The characteristics of Southern African coals*

by R. FALCON† and A.J. HAM‡

SYNOPSIS

This paper summarizes the characteristics of Southern African coals, presents a fundamental approach to the combustion performance of coal, and reviews some of the recent developments in the fields of technological evaluation and boiler design for coals typical of this region. This includes a summary of the petrographic constituents of coal, highlighting the differences between the Palaeozoic coals of the northern and southern hemispheres (Laurasia and Gondwana respectively), and the effects of these properties on the combustion performance of coal as seen in terms of laboratory, pilot-scale, and full-scale operating conditions. Recent developments in boiler design linked to advanced characterization studies and commercial experience have led to unprecedented use, with maximum effect, of the low-grade, high-ash, high-inertinite coals typical of some parts of this region. In the light of this success, more adequate understanding and better methods of assessment of the coals typical of the Gondwana region are called for, particularly in the light of the high premium for high-grade coal and the more cost-effective low-grade coals on the international steam markets.

SAMEVATTING

Hierdie referaat gee 'n opsomming van die eienskappe van Suid-Afrikaanse steenkool, bied 'n fundamentele benadering van die verbrandingsprestasie van steenkool en gee 'n oorsig oor sommige van die onlangs ontwikkelings op die gebied van tegnologiese evaluering en ketelontwerp vir steenkool wat tipsies is van hierdie streek. Dit sluit 'n opsomming in van die petrografiese bestanddele van steenkool met die klem op die verskille tussen die Paleosioise steenkool van die noordelijke en die suidelike halfrond (onderskeidelik Laurasia en Gondwana) en die uitwerking van hierdie eienskappe op die verbrandingsprestasie van steenkool soos gesien in terme van laboratorium-, proefaanleg- en volekaanse bedryfstoestande. Onlangs ontwikkelings in ketelontwerp, lesme met gevorderde karakteriseringstudies en kommerciële ontwikkeling, het gelei tot 'n ongerekende gebruik, met maksimaal effek, van die laaggraadse, asryke en inertiensyetye steenkool wat tipsies is van sommige dele van hierdie streek. In die lig van hierdie sukses is daar 'n beter begrip en beter evalueringsetjies nodig vir die steenkool wat tipsies is van die Gondwana-streek, veraal in die lig van die wyspremie vir hooggraadse steenkool en die meer koste-effektywes laergraadse steenkool op die internasionale stoommarkte.

INTRODUCTION

Until relatively recently (the early 1970s), the evaluation of coal, and the parameters used for the cost-effective operation or the design of boilers, were limited to conventional proximate analyses and determinations of calorific value and ash and, if necessary, ultimate analyses. However, with the introduction of large-scale international trading in steam-raising coal, many of the parameters conventionally used in specifications were found to be insufficient, and in many cases proved to be inadequate for predicting the performance of coals despite falling within acceptable limits of the specifications. This phenomenon is particularly hazardous when one attempts to predict or guarantee, for example, the combustion performance of coal or the organic efficiency of combustion appliances without prior operating experience of the coal type.

For too long the view has been held that operational conditions are more important than the nature and properties of coal. Sufficient problems have now been encountered to suggest that boilers must be designed to match coal types or, conversely, that coals should be characterized in greater depth to match the operational characteristics of existing boiler plants. Calls for further investigation into combustion performance have gained momentum in many countries of the world, particularly those that rely on equipment designed for coals apparently different from their own, or that are obliged to import their feedstocks from other regions in the world or, even in some cases, from different collieries in the same region.

Problems of combustion performance are confined not only to conventional utility or power-generation companies, but also to smaller domestic and industrial users. Similar problems are encountered in the fields of fluidized-bed combustion and gasification. The combustion performance of coal therefore needs to be seen in its widest context, i.e. in terms of different combustion systems (operating from 800°C in domestic units up to 1500°C in furnaces of conventional power-station boilers); and of different-sized products (from pulverized fuel of less than 100 μm to lumpy coal of up to 35 mm in size) and in terms of different grades, ranks, and types of feedstocks, ranging from lignite to anthracite and chars.

One of the main reasons for the problem now being encountered is that the origin, nature, constitution, and maturity of coals vary markedly between different seams, coalfields, and regions of the world. Conventional analyses do not provide sufficient information to characterize these variations, because many of the more obvious problems have been related to slagging and fouling. A wealth of information is available on inherent mineral matter and the subsequent ash content of the coal. Little cognizance, however, has been taken of the inherent organic
matter comprising coal. Different types of organic constituents have been recognized by petrographers and coal chemists for many decades, and the differences in their properties have been fundamental to the applications of petrography, particularly in characterizing and defining coals suitable for carbonization and, more recently, liquid-coal conversion routes such as liquefaction, hydrogenation, and pyrolysis.

Research-and-development conducted over the past five years has indicated that organic matter also significantly influences combustion behaviour, ignition, and flame stability.

The purpose of this paper is to review the organic constituents of coal, including a brief discussion on the major differences between the coals of Palaeozoic age from the northern and southern hemispheres, and to relate the properties of these constituents to the major processes occurring in combustion, and specifically to discuss them in terms of certain test cases investigated recently. Finally, a revaluation of coal on the basis of petrographic characterization is proposed in order to supplement existing conventional parameters.

FACTORs INFLUENCING COMBUSTION

Combustion is the generation of thermal energy as a result of the oxidation of the combustible constituents of coal in the presence of heat. Although heating is initially supplied from an external source, the process of oxidation is itself a highly exothermic reaction, thus supplying its own continuing source of heat. The process of combustion is a series of reactions in which oxidation and heat generation lead to devolatilization of the organic matter. During this pyrolytic stage, tars and gases escape, leaving solid carbon-rich residues known as char or coke; these, in turn, are themselves oxidized and consumed until, at elevated temperatures, no organic residue remains at all. While each stage of the process requires energy to initiate reaction (also known as activation energy), these processes produce thermal energy during the course of reaction; the higher the temperature, the faster the rate of reaction.

There are many factors that influence the efficient combustion of coal. In general, they can be divided into inherent or intrinsic ones such as the organic and inorganic composition of the coal, its rank or degree of maturity, porosity, exposed surface area, moisture content, degree of weathering or heat-effect, size of particle, state of oxidation, and characteristic initial or ignition temperature, and peak combustion temperature. The second category, the external group, includes factors influencing the combustion process in terms of operating conditions: these include particle size, throughput, environmental temperature, temperature and velocity of the combustion air, the nature of mixing solids and gas, the design and spacing of the burners, and the residence time of the combustible particles in the furnace.

As the external factors are beyond the scope of the present review, only the inherent factors are discussed in this paper. The significance of these relative to the petrographic characteristics of coal is then discussed.

ORIGIN AND FORMATION OF COAL

In a comparison of coals in a global context, Southern African coals and those from other Gondwana provinces (India, Australia, and South America) have been found to be characteristically rich in minerals, relatively difficult to beneficiate, and highly variable in rank (maturity) and organic-matter composition. These characteristics provide the major differences between the Carboniferous coals of the northern hemisphere (i.e. the Laurasian region) and those found in the southern hemisphere (the Gondwana region).

Such differences have been attributed to conditions reigning at the time the coal was formed and to the subsequent history of geological events in each region. For example, unlike the hot, humid coastal Carboniferous coal-forming swamps of the northern hemisphere, the Permian swamps in the south formed under cold (increasing to warm) temperate conditions associated with the waning of a massive ice age. The coal-bearing sediments accumulated in relatively stable continental depressions along the margins of glacial valleys, continental lakes, and shallow inter-continental seas. Highly varied topographic and sedimentary environments existed, resulting in various degrees of degradation of the plant matter. Some vegetation accumulated in situ, while other forms were washed by seasonal floods into open waters such as lakes, deltas, and shallow seas. The latter was often accompanied by much mineral matter washed down from mountainous regions in the hinterland.

In terms of vegetation, the coal swamps of the northern hemisphere were characterized by giant water-loving sub-tropical equatorial types of lycopod horsetails and fleshy-barked trees, with abundant ferns. The Gondwana region, on the other hand, was characterized by vegetation ranging from sub-arctic through cold-cool-temperate deciduous (probably hardwood) forests to warm savannah-like woodlands with reed-infested swamps. Such vegetational differences resulted in different types of plant tissues, and varying proportions of plant organs such as leaves, pollen, and waxy plant excreta.

These combined conditions in the southern hemisphere gave rise to variable, generally mineral-rich peat-forming swamps, which developed into widespread, relatively thick, coal seams with the passage of time. As they were subsequently never subjected to any great depth of burial, as was the case with the Laurasian coals, the seams in Southern Africa are relatively shallow and almost horizontal in dip, and are therefore generally easier to mine than their Laurasian counterparts.

With time, temperature, and pressure, vegetation increases in 'maturation' or rank. In the northern hemisphere, increases in rank were relatively consistent on a regional basis owing to the rapid subsidence and deep burial of the coal-bearing strata and the effects of elevated pre-historic temperatures at depth for considerable lengths of geological time. In the Gondwana provinces, however, the coal-bearing strata have remained at generally shallow depths, but they have been subjected to frequent intrusions of hot igneous (volcanic) lavas in vertical and horizontal streams through the strata. This has resulted in highly uneven increases in maturation or rank within very localized areas due to the varying sizes and types of intrusions.

In general, therefore, South African coals are less mature than most of their European equivalents. How-
ever, the existence of igneous activity in some regions has resulted in rapid heating effects on coals in certain areas, particularly in the proximity of sills and dykes. Such heating effects have contributed to the formation of anthracites, burnt coals or, in some cases, just moderately heat-affected bituminous coals. The last-named are sometimes termed anthracite on the basis of their chemical and proximate analyses.

The coal-bearing Karoo Supergroup in South and Central Africa is shown in Fig. 1, and the distribution of the main coalfields in the Karoo Basin is indicated in Fig. 2.

Within Southern Africa, there are also regional differences. For example, the Main Karoo Basin was once open to the sea. Parts of the shoreline differed from others in terms of stability, configuration, and nature of the hinterland, thus giving rise to different geometrical developments of the seams, different environments of accumulation, and different suites of minerals and trace elements.

The Springbok Flats, Waterberg, and other small basins in the northern Transvaal, on the other hand, were small, shallow, fault-bound fresh-water basins with relatively similar geological histories. Their restricted environments of accumulation permitted relatively consistent qualities for each specific period of coal-forming times.

As a result of these regional differences, a considerable diversity of coal types (organic composition), grades (mineral-matter composition), and rank (maturity) is found within the coal measures in Southern Africa. These differences can be of considerable qualitative, quantitative, technological, and economic significance. The coals of Carboniferous age in the northern hemisphere are much less diverse.

CHARACTERIZATION OF COAL

The multiplicity of coal types and the vast number of possible end-uses calls for detailed characterization, classification, and evaluation of this commodity. Such characterization can be carried out on two levels: empirical and fundamental. Some of the tests that are carried out are simple, while others require involved manipulations, sophisticated equipment, and complex interpretations.

Empirical Levels

The empirical determinations include two main analytical classifications: proximate (meaning 'first' and not to be confused with 'approximate'), and ultimate analyses.

Proximate Analyses

Proximate analyses are used to determine the following.

(a) **Inherent moisture**, which is the water that is retained within the pores and fissures of coal after all the surface moisture has been removed.

(b) **Ash content**, which is the residue that remains after the complete combustion of the coal. The ash is made up of oxides of iron, aluminium, titanium, magnesium, calcium, and silica. The relative proportions of these various constituents determines the ash-fusion temperature, which is the temperature at which the ash begins to soften and then melt. This temperature is important to users of coal whose processes require relatively high temperatures. Molten or semi-molten ash can cause considerable difficulties inside process vessels.

(c) **Volatile matter**, which is derived from two sources: organic matter and mineral matter. The organic matter produces tars, oils, hydrocarbon gases, hydrogen, and oxides of carbon, which are driven off from the coal as the temperature is increased. The organically derived volatile matter in coal has a very significant bearing on its ignition and combustion characteristics. The inorganic matter produces incombustible volatiles such as carbon dioxide from carbonate minerals, sulphur oxides from pyrite minerals, and water (of crystallinity) from some clay minerals. These components are driven off with the volatile matter and, if present in sufficient quantities, can be deleterious to the performance of a coal.

(d) **Fixed carbon**, which is part of the organic content of coal that remains as solid carbon after the volatile matter, ash, and moisture have been removed. The forms of carbon remaining after devolatilization may vary considerably in structure (porosity), texture (nature of the matrix), and rates of reactivity.

Ultimate Analyses

Ultimate analyses, as the name implies, divide the coal into its ultimate chemical components, which are the elements carbon, hydrogen, oxygen, nitrogen, and sulphur.

In addition to these two groups of empirical analyses, other very important characteristics of coal need to be quantified. The most important of these are as follows.

**Calorific value**, which is a measure of the 'heat' content or 'energy' value of the coal. This is one of the most important commercial parameters for coal, and is expressed to a number of different bases (e.g. with or without moisture or ash). In South Africa, this value is usually expressed in terms of megajoules per kilogram of coal but, in other countries of the world, units such as British thermal units (Btu) per pound of coal (United Kingdom) and kilocalories per kilogram of coal (USA, Europe, and the Far East) are also used.

**Swelling index** is used as a means of determining the expandability of a coal, and therefore its potential suitability to form 'coke' for the reduction of ore in metallurgical processes. This particular test demonstrates the peculiarity of some coals which, when heated under specific conditions, become plastic and swell to become porous lumps of carbon-enriched char with the simultaneous evolution of volatile matter.

There are up to sixty analyses apart from those already mentioned that are used to evaluate the physical, chemical, and technological properties of coal. These are used for specific purposes, e.g. gasification, liquefaction, carbonization (coke manufacture).

Of importance to further combustion testwork are thermogravimetric analyses and drop-tube furnace tests. Both are methods of assessing the rate of devolatilization and carbon consumption (or combustion reactivity) of coals under various experimental conditions, each set to emu-
Fig. 1—Distribution of the coal-bearing Karoo Supergroup in South and Central Africa

148 MAY 1988 JOURNAL OF THE SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY
late boilers of different types. Unless used in conjunction with fundamental analyses, these results must be regarded as empirical in nature.

**Fundamental Levels**

Apart from characterizing coal in terms of its empirical (i.e. chemical and physical) properties, coal can be classified according to its basic or fundamental components, i.e. organic and inorganic constituents that are the ‘building bricks’ of coal. Unlike empirical tests, the fundamental or petrographic analysis of coal is made with a microscope. The fundamental aspects of coal formation are illustrated in Fig. 3.

The fundamental composition of coal falls into three major categories; organic matter, mineral matter, and rank or degree of metamorphism.

**Organic Matter Content**

The organic matter in coal includes the fragmented and partially decomposed organic remains of the original vegetable matter. Such microscopically recognizable units of organic matter are termed macerals, just as minerals are used to refer to the inorganic constituents of rock and orebodies. A wide variety of forms occur, but these can be combined into three groups of macerals: the vitrinite group, the liptinite (or exinite) group, and the inertinite group, on the basis of their common chemical, physical, optical, and technological properties.

For the purpose of combustion assessment, macerals are conventionally separated into ‘reactive’ types, i.e. on being heated, they will devolatilize, change in structure, texture and form, and ultimately ignite and combust rapidly in the presence of oxygen. ‘Unreactive’ types are slow to change (if at all), and they require more heat and oxygen in order to ignite and a longer time to burn out. The terms reactive and unreactive are relative and not absolute descriptions, and refer mostly to the low to medium ranks of coal.

Reactive macerals conventionally include vitrinite (the viscous coking–caking component) and exinite (the main tar and hydrogen producer); the unreactive macerals include inertinite. However, recent studies, particularly of coals from the southern hemisphere (Gondwana), have indicated that certain constituents within the inertinite group are semi-reactive. These constituents can comprise up to 60 per cent of the inertinite group, and as such they may represent a very important part of the organic matter. Total reactive macerals in the southern hemisphere therefore include vitrinite, exinite, and part of the inertinite.

In terms of chemical properties, in low-rank bituminous coals, vitrinite is moderately rich in volatile matter; exinite is extremely rich in volatile matter, and hydrogen in particular; and inertinite is relatively impoverished in volatile matter and hydrogen. At this rank, vitrinite is characterized by some moderately sized aromatic nuclei surrounded by peripheral aliphatic groups, the whole forming molecules that are randomly orientated relative to the bedding plane. With increasing rank, the aliphatic peripheral groups (OH, COOH, CH3) are lost, and the aromatic nuclei become larger and aligned in a more orderly fashion parallel to the bedding plane. Thus, carbon content and aromacity diagnostically increase in vitrinite with rank.

Exinite in low-rank coals is much less aromatic than vitrinite, and the size of the aromatic nuclei is smaller.
In general, exinite has an aliphatic–aromatic skeleton with aliphatic side chains that are extremely rich in peripheral groups. On being heated, therefore, this maceral group yields much more volatile matter than vitrinite, including exceptionally high proportions of tar and bitumen. With increasing rank, the yield of products changes from predominantly gaseous to liquid, and then back to gaseous, and finally, when all the aliphatic groups are lost and aromaticity has increased, it becomes relatively inert, stable, and indistinguishable from vitrinite. This stage occurs in the mid volatile bituminous range of rank.

Inertinite, in contrast, is much more aromatic than vitrinite and exinite in the low ranks. The aromatic nuclei are bigger and randomly orientated, and the aliphatic chains are fewer and shorter. This explains why inertinite is denser and richer in carbon-structured molecules, and characterized by relatively low contents of volatile matter. This group does not change significantly in structure or in volatile matter with increasing rank.

A comparison between the Carboniferous coals of Europe and America, and those of Permian age in Southern Africa and elsewhere in Gondwanaland indicates that the coals of the northern hemisphere possess, almost exclusively, very high vitrinite contents (average 80 per cent), and therefore high proportions of reactive macerals. Those of the southern hemisphere, by contrast, are variable but on average are characterized by much higher inertinite contents (some semi-reactive), with vitrinite contents averaging approximately 40 per cent. The exinite proportions are highly variable in all coals but, with exceptions, they usually range from 2 to 10 per cent in Southern African coals. Thus, the total reactive macerals of Gondwan-type coals, when the semi-reactive forms are included, can be almost as high as those of the northern hemisphere, although the proportion of the basic constituents may vary considerably.

In terms of combustion, the significance of the organic matter lies in the fact that the maceral groups possess different degrees of reactivity (i.e. volatile emission and char reactivity) and rates of oxidizability (adsorption and reaction in the presence of oxygen). Vitrinite both in untreated and in char form has been found to be readily oxidizable, particularly in low-rank coals, while exinite in its neutral state, being even more reactive and volatile-rich, is considered to oxidize at a far more rapid rate than vitrinite; inertinite in its natural and charred forms, being less reactive and low in volatile matter (and hydrogen in particular), oxidizes at a far slower rate, particularly in bituminous coals.

The organic-matter content can also be described in terms of associations of macerals with one another into layers or bands greater than 50 \( \mu \)m in width. Such associations are termed microlithotypes. They may consist of pure macerals, a mixture of two macerals, or all three maceral groups. The chemical and physical properties of the macerals comprising these bands impart to that band its basic properties. Where microlithotypes are contaminated with more than 20 per cent mineral matter (or 5 per cent pyrite) in an intimate mixture of maceral and mineral inclusions, they are referred to as carboninertites irrespective of the macerals present.

Microlithotypes, or the types of maceral associations, play extremely important roles in terms of the strength, density, liberation, combustion, gasification, and coking behaviour of coal. For example, two coals may contain the same amounts of volatile matter, fixed carbon, and ash, and indeed maceral content, but the macerals may be associated in well-banded discrete homogeneous layers, or in mixed heterogeneous layers. In the latter case, too many contaminants in a band will prevent the formation of large pores and will seriously affect the structure, and ultimately the behaviour, of such bands in coking and combustion. The distribution and proportions of such bands are now becoming important in the technological evaluation of coal.

The nature and proportions of the organic forms determine the type of the coal.

**Mineral Matter Content**

In contrast to the analyses of macerals and microlithotypes, analyses of mineral distribution are performed on bands or whole coal particles (50 to 300 \( \mu \)m in size). The relationship between the types, forms, sizes, and proportions of mineral groups and the organic-matter host with which they are intimately inter-
grown are thus quantified. The proportions of mineral matter per particle or band of coal can be grouped as follows: 0 to 0.5 per cent, 0.5 to 25 per cent, 25 to 50 per cent, and 50 per cent. Such mineral matter can take the form of finely divided and evenly distributed grains or aggregates; large irregularly distributed aggregates or nodules, lenses or bands; or secondary precipitates in cracks and fractures within coals.

The total constituents of the mineral matter determine the grade of a coal; the size, shape, form, type, and degree of intergrowth of the minerals in the organic matrix provide useful information concerning the hardness and abrasiveness index, the potential pollution, and the possibility of liberating such minerals in the beneficiation of coals rich in these minerals. The identification of certain minerals (e.g. calcite, kaolinite) is also important for qualitative predictions of drops in ash-fusion temperature, the origins of relatively high proportions of inert mineral-derived gases in the volatile matter, and some variations in calorific value and inherent moisture content. Some clays, for example, possess high proportions of water within their crystalline structures and, on being heated, yield very high proportions of their mass in the form of water vapour; similarly, carbonates yield relatively high proportions of carbon dioxide, and pyrite yields sulphur-rich gases.

In terms of combustion, the type, form, and distribution of minerals is very important. Small (smaller than 20 µm) nodules may be trapped in the host organic matter and therefore be evenly and widely dispersed. Such forms can serve as contaminants or inhibitors in devolatilization and swelling processes; they also form globules of slag after melting and coalescing, thus contributing to coarse ash (if found in the form of large aggregates or abundantly distributed as carbominerite) or as small spheres in fly ash if very finely divided and well dispersed in the original matrix particle. Larger nodules and cleats are likely to be liberated more easily and to drop out of the combustion zone, thus contributing to bottom ash.

**Rank**

Rank refers to the degree of maturity or metamorphism (i.e. coalification) achieved by a coal through the processes of time, temperature, and pressure as a result of depth of burial or proximity to heat following peat accumulation. The progressive change from peat into coal passes through a number of stages, i.e.

- peat → lignite (brown coal) → bituminous → semi-anthracite → anthracite → graphite.

The position (or level reached) in this coalification series is called the rank of a coal.

With increasing rank, significant and progressive changes in the physical, chemical, and technological properties of the macerals take place, particularly in the vitrinite and exinite maceral groups. The inertinite group, however, being a carbon-rich, dense, and relatively inert product as a result of oxidation prior to or during original swamp accumulation, for the most part maintains its original structure, form, and chemistry and undergoes very little change throughout the coalification series. The effect of rank on the volatile matter in a coal is illustrated in Fig. 4.

### Table: Proportion of Mineral Matter per Band of Coal

<table>
<thead>
<tr>
<th>Rank</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH VOL.</td>
<td>0,60 44,0 77,5 36,0</td>
</tr>
<tr>
<td>MED. VOL.</td>
<td>0,80 40,4 68,8 28,2</td>
</tr>
<tr>
<td>LOW VOL.</td>
<td>1,00 35,4 57,2 23,0</td>
</tr>
<tr>
<td>1,20</td>
<td>29,6 43,9 19,7</td>
</tr>
<tr>
<td>1,40</td>
<td>25,3 31,5 17,5</td>
</tr>
<tr>
<td>1,60</td>
<td>21,2 21,6 17,2</td>
</tr>
</tbody>
</table>

![Fig. 4](image)

**Fig. 4** — The effect of rank on the volatile-matter content (on a dry, ash-free basis) of the three major groups of macerals (Isor, personal communication, 1981) RSF = Reactive semifusinite RV = reflectance of vitrinite

The quantitative determination of rank in coals rich in reactive macerals (vitrinite and exinite), as is the case in Europe and the USA, can be achieved satisfactorily by determination of the proportions of volatile matter or carbon content and, within specific ranges of rank, the hydrogen or moisture content. However, the use of volatile matter, the most common parameter, as a measure of rank is not reliable in coals relatively rich in mineral matter (i.e. high-ash, low-grade coals). For example, up to 60 per cent of the volatile matter in coal has been found to be contributed by the thermal dissociation of minerals. Calcite and other carbonate minerals contribute carbon dioxide, clay minerals contribute water vapour and basic oxides, and pyrite loses sulphur in the production of sulphurous gases. In addition, the presence of inertinite macerals introduces a higher carbon and lower volatile-matter content than vitrinite at the same rank, thus super-imposing another source of carbon from that achieved by rank alone.

Similarly, the presence of unusually high proportions of exinite in a coal leads to anomalously high contents of volatile matter and relatively low contents of fixed carbon. Volatile matter and carbon are thus not reliable indicators of rank, particularly in highly variable mineral- and inertinite-rich coals such as those characteristic of many countries in the southern hemisphere.

As a result, a more standardized method of rank determination has been proposed and is now widely used on the international market, viz the measurement of light reflected off the surface of polished vitrinite particles determined under oil immersion. This method has been chosen because the optical reflectance of vitrinite increases regularly and progressively with increasing rank, irrespective of the proportion of macerals and minerals present. This increase in light from medium grey (0.5 per cent light in low-rank bituminous coals) to white (up to 10 per cent light in meta-anthracites) is consistent with increase in carbon content and aromaticity with rank.

In comparing the Carboniferous coals of Europe and America with the Permian coals of Southern Africa (and other Gondwana countries), Stach et al. established that, where the coals in the northern hemisphere accumu-
lated in association with large, rapidly subsidng geosynclines with accompanying deep burial, relatively intense tectonic stresses, and pressures from thick overlying strata, the rank of the coals is relatively high. Geothermal temperatures at such depths would have also contributed significantly to the processes of coalification or maturi-
ty. In contrast, the coals of Southern Africa accumulated on shallow shelves on continental platforms, and have, with very few exceptions, never been subjected to deep burial and mountain-forming processes. Some coalfields, however, have been permeated by significant numbers of igneous intrusions in the forms of horizontal or vertical sills and dykes, and ultimately by vast outpourings of lavas on the surfaces of the ancient Karoo landscape, thereby giving rise to the Drakensberg (basaltic) Moun-
tains. Localized areas of heat-affected coals are therefore common in Southern Africa, progressing in some areas up to meta-anthracite and graphite in rank, but the rank of the host coal some distance away from the heat source has in many cases remained at a normal unheated level.

In summary, the major differences between the coalfields in Europe–North America and those in Southern Af-

can be expected in the ranges of rank, viz the bulk of the coals of Europe and North America lie in the mid to low vola-
tile bituminous range grading to anthracite, while the Southern African and other Gondwanaland coals generally range from sub-bituminous to mid-bituminous ranges, with the exception of locally heat-affected regions.

The rank of coal is a very significant factor in terms of combustion. Low-rank coals, being higher in micro-

porosity, moisture content, volatile matter, and reactivi-
ty, are more oxidizable than coals of higher rank. Thus lignites, sub-bituminous, and low-rank bituminous coals are particularly reactive to oxidation and combustion, based on their inherent properties. This fact is particularly significant since most of the coals of Southern Africa and other Gondwana countries fit into this category.

In addition, recent tests have indicated that rank plays a direct role in controlling the ignition and peak combus-
tion temperatures of a coal, the rate and degree of devolatilization, 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. Such factors are vitally important in the compat-
ible blending of coals in combustion and in the selection of operating temperatures in low-temperature furnaces and fluidized-bed operations. High-rank burnt coals, like well-oxidized coals and inertinite particles, are more difficult to ignite, require higher temperatures, and possess different peak combustion temperatures, rates of devolatilization, and rates of char reactivity from those of coals that are lower in rank, non-oxidized, and reactive in composition.

COMBUSTION BEHAVIOUR AND COAL CHARACTERISTICS

The combustion behaviour of the three maceral groups is listed briefly in Table I, together with their major characteristics in hard coal.

This section briefly reviews several case histories of their performance in relation to their organic composi-
tion.

Among the first authors to discuss the effect of maceral composition on boiler performance were Yavorski et al. (1968), who attempted to establish the optimum operating conditions in a pulverized-fuel boiler and the reasons for the varying performance of two coals from the Kuznetsk region.

These authors state that calorific value and volatile-matter content do not assist in the prediction of the burn-

out characteristics of the coals; on the other hand, the petrographic characteristics quantified the difference between the coals and, furthermore, affected the pro-
cesses of ignition and combustion and the efficiency of combustion, and variations in the percentage volatiles in the flue gas. The testwork indicated that an increase from 45 to 57 per cent reactive macerals caused a decrease in the char, a decrease in the unburnt carbon by 1.6 to 2.2 per cent in the flue gases, and an increase in boiler efficiency in certain load ranges from 1.7 to 2 per cent.

Variations in petrographic composition were also said to affect the temperature distribution over the height of the furnace chamber. In addition, with increasing reactive macerals, the flame core tended to shift towards the burners and the temperature increased in that region by 50 to 120°C; high concentrations of reactivates also resulted in an increase in heat release due to higher and more rapid rates of burn-out. Finally, analysis of the char in the flue gas indicated that those particles were composed of inertinite and previously oxidized vitrinite. These results therefore indicated a clear interrelationship between operating conditions in a pulverized-fuel boiler and the petrographic composition of the coal feedstocks and chars.

Two years later (1970), the behaviour of individual macerals in a laboratory-scale situation was described. Here, a thin section of coal was heated in a hot-stage microscope and the behaviour recorded by ciné photograph at the Australian Council for Scientific and Indu-

trial Research Organisation (CSIRO). Under control-
led conditions of heating rate and environment, it was observed that, during the initial devolatilization stage, vitrinite and exinite became opaque while inertinite became friable and fragmented. Following this pyrolysis stage, the process of combustion in the char stage was fastest in the case of exinite, followed by vitrinite, and finally by inertinite, i.e. in decreasing orders of magni-
itude.

Following these two initial reports, pilot-scale pulver-
ized-fuel combustion experiments were conducted on two West Canadian and one United States coal by Nandi et al. The combustion performance of these coals was found to be inversely related to the inert contents of the coals, i.e. coals rich in inert macerals produced fly ash with higher levels of unburnt carbon because these macerals were found to persist through the flame in a partially reacted form. These authors suggested that such coals will require a combination of higher combustion air temperatures, higher excess air levels, and longer residence times to achieve combustion efficiencies similar to coals with higher contents of reactive macerals. Higher combustion air temperature, longer residence time, and finer particles would achieve the same results without higher excess air.

In 1983, Sanyal documented the results of full-scale horizontally fired, pulverized-coal combustion in a 350 MW power station using two coals: a Polish reactive-
### Table I

**A Summary of the Major Characteristics of the Three Maceral Groups in Hard Coal**

<table>
<thead>
<tr>
<th>Maceral Group</th>
<th>Plant Origin</th>
<th>Reflectance</th>
<th>Chemical Properties</th>
<th>Technological Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VITRINITE</strong></td>
<td>Woody trunks, branches, twigs, stems, stalks, bark, leaf tissue, shoots</td>
<td>Dark to medium grey</td>
<td>High vol. to medium volatile</td>
<td>Bituminous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rank</td>
<td>Reflect light, %</td>
<td>Characteristic element</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 to 1.1</td>
<td>Oxygen-rich</td>
<td>Light hydrocarbons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.1 to 1.6</td>
<td>Hydrogenation/liquefaction</td>
<td>• Combusts with little smoke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pale grey</td>
<td>Low volatile</td>
<td>Bituminous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>White</td>
<td>Anthracite</td>
<td>2.0 to 10.0</td>
</tr>
<tr>
<td><strong>EXINITE</strong></td>
<td>Cuticles, spores, resin bodies, algae</td>
<td>Black-brown</td>
<td>High vol.</td>
<td>Bituminous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dark grey</td>
<td>Bituminous</td>
<td>0.5 to 1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pale grey</td>
<td>Bituminous</td>
<td>1.1 to 1.6</td>
</tr>
<tr>
<td><strong>INERTINITE</strong></td>
<td>As for vitrinite, and oxidized detrital organic humus</td>
<td>Medium grey</td>
<td>High vol.</td>
<td>Bituminous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pale grey</td>
<td>All bituminous coals and anthracite</td>
<td>1.6 to 10.0</td>
</tr>
</tbody>
</table>

Rich coal and an inertinite-rich Gondwana coal. Comparisons between the two coals using conventional proximate and ultimate analyses did not indicate a substantially different combustion performance. However, when the two coals were fired separately and were tested for furnace performance (by measurement of combustion and flue-gas temperatures at various heights in the furnace), it was established that the rate of combustion of the two coals was markedly different, i.e. the combustion of the Polish coal was completed earlier than that of the Gondwana coal. As a result, the temperature of the gas near the top of the furnace in the vicinity of the platen superheaters was cooler with the Polish coal than with the Gondwana coal. In the latter case, it is concluded that, as the combustion of inertinite-rich coals takes longer to complete, the particles in the vicinity of the superheaters were still burning, thus raising the temperatures in that region. Although these combustion characteristics were not identifiable or predictable on the basis of conventional testwork, they could be correlated with the maceral composition, i.e. the more reactive Polish coal possessed 65 per cent vitrinite, while the Gondwana coal possessed only 30 per cent. The latter was characterized by 64 per cent inertinite.

Since 1983, several publications concerning power generation by pulverized fuel have supported the claims of the researchers cited above. Ryk, in discussing the problems associated with the irregular qualities of imported steam coal to Swedish pulverized-fuel power plants, stated once more that standard analyses are insufficient for the prediction of burning performance. He cites the example of two coals originating from the same mine, which were imported on separate occasions. They contained the same volatile matter (34 per cent). The first coal had a Hardgrove Index of 44 and a relatively poor combustion performance (unburnt carbon in the ash ranging between 5 and 12 per cent). In contrast, the second consignment was slightly more difficult to pulverize (Hardgrove Index 41), but it burnt without difficulty. The major difference between the coals was the proportion of reactive and inert macerals, i.e. the poorly combusting coal contained much more inertinite and pseudo-vitrinite, while the better-combusting (although harder) coal contained more reactive macerals. As the boilers were relatively small, it would appear that the residence time was too short for the complete combus-

---

Analyses

Kl K2

Heat content
Gross calorific value, MJ/kg 31.57 31.8

Proximate analyses:
Total moisture, % a.r. 0.70 1.1
Ash, % a.r. 8.6 14.3
Volatile matter, % a.r. 32.5 24.3
Fixed carbon, % a.r. 57.8 59.8

Ultimate analyses:
C, % a.r. 75.6 70.1
H, % a.r. 5.2 4.0
N, % a.r. 1.9 1.5
O, % a.r. 7.1 8.5

Elements
S 1.32 0.44
Cl 0.26 0.01

a.r. = as received

In India, several authors recognized the high variability and deteriorating quality of run-of-mine coal and the need for additional petrographic characterization in order to ensure optimum efficiency in power stations. Inconsistent quality and inferior coal have already resulted in high outages (stoppages), leading to power failure and erratic power supply in some parts of the country, which have, in turn, disrupted industrial and agricultural sectors. Apart from the normal chemical and ash parameters of coal, Ghose emphasizes the need for boiler designers to take cognizance of the petrography of Indian coals, particularly at the design stage, and to ensure that the efficiency of conventional boilers is suited to Indian coal types.

In China, the expanded use of low-reactivity bituminous coals for pulverized-fuel firing is an important strategy for modernization. In 1983, more than 10 per cent of the coal used by power stations had more than 40 per cent ash and produced less than 16.8 MJ/kg (dry basis). Numerous operational problems were experienced, including poor ignition, poor flame stability, high carbon in fly ash, and accelerated erosion of boiler surfaces. Changes from low-ash to high-ash feedstocks resulted in reduced boiler efficiency, flame-outs, and boiler 'puffs'.

As the content of volatile matter was found to be unsatisfactory as an indicator of combustion stability, particularly when used on high-ash, high-volatile low-rank coals, other parameters were sought. Two analyses based on thermogravimetric analyses (TGA) were chosen, viz ignition temperature, and average combustion rate during the maximum burning period. As both parameters can be linked to rank and reactive–inert composition of coal, these results once more prove the relationship of the organic constituents of coal to its combustion. Results in China indicated that high-ash, high-volatile bituminous coals behave much like low-volatile bituminous or anthracite coals during combustion. For the burning of these inferior coals, the following modifications were made to the burners:

1. the cone angle of the secondary air port was increased from 9 to 13 degrees in order to increase the quantity of internally recirculated flame gases;
2. the cone position in a cone-stabilized burner was changed to increase the coal-exit area (decrease the primary air velocity); and
3. the swirl in the primary air–coal pipe on an annular burner was eliminated to delay mixing of the coal with secondary air.

These modifications have improved the combustion performance in many Chinese pulverized-fuel boilers.

Kautz explains the relationship of the inherent characteristics of individual macerals, minerals, and microlithotypes to the combustion performance of particles of pulverized coal. Initial tests indicated that particles of vitrinite- and exinite-rich coal, on being heated to 1100°C in a flow of nitrogen, swelled after one second, forming large, rounded porous particles (char). Continuous heating for one hour at 1100°C under nitrogen confirmed the swelling of these macerals. Particles that did not swell or change in form on being heated were inertinite macerals. Investigations of the char in the fly ash from power stations indicated that these remnants of combustion were composed of partially combusted porous chars (originally vitrinite and exinite), non-swollen particles (originally inertinite), and swollen and unswollen constituents in heterogeneous bands (originally mixed vitrinite and inertinite microlithotypes). Such forms have been described and named by a number of authors. Kautz and others suggest that such unburnt carbon results from temperatures that were too low, insufficient mixing of coal and air, particles that were too large to burn under the conditions prevailing in the boiler or, finally, different combustion behaviours or reactivities of the individual coal constituents.

**Drop-tube Furnace Investigations**

Based upon the need to obtain more specialized information on the combustion of the ever-increasing low-grade, high-ash and high-inertinite coals of the Gondwana region, further testwork was recently instituted on the combustion behaviour of specific types of coal particles, the rates of devolatilization in these particles, the forms of char that each produces, and the reactivities of each type of char. This is an ongoing field of endeavour at present, but preliminary results are now available.

An example of this type of investigation on particles of pulverized fuel is in the recent drop-tube furnace (DTF) tests conducted in Sweden at temperatures of 800 and 1000°C in air, with residence times from approximately 100 to 500 ms.

Two pulverized fuels (K1, a European vitrinite-rich low-ash coal, and K2, a Gondwana inertinite- and ash-rich coal) were investigated in detail. Their empirical and fundamental analyses are summarized in Tables II and III. The burning particles were extracted from the tube at intervals of 100 ms, and then quenched and analysed microscopically. The results are given in Table IV (results provided by one of the authors prior to international round-robin assessments). See also Figs. 5 to 7.

The results indicated that, at 800°C, K1, the vitrinite-rich coal, was dominated by rapidly devolatilizing particles, that produced char forms known as thin-walled cenospheres within 100 to 200 ms. They formed even more rapidly at higher temperatures (1000°C). These char forms...
TABLE III
PETROGRAPHIC ANALYSIS OF COALS K1 AND K2

<table>
<thead>
<tr>
<th>Maceral group</th>
<th>Average</th>
<th>Range</th>
<th>K1</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitrinite, %</td>
<td>76,4</td>
<td>73,8-81,0</td>
<td>21,9</td>
<td>17,6-28,0</td>
<td></td>
</tr>
<tr>
<td>Exinite, %</td>
<td>7,9</td>
<td>3,0-11,8</td>
<td>6,0</td>
<td>3,0-8,2</td>
<td></td>
</tr>
<tr>
<td>Inertinite, %</td>
<td>15,6</td>
<td>12,6-18,8</td>
<td>72,1</td>
<td>65,5-78,0</td>
<td></td>
</tr>
<tr>
<td>Semi-reactive inertinite, %</td>
<td>5,8</td>
<td>3,0-6,9</td>
<td>42,0</td>
<td>20,0-70,0</td>
<td></td>
</tr>
<tr>
<td>Mean random reflectance, V%</td>
<td>0,81</td>
<td>0,71-0,88</td>
<td>0,75</td>
<td>0,69-0,85</td>
<td></td>
</tr>
</tbody>
</table>

TABLE IV
PARTICLE-TYPE ANALYSES OF COALS K1 AND K2—TRANSITION, AND CHAR FORMS IN DROP-TUBE FURNACE
(Source: Falcon Research Laboratories, Inhouse report, 1987)

<table>
<thead>
<tr>
<th>Coal</th>
<th>Transition</th>
<th>Char forms</th>
<th>Mineral matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Unch.</td>
<td>Exin.</td>
<td>Vit.</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key to coal types:
- Coal (normal, non-heat-affected) particles:
  - I Unch. Exin. = Unchanged exinite
  - II Unch. Vit. = Unchanged vitrinite
  - III Unch. Int. = Unchanged inertinite

Transition (porosity beginning) particles:
- IV Por. Vit. = Porous vitrinite
- V Devol. Int. = Devolatilizing inertinite and mixed particles

Char (highly reflecting, porous, semi-porous) particles:
- VI Thin Cen. = Thin-walled cenosphere
- VII Thick Cen. = Thick-walled cenosphere
- VIII Honeycomb = Honeycombed multiporous char
- IX Mixd = Inert and reactive material mixed/in association

Key to the sampling time intervals:
- 6 100 ms
- 7 200 ms
- 8 300 ms
- 9 400 ms
- 10 500 ms

forms were consumed and broken up at very fast rates, from 400 ms onwards. In contrast, preliminary results from K2 (the inertinite-rich sample) indicate that, at 100 ms, a relatively high proportion of intact unheated coal was still present, accompanied by some thin-walled cenospheres and particles with incipient pore formation. At 200 ms, thin-walled cenospheres, vitrinite, and semi-reactive inertinite with pore formation and fused intact inertinite (least reactive forms) dominated the assemblage of particles. From 300 ms onwards, the more dense, thick-walled and less porous forms of char dominated, in association with the remaining thin-walled cenospheres and some unfused inert particles. By that stage, all forms of char, with or without pores, showed signs of increased reflectance (white colour), some degree of anisotropy (internal molecular change), and oxidation in response to temperature and the oxidizing atmosphere. These results, in association with those conducted simultaneously on a 10 MW boiler, indicate the following.

(a) Known macerals give rise to specific forms of chars:
- vitrinite to thin-walled cenospheres
Fig. 5—Particles of pulverized-fuel in a typical feedstock to a South African power station
A Particle of unchanged vitrinite
B Single cenosphere (from a vitrinite particle)
C Lacy cenosphere (from vitrinite and exinite)
D Semi-porous or lacy char (from heterogeneous particle with mixed reactive and semi-reactive components)

- semi-reactive semisinte to thick-walled ceno-spheres
- non-reactive fusinite or semisinte to unfused char
- mixed associations of reactive and inert macerals to honeycombed and mixed, partly porous chars.

(b) At similar temperatures, vitrinite-derived forms burn out faster than inertinite-derived forms (Fig. 6):
- at 800°C (400 ms), K1 had less than 10 per cent combustible matter left, and K2 had more than 70 per cent
- at 1000°C, K1 was completely devolatilized at 100 ms, and K2 from 200 ms onwards; at 800°C, the devolatilization of K2 was still far from complete at 500 ms.

(c) The proportions of unfused non-reactive chars are relatively low in the final samples of K2 (5 per cent at 500 ms). The remainder of the particles show varying degrees of porosity, thus indicating that all but a very small part of the inertinite group of macerals are reactive to some extent on being heated.

(d) The proportions of thick-walled chars were lower, and the thinner-walled varieties higher, in the 1000°C samples relative to the 800°C samples.

(e) With higher loads, higher proportions of unburnt carbon resulted from K2 than from K1:
- at a load of 80 per cent, K1 produced 22 per cent carbon and K2 40 per cent carbon
- at a load of 40 per cent, K1 produced 0 per cent carbon and K2 28 per cent carbon.

(f) Ignition conditions were more critical for K2 than for K1.

In general, therefore, quantitative assessments of the combustion performance of various particles relative to their temperature and varying combustion conditions were provided. In summary, the results proved clearly and quantitatively that both coals burn out faster with increasing temperature, that the combustion reactions begin earlier with higher temperatures, that all but the absolutely non-reactive coal particles react at higher temperatures, and that the overall combustion reactivity of K2 was slower than that of K1 both in the 10 MW boiler and in the drop-tube furnace.

The application of these results is self-evident especially to the combustion conditions necessary for widely varying coal types, and, more specifically, the low-grade highash coals of the future.

**Thermogravimetric Analyses**
Recent investigations into thermogravimetric analyses of coals of different ranks, types, degrees of oxidation, and sizes have indicated that all these factors contribute
Fig. 6-A Two particles of pulverized fuel in feedstock to a drop-tube furnace —vitrinite (V) and inertinite (I)

B Two particles of char at 200 ms in a drop-tube furnace, showing a thin-walled cenosphere developing from a vitrinite particle (V) and an unchanged inertinite particle (I)

C Two particles of char at 500 ms in a drop-tube furnace, showing a very thin-walled cenosphere almost completely oxidized and consumed, and a particle of unchanged inertinite. Note the high reflectance and whiteness of the chars
Fig. 7—A Unchanged particle of vitrinite
B A single cenosphere (from a particle of vitrinite)
C Lacy cenosphere (from vitrinite and exinite)
D Semi-porous or lacy char (from a heterogeneous particle of mixed reactive and inert components)
E A partially fused semi-porous or solid char (from a particle with semi-reactive and inert components)
F Unfused semi-porous to solid char (from inert fusinite)
significantly to the activation energies required to effect changes during combustion; the temperatures of ignition, initial combustion devolatilization, and peak combustion, and burn-out times. The results indicate that increases in rank and inertinite content, and the presence of large particles and oxidized particles (including oxidized vitrinite), cause increases in the temperatures at which ignition, devolatilization, and peak burning take place. Conversely, smaller particles, more reactive particles, and lower ranks of coal begin the combustion processes earlier\textsuperscript{16-20}. Some of the results are illustrated in Fig. 8.

The significance of these results lies in the new appreciation of such interrelated factors as type, rank, size, and oxidation state. This information also indicates the necessity of ensuring the compatibility of various blends of coals; alternatively, the advantage of blending acceptable and unacceptable coals for mutual benefit may now be better understood. Of further interest is the possibility of being able to predict the combustibility of wide ranges of coals on a relative scale based on their organic composition and rank, and confirmed by thermogravimetric analysis and drop-tube tests, provided that reasonable control is kept on the size distribution, that the coals are not oxidized, and that the ash contents are not too different.

**Design of Power-station Boilers**

Recent developments in the design of power-station boilers for the combustion of low-grade coals have demonstrated that high ash (more than 42 per cent), inertinite-rich coals can be effectively burnt in conventional opposed fired pulverized-fuel boilers. For example, at Eskom's 6 × 600 MW Lethabo Power Station, the coal described in Table V is safely and effectively utilized without oil support above 45 per cent MCR. The loss of unburnt carbon in the dust amount to less than 0.5 per cent. These boilers incorporate several design features specified by Eskom, some of which are reported by Ham and Dickson\textsuperscript{21}.

**TABLE V**

<table>
<thead>
<tr>
<th>Analyses</th>
<th>Range</th>
<th>Characteristics of 'Design coal'</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate and other analyses</strong> (air dried)</td>
<td>Calorific value, MJ/kg</td>
<td>12-17</td>
</tr>
<tr>
<td></td>
<td>Moisture content, %</td>
<td>2,5-6,0</td>
</tr>
<tr>
<td></td>
<td>Ash, %</td>
<td>34-58</td>
</tr>
<tr>
<td></td>
<td>Volatile matter, %</td>
<td>9-22</td>
</tr>
<tr>
<td></td>
<td>Fixed carbon, %</td>
<td>19-39</td>
</tr>
<tr>
<td><strong>Petrographic analyses (including mineral matter)</strong></td>
<td>Vitrinite, %</td>
<td>1,5-28</td>
</tr>
<tr>
<td></td>
<td>Exinite, %</td>
<td>0-8,4</td>
</tr>
<tr>
<td></td>
<td>Inertinite, %</td>
<td>43-66</td>
</tr>
<tr>
<td></td>
<td>Total reactive macerals, %</td>
<td>8-33</td>
</tr>
<tr>
<td></td>
<td>Mineral matter</td>
<td>18-31</td>
</tr>
<tr>
<td></td>
<td>Mean random reflectance, V%</td>
<td>0,51-1,8</td>
</tr>
</tbody>
</table>

**COMBUSTION IN RELATION TO PETROGRAPHY**

The mechanisms involved in the processes of combustion and the differential rates of reaction have been well documented in the literature and fall outside the scope of this paper. However, it appears that the theories are often confusing and contentious, and much has still to be investigated. For this reason, the observations and interpretations by Kautz\textsuperscript{2} and Shibaoa and Ramsden\textsuperscript{1} of coal behaviour in relation to the hot char emanating from a burner flame are important, and may be applicable in principle to most types of combustion.

As particles of vitrinite and exinite in bituminous coals are rich in volatile matter, they degasify and swell rapidly when they reach the flame of the burner, increasing their microscopically observed porosity, and therefore their surface area, and they begin to burn-out in the proximal and hottest zones of the flame (1200 to 1500°C according to the type of burner). These hot zones are produced by the combustion of volatile components at the point of entry.

Inertinite macerals, on the other hand, fail to degasify and swell, thus producing a limited surface area for ignition and combustion. Such processes begin to take place on the outer surfaces of the particles as they pass through the hottest zones, and continue as these particles have passed into the lower temperature zones in the distal portions of the flame. If the particles are too large or the time in the hot zones is too short, complete burn-out cannot take place before the particle passes into the cooler regions of the furnace and ultimately through the convection banks in the boiler, and the particles pass through as unburnt carbon or char in the fly ash.

This description suggests that, contrary to much pub-
lished data, combustion is largely a surface reaction, limited mainly to the exposed outer surfaces of coal particles and the inner surfaces of the pores created during swelling of the vitritine and exinite macerals. Although sub-microscopic porosity is often invoked to explain the diffusion mechanisms in combustion, it does not appear to play as important a role as originally proposed, at least in coal particles larger than 0.1 mm in size.

In terms of reactivity in relation to oxygen, it has also been accepted that oxidation attacks the aliphatic chains of the coal molecules first. Thus vitritine and exinite, being considerably more aliphatic than inertinite in all ranks, are the first maceral constituents to react to the processes of both oxidation and devolatilization. In these cases, bond breakages on the aliphatic chains during early oxidation create active sites on the aromatic units, which react further at elevated temperatures by absorption and desorption of oxygen, carbon monoxide, and carbon dioxide during the combustion of char. In the case of inertinite, however, the aliphatic components are reduced as the macromolecules are composed mostly of carbon-rich aromatic nuclei. Owing to the lack of swelling as a result of low volatile content, and to the low proportions of active sites as a result of fewer aliphatic chains, oxidation is limited mainly to the margins of the particles, with the result that combustion is initially far slower than that of vitritine and exinite.

These conclusions are drawn from the process of oxidation as outlined by Van Krevelen and others, and from a comparison drawn between the processes of hydrogenation and combustion based upon the recent work of Shibaoaka.

Although the description given above pertains to the combustion of pulverized coal, the principles are the same for other forms of combustion. For example, in industrial boilers such as chain-grate stokers, recent research in South Africa has highlighted the importance of a consistent petrographic feedstock of reactive macerals relative to inert ones in order to ensure timely and efficient ignition and burn-out. This is in addition to the normal specifications of non-cooking coals with low swelling indices (important for permitting free air flow through the bed), moderate ash content, and restricted fine sizes.

Similar problems in combustion performances have been encountered in gasification processes and in fluidized-bed combustion in Southern Africa. In many cases additional testwork using thermogravimetric analyses has been employed. In some instances, however, the correlation between these results and performance has been in question. In such cases, petrographic examination and mineral analyses have highlighted the problem. Differences in parameters such as coal size, operating conditions, and air-mix requirements are well known; however, recent research investigations have now shown that the organic composition and rank are as applicable in these fields as they are in the combustion of pulverized coal.

SUMMARY AND CONCLUSIONS

This paper has reviewed the differences in fundamental composition between Palaeozoic coals of the northern and southern hemispheres and has related these aspects to combustion, especially of pulverized fuel. These points can be summarized as follows.

The Significance of Coal Characterization in Combustion

For general as well as practical purposes, the coals of Southern Africa differ from European and other Laurasian coal in being variable between regions and seams, and in generally possessing relatively high ash-fusion temperatures, characteristic low sulphur, sodium, potassium, iron, and chlorine contents, and relatively high ash and inertinite contents. These qualitative differences impose specific characteristics to these coals, many of which have recently been turned to advantage, as shown in one of Eskom's power stations (Lethabo).

The significance of these differences lies in the combustion performance of the coals from each region. In terms of boiler design, the inertinite-rich, lower-volatile coals of Gondwana have been shown to burn well with a strong hot flame but, for maximum ignition and combustion, they require slightly finer pulverizing, i.e. not less than 75 per cent below 75 μm, slightly higher secondary-air temperature, and longer residence times in the furnace.

Such modifications, when applied to high-ash coals, have the added advantage of thermally cracking the ash-rich and detrital forms of coals, thereby imposing self-inflicted breakdown into size ranges and so enhancing combustion performance. However, of concern under these circumstances is the ash-fusion temperature of individual particles of ash at these elevated temperatures. Under these conditions, minerals may begin to melt, and in this viscous condition have been known to adhere to the burner surrounds and furnace walls within the furnace zone, and even the convection bank inlet zone. Adequate spacing between the burners and furnace side walls has been found to prevent such effects. This provision serves to provide additional burn-out time for the particles and therefore a cooling-down effect prior to contact with any surfaces.

In terms of pollution, the relatively high ash-fusion temperatures, lower sulphur and chlorine contents, low sodium, potassium, and iron contents that are characteristic of the Southern African coals render them acceptable for utility purposes. Coals with such characteristics preclude the need for costly removal of pollutants, whether by mine beneficiation or atmospheric methods.

The evidence summarized in this paper indicates that the coals of the Gondwana region, and Southern Africa in particular, are not necessarily poor only different. Their fundamental nature has brought about an evolution in the form of improved boiler-plant design and fuel processing for third world countries. Such developments are likely to be more evident as the remaining high-grade feedstocks for the international steam-coal trade are used up and the use of low-grade products becomes more cost-effective in the longer term.

Characteristics of Laurasian and Gondwana Coals

The characteristics of coals in the Laurasian and Gondwana provinces can be summarized as follows.

1. Sufficient evidence exists to prove that conventional analyses, as defined by ASTM, ISO, and other standards organizations do not reveal the true nature and performance characteristics of coal, i.e. coals of
similar proximate and ultimate analyses may exhibit completely different technological behaviour.

(2) Coals from different regions of the world, and indeed within one coalfield or one seam, may vary considerably in their fundamental composition, and therefore in their performance, despite similar results from chemical or empirical analyses.

(3) The petrographic characteristics (i.e. organic composition and rank) of coals have been shown to play a very important role in combustion behaviour, and they therefore need to be considered as equally important as those of minerals and their resultant ashes in the combustion assessment of a coal.

(4) Changes in environmental regulations, the exhaustion of reserves, and changes in transport economics all present opportunities for changes in the sources of fuel supply both domestically and internationally. This results in potential exposure to widely variable types of coal.

(5) As present tests are inadequate for the full characterisation of coals, and as sources of supply may vary more readily than in previous decades, it is extremely desirable to extend the tests to be carried out on coals from new sources before any design or construction work is begun on proposed combustion systems or, conversely in the case of existing systems, to ensure that coals are selected on the basis of compatibility with the requirements of a specific system.

Despite the fact that modern combustion equipment can be designed to accommodate any type of fuel, thus overcoming the ever-increasing problem of the poorer qualities and lower grades of coal being mined, it is necessary to establish better evaluation, characterisation, and specification of feedstocks than has been the custom in the past. Towards this end, new characterisation tests and analyses are already playing a very important and integral role. This development has been substantiated by the fact that, in the newly proposed International Classification for Hard Coal, three new specifications have now been added to the conventional ones of volatile matter, calorific value, and caking–cooking capacity—namely, the petrographic parameters of

(i) vitrinite reflectance, determining rank,
(ii) distribution of inertinite, determining the proportion of inert organic matter, and
(iii) blend characteristics of a coal, determining the compatibility of the various ranks within a blend in order to maintain efficient quality control.

In terms of technological importance, coal petrography, thermogravimetric analyses, and drop-tube furnace tests have now become recognised as functional and fundamental tools in the evaluation and characterization of coal for combustion purposes. They provide a further dimension to the understanding of its constitution, and a supplement to the empirical analyses conventionally used to characterize this important fuel commodity.

REFERENCES

5. KAUST, K. Importance of maceral content in regard to the properties of coals in worldwide origin, and its effects on combustion chamber design of large dry furnaces. V.G.B. Krafts- werktechnik 62, Heft 3, Mar. 1982, p. 205.
11. GHOSE, S. Impact of quality on non-coking coals in the power generation problems in India. Dhanbad (India), Central Fuel Research Institute, Internal report, 1983.
17. COMBUSTION WORKING GROUP. Reports.
18. CUMMINGS, P. Personal communication.
19. ANDERSON, Personal communication.
23. STURBINGTON and VLEESKENS. Personal communication.
**Workshop on applied measurements**

The 1st IFAC Workshop on Applied Measurements in Mineral and Metallurgical Processing is to be held in Sabi-Sabi Game Park, Transvaal, South Africa, from 11th to 14th October, 1988.

This is the first workshop of the IFAC’s Application Committee’s Working Group in Mining, Mineral and Metal Processing, which is specifically concerned with the application of process measurements in mineral and metallurgical processing.

It is intended that this meeting will provide the platform for researchers, developers, and users to discuss details of the techniques that can lead to wider use and benefit in the industry. The meeting is also intended to help identify shortcomings and possible areas of research in this important field.

The Workshop will be of interest to technologists, engineers, and metallurgists concerned with the implementation of measurement and control techniques in the mineral and metallurgical industry, and to research and development personnel who wish to make their science and knowledge available to the benefit of the industry.

Sabi-Sabi is set in the Sabi Sand Wildtuin (Game Park), one of the World’s largest private game reserves, adjacent to the famous Kruger National Park and situated in 70 000 hectares of Lowveld bushveld, 500 kilometres northeast of Johannesburg, near Skukuza. All African species indigenous to the area are to be found in the reserve, including lion, leopard, rhino, buffalo, hippo, giraffe, cheetah, hyena, wild dog, and many antelope species.

The provisional programme is as follows:

1. **Measurements in Mineral Processing** (3 Sessions)
   - Media charging based on Kalman filter estimates of volumetric mill filling, J.A. Herbst, Control International Inc., Utah, USA.
   - A computer-based automatic flowmeter calibration rig, B.E. White, Rustenburg Platinum Mines, RSA.
   - Flow measurement in slurries with switched d.c. field, R. Schaefler, Flowtec, Switzerland.
   - Unique conveyor mass flow measurement and mass balancing techniques, J.H. Potgieter, De Beers Diamond Research Laboratory, RSA.
   - Sensing techniques in ore sorting, P. Wolf, Flow Electronics (Pty) Limited, RSA.
   - Realtime measurement of the size distribution of rocks on a conveyor belt, T.B. Lange, Mintek, RSA.
   - The feasibility of an on-line measurement of size distribution of a slurry, P. de W. Mailer, Mintek, RSA.
   - The feasibility of on-stream X-ray fluorescence analysis for precious metals, P.J. Jerman, Bateman Process Instrumentation, RSA.
   - In search of on-line process measurements in gold extraction, D.A. Vetter and Q. Lyon, Mintek, RSA.

2. **Measurements in Metallurgical Processing** (2 Sessions)
   - Modern blast furnace instrumentation, Y. Yoshitani, University of Nagaoka, Japan.
   - Measurement and control techniques in a basic oxygen furnace, G.F. Rautenbach, Iscor, RSA.
   - The management of energy in an integrated steel works, De B. Cilliers, Iscor, RSA.
   - Wall thickness measurement of hot tubes at 1230°C with a laser ultrasonics system, R. Keck, Betriebsforschungsanstalt, FRG.
   - Non-intrusive on-line measurement of massflow for pneumatically conveyed solids by using correlation measuring techniques, T. Boeck, Endress & Hauser, FRG.
   - Digital signal processing procedures in eddy current test instrumentation, J.O. Gray and M.R. Bahramparvar, University of Salford, UK.

Enquiries should be directed to:

**Workshop Secretariat**
Mintek
Private Bag X3015
Randburg 2125
South Africa.
Telephone: (011) 793-3511
Facsimile: (011) 793-2413
Telex: 4-24867 SA.

---

MAY 1988
JOURNAL OF THE SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY