TESTING AND VALIDATION OF COAL COMBUSTION PREDICTION INDICES FROM CONVENTIONAL LABORATORY ANALYSES

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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(Signature of candidate)

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ABSTRACT

This study reports on the testing and validation of combustion prediction indices derived from the conventional laboratory analyses of coal. This involved the actual testing of coal samples using the pilot-scale combustion test rig, the Drop Tube Furnace (DTF), petrographic analysis and the normal conventional laboratory analysis. The indices covered in the study were Fuel Ratio (FR), Hydrogen to Carbon ratio (H/C ratio) and maceral-based indices. The anomalies encountered in the study were also investigated.

The investigation was based on ten low-grade Bituminous coal samples (A–J). Each of the ten samples was sub-divided into two; the bulk sample of approximately 1.2 tons was taken for the pilot-scale combustion tests and the remainder for the laboratory bench-scale tests. A portion of the laboratory sample was used for DTF and petrographic analyses. All ten bulk samples were fired in the combustion test rig. An attempt was made to keep all major combustion parameters constant for all samples. The fineness of all samples was kept at approximately 70% -75µm particles and the excess oxygen at approximately 6%. The burnout times of both the parent feed coals and their char products were used to test the indices.

There was no clear correlation between the burnout times of the parent coals in the combustion test rig and the indices obtained from the conventional laboratory test results, viz. FR and H/C ratio. There was also no clear correlation between the burnout times

of chars in the DTF and the above indices. This can be attributed to the fact that the conventional laboratory analyses, on which these indices are based, are performed at lower temperatures as compared with combustion conditions in the combustion test rig and the DTF. However, the char burnout times in the DTF showed a strong linear correlation (R^2 = 0.89) with the *Fuel Ratio obtained from DTF volatile matter*, which was corrected by subtracting the mineral volatiles. This relationship was not obtained from the burnout of parent coals in the combustion test rig. This proved that the high temperature combustible volatile matter relates better to high temperature combustion performance in the DTF.

The petrographic nature and rank of most parent coal samples had a strong influence on the combustion performance in the combustion test rig. Namely, there was a strong correlation between the burnout times of the parent coals and the maceral-based indices, i.e. Burnout times versus vitrinite content showed a linear correlation (R^2) of 0.91, burnout times versus Reactivity Index (RF) showed a linear correlation (R^2) of 0.96 and burnout times versus Maceral Index (MI) showed an exponential correlation of 0.85. However, there was no clear correlation between the above indices and the char burnout times in the DTF.

Of the ten coals tested, three showed consistently anomalous correlations including burnout results, i.e. coals E, H and J.

The relatively slow burnout time of Coal E (1.20 seconds) in the combustion test rig was not commensurate with the high vitrinite content of 42.2% and the volatile matter of 22.5%. The full survey of the analytical results indicated that Coal E, apart from having the highest proportion of -75micron fines in the feed sample (85%), the lowest Abrasive Index (22 mgFe), the highest Hardgrove Grindability Index (67) and possessing a significant proportion of weathered and oxidised particles, most notably exhibits a range of rank that extends from Sub-bituminous to well into the Mid Bituminous coking range of rank (0.5 to 1.3 RoVr%). This evidence indicates (a) that the coals which fall normally in the Low Rank Bituminous C range, have been heated relatively significant and (b) most importantly, have passed into the range in which vitrinite macerals become “cokified”. This infers that the vitrinite in the higher ranking coking range would soften, swell, become porous, fuse with other particles and then harden. During this process the texture of the walls of the gas pores become *semi-crystalline,* developing mosaic structures (a form of semi-graphitisation) on exposure to high temperatures

Thus, due to the high vitrinite content and extended rank into the coking range, it has been concluded that a significant proportion of the coaly material has become “cokified” and semi-graphitised. Such lower rank material, which is normally highly reactive to combustion in the presence of oxygen at lower temperatures, becomes inert above a specific temperature after undergoing severe molecular re-ordering and resolidification. This unusual condition, in addition to the presence of oxidised materials in this coal, is considered to be responsible for the anomalously long burnout time of a supposedly reactive coal.

Coal H exhibited a longer burnout time of 1.55 seconds in the combustion test rig. This has been attributed to the fact that this coal has a significant quantity of long-term weathered and oxidised material as indicated by the highest proportion of discoloured coaly particles (9.2%) along with the relatively high cracking and fissuring (20.6%) that arises with weathering. This is commensurate with the fact that this sample was derived from an old stockpile as indicated in Table 3.1. The long burnout time of this coal is considered to be due to the presence of weathered material which gives rise to limited volatile release, slow ignition and slower rates of combustion.

Coal J possessed the shortest burnout time in the combustion test rig (0.75 seconds) but it also possessed, by far the highest proportion of coaly material exhibiting abnormal conditions (55.6% compared to the next highest value, 37% in sample H) of which 29.6% was heat-affected and 17.4% cracked and fissured and possibly desiccated. This sample also possessed a low vitrinite content (11.2%), the lowest MI value (0.028), the lowest volatile matter content (17.7% based on proximate analyses) and the widest range of vitrinite reflectance (0.5 to 2.2 RoVmr%) thereby confirming the extensive levels to which the coal had been burnt. The unexpectedly fast burnout time of what would otherwise have been considered a relatively slow burning, difficult to ignite coal appears, in this case, to be attributable to the combustion response to high temperature exposure of the extensively heat-affected, desiccated and cracked material in the combustion test rig. Thermal shock is therefore considered to have taken place, namely, material such as that described above has been known to explode and shatter into smaller particles when exposed to instant high temperatures. The result is the provision of small particles with higher surface areas which leads to rapid and efficient combustion. This process has been identified in other similar South African coals, as reported by Falcon (1992). This has been termed ‘deflagration’. The occurrence of the highest flue gas temperature as reported in the combustion test rig tests when burning this coal further confirms the presence of higher rank (burnt) coals.

The results of this work therefore indicate that coal combustion performance in the combustion test rig is most closely correlated to the petrographic parameters, i.e. vitrinite content, Maceral Index (MI) and Reactivity Index (RI), except when coals are oxidised, burnt, high ash or liable to potential deflagration due to incipient cracking in the original coal.

The conventional laboratory analyses, and the Fuel Ratio (FR) and Hydrogen to Carbon Ratio (H/C) derived from them, cannot be correlated with coal combustion performance in either the DTF or the large scale combustion test rig.

Furthermore, the burnout results of the chars tested in the DTF cannot be correlated with the burnout results of the normal parent coals obtained in the combustion test rig. This is considered to be due to the differences in sample preparation prior to testing and to variations in combustion conditions between the two test units.

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ABBREVIATIONS AND ACRONYMS

FR – Fuel Ratio

H/C – Hydrogen to carbon ratio

DTF – Drop tube furnace

MI – Maceral index

RI – Reactivity index

1 INTRODUCTION

1.1 Growing Demand for Electricity in South Africa

The growing demand for electricity has led to an increase of coal consumption by Eskom, the South African main power utility. This was evident in the Eskom Annual Report of 2005, where coal consumed increased from 76.8Mt in 1994 to 136.4Mt in 2005. The 43.7% increase in coal consumption resulted in a 41% increase in electricity generated. During this period the average ash content increased from 28.7% to 29.6% while the average heat value has decreased from 19.95MJ/kg to 19.36MJ/kg.

The above led to a slight shortage of coal resulting in multiple coal sources supplying affected coal-fired power plants. On the other hand, coal sources with known qualities are nearing depletion due to the lucrative export market. The power utility is thus faced with the problem of the utilisation of low grade coals for power generation. This includes processed discards mixed with ultra fines. The characterisation of coal prior to utilisation in the power station has gradually become a vital step in order to ensure the efficient operation of power plants.

1.2 Pre-qualification of Coal Sources

Currently, the utility has embarked upon the pre-qualification of all potential sources of coal by taking samples for testing prior to utilisation. The testing involves conventional laboratory analyses and, where possible, the combustion test rig. This exercise has proved to be very informative and useful in decision making, but expensive and time-consuming. Hence, certain combustion prediction indices derived from conventional laboratory analyses are used with caution. When these indices were tested against the actual coal combustion behaviour combustion test rig, certain anomalies were detected. The Fuel Ratio, hydrogen/carbon ratio and the plot of these indices showed anomalies when compared to the actual behaviour of some coals in the combustion test rig.

1.3 Overall Purpose of the Study

The main purpose of this study was twofold. Firstly, to see whether the current indices derived from conventional laboratory analyses could be validated and could account for anomalies. The second purpose was to find other relationships and expressions that can better predict the combustion performance of coal.

2. BACKGROUND AND LITERATURE REVIEW

2.1 REVIEW OF COMBUSTION ISSUES

This section covers some of the work already done on the combustion and burnout of both pulverised coal and char. It also covers some of the factors affecting combustion, namely volatile matter, coal carbon chemistry, rank and mineral matter. Some combustion prediction indices are also covered in this section.

2.1.1 Combustion of Pulverised Coal

As the cloud of pulverized coal particles (pf) is introduced into the boiler it is ignited by radiation emanating from the adjacent flame. The stability of flame propagation depends on the air/Fuel Ratio, percentage volatile matter and the mineral matter in the coal.

The burning of pf with the transporting air undergoes different stages during combustion, i.e. a heterogeneous form of combustion rather than a single stage homogeneous process. This requires that the volatile matter be released and burned first, and the remaining carbon residue burned last. These two steps occur within the volume of air supporting, and immediately surrounding the burning coal particle, so that the combustion of the residue is in the atmosphere in which the concentration of oxygen is continuously decreasing. Hence, to obtain high carbon efficiency, that is, low carbon loss and low excess air, the time of residence in the primary furnace must be longer than that needed for air to flow through the fuel bed, in order to allow the remaining oxygen to reach the particle. The residence time of a coal particle is mainly affected by the volatile matter content and the level of fineness or size. The residence time decreases with the increase in volatile matter and increases with the increase particle size. (Lowry 1963).

Khitrin (1957) reported that the combustion of coal particles is affected by the relative velocity between the fuel and the gases contributing to combustion, the residence time of coal particles in a furnace and the increased pressure, which is favourable for higher rates of heat transfer per unit volume.

According to, Essenbigh(1957) the time required to burn a particle is proportional to the square of its initial diameter. The factor of proportionality depends on the nature of material being burned. By generalisation of the particle size and partial pressure of oxygen, an expression was derived for the reaction rate in the pf flame in terms of oxygen partial pressure. The variable of partial pressure was then compared on basis of: perfect mixing with pre-assigned values of excess air and coal dust density and the average size of all burning particles. All the above facts boil down to the conclusion that any particle of coal will burn out only if enough time is available.

All values obtained from the expressions so developed, can only be verified by actual analytical methods taking into account the important factors that govern particle residence time in the industrial furnace.

2.1.2 Char Combustion

The char combustion is believed to be controlled by the physical and chemical characteristics of char due to very slow kinetics of char combustion compared to devolatilisation. Char reactivity is controlled by the chemical reaction between char and oxygen and/or pore diffusion of gases in and out of char particle. During combustion, oxygen from the reacting gases is transferred to the outer surface of char and also into the internal pores, followed by adsorption, and initiation of carbon oxidation, and subsequent transportation of product gases away from char. As char pores contribute to most of the char surface area and aid inward diffusion of oxygen and outward diffusion of product gases, char porosity is believed to be a rate-controlling step in char combustion. Thus, the char reactivity is dictated by its physical and chemical properties, such as carbon structure, surface area or porosity, and mineral matter, which in turn are closely dependent on coal properties. (Gupta 2005)

2.1.3 Factors Influencing Combustion

According to Falcon (1988) combustion is mainly influenced by intrinsic properties such as the organic and inorganic composition of the coal, its rank, porosity, exposed surface area, moisture content, degree of weathering or heat-effect, state of oxidation, and characteristic initial or ignition temperature, and peak combustion temperature.

The second category, are factors influencing the combustion process in terms of the operating conditions: these include particle size, throughput, environmental temperature, temperature and velocity on the combustion air, the nature of mixing solids and gas, the design and spacing of burners, and the residence time of the combustible particles in the furnace. However, this study does not cover all the all the factors mentioned above, only those that contribute to the prediction indices will be considered.

2.1.3.1 The Role of Volatile Matter in Combustion

According to Pitman (2002), a coal consists of minerals and macerals. Both components react when exposed to high temperatures on entering the boiler. This reaction entails the loss of the volatile components by a process, which is dependent on the nature of the material, the size of the particles, the heat-up rate, the final temperature and duration of exposure to high temperatures.

The volatile constituents can be combustible or incombustible, and obviously this determines whether they contribute to the combustion process or not. It is thus safe to assume that a large portion of organic volatile matter is combustible, and that the inorganic volatile matter is incombustible. The latter volatile component is derived mainly from carbonates (releasing CO_2), pyrite (releasing SO_2) and clays (releasing H_2O).

The organic volatile matter is complex in nature, but mainly consists of light hydrocarbons ranging to tars in the primary stages of ignition. As the coal is heated-up, the nature of the volatile matter changes, due to the increasing availability of energy promoting side reactions, depolymerisation and cracking. Typical products would be CO, CO_2, CH_4 and H_2O.

The incombustible volatile matter is undesirable, and can be in sufficient quantities to quench the ignition process. This type of volatile matter can be quantified by determining the concentrations of the source materials within the coal, e.g. carbonates with ultimate or mineralogical analyses, pyrite and clays with mineralogical analyses.

The heat content of volatile matter represents the heat available to ignite the devolatilised residue, the char. This heat content can be measured by using a drop tube furnace (DTF), which also measures the actual amount of energy required to ignite the char.

However, there are two other methods of measuring the heat content in volatile matter. The Direct Method involves capturing the volatile matter constituents and analysing them and thereafter calculating the mass and weighted heat content. The Indirect Method involves measuring the heat content of coal before charring and the heat value of char then subtracting that of the char.

2.1.3.2 Effect of Carbon Chemistry on Combustion

According to Gupta (2005), the char reactivity relates coal burnout, which is often related to volatile matter and its maceral constituents. Macerals are classified into three main groups, namely liptinite, vitrinite, and inertinite. The relative abundance of these groups is often used to identify the differences in combustion behavior of coals due to their well-known influence on the char physical structure.

According to Falcon (1988), the maceral groups possess different degrees of reactivity (i.e. volatile emission and char reactivity) and rates of oxidisability (adsorption and reaction in the presence of oxygen). Vitrinite both in untreated and in char forms has been found to be readily oxidisable, particularly in low-rank coals. Liptinite, in its natural state, is even more reactive and volatile-rich, is considered to oxidise more rapidly than vitrinite. Inertinite in its natural and charred forms, is less reactive and low in volatile matter (hydrogen in particular), oxidises at a far lower rate, particularly in bituminous coals.

The influences of char morphology, surface area, and bulk porosity on the combustion kinetics and subsequently the final burnout were not covered in this investigation.

2.1.3.3 Effect of Rank on Combustion

The rank refers to the degree of metamorphosis of coal and is determined by vitrinite reflectance. The rank plays a direct role in controlling the ignition and peak combustion temperature of a coal, the rate and degree of devolatilisation, and the reactivity (relative to the carbon dioxide) of the char ultimately produced from a coal. The temperatures, at which these processes occur, increase with increasing rank. (Falcon 1988)

2.1.3.4 Effect of Coal Mineral Content on Combustion

The type, form and distribution of minerals in coal are very important in combustion. Small nodules trapped in the host of organic matter can serve as contaminants or inhibitors in devolatilisation and swelling processes; they can also form globules of slag after melting and coalescing, thus contributing to coarse ash or as small spheres in fly ash. Large nodules and cleats are likely to be liberated more easily and drop out of the combustion zone, thus contributing to bottom ash. (Falcon 1988)

The influence of coal minerals on the combustion behaviour of coals can either be catalytic or inhibitive. Some coals show a significant positive impact of minerals on the combustion performance up to 1450°C, while others show a negative impact. Illite decomposition is believed to promote the char reactivity of bituminous coals at 1200°C, but the char reactivity cannot be conclusively related to the total mineral content of coals. (Gupta 2005)

The inhibitive effect of high-mineral coals is attributed to physical blockage of active char surface area and pores by inert mineral phases such as kaolinite and quartz. The negative influence of silica and alumina phases on the coal-burning rate is also significant, particularly when most of coal silica occurred as quartz and kaolinite. (Gupta 2005)

2.1.4 The Coal Burnout Time and Combustion Efficiency

The burnout time refers to the residence time of a coal particle in a boiler to reach 98% combustion efficiency. There are several ways to improve the combustion efficiency of coal particles within a short residence time in a boiler. For example, combustion efficiency can be controlled by modifying the location and the mode of pf injection, using oxygen-rich or hotter gases as carriers. However, coal properties still have a strong effect on the overall combustion performance.

For example, the vitrinite-rich coal usually has fast burnout times of particulate smaller than 75 µm at 1400°C. On the other hand, an inertinite rich coal has longer burnout times (Pitman 2002).

2.1.5 Combustion Prediction Indices

The prediction of combustion behaviour of coals is more cost effective than the actual experiments in a pilot scale plant, which requires a large quantity of coal and is quite expensive to run. The prediction indices are thus the preferred mode by most power utilities. Most of these indices are related to the nature and characteristics of coals. (Helle, et al, 2001)

The indices to predict the burnout and flame stability rely on standard laboratory analyses of parent coals. They include such indices as the Fuel Ratio, hydrogen/carbon ratio and those that relate to the maceral composition of coal. The indices that are preferably used for ignition and flame stability are those that relate to heating value and volatile matter characteristics. (Helle, et al, 2001)

2.1.5.1 Fuel Ratio and Hydrogen/Carbon Ratio

The Fuel Ratio (FR), which refers to fixed carbon divided by volatile matter, is commonly used as an indicator of the expected combustion performance of coals. Unexpectedly, on some occasion, low volatile matter coal displays a better performance. This unexpected combustion behaviour can be attributed to the organic and inorganic compositions of coal. The role of the carbon structure and minerals during coal combustion is crucial to account for this behaviour. (Gupta 2005)

The FR is also used to indicate the flame stability and the reactivity potential of coal. In theory, a low Fuel Ratio implies high volatile matter content relative to the fixed carbon. As hydrogen is an important carbon based element in the volatile matter, any coal with a low Fuel Ratio should technically have a correspondingly high hydrogen/carbon ratio (H/C). (Van Alphen 2007). A coal with such characteristics may be expected to ignite easily and burn out rapidly.

A deviation from this trend suggests that either the coal characteristics have changed (heat affected or weathered) or the fixed carbon, volatile matter, hydrogen and carbon analyses are incorrect. Alternatively, the proximate volatile matter is not a true indication of organically derived volatile matter, but a mixture of combustible organically derived moisture and incombustible mineral derived volatile matter. The mineral corrected FR and H/C plot could thus be used to predict the reactivity and combustion characteristics of coal. (Van Alphen 2007)

2.1.5.2 Maceral-based Indices

The maceral index, MI, has been recently developed. This index is based on maceral composition, mean vitrinite reflectance and heating value (Su et al: 2001). The maceral index is determined from the expression below:

$$\mathbf{MI = [(L + V/R^2) \div I^{1.25}] \times (CV/30)^{2.5}]} \qquad \mathbf{(2.1)}$$

Where: L = liptinite

V = vitrinite content
I = inertinite
R = mean vitrinite reflectance
CV = heat value in MJ/kg (air-dried)

The coal reactivity index, RI, is also based on the maceral composition and forms part of MI, but excludes the heat value. This index is derived from the following expression:

$$\mathbf{RI = (L + V/R^2) \div I^{1.25}} \qquad \mathbf{(2.2)}$$

Where: L = liptinite
V = vitrinite content
I = inertinite
R = mean vitrinite reflectance

Both expressions are based on trends observed in the burnout of coal as follows:

- The high volatile liptinite burns out rapidly.
- Vitrinite burns out at a rate that depends on its reflectance.
- Inertinite is generally, but not always, difficult to burn.
- Other factors being equal, the burnout depends on the heat release of the coal.

2.2 Specific Aims of the Study

The study aims at relating the prediction indices to the actual combustion performance of both parent coals in the combustion test rig and the chars in the DTF.

The study also aims at using coal petrography and mineralogy to account for anomalies and suggesting other indices that can be used to predict combustion behaviour of coals.

2.3 Hypotheses

The following are hypotheses on which this work is being conducted:

- The Drop Tube Furnace [DTF] can produce reliable data than can be used to validate the combustion prediction indices derived from conventional laboratory analyses.
- The data obtained from petrographic analyses and coal mineralogy can be used to account for coal combustion anomalies.
- The expressions obtained from petrographic analyses can be used as prediction indices for combustion behaviour of coal.

2.4 Key Guiding Questions of the Study

- Are the laboratory analyses reliable as input to predict combustion performance of parent-coal in the combustion test rig? If not, what other factors should be considered for combustion performance of coal?
- Are the indices derived from conventional analyses reliable to predict combustion behaviour of coal (burnout time)?

- What is the relationship between the indices derived from conventional laboratory analyses and the coal petrography?
- Can the indices derived from petrographic analyses predict combustion performance of coal better than the current indices (FR and H/C)?
- Can petrographic analyses and coal mineralogy account for anomalies in combustion performance of coal?

2.5 Variables of the Study

The variables examined included the burnout times of parent-coals in the combustion test rig and chars in the DTF, the H/C, the FR and the maceral derived indices.

3 METHODOLOGY

3.1 The Procedure

The procedure involved:

- Actual coal sampling from different collieries,
- selecting coal samples for the study,
- performing conventional laboratory analyses on the samples,
- charring the selected parent coal samples and combusting the resultant chars in the DTF,
- combustion of the selected parent coal samples in the pilot-scale power plant,
- performing petrographic analysis and
- determining the mineral composition of coal samples.

3.2 Sampling

The coal samples were taken from various collieries belonging to potential suppliers of coal to various power plants. Approximately two ton bulk sample was taken from each source. Mainly manual sampling methods were used to extract a representative sample using ISO 18283:2006 and ISO 13909-4:2001 standards as guidelines.

3.3 Sample Selection for the Investigation

As this investigation formed part of the routine evaluation of potential coal sources, it was difficult to include other coals that were not on the list for pre-qualification process. The selection of the samples was then based on the priority list for pilot scale combustion testing as part of the pre-qualification process. Using this criterion, ten samples were then tested. See Table 3.1

A laboratory test sample was representatively extracted from each bulk sample and the remainder was used for pilot scale combustion test. Each laboratory sample was used for the conventional laboratory analyses, the DTF tests as well as for the petrographic analyses.

Table 3.1 Samples for the study

SAMPLE	DESCRIPTION
Coal A	C-lower product
Coal B	2 seam middlings
Coal C	2 Seam middlings
Coal D	2 seam raw
Coal E	Ultra fines
Coal F	2 seam composite
Coal G	1 seam raw
Coal H	- 40mm product
Coal I	Full 2 seam raw
Coal J	Low volatile coal

3.4 Laboratory Analyses

The analyses were done at the in-house coal laboratory using standard ISO methods. The following analyses were performed on the ten selected samples:

3.4.1 Proximate Analyses

The inherent moisture, also referred as the moisture in the analysis sample, was determined by drying a test sample (-212µm) in an oven at a 105 - 110°C according to ISO 331:1983.

The volatile content was determined by heating a test sample at 900°C (±10°C) at a rate of 100°C/min for 7 minutes exactly in the absence of air as per ISO 562:1981.

The ash content was determined as the residue left after coal test sample was incinerated at 815°C in a ventilated furnace, as per ISO 1171:1997.

The fixed carbon was determined as the difference of 100 minus volatile content, inherent moisture content and ash content. It should be noted that the fixed carbon represents the combustible portion of the coal sample after the inherent moisture content, ash content and volatile matter are removed.

3.4.2 Calorific Value [MJ/kg]

The heat content was determined at a constant volume by burning a known weight of the sample in a bomb calorimeter under conditions of excess oxygen, and measuring the amount of heat that evolved. The value so obtained is normally expressed as the gross calorific value as it includes the latent heat of the water vapour in the products of combustion. In actual operation of the boilers, the water vapor in the combustion gas leaving the boiler is not cooled below its dew point, and therefore, the latent heat is not available for making steam. The latent heat can be subtracted from the gross calorific value to give the net calorific value. (ISO 1928:1995)

3.4.3 Total Moisture [%w/w]

The total moisture content was expressed as the sum of the residual moisture content after air-drying the sample plus the surface moisture content. The surface moisture was determined by the weight loss of a coal sample dried at atmospheric conditions, at 40°C. The residual moisture was determined by the weight loss of the air-dried sample subjected to 105°C until constant mass.(ISO 589:2003)

3.4.4 Total Sulphur [%w/w]

A high temperature combustion method was used, where a test sample was burnt in oxygen at 1200°C; the resultant sulphur oxides and chlorine were absorbed in hydrogen peroxide. The instrument, CS500, Sulphur and Carbon analyser operated according to ASTM D4329 method was used. The analyser is capable of doing the chlorine correction automatically.

3.4.5 Ultimate Analysis

The carbon and hydrogen were determined simultaneously, according to ISO 609:1975 and 625:1975. This involves the conversion of carbon to carbon dioxide by burning approximately 500 mg of a test sample in an oxygen stream. Chlorine and sulphur oxides are removed by hot silver gauze and water by magnesium chlorate. The resultant carbon dioxide is collected by absorption on soda asbestos or soda lime and the carbon content is obtained by calculation.

The weight of water collected by magnesium chlorate represents the hydrogen content of the coal plus the inherent moisture content present in the air-dried sample. The inherent moisture content has already been determined in the proximate analysis; thus the hydrogen content can be obtained.

For the nitrogen content, a coal sample was heated with concentrated sulfuric acid in the presence of a suitable catalyst, in accordance with ISO 332:1981 and 333:1983. This process destroys the organic material and converts the nitrogen to ammonium sulphate. Ammonia is then released by steam distillation, absorbed in boric acid solution and titrated directly with 0,1N sulfuric acid.

The oxygen content is calculated as the balance in the organic coal structure, after carbon (C), hydrogen (H), nitrogen (N_2), sulphur (S), inherent moisture content (M), ash content (A) and assuming that the organic chlorine (Cl) is 50% of the total chlorine content, have been accounted for, that is:
$O_2 = 100 - (M + A + C + H_2 + N_2 + S + 0{,}5Cl)$

3.4.6 Ash Elemental Oxides

The laboratory used the instrumental method, atomic absorption spectrophotometry, to analyse for the major oxides in the ash. This technique measures elements after they have been brought into solution. The solution is aspirated into a flame placed in the light path of emission from a hollow cathode lamp made of the element to be measured. The changes in the energy level of the beam are cause by atom of the element in the flame. These changes are measured and converted into concentration of the elements being measured. (ASTM D3682)

3.5 Petrographic Analysis

The petrographic analysis of coal was done microscopically by a registered ICCP accredited Petrographer, Dr NJ Wagner.

The samples were set in cold mount epoxy resin, ground and polished according to ISO 7404-2. The vitrinite reflectance analysis was carried out according to ISO 7404-5 on a mean random basis.

Maceral group, microlithotype group and mineral group analysis were undertaken to obtain an indication of the organic and inorganic matter components; that is the macerals and mineral matter, and their relationship (conducted according to ISO 7404-3 and 4 and the current South African analytical methods).

The abnormal condition analysis was included to provide an indication as to the condition of the coals and to determine any unusual features such as extensive fissuring and cracking, pseudo-vitrinite, heat effect and porous particles. (Wagner 2007 article in International Journal Coal Geology)

3.6 Drop Tube Furnace [DTF]

The DTF was used for both charring of the parent coal and the actual char combustion. The parent coal sample was first ground to fineness of less than 75µm.

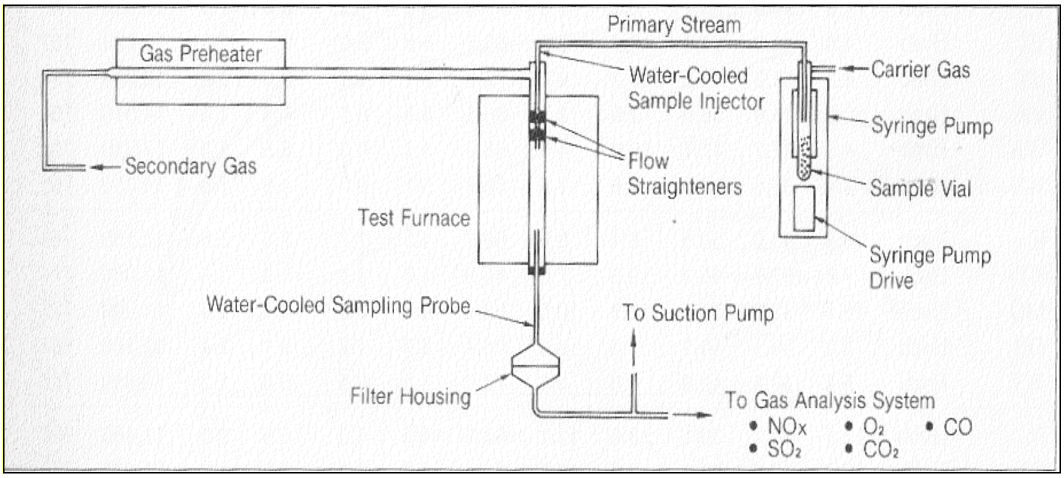


Figure 3.1 Schematic drawing of a DTF (Eskom GLP Course)

The charring was done by driving off the volatile matter of the -75µm sample at 1400°C in a nitrogen atmosphere under heating rates similar to those experienced in a pulverised coal fired boiler. The char was sampled at the exit of the furnace and the portion thereof was subjected to normal laboratory analysis. From this test the high temperature volatile matter content was determined, as well as the heat in the volatile matter.

Thereafter, the char sample was combusted in the DTF at temperatures (1000°C, 1200°C and 1400°C) in an oxidizing atmosphere of approximately 3% O_2. The products from the char combustion were sampled on a time basis and the results were plotted in a curve indicating the combustion efficiency against time in seconds. This test was repeated for the three temperatures, viz. 1000°C, 1200°C and 1400°C. Only 1400°C test results were considered for this study.

3.7 Pilot Scale Combustion Test rig

The pilot scale combustion test rig is a tool normally used for testing flame behavior, flame shape, flame length and slagging/fouling behaviour of the ash within the combustion environment. These tests can be performed with different pf sizes, different pf feed rates and under different excess air conditions.

For this study the Test rig was used to measure the burnout times of the parent-coal samples and flue gas temperatures at 98% combustion efficiency. All samples used for this study were ground to ±70% less than 75µm.

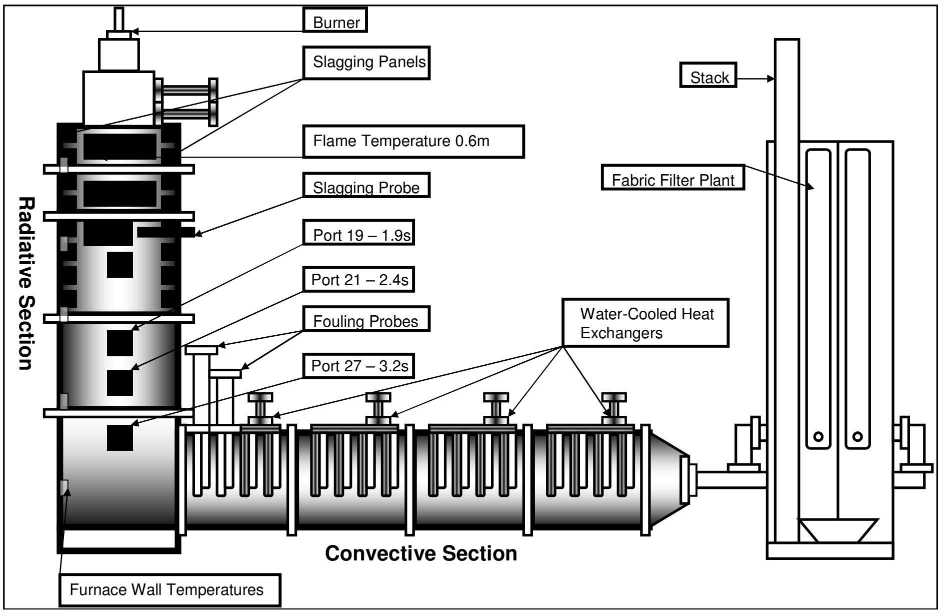


Figure 3.2 Pilot Scale Test rig (Rajoo 2007)

3.8 Coal Mineralogy

Mineral proportions were based on the AA ash elemental proportions, total sulphur and ash %. A model was used through the assistance of Dr Chris Van Alphen, which assumes that each common coal mineral has a unique elemental composition. It assigns specific elements to specific minerals and determines the mass %. To determine the K-bearing minerals, it assumes that the ratio of microcline: muscovite/illite is 50:50. The total sulphur is used to determine the proportion of pyrite. The remaining Fe is used to determine the proportion of siderite.

The model also determines the proportion of mineral derived volatiles and uses this value to determine ash %. Included in the model are additional parameters which are used to check the validity of the analysis. The CO_2 and Calorific Value are other examples of what may also be predicted with this model (Van Alphen 2007).

4. RESULTS

All results are tabulated in Appendices A to C.

4.1 Proximate analyses and the Fuel Ratios (FR)

The volatile matter contents of the ten coals varied from 17.7% to 23.2%, being typical of current power station supplies. The proximate FR (fixed carbon ÷ volatile matter) varied from 1.92 to 3.10.

Table 4.1 Proximate analysis and the Fuel Ratios

Sample	**Proximate Analyses (air-dry basis)**				**Active Volatile Matter % (OVMad)**	**Proximate FR**	**Active FR**
	Analytical Moisture %	Ash Content %	Volatile Matter %	Fixed Carbon %			
Coal A	2.4	30.2	21.3	46.1	18.1	2.16	2.54
Coal B	3.2	26.9	21.1	48.8	18.6	2.31	2.62
Coal C	1.7	29.8	21.6	46.9	18.8	2.17	2.50
Coal D	4.1	25.5	21.9	48.5	19.4	2.21	2.50
Coal E	2.2	32.2	22.5	43.1	19.5	1.92	2.21
Coal F	1.9	24.1	21.4	52.6	18.9	2.46	2.79
Coal G	3.1	28.3	20.8	47.8	18.2	2.30	2.63
Coal H	2.8	28.0	23.2	46.0	20.5	1.98	2.24
Coal I	1.2	34.3	20.1	44.4	16.4	2.21	2.71
Coal J	3.3	24.1	17.7	54.9	15.2	3.10	3.61

The active volatile matter (**OVM_{ad}**) refers to organic volatile calculated using the Parr formula 1 (Esterhuizen 2002).See below.

$$OVM_{ad} = 100 - (M_{ad} + MM_{ad} + FC_{ad}) \qquad (1)$$

Where: OVM_{ad} = air-dry % organic volatile matter
M_{ad} = air-dry % moisture content
MM_{ad} = air-dry % mineral matter content
FC_{ad} = air-dry % fixed carbon content

The mineral matter content was calculated using the following formula 2 (Esterhuizen 2002).

$$\mathbf{MM_{ad} = 1.08\ A_{ad} + 0.55\ TS_{ad}} \qquad (2)$$

Where: MM_{ad} = air-dry % mineral matter content

A_{ad} = air-dry % ash content

TS_{ad} = air-dry % total sulphur content

The last column in the Table 4.1 shows active FR (fixed carbon / active volatile matter) of the coal samples. Comparison between the FR using conventional proximate analyses and active FR using only the combustible volatile matter shows differences in some samples, for example coal A, E and J. All others are relatively similar and change proportionately. The active FR results are shown to be higher in all instances than proximate-based FR. This is because the incombustible volatiles have been removed in the active FR results thereby increasing the FR proportionately. This in turn implies lower capacity to combust than may be expected using the proximate FR.

4.2 Ultimate analyses and Hydrogen/Carbon Ratios (H/C)

The ultimate analyses performed on the coal sample showed a narrow range for both carbon and hydrogen. The H/C varied from 0.0433 to 0.0655.

Table 4.2 Ultimate analyses and H/C

Sample	**Ultimate Analyses (Air-dried basis)**		
	Carbon[%]	Hydrogen[%]	H/C
Coal A	54.69	3.02	0.0552
Coal B	56.68	2.67	0.0471
Coal C	55.19	3.12	0.0565
Coal D	55.09	2.91	0.0528
Coal E	52.97	3.47	0.0655
Coal F	59.23	3.07	0.0518
Coal G	53.98	2.34	0.0433
Coal H	53.60	2.32	0.0433
Coal I	51.35	2.68	0.0522
Coal J	52.89	2.93	0.0554

Table 4.2 above contains the Carbon and Hydrogen values of the ten parent coal samples performed on air-dried test samples. The last column on the right shows the H/C of all samples.

4.3 Drop Tube Furnace Results and the Fuel Ratios

The Table 4.3 below shows high temperature [1400°C] volatile matter obtained from five samples tested in the DTF.

The five samples were chosen based on the following:

- Coals C and F had nearly same volatile matter content (21,6% and 21.4% respectively), but huge difference in ash content (29.8% and 24.1% respectively)

- Coal H had highest volatile matter content (23.2%) and the longer residence time (burnout time) in the test rig of 1.55 seconds.
- Coals I and J showed low volatile content (20.1% and 17.7% respectively), but better burnout times in the test of 1.20 sec and 0.75 sec respectively.

The mineral volatiles were based on the mineral proportions, as explained in section 3.8 of this report. The values thereof are given in Table 4.3.

The combustible volatiles (DTF volatile matter minus mineral volatile matter), varied from 17.77% to 23.73% and the corresponding Fuel Ratios varied from 2.35 to 3.18.

Table 4.3 DTF Results and the Fuel Ratios (C, F, H, I, J)

Parameters	**Unit**	**Coal C**	**Coal F**	**Coal H**	**Coal I**	**Coal J**
Volatiles by DTF(VM_{DTF})	%	30.50	27.50	29.60	23.20	27.20
Mineral Volatiles	%	7.26	6.77	6.82	5.43	4.10
Combustible Organic Volatiles	%	23.73	20.73	22.78	17.77	23.11
Fixed Carbon (DTF)	%	54.70	65.99	59.70	54.70	56.40
Fuel Ratio (using combustible volatiles)		2.35	3.18	2.62	3.08	2.44
BURNOUT TIME	**Sec**	**1.4**	**1.7**	**1.6**	**1.7**	**1.5**

4.4 Pilot Scale Combustion Results

The Figures 4.1 and 4.2 below show the combustion profiles of the coal samples used in the investigation. The solid line-curves in Figures 4.1 and 4.2 show combustion profiles obtained in the test rig during the combustion of the parent coal samples. The dotted lined-curves show the flue gas temperatures measured in the test rig during the combustion process.

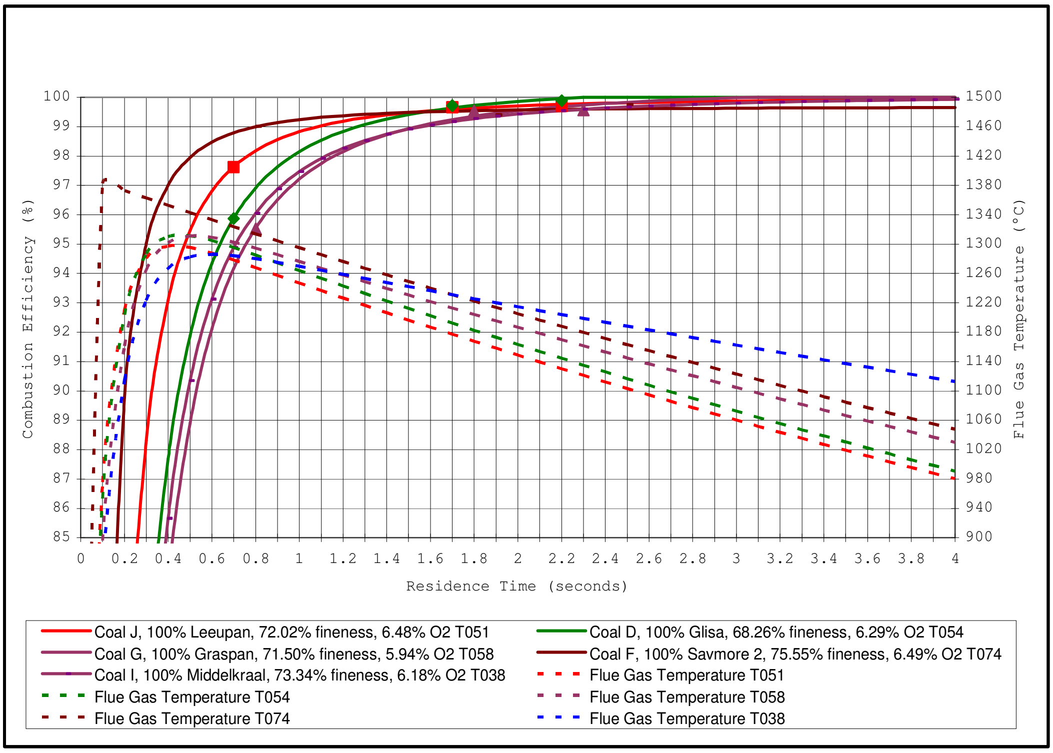


Figure 4.1 Test rig Profiles for Coal D, F, G, I and J (Rajoo 2007)

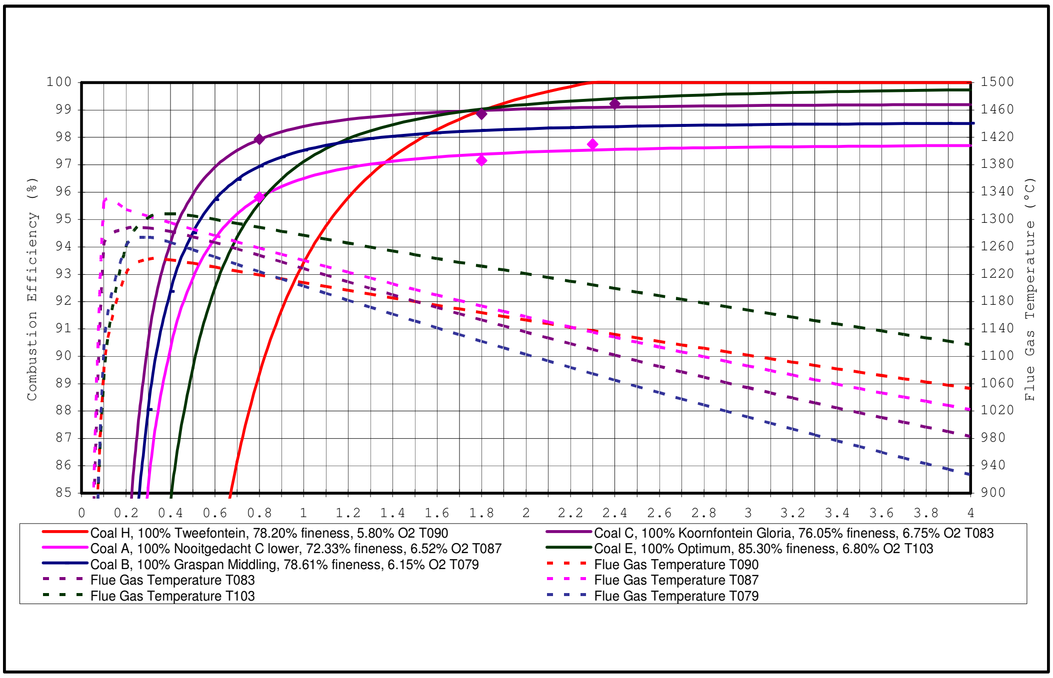


Figure 4.2 Test rig Profiles for Coal A, B, C, E and H (Rajoo 2007)

The results showed that it was difficult to keep the combustion parameters constant for all samples during the combustion tests in test rig. This was evident by the fact that the excess oxygen in the results ranged from 5.8% to 6.8% and the flue gas temperatures varied from <1020°C to 1340°C. The burnout times varied from 0.6 to more than 4 seconds (Table 4.4). It should be noted that coal A never reached 98% carbon burnout, and therefore a comparison of burnout times to that level of completeness between coal A and other coal samples was not possible. For this reason coal A was in all further comparisons.

Table 4.4 Combustion Results from the Test rig

Sample	**Burnout Time (sec)**	**Flue gas Temperature (°C)**	**Excess O_2 (%)**	**Fineness % - 75µm**
Coal A	>4.00	<1020	6.52	72.23
Coal B	1.50	1140	6.15	78.60
Coal C	0.80	1250	6.75	76.05
Coal D	0.95	1230	6.29	68.26
Coal E	1.20	1260	6.80	85.30
Coal F	0.60	1340	6.49	75.55
Coal G	1.15	1260	5.94	71.50
Coal H	1.55	1180	5.80	78.20
Coal I	1.20	1220	6.18	73.34
Coal J	0.75	1270	6.49	72.02

Table 4.4 above shows the results of the combustion tests of the parent-coal samples in the test rig. The values listed in the table were obtained from Figures 4.1 and 4.2 above.

4.5 Petrographic Analysis Results

The detailed results are tabulated in Appendix C, tables C1 - C5.

Coal A was heat affected and some particles showed devolatilisation with high reflectance of vitrinite (RoV), maximum of 2.5%. It also showed the highest vitrinite content of 52.0% for all ten coals.

Coal B showed lots of liptinite associated with inertodetrinite.

Coal C showed unusual clay / quartz minerals and pyrite primarily in vitrinite.

Coal D showed very rich liptinite particles and high proportion of fissuring in inertodetrinite particles with carbonate nodules; this was associated with possible in-situ weathering.

Coal E showed high proportions of fines and few heat affected particles. The range of RoV (0.56 -1.31%) extended into the coking range, i.e. mid - Bituminous. It also showed high vitrinite content of 42.2%.

Coal H showed high oxidation, 9.2%, in the form of discolouration. This was not typical of a run of mine coal stockpile. This is true because the sample originated from a processed discard dump. It also showed some fresh coal particles, possibly due to the blending material used to upgrade the dump coal to meet the power station specification. Some particle were intensely weathered, possibly those which were exposed in the dump stockpile for quite sometime. Unusual minerals were observed in some of the particles, possibly related to those from the old heat affected dump.

Coal I showed in-seam devolatilisation, hence relatively low volatile matter content of 20.1% (air-dried). It also showed pores, cavities and cracks in-filled with pyrite, some of which were partially leached out resulting in mineral alteration, which is indicative of stockpiling.

Coal J showed a wide range of reflectance values which proved that the coal had been heat affected (29.6% by volume) to a considerable extent and was highly cracked and fractured, probably related to weathering. It showed the highest quartz and clays, 89.2%. See detailed results in Appendix C.

4.6 Coal Mineralogy

Coal E showed the highest illite content of 1.99% followed by Coal J with 1.90%. Coal J showed the lowest content of kaolinite content of 12.59%. The quartz content was the highest in Coal A. Coal D showed the highest mineral volatile of 7.33%, while coal J was the lowest with 4.10%. Table 4.5 shows the detailed results.

Table 4.5 Mineral proportions in coal samples

Mineral	Coal A	Coal B	Coal C	Coal D	Coal E	Coal F	Coal G	Coal H	Coal I	Coal J
Pyrite(S) (%)	1.30	1.12	0.99	1.55	1.46	2.56	1.29	2.01	2.07	1.12
Calcite (%)	0.27	2.90	2.06	3.10	1.15	4.07	2.17	3.31	0.00	0.92
Dolomite (%)	0.60	2.67	3.32	3.49	1.89	2.00	2.06	1.36	0.54	1.17
Apatite (%)	0.04	0.21	0.94	0.17	0.37	0.41	0.06	0.79	0.31	0.10
Microcline (%)	0.93	0.27	0.46	0.42	1.29	0.53	0.28	0.38	1.20	1.24
Illite (%)	1.39	0.40	0.69	0.63	1.99	0.84	0.41	0.59	1.82	1.90
Kaolinite (%)	16.74	21.18	27.03	22.15	21.08	14.28	20.20	23.57	28.69	12.59
Quartz (%)	11.51	4.33	6.91	1.14	7.20	7.61	7.11	2.58	2.71	8.63
Siderite (%)	0.15	0.69	0.12	0.75	2.22	1.19	1.04	0.00	0.00	1.70
Rutile (%)	0.35	0.48	0.61	0.53	0.51	0.29	0.46	0.50	0.72	0.28
Coal (%)	66.73	65.74	56.87	66.07	60.85	66.20	64.91	64.90	62.26	70.34
Mineral matter (%)	33.27	34.26	43.13	33.92	39.15	33.80	35.08	35.09	37.73	29.66
Mineral volatiles (%)	3.57	6.47	7.26	7.33	6.22	6.77	5.88	6.82	5.43	4.10
Ash (%) calculated	29.70	27.79	35.87	26.59	32.92	27.02	29.21	28.27	32.30	25.56

Illite decomposition is believed to promote the char reactivity of bituminous coals at 1200°C, but the char reactivity cannot be conclusively related to the total mineral content of coals.

The inhibitive effect of high-minerals is attributed to physical blockage of active char surface area and pores by inert mineral phases such as kaolinite and quartz. The negative influence of silica and alumina phases on the coal-burning rate is also significant, particularly when most of coal silica occurred as quartz and kaolinite.

5. DISCUSSION AND INTERPRETATION

5.1 Burnout versus Combustion Conditions in the Test rig

When excluding Coal A (burnout of more than 4 seconds), the results showed a linear correlation (R^2) between excess oxygen and the burnout times of 0.67 as determined in the test rig, see Figure 5.1. There was also a strong linear correlation (R^2) between flue gas temperature and the burnout times of 0.80 (Figure 5.2). However, there was no relationship between the fineness of the sample and the burnout times.

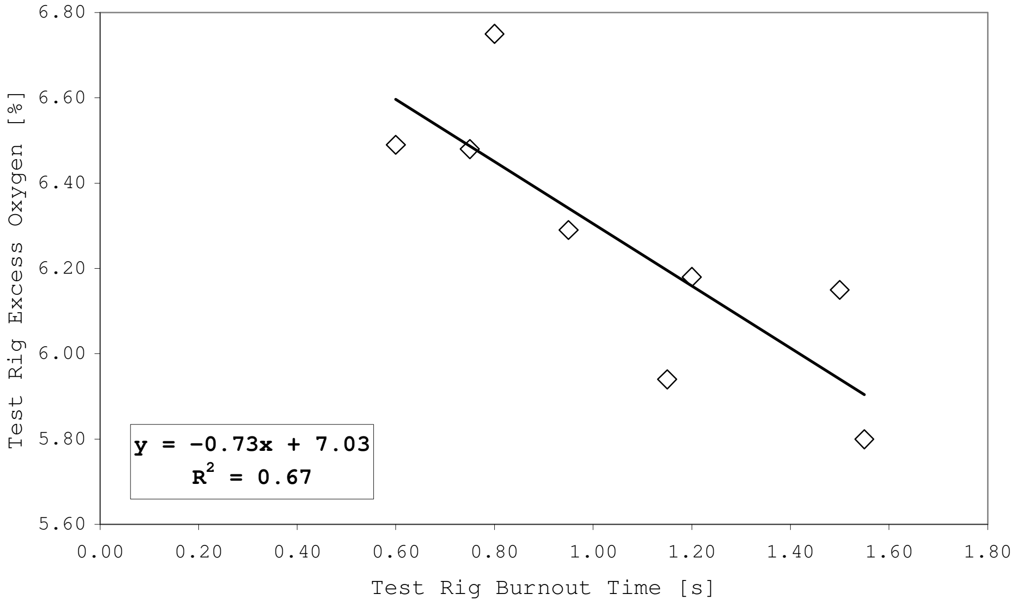


Figure 5.1 Relationship between Excess O_2 and burnout times determined in the test rig

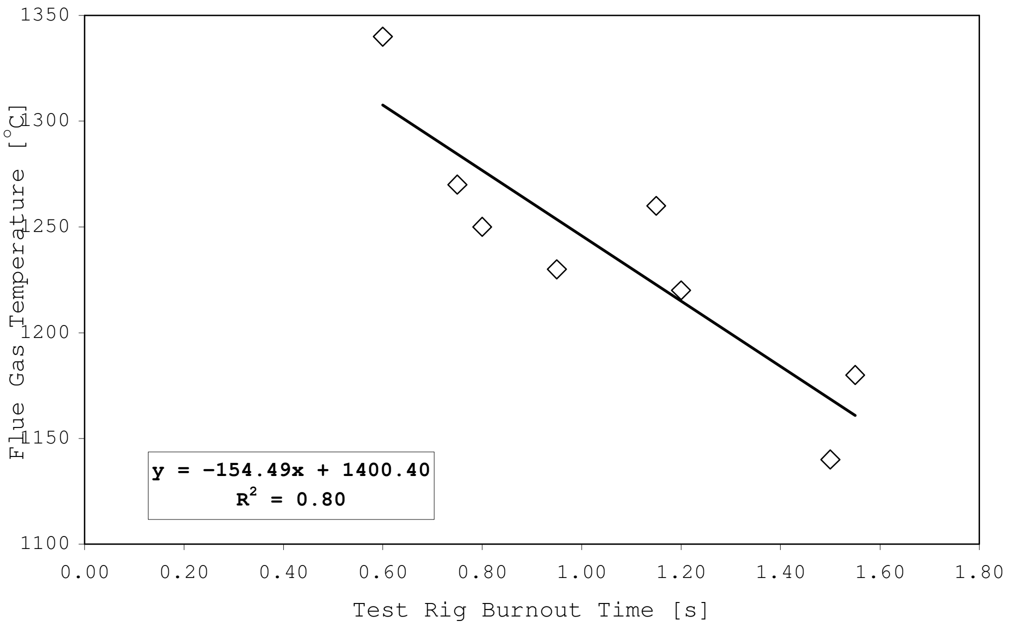


Figure 5.2 Relationship between Flue gas Temperature and Burnout time determined in the test rig

5.2 The Hydrogen/Carbon Ratio versus Fuel Ratio Plot

Figure 5.3 below illustrates the Hydrogen/Carbon ratio (H/C) versus the active Fuel Ratio (FR), using combustible volatile matter for all samples under investigation.

For coal to exhibit the ideal test rig burnout time, i.e. less than two seconds, it must lie in the top left quadrant, as established by Eskom research (Rajoo, pers. comm.) This means that the H/C must be more than 0.052 and the active FR must be less than 2.30. The least acceptable coals would fall in positions where FR is greater than 2.30 and H/C less than 0.52.

The results in Figure 5.3 indicate that all but two coals fall out of the acceptable FR range (apart from coals H and E) and five fall below the acceptable H/C range, although some coals fall near the boundaries of both FR and H/C. Coal J appears to be the least acceptable coal of all in terms of FR and coal H, G and B in terms of H/C. The only acceptable coal appears to be coal E.

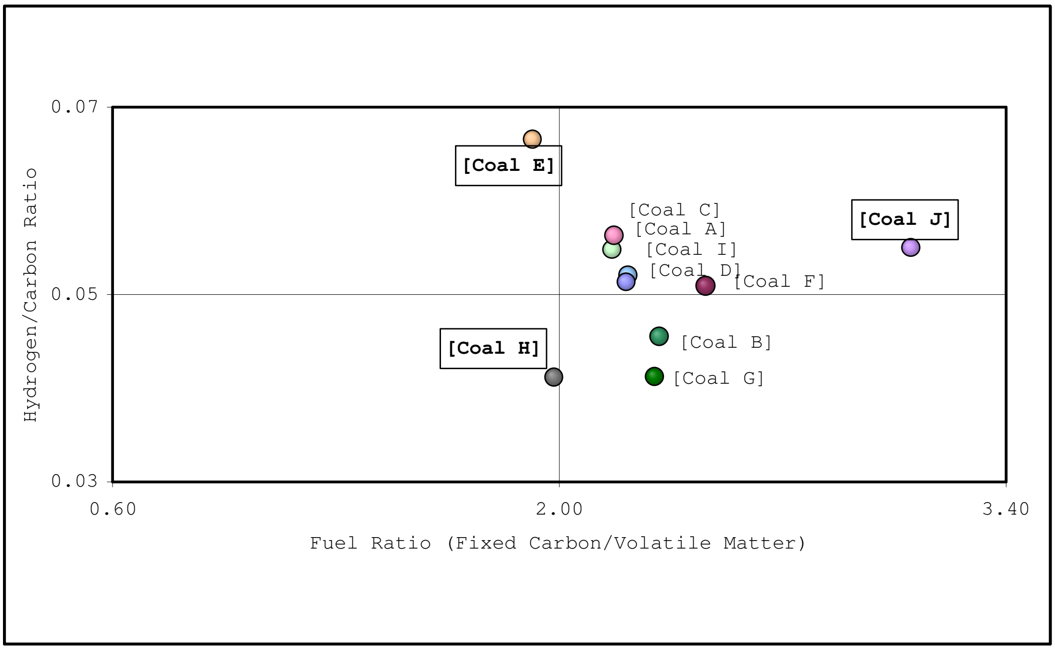


Figure 5.3 Hydrogen/Carbon Ratios versus Fuel Ratios Plot

The worst performing coal in terms of proven burnout time in the test rig was Coal A, with burnout time of more than 4 seconds in the test rig, but this coal was found to lie borderline and moderately acceptable among reasonable performing coals in Figure 5.3 above. The long burnout time for coal A was investigated and the petrographic results indicated that a fair proportion of the coaly material was heat affected and some particles showed devolatilisation. This was not shown by conventional chemical laboratory analyses.

Coal A was out performed by both Coal B and Coal G in the test rig, i.e. coals B and G burnt out more quickly, although these two coals were predicted to be the worst performing according to FR and H/C. Coal B and Coal G showed test rig burnout times of 1.50 and 1.15 seconds respectively.

Coal E was predicted to be the best in terms of FR and H/C, but was out performed by Coal F in the test rig burnout test. However coal F was predicted in terms of FR and H/C to be more difficult to combust than coal E. The burnout times for coals E and F were 1.22 seconds and 0.60 seconds respectively.

Coal H with an acceptable FR of 1.98 (Table 4.1) and less than acceptable H/C of 0.0433 (Table 4.2) was anomalous in that it was one of the longest burning coals with the test rig burnout of 1.55 seconds (Table 4.4). The petrographic analyses indicated that this coal was largely oxidised.

Coal J with the highest and least acceptable FR of 3.10, was found to be anomalous in that it was the second best combusting coal in terms of the test rig burnout, with a time of 0.75 second.

5.3 The Burnout Time versus Hydrogen/Carbon Ratio

The test rig burnout times of the samples were plotted against their respective H/C ratios. There was a very weak correlation between the two variables, $R^2 = 0.16$. Figure 5.4 below shows a plot of test rig burnout time versus H/C of samples, excluding Coal A.

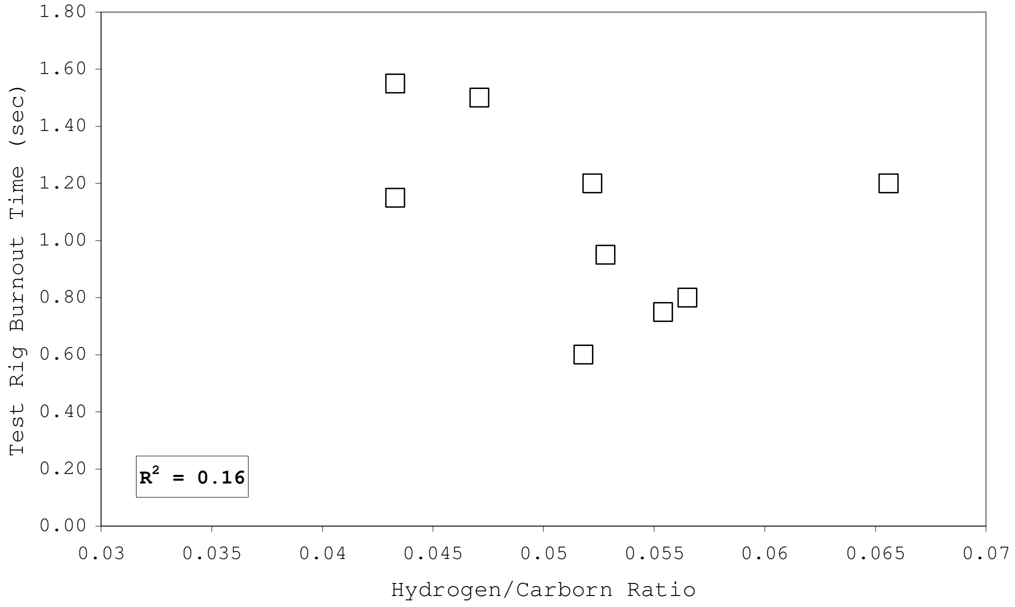


Figure 5.4 Test rig Burnout times versus Hydrogen/Carbon

5.4 The Burnout Times versus Fuel Ratios

The test rig burnout times of the parent coal samples were plotted against the Fuel Ratios derived from proximate analysis as determined by conventional laboratory analyses and corrected for mineral matter. There was no significant correlation between the two variables, $R^2 = 0.30$. Figure 5.5 below shows a plot of Test rig burnout times versus the Fuel Ratios of samples, excluding coal A whose burnout time could not be determined in the test rig.

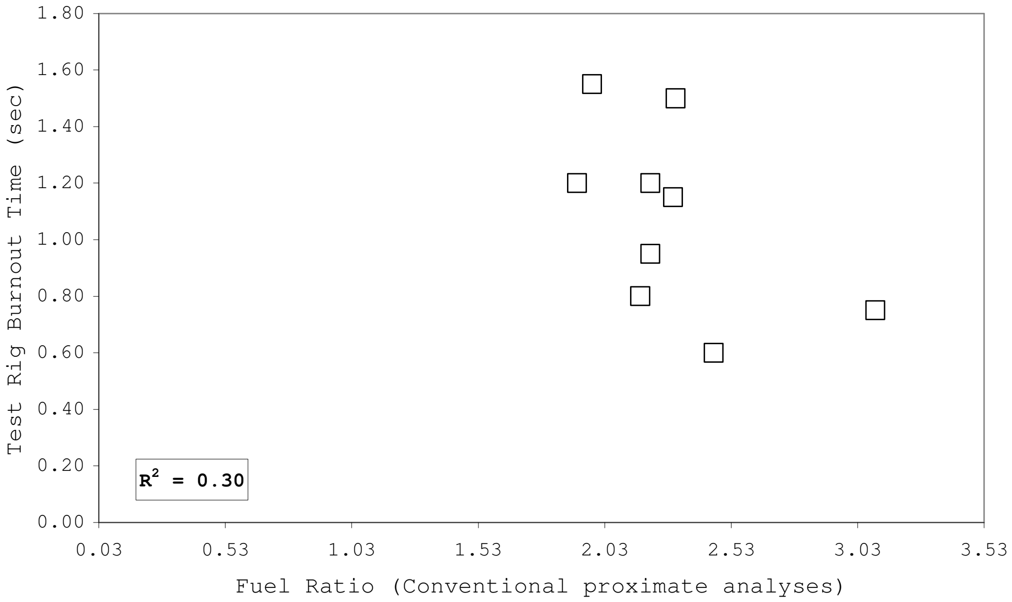


Figure 5.5 Burnout times versus FR from proximate analysis

The weak correlation displayed above can be attributed to the difference in temperature at which the variables are determined. The proximate analyses, on which the Fuel Ratio is based, are determined at temperatures less than 1000°C. The burnout is determined at temperatures higher than 1000°C, under boiler combustion conditions.

When comparing the test rig burnout time and FR using DTF proximate volatiles corrected for mineral matter, the five coals that had been tested by the DTF test also showed poor correlation, R = 0.002, see Figure 5.6. These results collectively indicate that neither forms of FR relate to the burnout in the test rig.

There was, however, a clear linear correlation of 0.89 between the Fuel Ratios based on the proximate analyses taken from the DTF results and the char burnout times for the five coals tested in the DTF. The volatile matter used was corrected for mineral volatiles and only combustible volatile matter was considered in this case, see Figure 5.7 below.

The results indicate a linear relationship, showing that the higher the combustible volatiles (mineral matter free volatiles) as determined in the DTF, the shorter the burnout time of the char. This relationship was not clear when using conventional proximate analyses for the FR (R^2 = 0.0085).

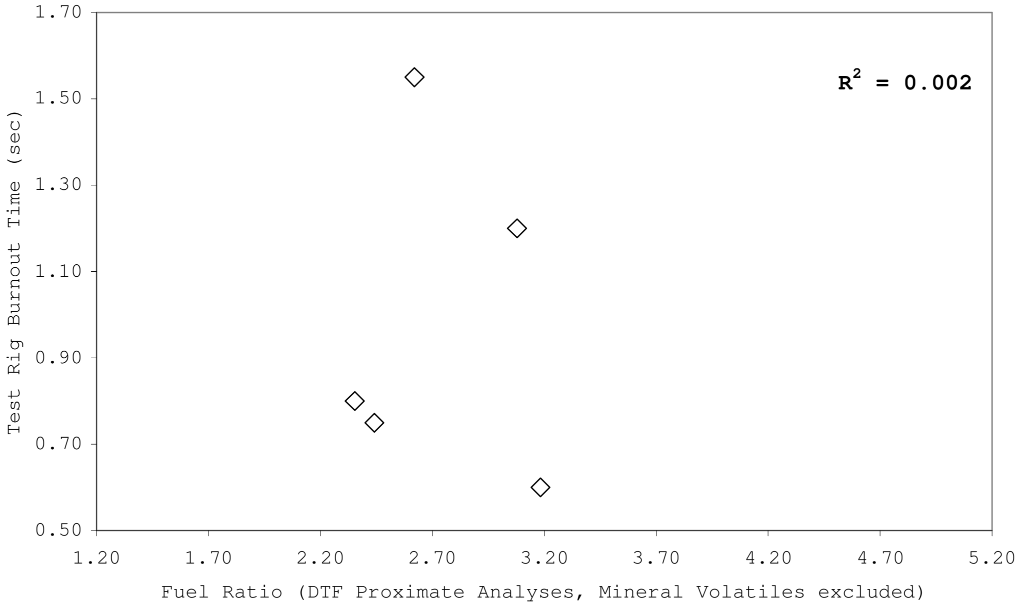


Figure 5.6 Test rig coal burnout times versus Fuel Ratios

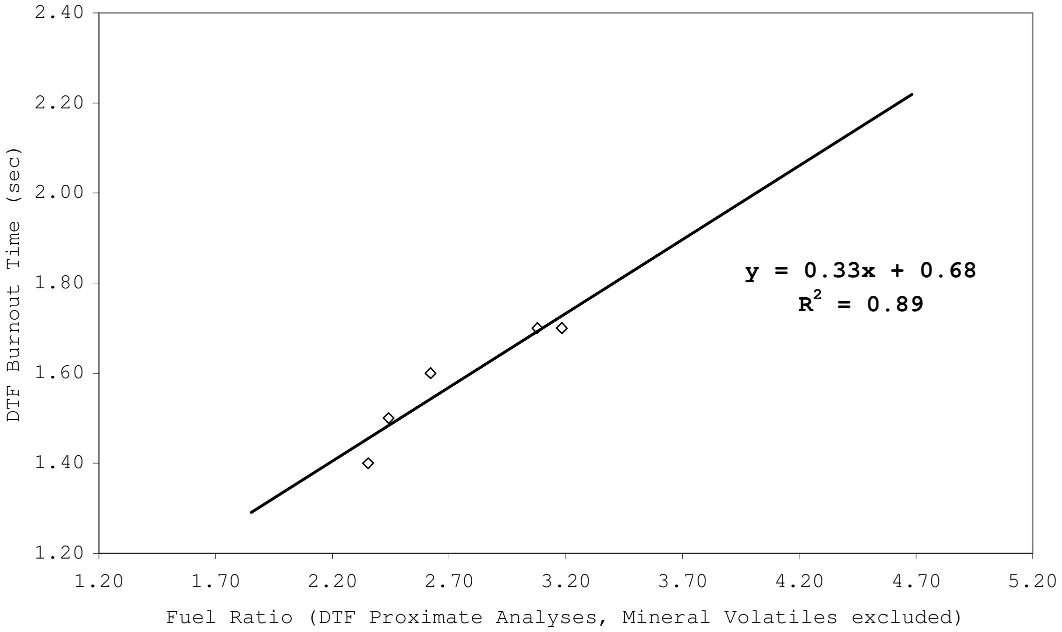


Figure 5.7 DTF Char burnout times versus Fuel Ratios

The difference in correlations between using conventional and DTF proximate analyses when calculating the FR in the relationships discussed above is due to the fact that the volatile matter of proximate analysis was determined at 900°C and that of DTF at 1400°C.

It should be noted that the volatile matter as determined during proximate analysis does not represent the actual volatile matter released under boiler conditions, where the actual temperature reaches 1600°C at rates of 10000°C/second. The proximate analysis only measures the low temperature volatile matter at 900°C that cannot be related to the actual coal combustion under boiler conditions at high temperatures.

5.5 Relationship between Fuel Ratio and Coal Petrography

The total reactives from the parent coal petrographic analyses were plotted against the FR derived from conventional proximate analysis. There was no significant correlation between the two variables (R^2 = 0.20), see Figure 5.8 below.

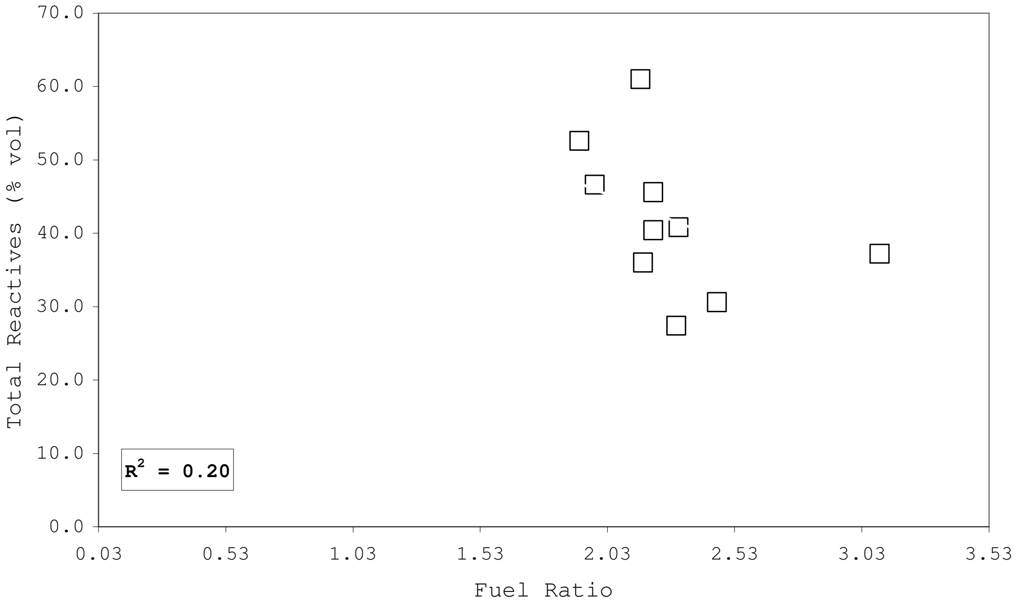


Figure 5.8 Total Reactives versus Fuel Ratio of parent coal

5.6 Relationship between H/C Ratio and Coal Petrography

The total reactives from the parent coal petrographic analyses were plotted against the H/C derived from ultimate analysis. There no significant correlation between the two variables (R^2 = 0.18), see Figure 5.9 below.

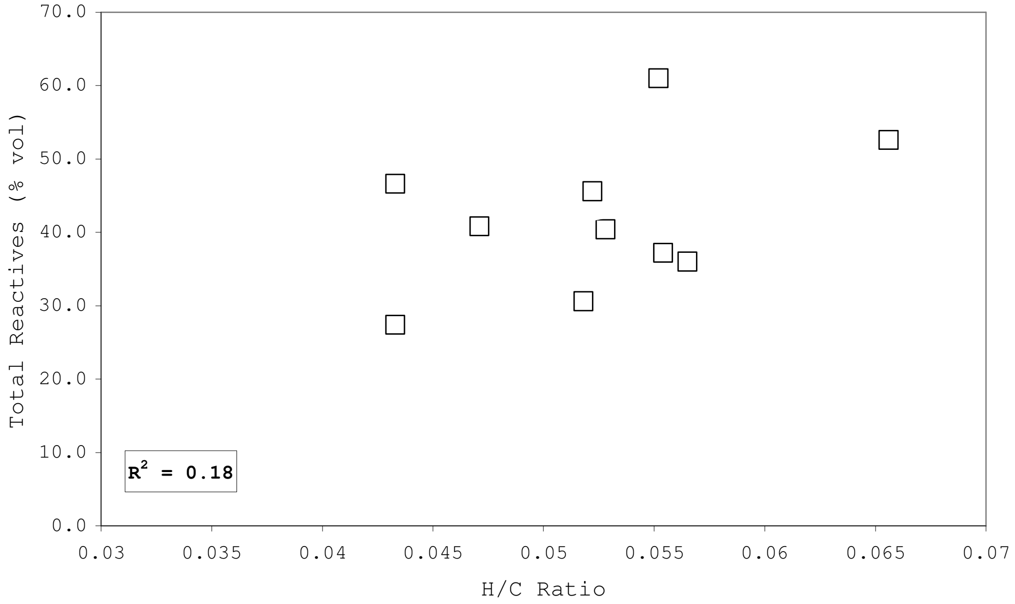


Figure 5.9 Total Reactives versus H/C of parent coal

5.8 Relationship between Test Rig Burnout, Coal Petrography and Other Indices

The burnout times of all parent-coal samples in the test rig were correlated with petrographic analyses and maceral-based indices, see Table 5.1 and Figures 5.10 - 5.12 below.

In all relationships, significant correlations were found with one exception, namely, results relating to coal A. A careful investigation of the nature of coal A was undertaken. The results indicated that coal A had the highest vitrinite content (52.0%), i.e. the highest proportion of reactive maceral component, but exhibited an unexpectedly long burnout time of more than 4 seconds. On investigation it was established that the vitrinite reflectance analysis showed the highest standard deviation of 0.529 and a range of vitrinite reflectance values from 0.59 - 2.5%. These results indicate that coal A was heat affected and partly burnt and hence disregarded for further discussion as it is an extremely anomalous sample taking well beyond the acceptable 2 seconds burnout for Eskom requirements.

Table 5.1 Test rig Burnout times, Vitrinite and Indices

Sample	Burnout Time (sec)	Vitrinite Content (%)	RoVmr (%)	Std Dev RoVmr%	Reactivity Index (RI)	Maceral Index (MI)
Coal A	>4.0	52.0	0.93	0.529	0.648	0.232
Coal B	1.50	7.8	0.67	0.069	0.090	0.039
Coal C	0.80	13.0	0.74	0.079	0.130	0.056
Coal D	0.95	12.2	0.71	0.083	0.120	0.048
Coal E	1.20	42.2	0.82	0.109	0.139	0.231
Coal F	0.60	13.8	0.72	0.094	0.107	0.067
Coal G	1.15	11.4	0.69	0.089	0.097	0.051
Coal H	1.55	17.2	0.73	0.093	0.603	0.056
Coal I	1.20	11.4	0.73	0.152	0.144	0.037
Coal J	0.75	11.2	0.87	0.382	0.076	0.028

The test rig burnout times of the parent coal samples were plotted against the vitrinite content, see Figure 5.9 below. There was a strong linear correlation (R^2) of 0.91 between burnout time and vitrinite content, except for Coal E, Coal H and Coal J, which were moderately anomalous (within the Eskom acceptable 2 seconds). The burnout times of these coals were not commensurate with their vitrinite contents as illustrated in Figure 5.10; the detailed discussion is covered in section 5.8 of this report.

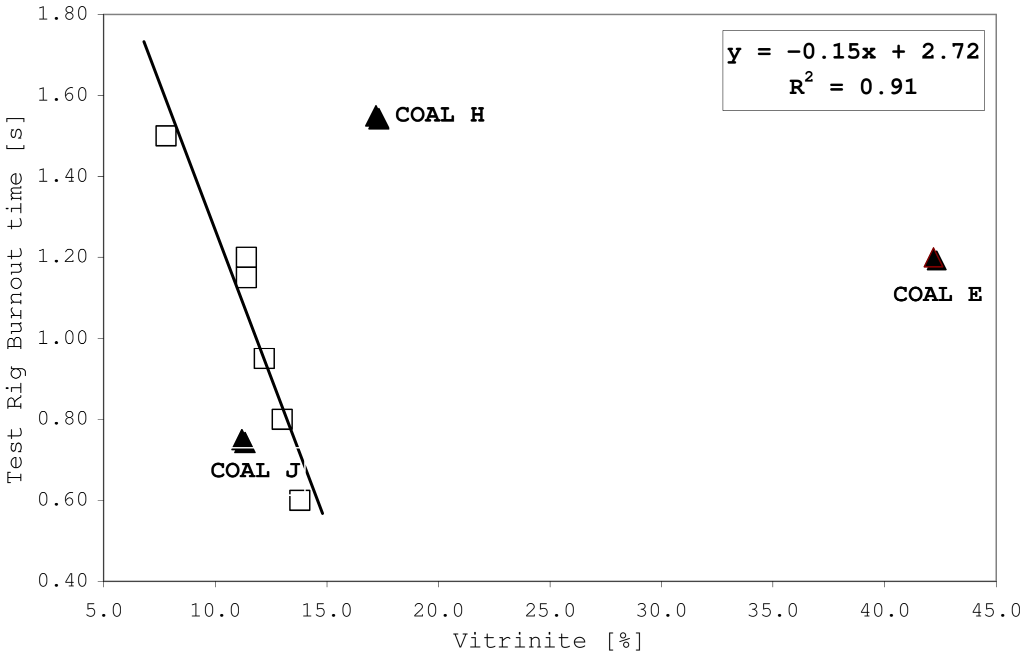


Figure 5.10 Burnout time of parent coal versus Vitrinite

The plot of the combustion test rig burnout times of parent coal samples against the Reactivity Index (RI) showed a strong linear correlation (R^2) of 0.96. This was realized when Coal E, Coal H and Coal J were excluded. Figure 5.11 below, shows the above relationship and the anomalies (covered in section 5.9) in terms of the behaviour of the three coal samples, i.e. Coal E, Coal H and Coal J.

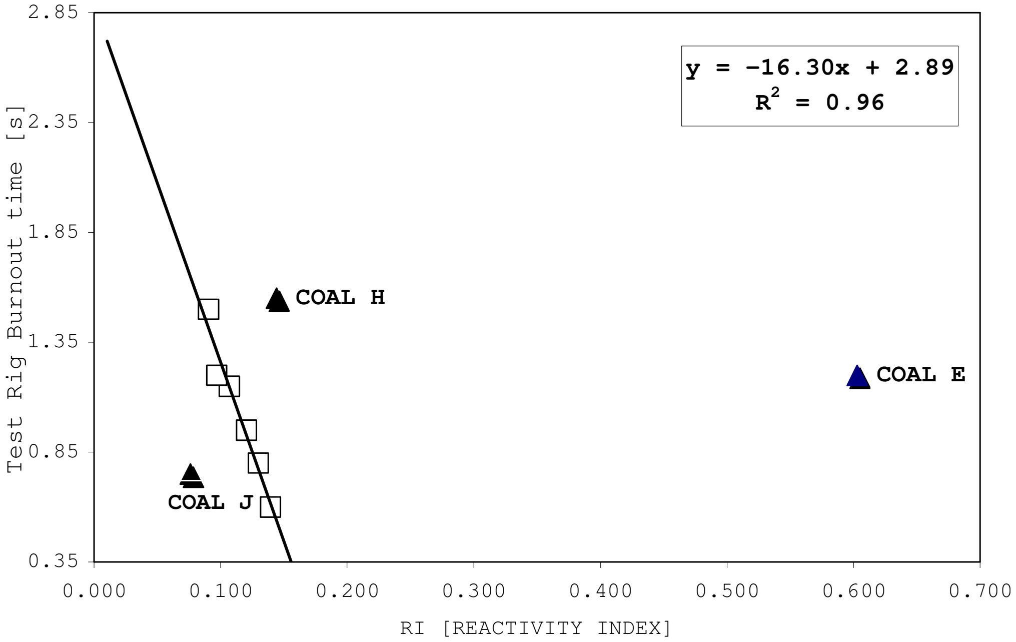


Figure 5.11 Burnout time of parent coal versus RI

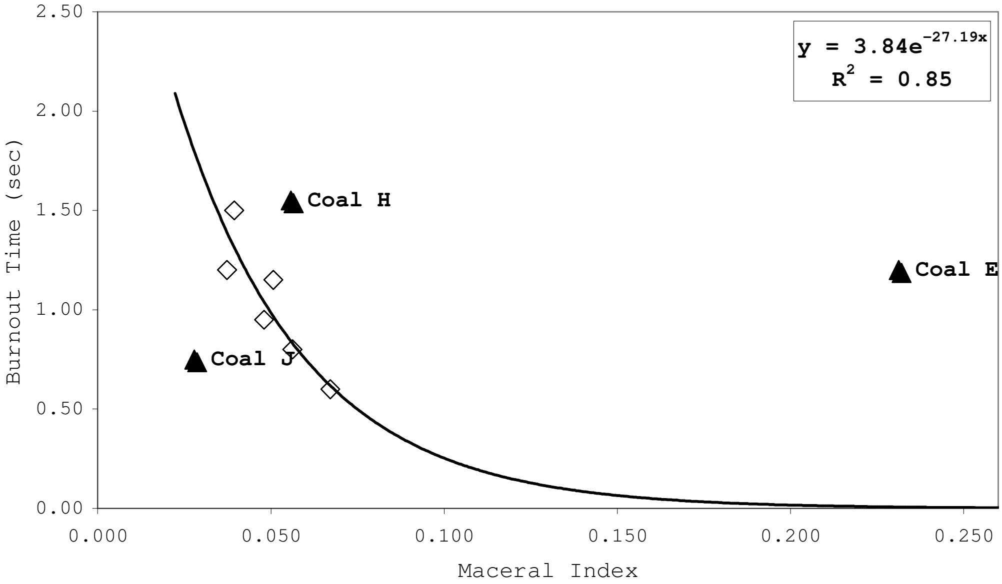


Figure 5.12 Burnout time of parent coal versus Maceral Index

The burnout times of the parent coal samples in the test rig were further plotted against the Maceral Index (MI) of respective coal samples. It was found that there was a strong exponential correlation of 0.85. This was also realized when Coal E, Coal H and Coal J were excluded. Figure 5.12 above shows the relationship between burnout times of parent coal samples and the Maceral Index values.

5.8 Comparison between Test rig and Drop Tube Furnace

Both the combustion test rig and the Drop Tube Furnace (DTF) were used for combustion behaviour. The test rig was used for parent coal samples. The DTF was used for both charring and char combustion. The important parameter for the study was the burnout time of samples in both instruments. Only five samples were tested in both instruments, as discussed in section 4.3 of this work, see Table 5.2 and Figure 5.13 below.

Table 5.2 Comparison between Test rig and DTF results

SAMPLE	**Burnout (sec)**	
	Test Rig	**DTF**
Coal C	0.80	1.40
Coal F	0.60	1.70
Coal H	1.55	1.60
Coal I	1.20	1.70
Coal J	0.75	1.50

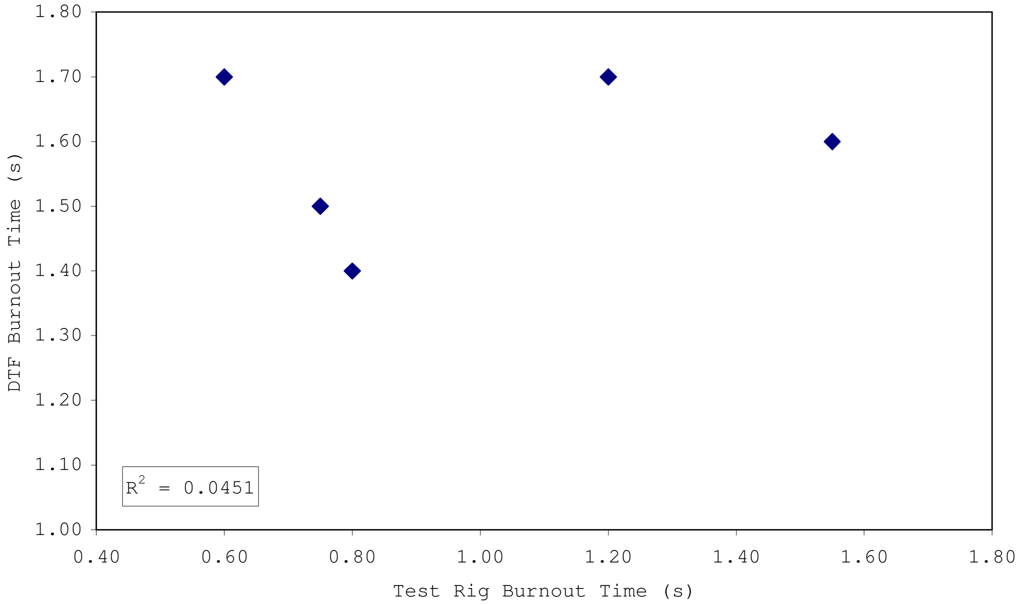


Figure 5.13 Comparison between Test rig and DTF results

The results above show that the parent coal samples in the combustion test rig had shorter burnout as compared to their respective chars in the DTF. This can be partly attributed to the following:

- The difference in the stoichiometric air. In case of the DTF, it is in the order of 300-600%, and in the test rig it is in the order of 20-30%. The DTF deliberately combusts above stoichiometric requirements to avoid diffusion control in the combustion process.
- The presence of the high temperature volatile matter in the parent coal particle, which was not the case with the char particles in the DTF. The heat content of the volatile matter emanating from the devolatilisation of the parent coal particle helps in the ignition process. This in turn shortens the burnout time.

- The charring process, which the coals undergo prior to testing in the DTF, induces significant changes in the molecular structure of the chars relative to the original raw coal, may well be partly responsible for the differences in burnout performance between the two combustion test processes.
- The differences in load, residence time and rate of heating between the two test procedures may also contribute to some extent to the differences in combustion behaviour, but these factors are not considered to be significant as optimum combustion conditions were encountered in all combustion tests.

The DTF was mainly used for charring and measuring high temperature volatile matter, which was of great benefit to this study. The combustion test rig was used to test combustion behaviour on large quantity of samples, which also benefited the study.

5.9 Anomalies in the Results

The anomalies shown by the Coal E, Coal H and Coal J are explained below and their results are in Table 5.3 below.

Table 5.3 Analyses of Coal E, Coal H and Coal J

Measured Parameter	**Unit**	**Coal E**	**Coal H**	**Coal J**
Test rig Burnout	**sec**	**1.20**	**1.55**	**0.75**
Volatile Matter(air-dry)	%	22.5	23.2	17.4
Ash (air-dry)	%	32.2	28.0	30.4
Mineral Volatile (air-dry)	%	6.22	6.82	4.10
Vitrinite Content	%	42.2	17.2	11.2
Total Reactives	%	52.6	46.6	37.2
Total Inerts	%	47.4	53.4	62.2
Reflectance of Vitrinite	RoVmr%	0.82	0.73	0.87
Standard Deviation	RoVmr%	0.109	0.093	0.382
RoVmr% Range Minimum	%	0.56	0.55	0.50
Maximum	%	1.31	1.04	2.20
Total Cracks and Fissures	%	5.0	20.4	17.4
Heat Affected	%	1.0	1.6	29.6
Discolouration	%	2.6	9.2	0.2
Total Abnormal Condition	%	12.2	36.8	55.6

COAL E

The relatively slow burnout time of Coal E (1.20 seconds) in the combustion test rig was not commensurate with the high vitrinite content of 42.2% and the volatile matter of 22.5%. The full survey of the analytical results indicated that Coal E, apart from having the highest proportion of -75micron fines in the feed sample (85.3%), see Figure 5.13 below, the lowest abrasive Index (22mgFe), the highest Hardgrove Grindability Index (67) and possessing a significant proportion of weathered and oxidised particles, most notably exhibits a range of rank that extends from Sub-bituminous into the Mid Bituminous coking range of rank (0.5 to 1.3 RoVmr%), see Figure 5.14.

This evidence indicates (a) that the coals which fall normally in the Low Rank Bituminous C range, have been heated relatively significantly and (b) most importantly, have passed into the range in which vitrinite macerals become “cokified”. This infers that the vitrinite in the higher ranking coking range would soften, swell, become porous, fuse with other particles and then harden. During this process the texture of the walls of the gas pores become semi-crystalline developing mosaic structures (a form of semi-graphitisation) on exposure to high temperatures

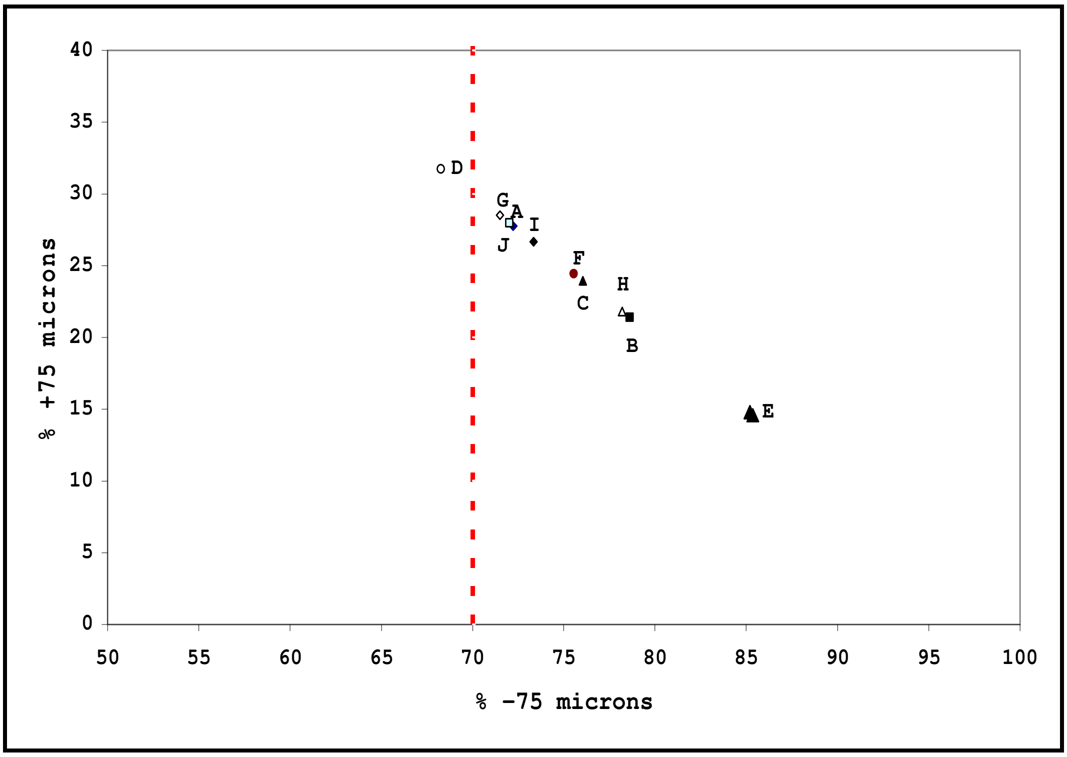
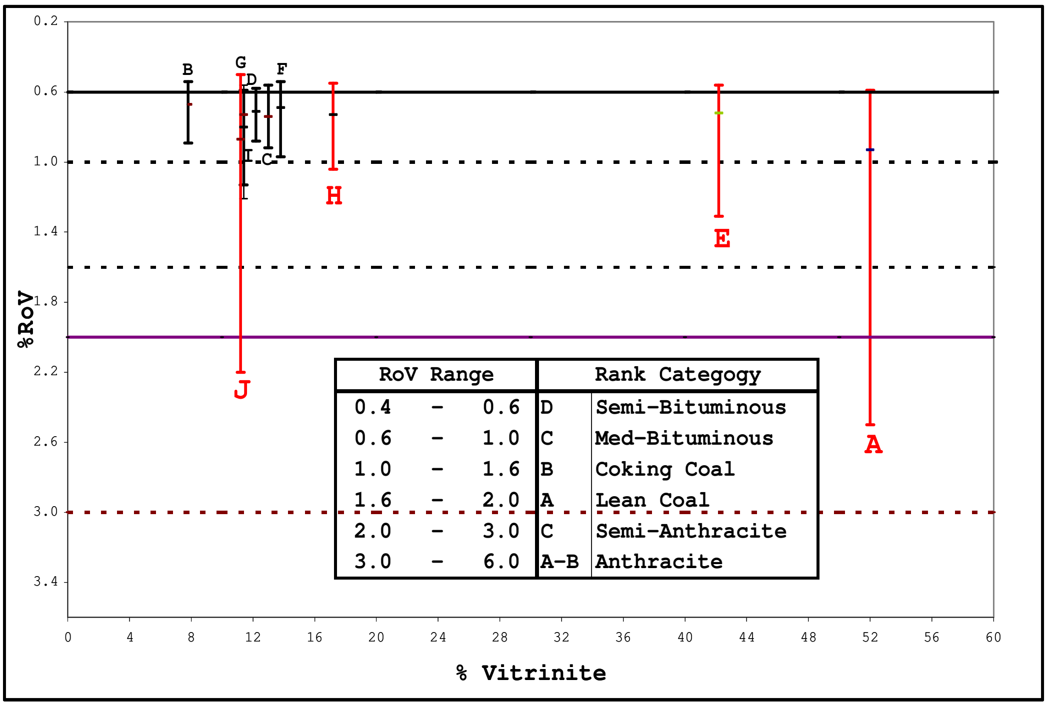


Figure 5.14 Fineness of the parent sample % +75µm versus % -75µm



RoV Range			Rank Categogy
0.4 - 0.6	D	Semi-Bituminous
0.6 - 1.0	C	Med-Bituminous
1.0 - 1.6	B	Coking Coal
1.6 - 2.0	A	Lean Coal
2.0 - 3.0	C	Semi-Anthracite
3.0 - 6.0	A-B	Anthracite

Figure 5.15 RoVmr% versus Vitrinite content

Thus, due to the high vitrinite content and extended rank into the coking range, it has been concluded that a significant proportion of the coaly material has become “cokified” and semi-graphitised. Such material, which is normally highly reactive to combustion in the presence of oxygen at lower temperatures, becomes inert above a specific temperature after undergoing severe molecular re-ordering and resolidification. This unusual condition, in addition to the presence of oxidised materials in this coal, is considered to be responsible for the anomalously long burnout time of a supposedly reactive coal.

COAL H

Coal H exhibited a longer burnout time of 1.55 seconds. This has been attributed to the fact that this coal has a significant quantity of long-term weathered and oxidised material as indicated by the highest proportion of discoloured coaly particles (9.2%) along with the relatively high cracking and fissuring (20.6%) that arises with weathering. This is commensurate with the fact that this sample was derived from an old stockpile. The long burnout time of this coal is considered to be due to the presence of weathered material which gives rise to limited volatile release, slow ignition and slower rates of combustion. This situation can also be attributed in part to the higher incombustible mineral volatiles, 6.82%.

COAL J

Coal J possessed the shortest burnout time in the combustion test rig (0.75 seconds)but it also possessed, by far the highest proportion of coaly material exhibiting abnormal conditions (55.6% compared to the next highest value, 37% in sample H) of which 29.6% was heat-affected and 17.4% cracked and fissured and possibly desiccated. This sample also possessed a low vitrinite content (11.2%) and Maceral Index, the lowest volatile matter content (17.7%) based on proximate analyses) and the widest range of vitrinite reflectance (0.5 to 2.2 RoVr%) thereby confirming the extensive levels to which the coal had been heat affected.

The unexpectedly fast burnout time of what would otherwise have been considered a relatively slow burning, difficult to ignite coal appears, in this case, can be attributed to the combustion response of the extensively heat-affected, desiccated and cracked material to the high temperature exposure in the combustion test rig. Thermal shock is therefore considered to have taken place, namely, material such as that described above has been known to explode and shatter into smaller particles when exposed to instant high temperatures. The result is the provision of small particles with higher surface areas which leads to rapid and efficient combustion. This process has been identified in other similar South African coals as reported by Falcon (1992). This has been termed ‘deflagration’. The presence of the highest flue gas temperature by this coal further confirms the presence of high rank (burnt) coals.

5.10 Summary of the Findings

The summary of the results with respect to correlations and relationships between the various parameters is presented in Table 5.4.

The results indicated that the strongest linear relationship (R^2) exists between the burnout times of the coal samples in the combustion test rig and two of the petrographic related indices, viz. Reactivity Index (0.96) and Vitrinite% (0.91). The Maceral Index showed a strong exponential relationship with R^2 of 0.85.

In addition there was a strong linear relationship between the burnout times in the combustion test rig and (i) flue gas temperatures (0.80) and (ii) excess oxygen (0.67). The latter indicates that the longer the burnout time the higher the flue gas temperature and greater the excess oxygen required for combustion.

However, there was no clear relationship between the burnout in the combustion test rig and the Fuel Ratio and H/C ratio (0.30 and 0.16 respectively).

In terms of burnout times of the chars in the ***drop tube furnace***, the only significant relationship was found to be with the Fuel Ratio but only when using the high temperature volatile matter content derived from devolatilisation of the coals to char in the drop tube furnace. The correlation factor here was found to be 0.89. No other clear correlations were found with DTF burnout times. There was no correlation between DTF burnout time of char and the test rig burnout times of the coals tested in the test rig.

Table 5.4 Summary of the Findings

Relationship of Index and Combustion	**Relationship Type**	**Correlation R^2**
Excess O_2 versus parent coal burnout (Test rig)	Linear	0.67
Flue gas temperature versus parent coal burnout(Test rig)	Linear	0.80
Parent coal burnout versus Hydrogen/Carbon ratio (Test rig)	Linear	0.16
Total Reactives versus Hydrogen/Carbon ratio	Linear	0.18
Parent coal burnout versus Fuel Ratio (Test rig)	Linear	0.30
Total Reactive versus Fuel Ratio	Linear	0.20
Char burnout versus DTF mineral corrected Fuel Ratio (DTF)	**Linear**	**0.89**
Parent coal burnout versus % Vitrinite (Test rig)	**Linear**	**0.91**
Parent coal burnout versus Reactivity index (Test rig)	**Linear**	**0.96**
Parent coal burnout versus Maceral index (Test rig)	**Exponential**	**0.85**

In summary, the ***Fuel and H/C ratios*** were found to have no clear relationships either with the burnout times of the coals in the combustion test rig or with the burnout times of the chars in the DTF, except when high temperature volatiles were used in the calculation of the Fuel Ratio in the DTF burnout assessment. There is also no clear relationship between the fuel and H/C ratios and any of the other analytical or test parameters. By way of example, the correlation index, R^2, between the Fuel Ratio and the total reactives is 0.20 and that of H/C and the total reactives is 0.18.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of Conclusions

Based on the findings of the current research, the following conclusions could be drawn:

1. The **H/C ratio** cannot be applied with any degree of confidence as a predictive tool for estimating the burnout times of coals or chars when tested both in the combustion test rig and in the drop tube furnace.

2. The **Fuel Ratio** has no application as a predictive tool when testing coals in the combustion test rig and limited application when used in the drop tube furnace, and then only when using the specific high temperature volatiles such as those derived in the drop tube furnace.

3. The **strong relationship between the petrographic indices** and burnout in the combustion test rig would appear to indicate that petrography is a far more useful tool for predicting the burnout propensity of coal, but this does not appear to be possible when applied to chars tested in the drop tube.

These observations indicate that, despite the fact that the same feed coals (and therefore the same petrographic parameters) are used in both the combustion test rig and the drop tube furnace for each paired tests, the **combustion burnout times are**

significantly different. There is not even a common trend.

It is beyond the scope of this Research Report to establish the reasons for these outcomes, however the following concepts are put forward for further research. For example, it is suggested that the charring process which the coals undergo prior to testing in the drop tube furnace induces significant changes in the molecular structure of the chars relative to the original raw coal. This may well be partly responsible for the differences in burnout performance between the two combustion test processes. The differences in load, residence time and rate of heating between the two test procedures may also contribute to some extent to the differences in combustion behaviour, but these factors are not considered to be significant as optimum combustion conditions were encountered in all combustion tests in the test rig.

The results of this work therefore indicate that coal combustion performance in the combustion test rig is most closely correlated to the petrographic parameters, i.e. vitrinite content, Maceral Index (MI) and Reactivity Index (RI), except when coals are oxidised, burnt, high ash or liable to potential deflagration due to incipient cracking in the original coal.

The conventional laboratory analyses, and the Fuel Ratio (FR) and Hydrogen to Carbon Ratio (H/C) derived from them, cannot be correlated with coal combustion performance in either the DTF or the large scale combustion test rig.

Furthermore, the burnout results of the chars tested in the DTF cannot be correlated with the burnout results of the normal parent coals obtained in the combustion test rig. This is considered to be due to the differences in sample preparation prior to testing and to variations in combustion conditions between the two test units.

6.2 Recommendations

Arising from this research, the following recommendations are made:

- A study should be conducted to determine how mineral associations in South African coals influence their combustion characteristics. (catalytical and inhibitive effects of minerals on combustion)
- A further investigation into the influence of char morphology on combustion should also be conducted.

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APPENDIX A DTF ANALYTICAL RESULTS

Table B1 DTF and Laboratory Proximate Analyses

Parameter	Unit	Char proximate analysis (on air-dried basis)	Original proximate analysis (on air-dried basis)
Coal C			
Moisture	%	1.7	0.1
Ash content	%	29.8	45.1
Volatile Matter	%	21.6	0.1
Fixed Carbon	%	46.9	54.7
Coal F			
Moisture	%	1.9	0.2
Ash content	%	24.1	33.8
Volatile Matter	%	20.4	0.01
Fixed Carbon	%	53.6	65.99
Coal H			
Moisture	%	2.8	0.1
Ash content	%	28.0	40.9
Volatile Matter	%	23.2	0.01
Fixed Carbon	%	46.0	59.7
Coal I			
Moisture	%	1.2	0.01
Ash Content	%	34.3	45.3
Volatile Matter	%	17.4	0.01
Fixed Carbon	%	47.1	54.7
Coal J			
Moisture	%	3.3	0.2
Ash content	%	30.4	43.1
Volatile Matter	%	20.1	0.5
Fixed Carbon	%	46.2	56.4

APPENDIX B CONVENTIONAL LABORATORY RESULTS

Table B1 Proximate Analyses (air dried, % by mass)

SAMPLE	UNIT	A	B	C	D	E	F	G	H	I	J
Inherent Moisture	%	2.4	3.2	1.7	4.1	2.2	1.9	3.1	2.8	1.2	3.3
Ash	%	30.2	26.9	29.8	25.5	32.2	24.1	28.3	28.0	34.3	24.1
Volatile Matter	%	21.3	21.1	21.6	21.9	22.5	21.4	20.8	23.2	20.1	17.7
Fixed Carbon	%	46.1	48.8	46.9	48.5	43.1	52.6	47.8	46.0	44.4	54.9
FC/VM		**2.16**	**2.31**	**2.17**	**2.21**	**1.92**	**2.46**	**2.30**	**1.98**	**2.21**	**3.10**

Table B2 Ultimate Analyses (air dried, % by mass)

SAMPLE	UNIT	A	B	C	D	E	F	G	H	I	J
Carbon	%	54.69	56.68	55.19	55.09	52.97	59.23	53.98	53.60	51.35	52.89
Hydrogen	%	3.02	2.67	3.12	2.91	3.47	3.07	2.34	2.32	2.68	2.93
Nitrogen	%	1.47	1.20	1.24	1.31	1.24	1.46	1.05	1.14	1.16	1.29
Total Sulphur	%	1.40	0.59	0.80	0.82	0.76	1.12	0.68	0.76	1.74	1.06
Carbonate (as CO_2)	%	0.01	3.17	2.21	3.63	1.94	2.05	2.27	1.50	0.14	0.94
Oxygen	%	6.82	5.58	2.94	6.64	5.22	7.07	8.28	9.61	7.43	7.19
Hydrogen / Carbon		**0.0552**	**0.0471**	**0.0565**	**0.0528**	**0.0655**	**0.0518**	**0.0433**	**0.0433**	**0.0522**	**0.0554**

Table B3 Physical Analyses

SAMPLE	UNIT	A	B	C	D	E	F	G	H	I	J
Abrasiveness Index	mg Fe	772	208	215	164	22	251	410	238	115	246
Hardgrove Index		59	54	61	64	67	61	51	64	55	63
Gross C V (air dried)	MJ/kg	21.36	21.85	21.44	20.77	20.45	23.05	20.44	20.52	20.49	20.09
Total Mositure	%	5.60	4.40	6.30	7.40	4.50	4.50	4.50	9.10	7.90	7.80

Table B4 Ash Elementals (air dried)

SAMPLE	UNIT	A	B	C	D	E	F	G	H	I	J
Silicon - SiO_2	%	61.20	50.00	54.20	43.70	53.30	48.30	57.00	44.20	53.60	52.00
Aluminium - Al_2O_3	%	28.30	29.50	29.50	33.30	26.00	19.70	27.50	30.10	37.20	35.80
Iron - Fe_2O_3	%	5.70	4.20	2.00	5.70	7.00	9.40	5.30	4.20	4.20	3.50
Titanium - TiO_2	%	1.10	1.70	1.70	2.00	1.50	1.00	1.60	1.70	2.30	1.90
Phosphorus - P_2O_5	%	0.08	0.31	1.06	0.26	0.43	0.69	0.09	1.04	0.40	0.58
Calcium - CaO	%	0.50	8.00	6.40	9.50	3.50	10.50	5.70	8.10	0.30	3.30
Magnesium - MgO	%	0.60	2.80	2.70	3.90	1.60	2.00	2.10	1.30	0.50	0.90
Sodium - Na_2O	%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Potassium - K_2O	%	1.40	0.30	0.40	0.50	1.20	0.50	0.30	0.40	1.20	1.00
Sulphur - SO_3	%	0.40	2.30	2.10	2.60	2.80	6.80	2.40	7.10	0.30	3.00
Manganese MnO	%	0.01	0.03	0.02	0.06	0.06	0.05	0.05	0.04	0.01	0.02

APPENDIX C PETROGRAPHIC ANALYTICAL RESULTS

TABLE C1 MACERAL GROUP ANALYSES (% by vol.mineral matter free)

SAMPLE	A	B	C	D	E	F	G	H	I	J
VITRINITE	**52.0**	**7.8**	**13.0**	**12.2**	**42.2**	**13.8**	**11.4**	**17.2**	**11.4**	**11.2**
LIPTINITE	**3.0**	**5.6**	**7.2**	**5.6**	**4.8**	**5.0**	**8.0**	**2.4**	**3.6**	**4.6**
INERTINITE										
Reactive semi-fusinite	2.4	9.2	9.4	7.6	4.6	6.6	3.4	8.6	8.8	8.0
Inert semi-fusinite	25.0	34.4	42.6	32.4	34.2	40.8	55.0	32.0	29.4	40.4
Fusinite	2.0	3.6	3.4	3.4	6.0	0.6	1.6	5.2	2.2	3.2
Micrinite	0.4	0.8	2.0	0.6	1.4	2.4	1.2	1.4	0.8	0.6
Reactive inertodetrinite	3.6	18.2	6.4	15.0	1.0	5.2	4.6	18.4	21.8	13.4
Inert inertodetrinite	11.6	20.4	15.6	23.2	5.8	25.6	14.8	14.8	22.0	18.6
Total Inert Inertinite	**39.0**	**59.2**	**64.0**	**59.6**	**47.4**	**69.6**	**72.6**	**53.4**	**54.4**	**62.8**
Total Reactives	**61.0**	**40.8**	**36.0**	**40.4**	**52.6**	**30.6**	**27.4**	**46.6**	**45.6**	**37.2**
Total Reactive Inertinite	**6.0**	**27.4**	**16.2**	**22.6**	**5.8**	**11.8**	**8.0**	**27.0**	**30.6**	**21.4**

TABLE C2 MICROLITHOTYPE GROUP ANALYSIS (% by vol. organic & inorganic matter)

SAMPLE	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
VITRITE	**21.8**	**3.8**	**6.2**	**5.8**	**15.0**	**5.4**	**3.8**	**11.6**	**8.6**	**5.2**
INTERMEDIATE PARTICLES	**29.8**	**8.0**	**11.6**	**8.0**	**40.0**	**7.2**	**11.2**	**11.4**	**8.2**	**7.0**
INERTITE										
Semi-fusite	25.0	37.2	54.0	40.4	31.8	49.0	56.8	36.8	42.2	53.2
Inertodetrite	10.2	34.2	9.6	25.8	1.4	18.6	11.2	25.4	24.2	22.8
TOTAL	**35.2**	**71.4**	**63.6**	**66.2**	**33.2**	**67.6**	**68.0**	**62.2**	**66.4**	**76.0**
CARBOMINERITE	**6.4**	**9.6**	**14.2**	**11.4**	**7.0**	**13.4**	**11.4**	**8.6**	**9.8**	**6.6**
ROCK > 60%mm	**4.8**	**2.4**	**0.6**	**4.4**	**2.0**	**4.4**	**2.4**	**5.4**	**4.2**	**3.6**
LIPTITE										
Clarite	0.4	0.0	0.6	0.4	0.2	0.0	0.0	0.0	0.2	0.2
Trimacerite	1.0	0.8	1.8	0.8	0.4	0.0	1.0	0.4	0.2	0.4
Durite	0.6	4.0	1.4	3.0	2.2	2.0	2.2	0.4	2.4	1.0
TOTAL	**2.0**	**4.8**	**3.8**	**4.2**	**2.8**	**2.0**	**3.2**	**0.8**	**2.8**	**1.6**

TABLE C3 MINERAL GROUP ANALYSES (% by vol. inorganic matter)

SAMPLE	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
QUARTZ & CLAYS										
<25%	58.2	73.4	70.8	75.6	75.2	68.6	73.8	60.2	59.2	76.4
25-50%	8.6	6.8	11.0	3.2	3.2	3.8	7.4	12.0	15.6	9.8
>50%	4.6	1.4	0.4	2.0	1.2	0.6	1.8	4.2	5.8	3.0
TOTAL	**71.4**	**81.6**	**82.2**	**80.8**	**79.6**	**73.0**	**83.0**	**76.4**	**80.6**	**89.2**
PYRITE										
<25%	8.2	0.6	2.0	0.8	6.2	8.6	0.6	0.4	5.6	1.2
25-50%	1.6	1.2	0.8	0.4	0.2	1.4	0.8	0.0	1.0	0.6
>50%	0.2	0.8	0.2	0.2	0.0	0.4	0.0	0.6	1.4	0.0
TOTAL	**10.0**	**2.6**	**3.0**	**1.4**	**6.4**	**10.4**	**1.4**	**1.0**	**8.0**	**1.8**
CARBONATES										
<25%	0.6	6.0	6.0	7.4	2.0	9.6	8.2	4.4	0.0	1.4
>25%	0.0	0.8	1.0	1.4	0.0	2.4	0.6	2.0	0.0	1.4
TOTAL	**0.6**	**6.8**	**7.0**	**8.8**	**2.0**	**12.0**	**8.8**	**6.4**	**0.0**	**2.8**
UNUSUAL MINERALS	**0.2**	**0.0**	**0.6**	**0.0**	**1.6**	**0.0**	**0.2**	**1.0**	**0.0**	**0.2**
CLEAN COAL	**17.8**	**9.0**	**7.2**	**9.0**	**10.4**	**4.6**	**6.6**	**15.2**	**11.4**	**6.0**

TABLE C4 ABNORMAL CONDITION ANALYSES (% by vol.)

SAMPLE	A	B	C	D	E	F	G	H	I	J
FRESH COAL	**73.2**	**85.4**	**79.8**	**70.6**	**87.4**	**61.6**	**77.8**	**63.0**	**70.0**	**44.2**
ABNORMAL FORMS										
Fine Fissures PARTIAL	1.4	7.0	8.0	16.2	4.4	8.0	7.6	10.8	15.2	6.6
Fine Fissures EXTEN.	0.0	1.0	0.0	5.8	0.0	0.2	0.8	1.4	2.6	2.0
Cracks FEW	2.8	2.0	4.4	3.8	0.6	19.2	2.8	7.2	3.6	6.4
Cracks MANY	0.2	0.0	1.6	0.0	0.0	0.0	0.6	1.2	0.0	2.4
Total Cracks and Fissures	**4.4**	**10.0**	**14.0**	**25.8**	**5.0**	**27.4**	**11.8**	**20.6**	**21.4**	**17.4**
Leach Holes	0.0	0.0	0.4	1.0	0.0	0.0	1.4	0.0	1.6	3.8
Heat Affected	**18.0**	**0.0**	**0.4**	**0.0**	**1.0**	**0.0**	**0.0**	**1.6**	**0.4**	**29.6**
Porous Fusinite	3.0	3.2	1.8	1.8	2.0	4.4	1.4	3.4	3.4	4.6
Discolouration	**0.8**	**1.4**	**2.8**	**0.8**	**2.6**	**6.6**	**6.0**	**9.2**	**2.8**	**0.2**
Dessic. Cracks	0.4	0.0	0.8	0.0	1.4	0.0	1.6	0.8	0.0	0.0
Alteration Minerals	0.2	0.0	0.0	0.0	0.6	0.0	0.0	1.4	0.4	0.2
TOTAL ABNORMAL	**26.8**	**14.6**	**20.2**	**29.4**	**12.6**	**38.4**	**22.2**	**37.0**	**30.0**	**55.8**

TABLE C5 VITRINITE REFLECTANCE ANALYSIS

SAMPLE	A	B	C	D	E	F	G	H	I	J
RoVmr	0.93	0.67	0.74	0.71	0.72	0.69	0.80	0.73	0.73	0.87
Std Dev	0.529	0.069	0.079	0.083	0.109	0.094	0.089	0.093	0.152	0.382
Range Min (%)	0.59	0.54	0.56	0.58	0.56	0.54	0.59	0.55	0.56	0.50
Max (%)	2.5	0.89	0.92	0.88	1.31	0.97	1.13	1.04	1.21	2.2
RANK	H.AFF	Med C	Med C	Med C	Med C	Med C	Med C	Med C	Med C	Med C