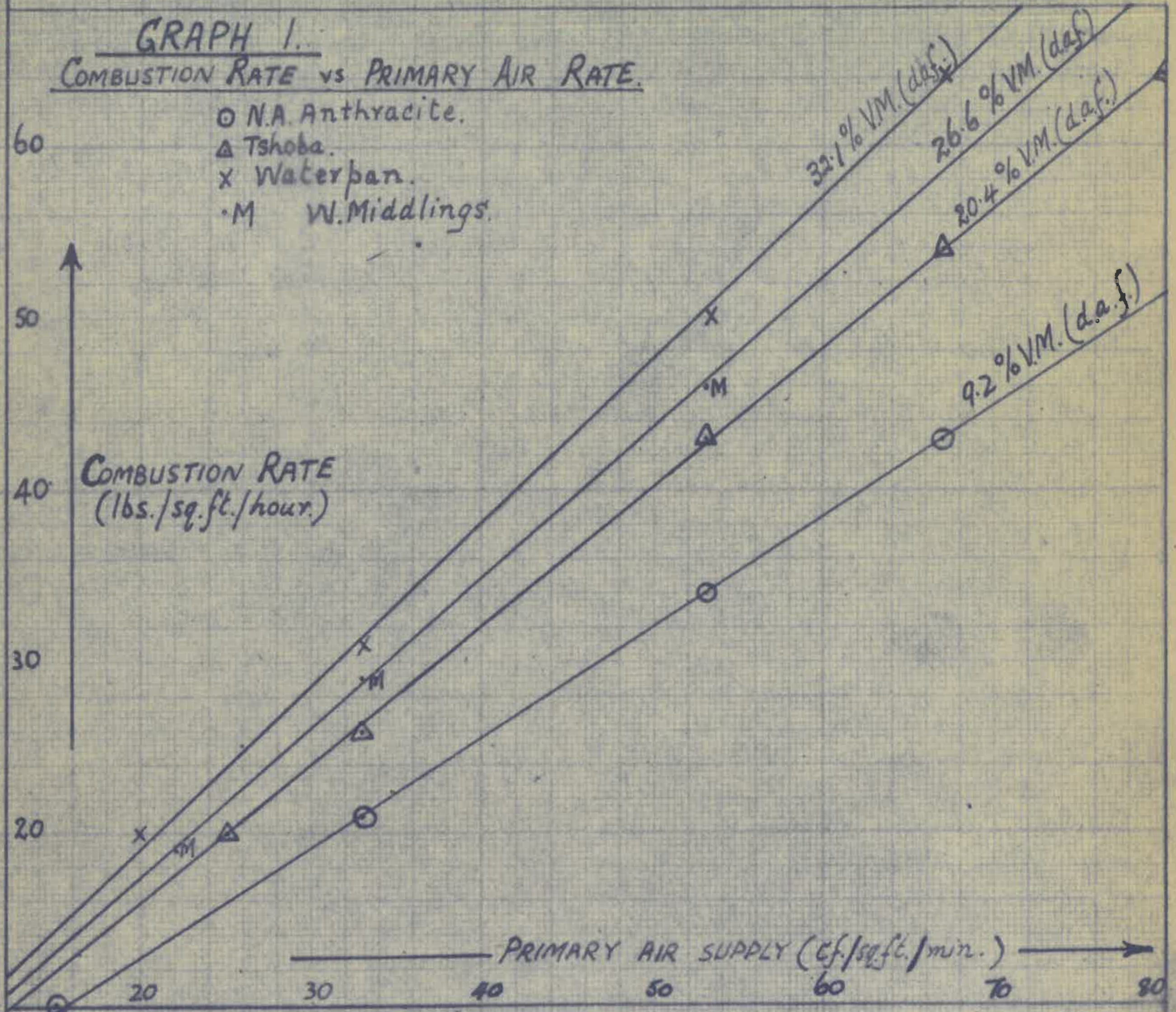
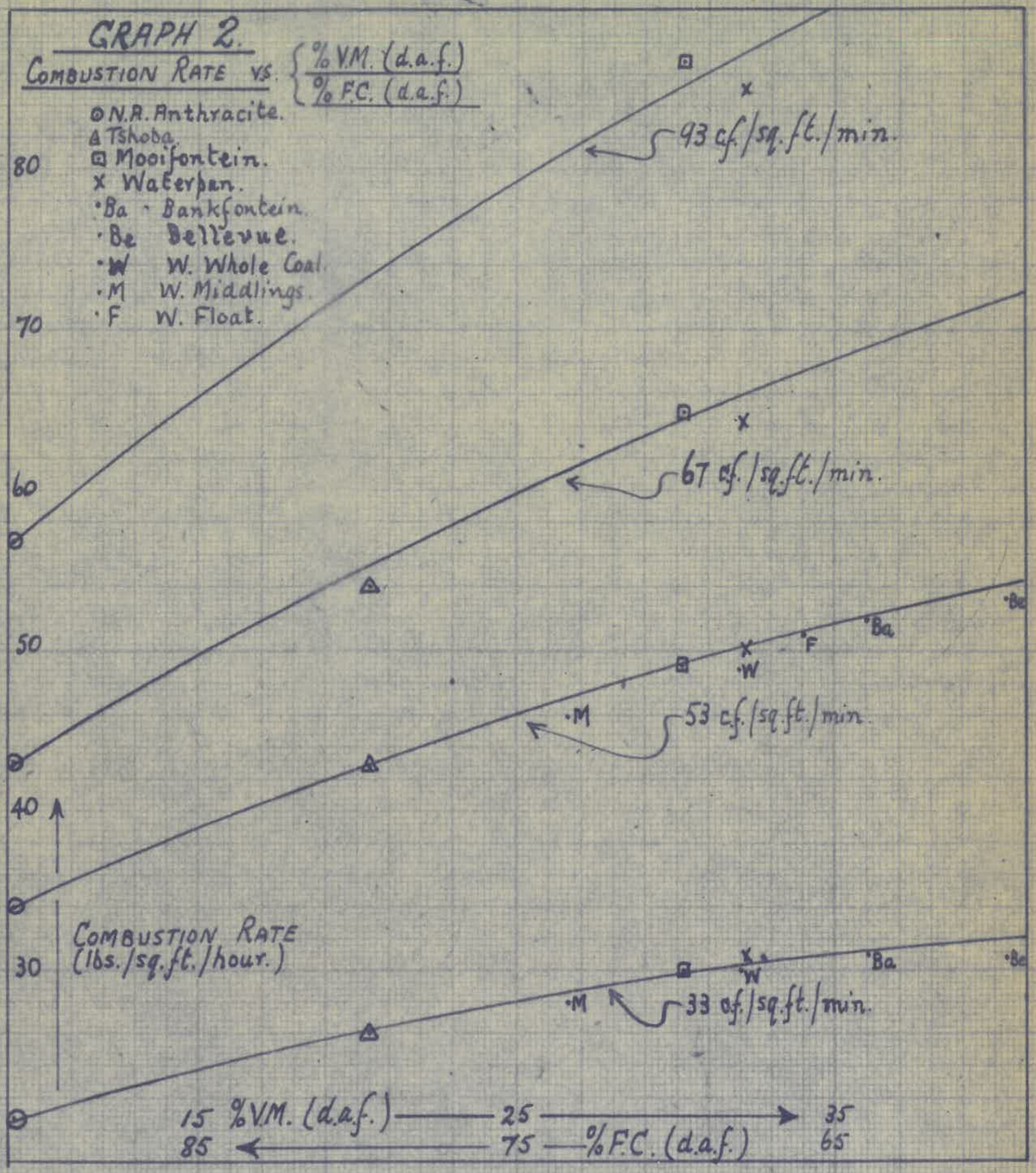
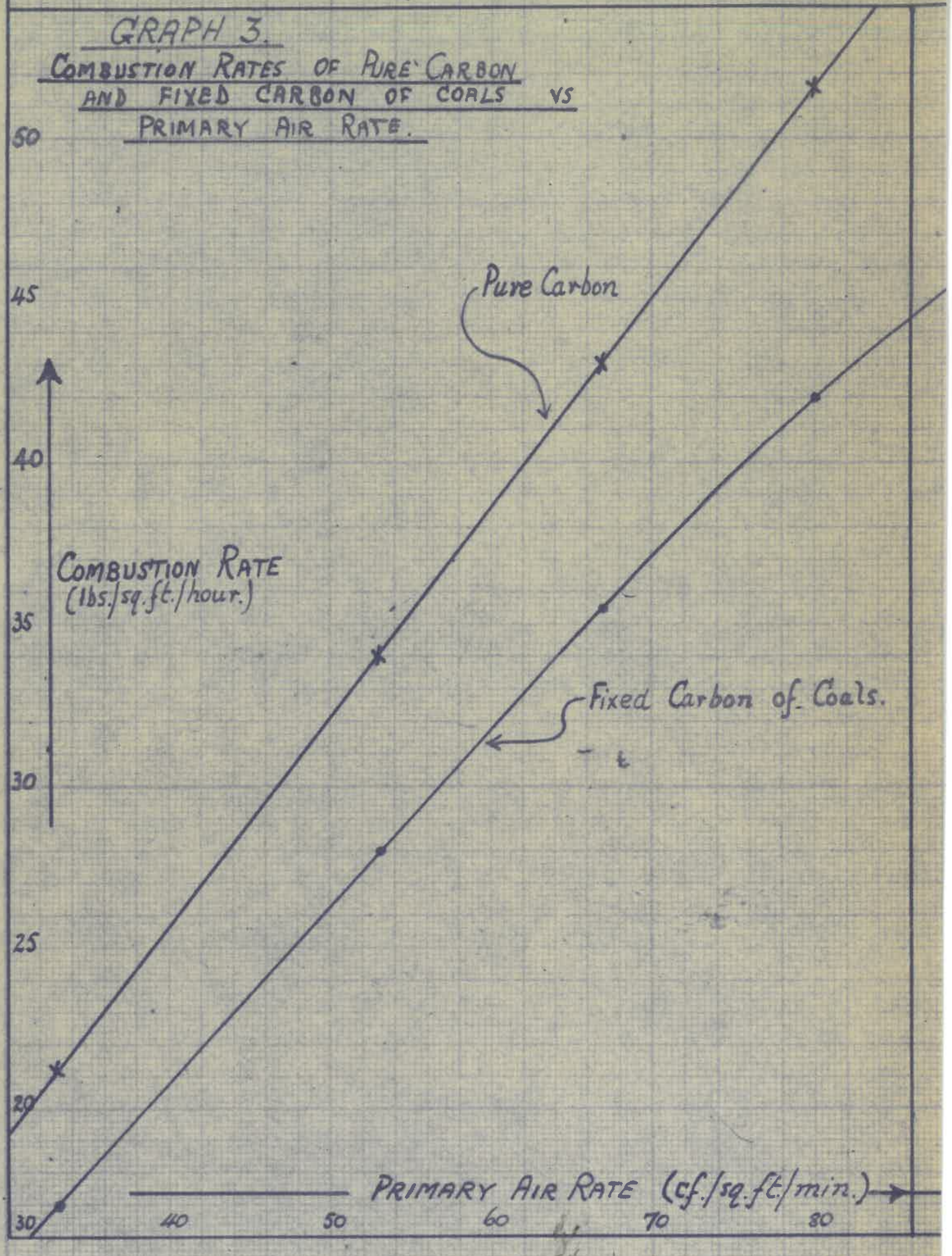
GRAPH I.

COMBUSTION RATE vs PRIMARY AIR RATE.



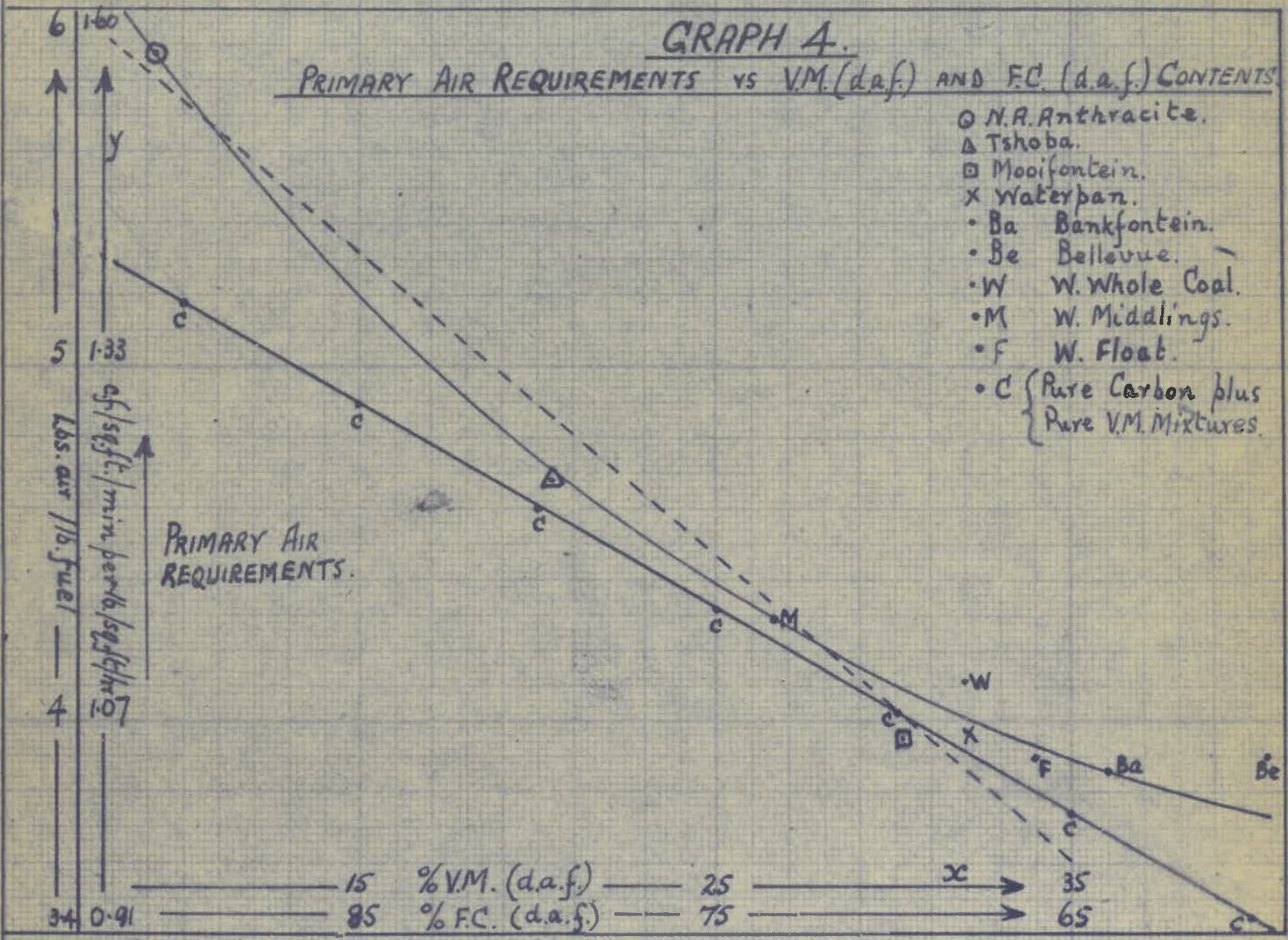

GRAPH 2.
COMBUSTION RATE vs. {%VM. (d.a.f.) / %F.C. (d.a.f.)}
⊙ N.R. Anthracite.
△ Tshoba.
⊡ Mooifontein.
x Waterpan.
·Ba - Bankfontein.
·Be Bellevue.
·W W. Whole Coal.
·M W. Middlings.
·F W. Float.
93 c.f./sq.ft./min.
67 c.f./sq.ft./min.
53 c.f./sq.ft./min.
33 c.f./sq.ft./min.
Ba
Be
F
W
M
80
70
60
50
40
30
COMBUSTION RATE (lbs./sq.ft./hour.)
15 %VM. (d.a.f.) 25 35
85 75 %F.C. (d.a.f.) 65

GRAPH 3.
COMBUSTION RATES OF PURE CARBON AND FIXED CARBON OF COALS VS PRIMARY AIR RATE.



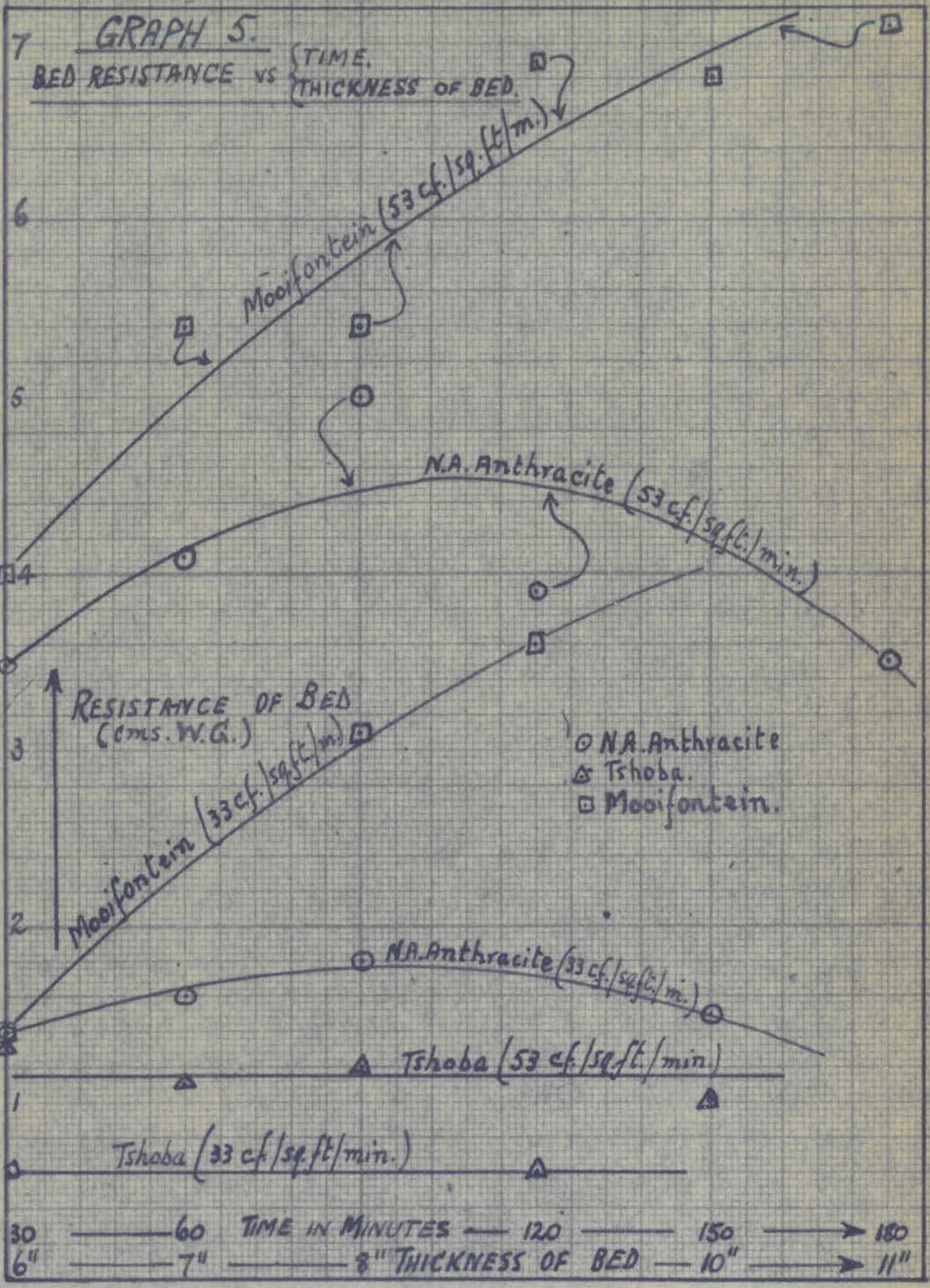
GRAPH 4.

PRIMARY AIR REQUIREMENTS vs V.M. (d.a.f.) AND F.C. (d.a.f.) CONTENTS



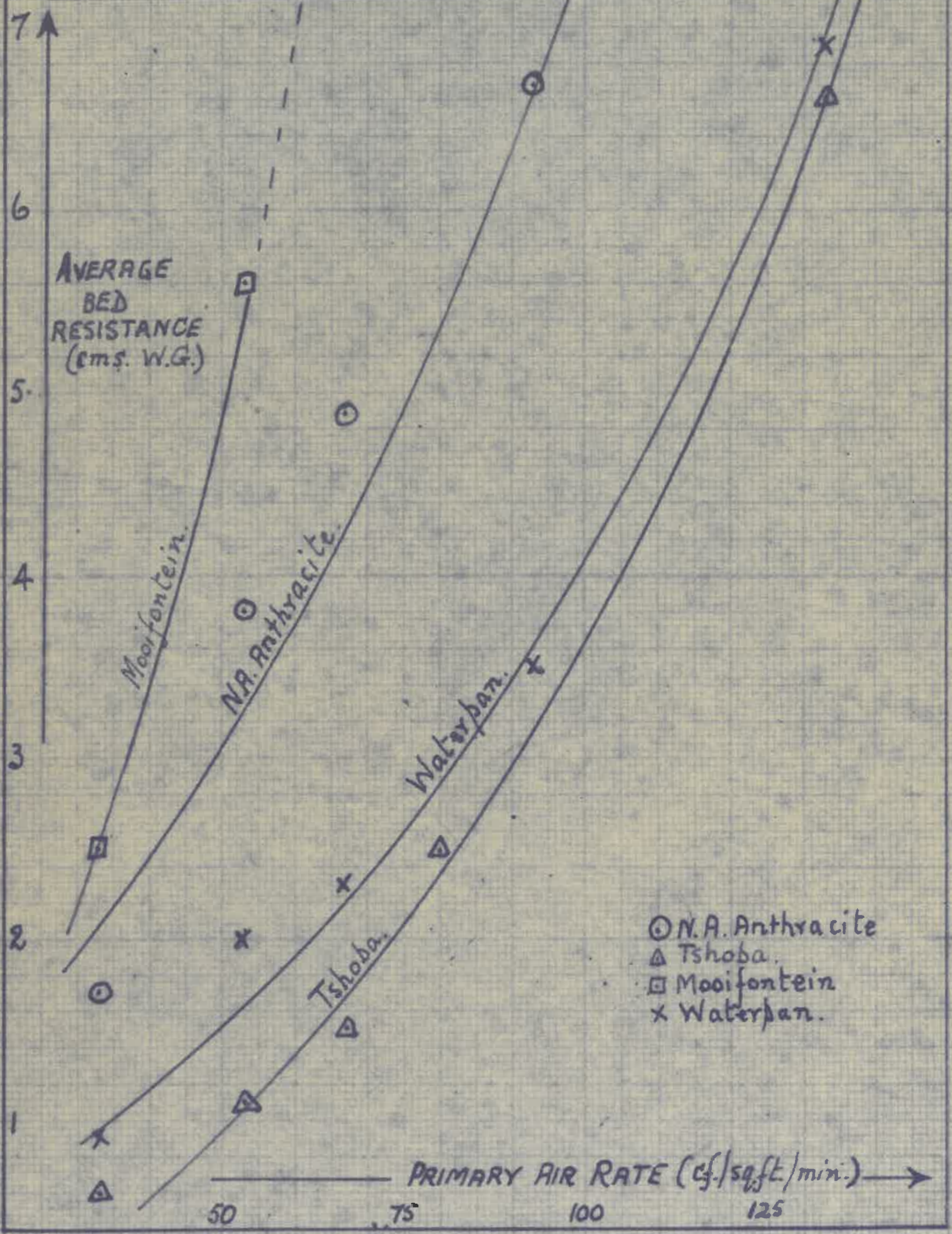
GRAPH 5.

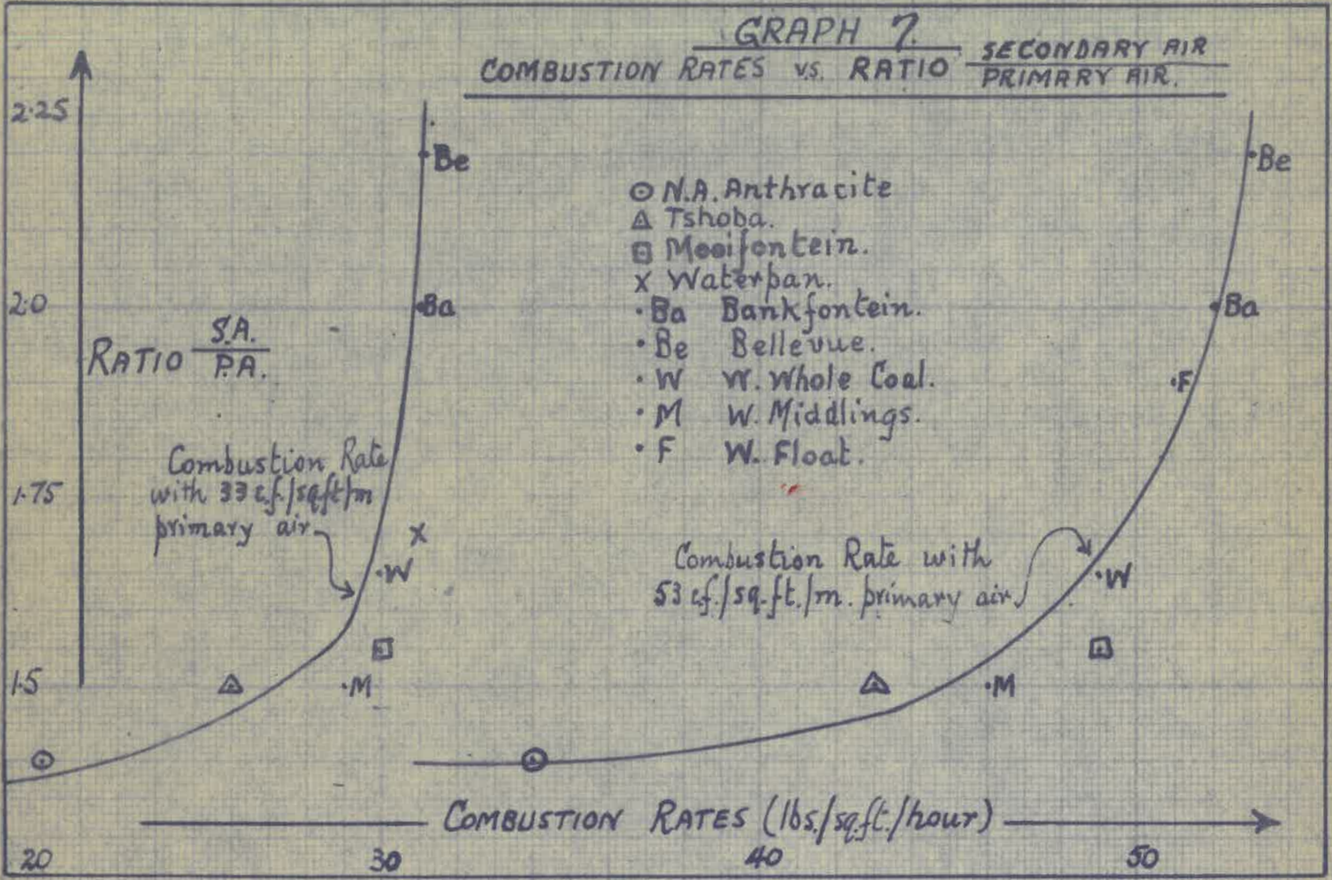
BED RESISTANCE vs {TIME. THICKNESS OF BED.

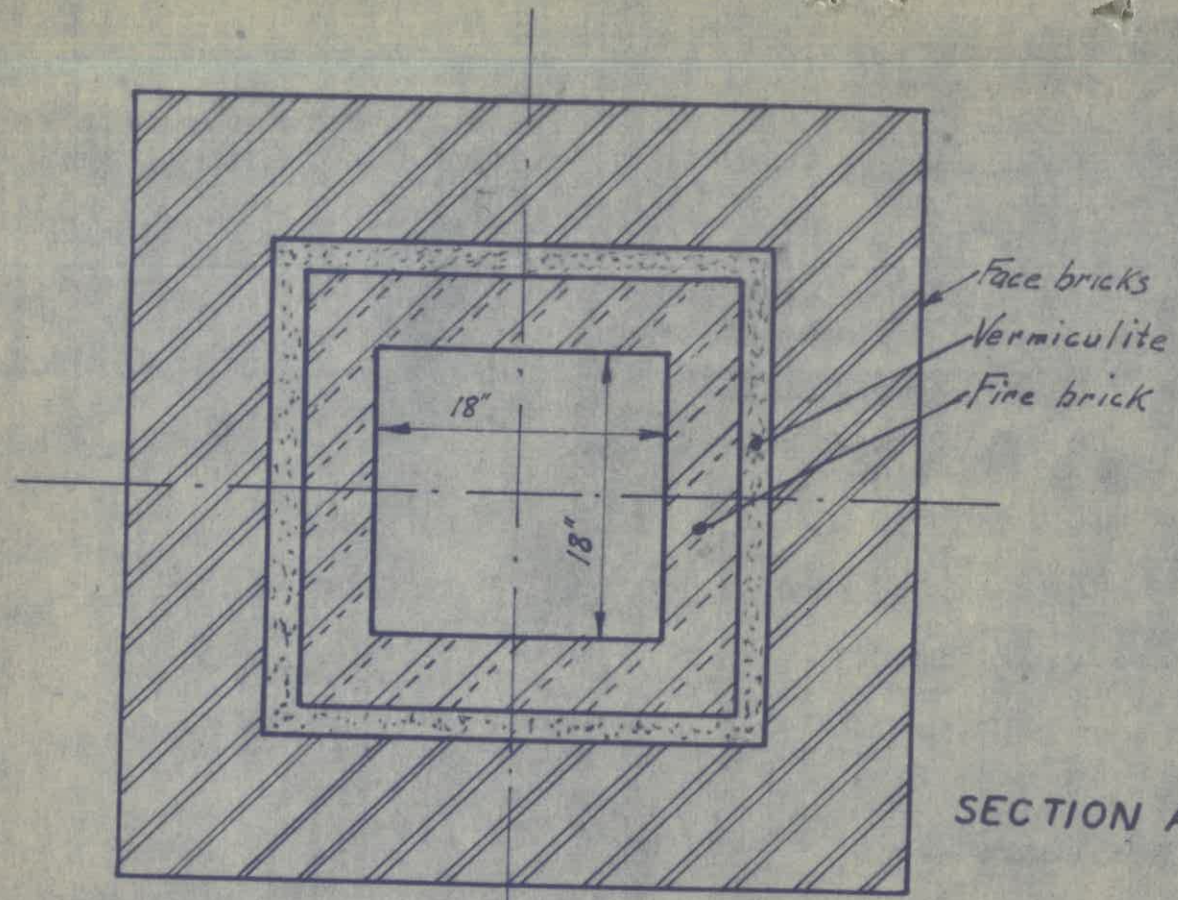


GRAPH 6.

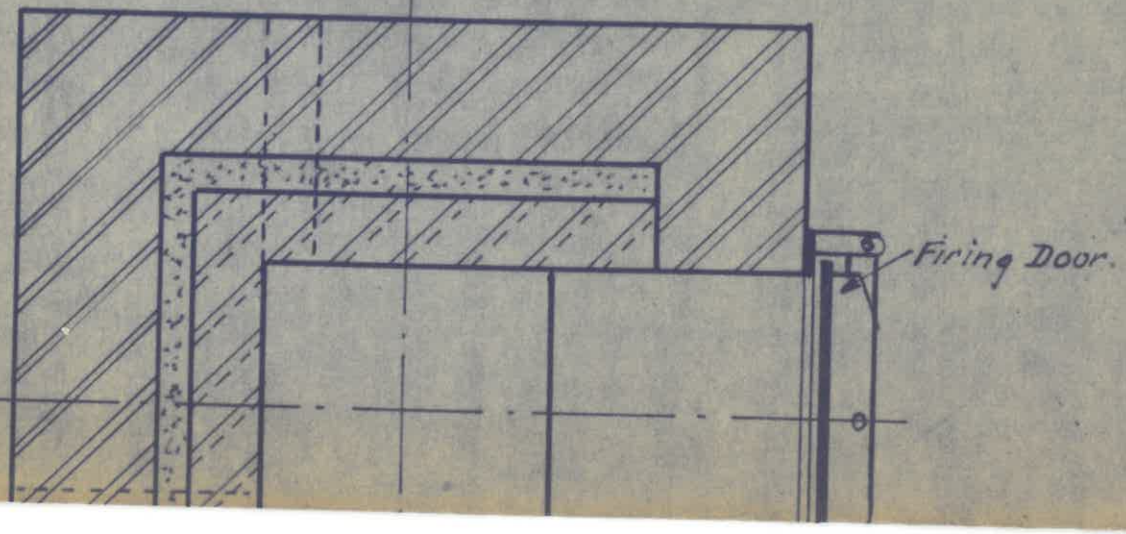
BED RESISTANCE VS PRIMARY AIR RATE.

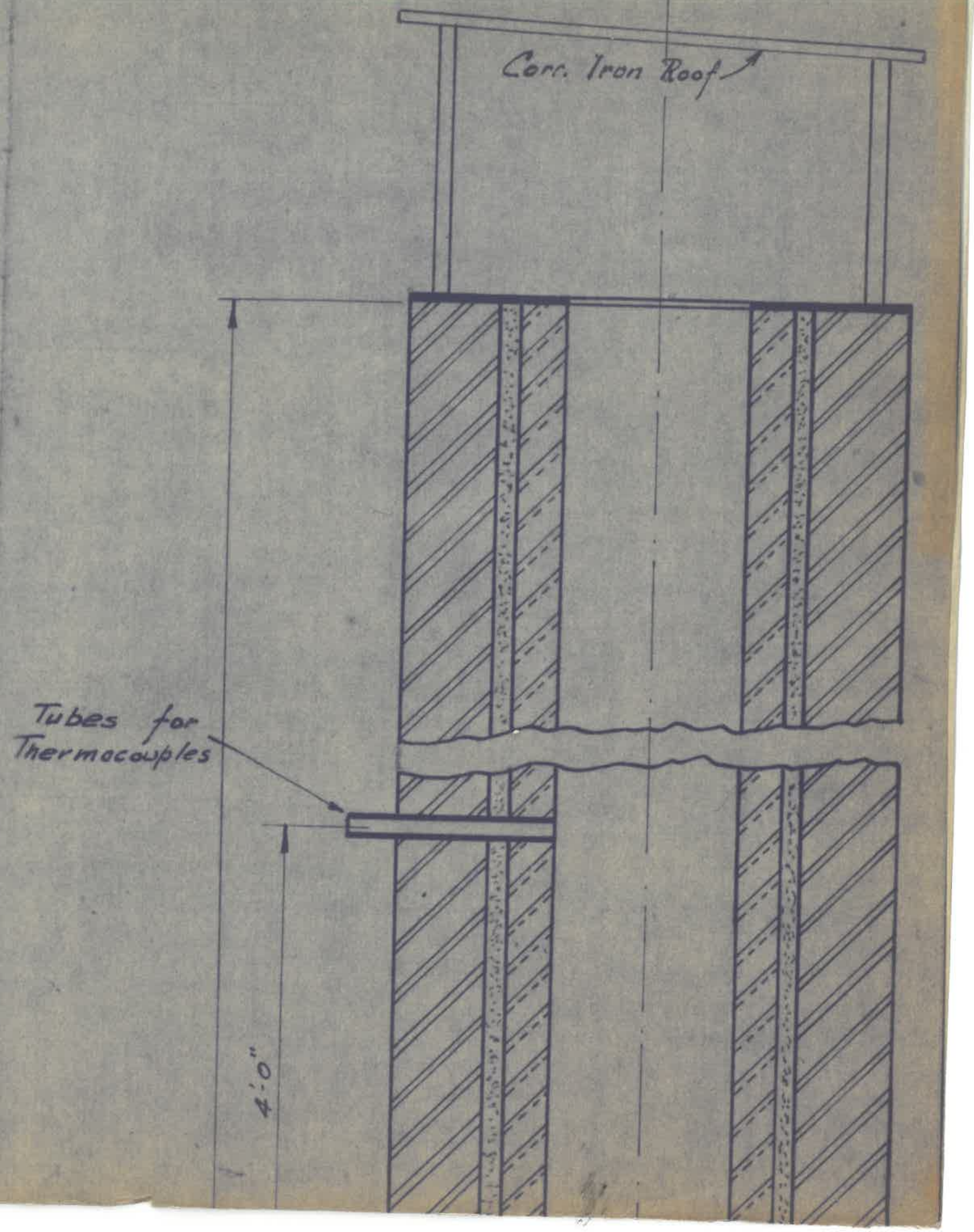


GRAPH 7.
COMBUSTION RATES vs. RATIO SECONDARY AIR / PRIMARY AIR.
○ N.A. Anthracite
△ Tshoba.
⊡ Mooifontein.
X Waterpan.
· Ba Bankfontein.
· Be Bellevue.
· W W. Whole Coal.
· M W. Middlings.
· F W. Float.
RATIO S.A./P.A.
2·25
2·0
1·75
1·5
Combustion Rate with 33 c.f./sq.ft./m primary air.
Combustion Rate with 53 c.f./sq.ft./m. primary air.
Be
Ba
W
M
F
X
COMBUSTION RATES (lbs./sq.ft./hour)
20
30
40
50


Face bricks
Vermiculite
Fire brick
18"
18"

SECTION A-A.


Firing Door.


Corr. Iron Roof
Tubes for Thermocouples
4'0"

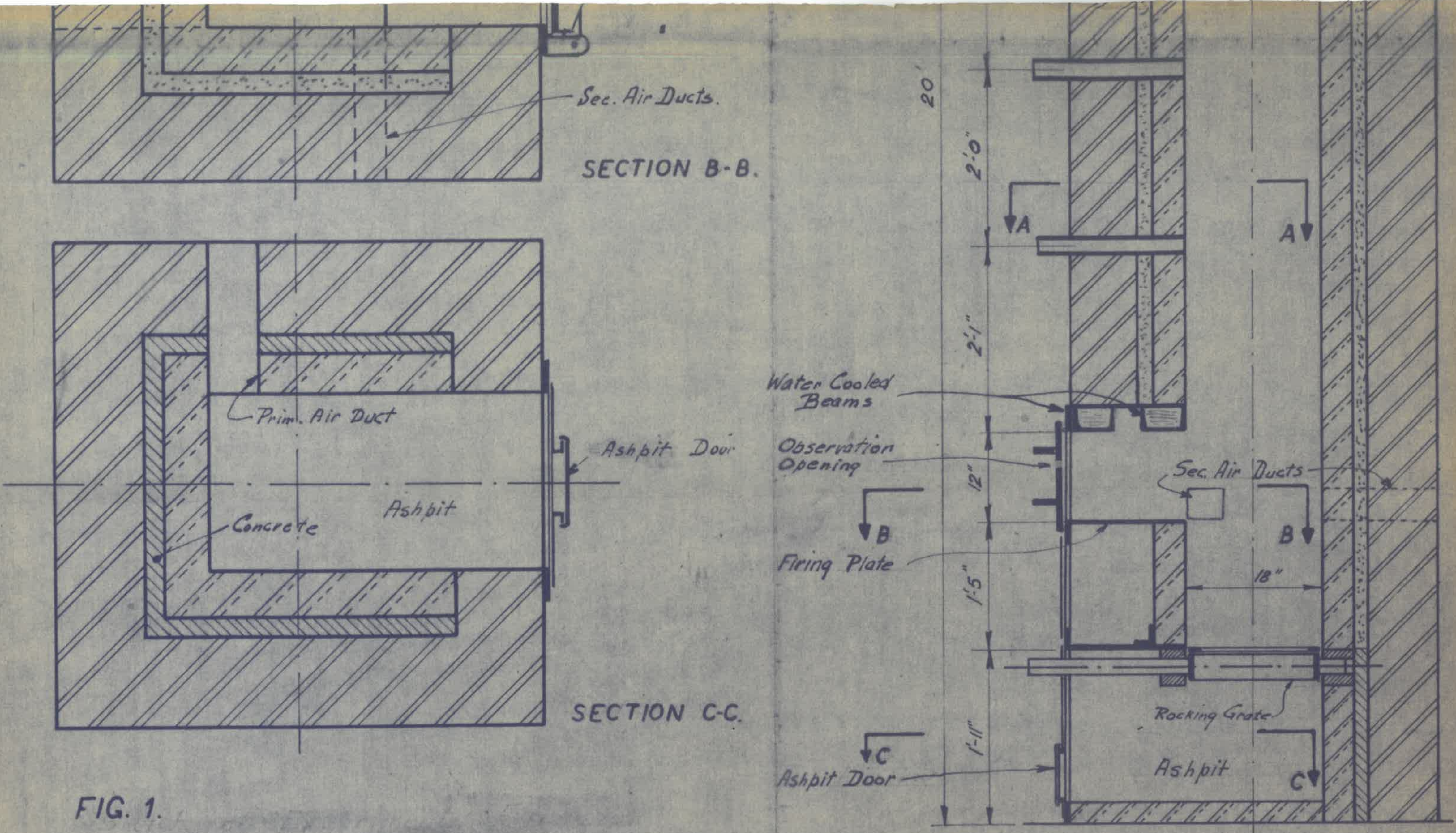


FIG. 1.

EXPERIMENTAL STACK.

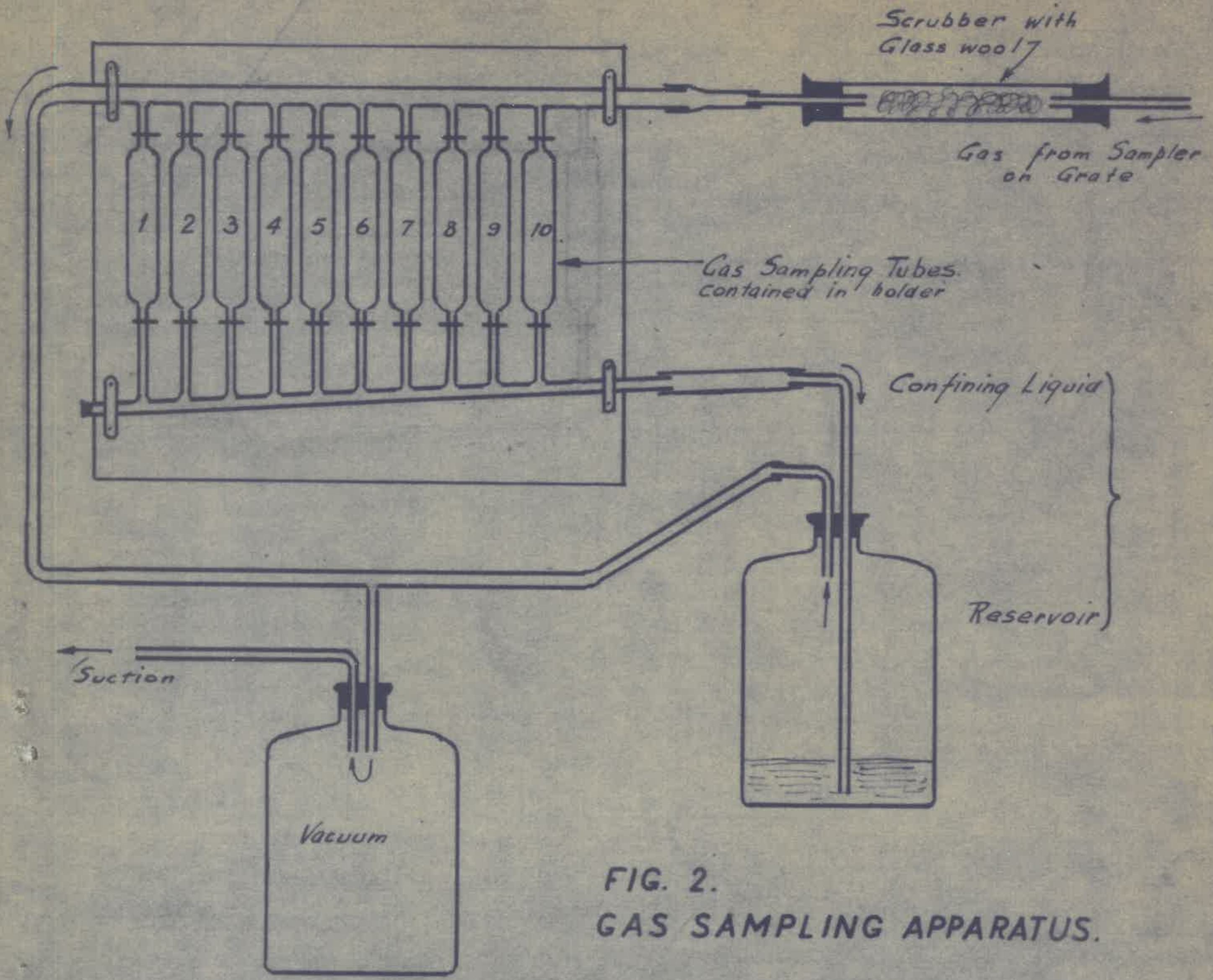


FIG. 2.
GAS SAMPLING APPARATUS.

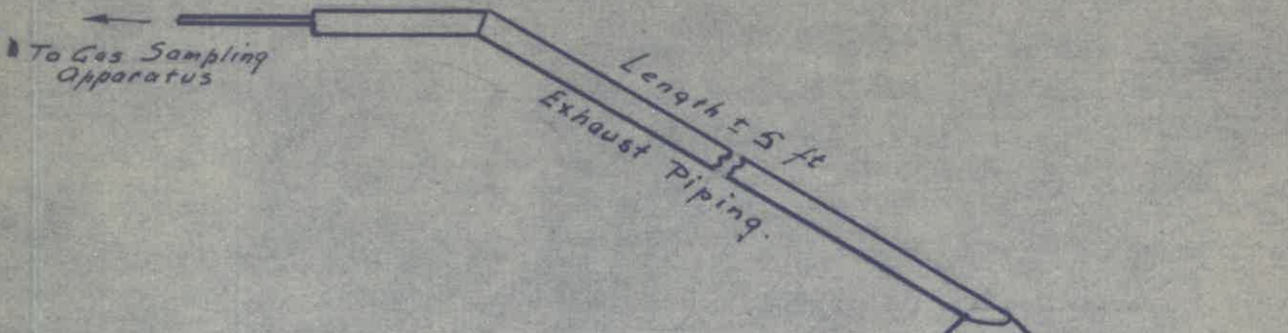
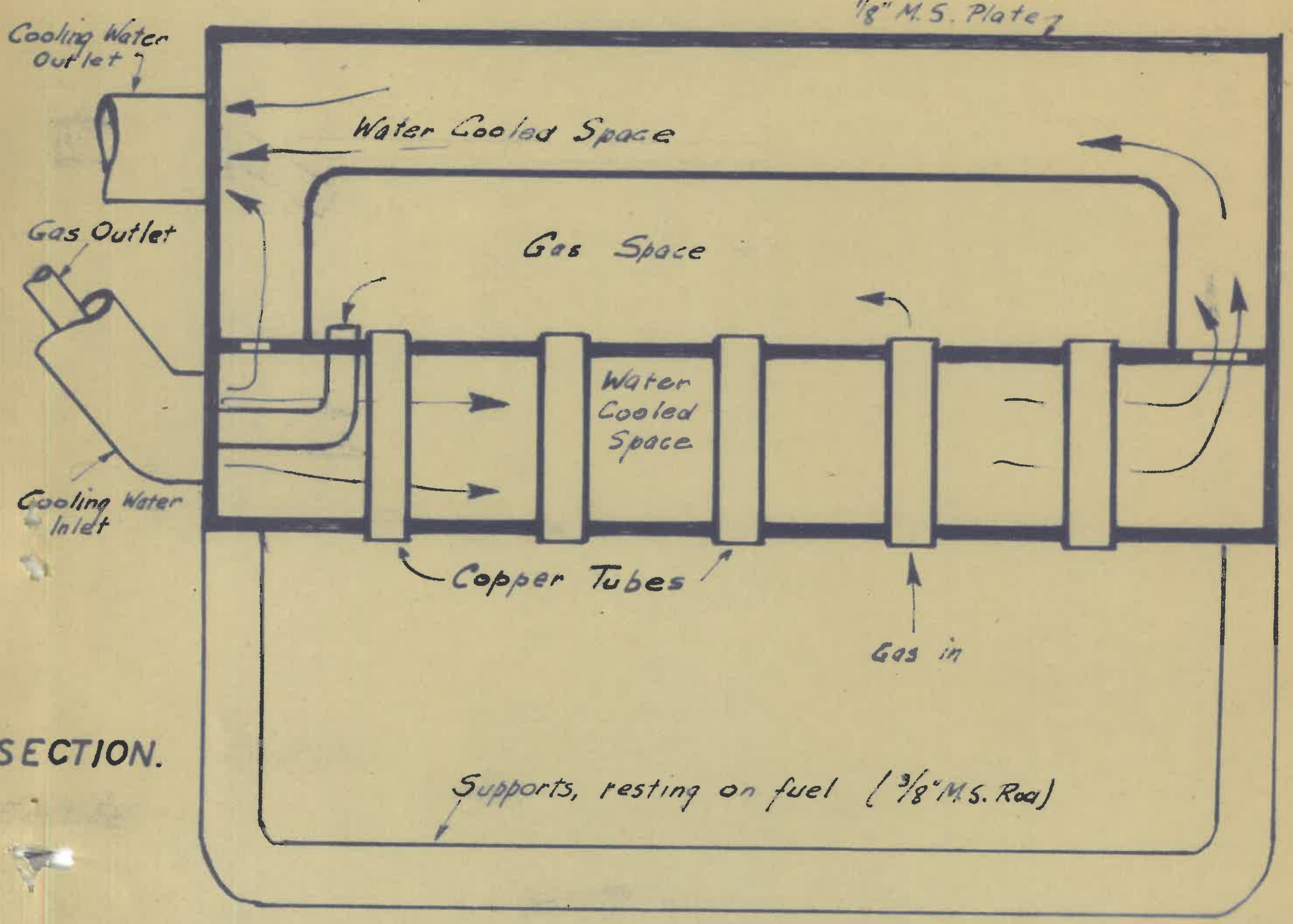
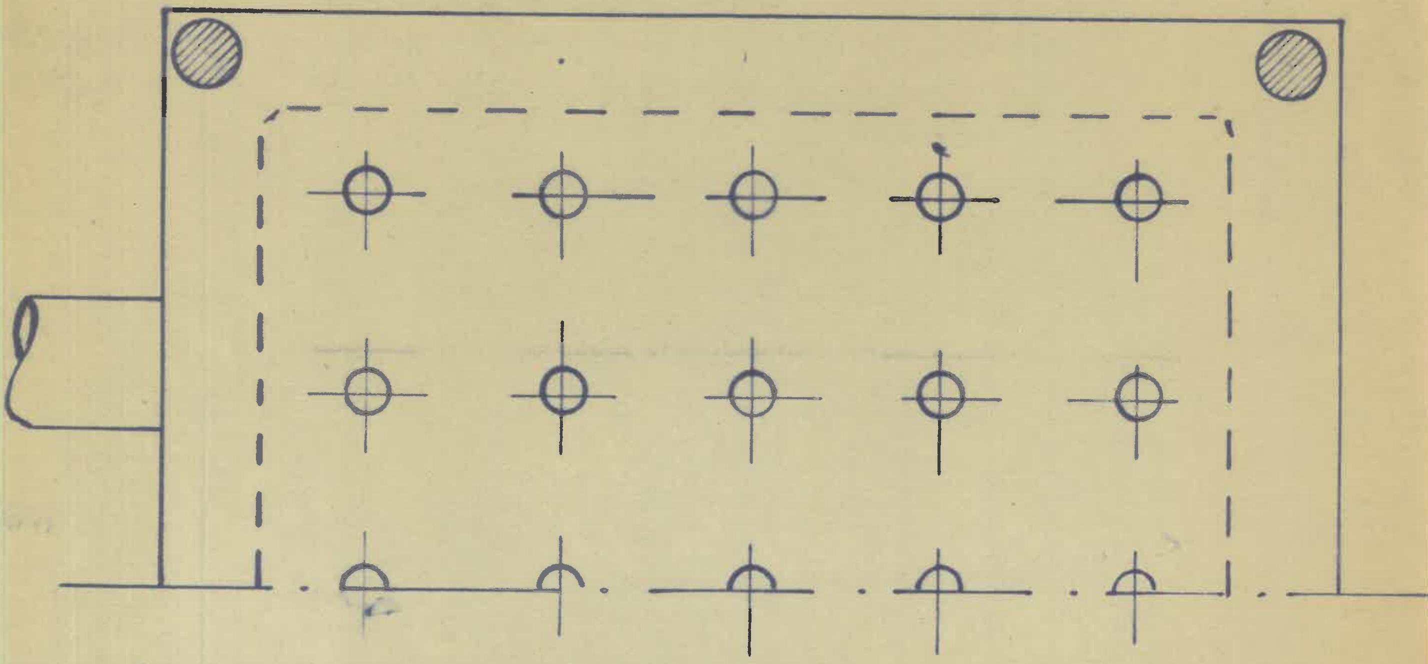


FIG. 3.
GAS SAMPLER, NOT COOLED.



SECTION.



PLAN, (HALF OF BOTTOM)

WATERCOOLED SAMPLER, FULL SIZE.

FIG. 4.

The Average Composition

Fuel	% V.M.	No. of tests	No. of gas series	C.Rate lbs/sq. ft/hr.	P.A. Rate cf/sq. ft/min.	% CO2	% O2
N.A.Anthracite	8.0	3	6	10	*15	3.3	0.3
		2	5	21	33	1.2	0.2
		5	3	34	53	0.4	0.3
		2	3	43	67	0.2	0.6
		1	2	57	93	0.2	0.5
		1	2	71	133	0.3	0.3
Tshoba	16.7	1	3	20	*25	6.7	0.4
		1	3	26	33	1.7	0.5
		3	5	43	53	2.4	0.5
		1	2	54	67	1.6	0.7
		1	2	64	80	0.9	0.3
		1	2	80	133	3.2	0.2
Mooifontein	22.6	2	4	12	* 12	3.0	0.3
		2	4	30	33	1.9	0.3
		4	3	49	53	2.4	0.3
		1	2	65	67	7.8	0.4
		1	2	87	93	8.7	0.1
		1	1	129	133	9.3	0.3
Waterpan	27.4	2	4	20	*20	5.6	0.2
		2	4	31	33	3.0	0.2
		3	3	50	53	4.1	0.4
		2	4	64	67	1.8	0.4
		1	2	85	93	3.9	0.4
		1	2	109	133	2.5	0.4
Bellevue	34.7	1	2	17	*18	2.9	0.3
		1	2	31	33	1.4	0.6
		1	2	53	53	3.6	0.3
Bankfontein	30.2	1	2	21	*21	11.1	0.5
		1	2	31	33	3.2	0.6
		1	2	52	53	4.1	0.2
Wolvekrans Whole coal	27.2	1	2	18	*20	7.3	0.5
		1	2	30	33	3.0	0.9
		1	2	49	53	1.7	0.6
Wolvekrans Middlings	22.3	1	2	19	*22	6.6	0.6
		1	3	26	33	2.1	0.5
		2	5	46	53	2.5	0.7
Wolvekrans Float	30.9	1	4	51	53	3.2	0.8

* Obtained by Natural Draugh

⌿ Includes illuminants

TABLE 9.

the Gas at Different Combustion Rates.

	% CH4	% H2	% Ill.	% N2	% Excess Air.	% Combust.	% O2 content	Equiv. N2 content	Av. Bed Resistance
.2	1.3	9.3	0.2	58.4	-46	37.8	17.2	64.7	-
.7	≠0.9	6.6	-	59.4	-50	39.2	17.3	65.1	1.5
.4	≠1.0	7.5	-	58.4	-51	40.9	16.9	63.6	3.8
.1	≠0.9	5.5	-	59.7	-50	39.5	17.4	65.5	4.9
.8	1.1	7.9	0.2	58.3	-50	40.8	16.6	62.4	6.7
.8	1.2	7.6	0.2	58.6	-50	40.6	16.5	62.2	10.6
.8	≠1.9	9.1	-	62.1	-37	30.8	17.0	63.9	
.1	≠1.7	7.8	-	58.2	-49	39.6	17.3	65.1	0.6
.5	1.8	10.3	0.2	57.3	-47	39.6	16.7	62.8	1.1
.9	≠1.9	7.4	-	58.5	-48	39.2	17.3	65.1	1.5
.2	≠1.5	8.8	-	57.3	-50	41.5	16.8	63.2	2.5
.1	1.6	5.2	0.3	61.4	-46	34.9	17.5	65.8	6.6
.1	1.9	8.3	0.4	57.0	-48	39.3	17.9	67.3	-
.6	1.5	7.8	0.4	57.5	-50	39.9	17.5	65.8	2.5
.2	≠1.7	9.2	-	56.2	-50	41.1	17.6	67.0	5.6
0.9	≠1.5	4.8	-	64.6	-37	27.2	18.7	70.3	4.8
0.1	≠1.4	4.5	-	65.2	-37	26.0	18.9	71.2	5.3
8.3	2.1	8.2	0.4	61.4	-35	28.6	18.8	70.8	8.3
3.1	≠2.3	8.0	-	60.8	-41	33.4	17.4	65.5	-
8.5	≠1.9	6.8	-	59.6	-47	37.2	17.5	65.8	0.9
4.9	≠3.2	12.1	-	55.3	-45	40.2	17.0	63.9	2.0
8.5	≠2.1	12.2	-	55.0	-49	42.8	16.5	62.1	2.3
7.4	≠2.2	8.1	-	58.0	-46	37.7	18.0	67.7	3.5
6.9	3.9	14.0	0.5	51.8	-46	44.8	16.4	61.7	6.9
8.2	4.8	11.4	1.2	51.2	-50	44.4	17.3	65.1	-
0.0	≠2.8	9.3	-	55.9	-49	42.1	17.0	63.9	1.4
4.4	5.1	15.3	1.3	50.0	-51	44.8	16.3	61.3	2.5
8.2	0.9	2.2	0.2	76.9	-15	11.3	15.7	59.0	-
6.7	4.1	11.5	0.6	53.3	-47	42.3	17.2	64.7	1.1
5.5	≠3.1	12.2	-	54.9	-46	40.8	17.1	64.3	1.8
.6	1.0	8.6	0.4	62.6	-36	29.2	17.6	66.2	-
7.0	1.5	9.0	0.3	58.3	-45	38.5	17.4	65.5	0.8
8.3	1.4	12.7	0.3	55.0	-48	42.4	16.5	62.1	1.5
2.0	0.7	5.8	0.3	64.0	-38	28.5	18.2	68.5	-
9.2	1.3	8.4	0.1	58.4	-47	38.9	17.2	64.7	0.7
7.9	1.8	9.3	0.2	57.6	-46	39.0	17.2	64.7	1.2
4.3	3.5	13.6	0.6	54.0	-44	41.4	16.4	61.7	1.9

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