# CHARACTERISATION OF SOME NIGERIAN COALS FOR POWER GENERATION

**BY**

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## DECLARATION

I declare that the work in this Dissertation entitled "Characterisation of Some Nigerian Coals for Power Generation" has been carried out by me in the Department of Mechanical Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

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## CERTIFICATION

This dissertification entitled **CHARACTERISATION OF SOME NIGERIAN COALS FOR POWER GENERATION** by Michael CHUKWU meets the regulations governing the award of the degree of Master of Science in Mechanical Engineering of the Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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## ABSTRACT

Five coal samples from Odagbo (Kogi State), Owukpa (Benue State), Ezimo (Enugu State), Amansiodo (Enugu State) and Inyi (Enugu State) weresubjected to proximate analysis, ultimate analysis, calorific value determination, petrographic and thermogravimetric analysis to determine their suitability for power generation. Tests were carried out at the laboratories of Advanced Coal Technology, South Africa (now Bureau Veritas Testing and Inspections South Africa, BV-TISA) and the Institute of Applied Materials of the University of Pretoria. Based on analysis of results of tests carried out, Amansiodo coal is a bituminous, low sulphur and medium ash coal; while Owukpa coal is a sub-bituminous A, low sulphur, low ash coal rich in huminites. In addition, Odagbo coal is a sub-bituminous B, medium sulphur, low ash coal rich in huminites; Ezimo coal is a sub-bituminous C, low sulphur, high ash coal; while Inyi coal is a sub-bituminous C, low sulphur, high ash coal.Between Odagbo and Owukpa sub-bituminous coals, Owukpa has a lower ignition temperature (283.63$^{o}$C) due to its higher volatile matter content (39.1%). However, Ezimo sub-bituminous coal, which has a lower volatile matter (31.1%) unexpectedly has the same ignition temperature as Owukpa (283.63$^{o}$C) due to its higher liptinite content (7.2%) when compared with that of Owukpa (2.9%). The five (5) coal samples analysed can be used for power generation using circulating fluidised bed combustion (CFBC) technology due to its tolerance of a widevariety of coals and particle sizes. Amansiodo coal is suitable for power generation using pulverised coal combustion technology based on comparison of its gross calorific value (27.48MJ/kg), ash content (8.6%), inherent moisture content (5.4%), sulphur content (0.92%), etc with requirements published by coal-fired power plant operators. Gross calorific values, inherent moisture and contents of Odagbo, Owukpa, Ezimo and Inyi sub-bituminous coals make them largely suitable for pulverized coal combustion when

compared with the coal fuel used for the Genessee Phase 3 power station in Canada. The ease of combustion of the coal samples in decreasing order is Odagbo, Owukpa, Inyi, Ezimo and Amansiodo. The ignition temperatures of the coals increase with decreasing volatile matter content, their calorific values are strongly correlated with the fixed carbon, elemental carbon, volatile matter and hydrogen contents in decreasing order.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the Study

Access to energy, especially electricity, is a driving force for economic and social development (Sambo*et al.,* 2009). Energy is a key factor in industrial development and in providing vital services that improve the quality of life. Traditionally, energy has been regarded as the engine of economic progress. Limited access to energy is a serious constraint to development in the developing world, where the per capita use of energy is less than one sixth that of the industrialised world(IAEA, 2005).It is widelyaccepted that there is a strong correlation between socio-economic development and theavailability of energy.

The electricity demand in Nigeria far outstrips the current epileptic supply. Nigeria is faced with acute electricity supply problems, which is hindering its development notwithstanding the availability of vast natural resources in the country (Sambo *et al.,* 2009). There are currently 23 grid-connected generating plants in operation in the Nigerian Electricity Supply Industry (NESI) with a total installed capacity of 10,396.0 MW and available capacity of 6,056 MW. Most generation is thermal based, with an installed capacity of 8,457.6 MW (81% of the total) and an available capacity of 4,996 MW (48% of the total). Hydropower from three major plants accounts for 1,938.4 MW of total installed capacity and an available capacity of 1,060 MW (KPMG Nigeria, 2013). Total power generation as at 11 December, 2014 stands at 3,385.9 MWe as displayed on the website of the Federal Ministry of Power (http://www.power.gov.ng).

The Nigerian government, in a bid to fix this problem, has developed a roadmap for power sector reform in Nigeria. Some parts of the roadmap read as follows (The Presidency, Federal Republic of Nigeria, 2010):

> "In view of the high capital costs and long lead times required to develop commercial power generation through solar, wind, nuclear and biomass, the Federal Government will focus its development efforts on hydro, coal and natural gas …the Federal Government is committing to focus on electricity generation in three areas, namely: Hydro, Coal and Natural Gas, of which the latter represents the largestresource for fuel-to-power… Nigeria will largely rely on hydro, coal and natural gas for generation of much of its power over the next decade".

From the foregoing, it is apparent that coal will play a significant role in the effort to achieve the much-needed improvement in electricity generation in Nigeria.

Coal is a solid, brittle, combustible, carbonaceous rock formed by the decomposition and alteration of vegetation by compaction, temperature and pressure. It varies in colour from brown to black and is usually stratified (Speight, 2005). Coal accounts for 41% of the world's energy source for electricity generation. This is distantly followed by gas (21%), hydro (16%), nuclear (13%), oil (5%) and other renewables (3%). Coal is the key fuel for generating electricity on almost all continents, with almost all developed and developing countries relying on coal for the stable and secure supply of electricity (World Coal Association, 2012).The 2011 Electricity information published by the International

EnergyAgency (IEA) showing the percentage contribution of coal for electricity generationin some countries is listed in Table 1.1.

**Table 1.1: Coal in Electricity Generation**

| Country | Coal usage for electricity (%) | Country | Coal usage for electricity (%) |
|---|---|---|---|
| Botswana | 100 | Zimbabwe | 46 |
| Mongolia | 96 | USA | 45 |
| South Africa | 93 | Germany | 42 |
| Poland | 88 | United Kingdom | 29 |
| PR China | 78 | Turkey | 28 |
| Australia | 77 | Japan | 23 |
| Kazakhstan | 75 | Netherlands | 21 |
| India | 68 | Vietnam | 18 |
| Czech Rep. | 56 | Russia | 16 |
| Morocco | 50 | Canada | 15 |
| Denmark | 49 | France | 5 |

Source: World Coal Association, 2012

Coal also provides an affordable and reliable source of electricity generation. A Comparison of electricity generation costs across international studies (US$/MWh) is shown in Table 1.2. This proves that coal still remains the cheapest source of electricity in the world today.

**Table 1.2: Comparison of Electricity Generation Costs across International Studies (US$/MWh)**

| | Researching Organisation | | | | | |
|---|---|---|---|---|---|---|
| Source | IEA/NEA (2005) | CBO (2008) | EC (2008) | EPRI (2008) | House of Lords (2008) | MIT 2009 |
| Coal | 28 – 75 | 56 | 52 – 71 | 64 | 82 | 62 |
| Gas | 44 – 69 | 58 | 65 – 78 | 80 | 78 | 65 |
| Nuclear | 33 – 74 | 73 | 65 – 110 | 73 | 90 | 84 |
| Biomass | 54 – 109 | n/a | 104 – 253 | 80 | 180 | n/a |
| Hydro | 69 – 262 | n/a | 45 – 240 | n/a | n/a | n/a |
| Wind | 50 – 156 | n/a | 97 – 181 | 91 | 146 – 162 | n/a |
| Solar PV | 226 – 2031 | n/a | 674 – 1140 | n/a | n/a | n/a |

Source: World Coal Association, 2012
IEA/NEA: International Energy Agency/Nuclear Energy Agency, CBO: Congressional Budget Office, EC: European Commission, EPRI: Electric Power Research Institute, MIT: Massachusetts Institute of Technology

The proportion of electricity generated from coal is currently on the increase. Under the International Energy Agency's reference scenario, annual electricity generation from coal

could more than double between 2004 and 2030. Even the alternative scenario of lower growth shows almost a 58% increase in annual coal-generated electrical units over the same period. Table 1.3 shows data from the reference scenario.

**Table 1.3: World Electricity Generation from Major Fuels, IEA Reference Scenario**

| | **Year** | **2004** | | **2015** | | **2030** | |
|---|---|---|---|---|---|---|---|
| **Fuel** | **Total Generation** | **TWh** | **% share** | **TWh** | **% share** | **TWh** | **% share** |
| | | **17, 408** | **100** | **24, 816** | **100** | **33, 750** | **100** |
| Coal | | 6, 917 | 39.7 | 10, 609 | 42.8 | 14, 703 | 43.6 |
| Oil | | 1, 161 | 6.7 | 1, 195 | 4.8 | 940 | 2.8 |
| Gas | | 3, 412 | 19.6 | 5, 236 | 21.1 | 7, 790 | 23.1 |
| Nuclear | | 2, 740 | 15.7 | 3, 108 | 12.5 | 3, 304 | 9.8 |
| Hydro | | 2, 809 | 16.1 | 3, 682 | 14.8 | 4, 749 | 14.1 |
| Renewables (excluding hydro) | | 369 | 2.1 | 986 | 4.0 | 2, 264 | 6.7 |

Source: International Energy Agency, 2007

Developing economies have a particularly strong dependency on coal for power production, and the rate of growth in coal's contribution to electricity supply in these countries will be greatest, as Table 1.4 shows.

**Table 1.4: Developing Countries Electricity Generation from Major Fuels,IEA Reference Scenario**

| | **Year** | **2004** | | **2015** | | **2030** | |
|---|---|---|---|---|---|---|---|
| **Source** | **Total Generation** | **TWh** | **% share** | **TWh** | **% share** | **TWh** | **% share** |
| | | **5, 754** | **100** | **10, 749** | **100** | **17, 001** | **100** |
| Coal | | 2753 | 47.8 | 5659 | 52.6 | 8979 | 52.8 |
| Oil | | 580 | 10.1 | 670 | 6.2 | 616 | 3.6 |
| Gas | | 983 | 17.1 | 1955 | 18.2 | 3389 | 19.9 |
| Nuclear | | 142 | 2.5 | 322 | 3.0 | 523 | 3.1 |
| Hydro | | 1239 | 21.5 | 1928 | 17.9 | 2827 | 16.6 |
| Renewables (excluding hydro) | | 56 | 1.0 | 215 | 2.0 | 668 | 3.9 |

Source: International Energy Agency, 2007

Available data show that coal of sub-bituminous grade occurs in about 22 coal fieldsspread in over 13 States of the Nigerian Federation. Table 1.5 shows the existing/potential coal mines in Nigeria (Kibiya, 2012).

**Table 1.5: Existing/Potential Coal Mines/Sites in Nigeria**

| S/N | Mines Location | State | Type of Coal | *Estimated reserves | *Proven Reserves | Mining method |
|---|---|---|---|---|---|---|
| 1 | Okpara Mine | Enugu | Sub- Bituminous | 100 | 24 | Underground |
| 2 | Onyeama | Enugu | Sub- Bituminous | 150 | 40 | Underground |
| 3 | Ihioma | Imo | Lignite | 40 | N.A | Open-cast |
| 4 | Ogboyoba | Kogi | Sub- Bituminous | 427 | 107 | Opencast/Underground |
| 5 | Ogawashi Azagba/ Obomkpa | Delta | Lignite | 250 | 63 | Opencast/Underground |
| 6 | Ezimo | Enugu | Sub- Bituminous | 156 | 56 | Opencast/Underground |
| 7 | Inyi | Enugu | Sub- Bituminous | 50 | 20 | Opencast/Underground |
| 8 | Lafia/Obi | Nasarawa | Bituminous (Cokable) | 156 | 21.42 | Opencast/Underground |
| 9 | Oba/Nnewi | Anambra | Lignite | 30 | N.A | Underground |
| 10 | Afikpo/Okigwe | Ebonyi/Imo | Sub- Bituminous | 50 | N.A | Underground |
| 11 | Amansiodo | Enugu | Bituminous (Cokable) | 1000 | N.A | Underground |
| 12 | Okaba (Odagbo) | Kogi | Sub- Bituminous | 250 | 3 | Opencast/Underground |
| 13 | Owukpa | Benue | Sub- Bituminous | 75 | 75 | Open |
| 14 | Ogugu/Awgu | Enugu | Sub-Bituminous | N.A | N.A | Underground |
| 15 | Afuji | Edo | Sub- Bituminous | N.A | N.A | Underground |
| 16 | Ute | Ondo | Sub- Bituminous | N.A | N.A | Underground |
| 17 | Doho | Gombe | Sub- Bituminous | N.A | N.A | Underground |
| 18 | Kurumu | Gombe | Sub- Bituminous | N.A | N.A | Underground |
| 19 | Lamja | Adamawa | Sub- Bituminous | N.A | N.A | Underground |
| 20 | Garin maigungu | Bauchi | Sub- Bituminous | N.A | N.A | Underground |
| 21 | Gindi Akwati | Plateau | Sub- Bituminous | N.A | N.A | Underground |
| 22 | Jamata Koji | Kwara | Sub- Bituminous | N.A | N.A | Underground |

Source: Kibiya, 2012 * Expressed in Million Tonnes

The proven reserves so far in the country are 639 million tonnes while the inferred reserves are about 2.75 billiontonnes, consisting approximately of 49% sub-bituminous, 39% bituminous and 12%lignitic coals. Up to the early 1960s, coal productionwas significant and dominated the commercial energy supply. It was also thepredominant source of energy for rail transportation and electricity generation (The Presidency, Federal Republic of Nigeria, 2003). Coal presently does not contribute to Nigeria's electricity generation. Of the new

generation stations under construction, only the Oji River Power Plant with a planned capacity of 20MW, is coal-fired (Sambo *et al.*, 2009).

With the development of cleaner coal utilisation technologies such as Carbon Capture and Storage (CCS), coal has shedthe toga of being called a "dirty fuel". The International Energy Agencydescribes CCS as "one of themost promising options for mitigatingemissions in the longer term" while theIntergovernmental Panel on ClimateChange (IPCC) concluded that CCSwas among the technologies with thelargest economic potential to reduceemissions from electricity generation (World Coal Institute, 2008).

Nigeria has made a commitment to pursue vigorously a comprehensive programme ofresuscitation of the coal industry and promote effective utilisation of coal for complementing the nation's energyneeds (The Presidency, Federal Republic of Nigeria, 2003). The Federal Government of Nigeria has awarded contracts for the provision of consultancy services for feasibility studies, detailed engineering design and drafting of contract documents for the development and construction of coal-fired power plants to be located in Enugu, Benue, Kogi and Gombe States (Ogbu, 2011). In addition, the Federal Government of Nigeria, in 2013, signed a Memorandum of Understanding with HTG/Pacific Energy Company Limited, with substantial technical partnership with Chinese experts, for a $3.7 billion coal-to-power projectscripted to provide an initial 1,200 MW power plant to be built at Enugu, using coal from the Ezimo mine (Adetayo, 2013).

With vast supplies of coal and against the backdrop of severe shortages in much needed supply of electricity, it is inevitable that Nigeria must move from rhetoric to concrete action in the development and addition of coal-fired electricity to the nation's electricitysupply mix.

## 1.2 Statement of the Problem

With a conservative peak load forecast of 8,900MW and an average generation of less than 4,000MW, the resultant massive load shedding has made Nigeria an unattractive environment for existing and prospective manufacturers. Manufacturers operating in Nigeria spend a weekly average of N1.8 billion on diesel to run their electric power generating sets (Iba, 2011). In addition, it is claimedby the Manufacturers Association of Nigeria (MAN) that an estimated 60 million Nigerians now own power generating sets for their electricity, while the same number of people spend a staggering N1.56 trillion ($13.35m) to fuel them annually. This is besides private power generation by industrial consumers, which is almost at the same level (Energy Commission of Nigeria, 2009). These reports paint a vivid picture of the problem bedeviling the country.

## 1.3 The Present Research

This research coveredthe characterisationof coal from five deposits in Nigeria which include Odagbo (Kogi State), Owukpa (Benue State), Ezimo (Enugu State), Amansiodo (Enugu State) and Inyi (Enugu State). Estimated reserves of these deposits are 250, 75, 156, 1000 and 50 milliontonnes, respectively (Kibiya, 2012). Analysis carried out include

determination of Proximate Analysis, Calorific Value, Ultimate Analysis, Ash Composition, Ash Fusion Temperature (in oxidising and reducing atmospheres),petrographic analysis and thermogravimetric analysis.

## 1.4 Aim and Objectives

The aim of this research is to characterise coalsfrom five deposits in Nigeria which include Odagbo (Kogi State), Owukpa (Benue State), Ezimo (Enugu State), Amansiodo (Enugu State) and Inyi (Enugu State), thereby enriching the repository of existing data on properties of Nigerian coals and make a strong case for the utilisation of these coals in power generation.

The specific objectives of the research are:

(i) To carry out proximate, ultimate and ash composition analyses of the coal samples.

(ii) The determination of calorific value of the coal samples.

(iii)To determine ash fusion temperature (in oxidising and reducing atmospheres) of the coal samples.

(iv) To carry out petrographic and thermogravimetric analyses of the coal samples.

(v) To compare results of the above analyses with reference values of coal properties for power generation in order to determine the suitability of the coal samples for power generation.

## 1.5 Significanceofthe Research

The quality of the coal used affects most of the costs associated with coal-fired power plants. Proper evaluation of the combustion performance of the coal to ensure optimum utilisation and minimum costs is therefore essential.

This research will help determine the suitability of some Nigerian coals for use in coal-fired power plants, not only in Nigeria, but as an export commodity to other coal-consuming countries around the world. This will assist the potential investor in Nigeria's power sector to make a decision on areas of the coal's performance that may be suspect,requiring further investigation by a larger-scale form of testing (pilot-scale simulation or full-scale testing) and also serve as a justification for investment in such a larger-scale testing.

The significance of this research is further underscored by the present dependence of Nigeria on natural gas- and hydro-powered electricity.The unreliability of natural gas supply due to frequent disagreement over appropriate pricing and pipeline vandalism and the susceptibility of hydro-electric power to weather has made the inclusion of coal-fired electricity into Nigeria's electricitygeneration mix imperative. The argument for nuclearpower has been punctured by recent safety concerns arising from the Fukushima nuclear disasteras raised in the website of Green Peace International (http://www.greenpeace.org).

With world industrial giants such as the United States of America, Peoples Republic of China, Germany, Australia, India and South Africa among countries heavily dependent on coal for electricity generation, Nigeria cannot exclude itself from benefitting from this resource which it has been richly endowed with.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Previous Researchon Nigerian Coals

Olaleye(2003)investigatedsome Nigerian coalsand showed that the relatively low ash and moisture contents, low sulphur content and medium to high calorific value, make Nigerian

coals compare favourably with other sub-bituminous coals in coal-producing countries of the world, thereby making them a good export commodity. They are superior as regards ease of ignition, combustion characteristics and freedom from clinker. The coals burn with a long flame and require large combustion space. They are acceptable boiler fuels if used in suitable appliances such as chain grate stokes or as pulverized fuel. Nigerian coals are suitable as energy fuel for electricity generation for the abandoned Oji Power Station in Enugu State and other proposed power stations at Kogi, Benue, Anambra and Delta States. With the current deregulation of power generation in the country, necessitated by the lack of sufficient power generation by the Power Holding Company of Nigeria (PHCN), Independent Power Producers stand better opportunities.

Kibiya (2012) collected and analysed five (5) coal samples from Lafia-Obi (Nasarawa State), Okaba (Kogi State), Lamja (Adamawa State), Okpara and Onyeama (Enugu State) to determine their properties and classify them by rank using proximate analysis. Auto-ignition temperatures, reactivity and activation energies of the various coal samples were also determined. Results obtained showed that Lafia-Obi coal could be ranked the highest as bituminous (low volatile) coal. Okpara and Onyeama coalsboth were both bituminous A coals, while Okaba coal was found to be sub-bituminous B coal. Lamja coal was found to be a lignite A coal. Findings also revealed a dependence of coal density, reactivity and activation energies on coal type and particle size. The study concluded that Lafia-Obi, Okpara and Onyeama coals may be used for power generation. Lamja and Okaba coals were not recommended for power generation because of their low calorific values.

Laudan (2008) analysed coal samples from Enugu State (Okpara West Area, Okpara West Bank and Onyeama) and Gombe State (Doho and Gamawa) to determine their physical properties and to classify them by rank using proximate analysis. An electric furnace fitted with a 3kW heating element capable of generating heat to a temperature of 900$^{o}$C was constructed and used to determine the auto-ignition temperatures, reactivity and activation energies of the various coal samples. Findings revealed that the reactivity and activation energies of the various coal samples depend on the coal type, source and particle size. While for some coals, the reactivity and activation energies increase with decrease in particle size (Okpara West Bank coal), in others, reactivity and activation energies decrease with decrease in particle size (Onyeama, Okpara West Area and Doho coals). However, in all cases, reactivity increases with increase in temperature.

Jauro and Chukwu (2011) investigated three Nigerian coals (Onyeama, Lafia-Obi and Gairin Maiganga) to determine their suitability in developing formed coke for use as blast furnace coke. Parameters that were usedincluded the shatter index, expressed as percentage stability and friability and mecum index. The highest cumulative percentage stability and the lowest cumulative percentage friability were observed in Lafia-Obi with values of 67.54% and 32.46%, followed by Onyeama with 66.92% and 33.08% and then Garin Maiganga with 55.04% and 44.96% respectively. Medium and low temperature carbonisation of Onyeama and Lafia-Obi coal samples gave an improved and satisfactory percentage stability and friability for semi-cokes.

Suleiman (1992) analysed the moisture content and volatile matter of some Nigerian coals. The results obtained showed that the three coal samples (Enugu, Lafia and Okaba) collected

have low moisture contents, and only the Lafia coal has low volatile matter, thus satisfying the metallurgical requirement for the production of coke.

Isah (1991) carried out proximate and ultimate analysis on Enugu, Lafia and Okaba coals to determine the percentage of ash and total sulphur. The Eschka method was used to determine the total sulphur present. The analysis showed that Lafia coals have high ash and sulphur contents, while Enugu coals have low ash and sulphur contents. The Okaba coals have a little bit higher ash and sulphur contents than the Enugu coals, but much lower values when compared to Lafia coals.

## 2.2 Review of Theoretical Basis for Coal Analysis

### 2.2.1 Coal classification

Coals are classified according to rank, type and grade. The *rank* of coal is its degree of maturation and is an indication of the extent of metamorphism the coal has undergone. Rank is also a measure of carbon content as the percentage of fixed carbon increases with the extent of metamorphism. Lignites and sub-bituminous coals are referred to as being low in rank, while bituminous coals and anthracites are classified as high-rank coals. The heating value of coals increases with increasing rank but begins to decrease in higher rank coals due to significant increase in volatile matter.

Coal *type* is determined by the ultimate microscopic constituents of coal called macerals. The three main groups are characterised by their appearance, chemical composition and optical properties. The three maceral groups are vitrinite (or huminite), exinite (or liptinite) and

inertinite, which in turn can be subdivided into finer classification. In most cases, the constituents can be traced back to specific components of the plant debris from which the coal formed. Petrographic analysis is used to determine maceral types.

The *grade* of coal refers to the amount of mineral matter that is present in the coal and is a measure of coal quality. Sulphur content, ash fusion temperatures and the quantity of trace elements in coal are used to grade coal. Formal classification systems have not been developed with regard to the grading of coal. Coal mineralogy can affect coal combustion and conversion to liquids and chemicals.

The American Standard for Testing and Materials (ASTM) classification system (ASTM D388) is popular in the industry. The ASTM D388 distinguishes among four coal classes, each of which is subdivided into several groups shown in Table 2.1 (Miller, 2005).

**Table 2.1: ASTM Coal Classification by Rank**

| Class/Group | Fixed Carbon[a] (%) | Volatile Matter[b] (%) | Heating Value[b] (Btu/lb) |
|---|---|---|---|
| **Anthracitic** | | | |
| Meta-anthracite | >98 | <2 | - |
| Semi-anthracite | 92-98 | 2-8 | - |
| | | | |
| **Bituminous** | | | |
| Low-volatile | 78-86 | 14-22 | - |
| Medium-volatile | 69-78 | 22-31 | - |
| High-volatile A | <69 | >31 | >14,000 |

| | | | |
|---|---|---|---|
| High-volatile B | - | - | 13,000-14,000 |
| High-volatile C | - | - | 10,500-13,500[c] |
| **Subbituminous** | | | |
| Subbituminous A | - | - | 10,500-11,500 |
| Subbituminous B | - | - | 9500-10,500 |
| Subbituminous C | - | - | 8300-9500 |
| **Lignite** | | | |
| Lignite A | | | 6300-8300 |
| Lignite B | - | - | <6300 |

[a]Calculated on dry, mineral-matter-free coal. Correction from ash to mineral matter is made by means of the Parr formula: mineral matter= 1.08[percent ash + 0.55(percent sulfur). Ash and sulfur are on a dry basis.
[b]Calculated on mineral-matter-free coal with bed moisture content.
[c]Coals with heating values between 10,500 and 11,500 Bru/lb are classified as high volatile C bituminous if they possess caking properties or as subbituminous A if they do not.

Source: Miller, 2005

***Anthracite*** is the highest rank of coal. It is used primarily for residential and commercial space heating. It is a hard, brittle, and black lustrous coal, often referred to as hard coal. It contains a high percentage of fixed carbon and a low percentage of volatile matter. The moisture content of fresh-mined anthracite is generally less than 15%. Its calorific value ranges from 23 to 29.5 MJ/kg on a moist, mineral-matter-free basis (Speight, 2005).

***Bituminous coal*** is a dense coal, usually black, sometimes dark brown, often with well defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke. Its moisture content is usually less than 20% by weight. Its calorific value ranges from 22 to 31.6 MJ/kg on a moist, mineral-matter-free basis (Speight, 2005).

***Sub-bituminous coal***is coal whose properties range from those of lignite to those of bituminous coal, used primarily as fuel for steam-electric power generation. It may be dull, dark brown to black, and soft and crumbly at the lower end of the range, to bright, black,

hard, and relatively strong at the upper end. Sub-bituminous coal contains 20 to 30% inherent moisture by weight. Its calorific value ranges from 17.9 to 25.3 MJ/kg on a moist, mineral-matter-free basis (Speight, 2005).

***Lignite*** is the lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish black and has a high inherent moisture content, sometimes as high as 45%. Its calorific value ranges from 9.4 to 17.9 MJ/kg on a moist, mineral-matter-free basis (Speight, 2005).

### 2.2.2 Coal utilisation

Combustion, carbonation (or coking), gasification and liquefaction have been referred to as the four "grand processes" of coal utilisation (Miller, 2005). Employing the combustion of pulverized coal (PC) in air to raise steam has been the mainstay of coal-based power generation worldwide for almost 100 years. The efficiency of a PC combustion unit depends on a variety of factors: steam conditions, quality of coal used, ambient conditions, plant design, and operational and maintenance practice. A number of advanced coal-fired power generation technologies, cleaner coal technologies (CCTs), as they are often called, have been or are being developed to improve thermal efficiency, to reduce and capture carbon dioxide emissions and to reduce other emissions (e.g. nitrogen oxides, sulphur dioxide and particulates).

#### *2.2.2.1 Pulverised coal combustion (PCC) technology*

Pulverised Coal Combustion is the most commonly used method in coal-fired power plants. The coal is ground (pulverised) to a fine powder, so that less than 2% is +300 µm and 70-75% is below 75 µm, for a bituminous coal. The pulverised coal is blown with part of the combustion air into the boiler plant through a series of burner nozzles. Secondary and tertiary air may also be added. Combustion takes place at temperatures from 1300-1700°C, depending largely on coal rank. The steam generated drives a steam turbine. Residence time of particles in the boiler is typically 2-5 seconds, and the particles must be small enough for complete burnout to have taken place during this time. The technology is well developed, and there are thousands of units around the world, accounting for well over 90% of coal-fired capacity. Pulverised Coal Combustion can be used to fire a wide variety of coals, although it is not always appropriate for those with high ash content (International Energy Agency, 2010).

The efficiency of a steam cycle is influenced by, among other factors, the pressure and superheat and reheat temperatures of the steam. Water/steam reaches the superheat stage where there is no distinction between the liquid and gaseous phases at about 22.1 MPa (221 bar) pressure (Burnard and Bhattacharya, 2011). Above this operating pressure of the steam, the cycle is supercritical and its cycle medium is a single-phase fluid; as a result there is no need to separate water from steam as in the boiler of a sub-critical cycle. Once-through boilers are therefore used in a supercritical cycle.Typical sub-critical steam cycle operating parameters are from 150 to 180 bar pressure andbetween 540$^{o}$C and 565$^{o}$C temperature for superheated steam, with reheat to similartemperatures. Steam cycle operating parameters for

supercritical (SC) plants typically are 245 bar pressure and540$^{o}$C to 570$^{o}$C for superheated steam, with reheat to similar temperatures. Ultra-supercritical (USC) plants operateat steam temperatures of around 600$^{o}$C or higher at present. A switch from sub-critical to currentUSC steam conditions would raise efficiency by around 4 to 6 percentage-points (Burnard and Bhattacharya, 2011).

For low to moderate ash coals, both SC and USC units are available from major boiler and turbine suppliers. These units run around 260 bar main steam pressure and steam temperatures up to 620°C for reheat steam, slightly lower for main steam. Supercritical units are beginning to be introduced in India for high-ash coals. Operating experience at India's Sipat and Barh plants, and the new units to be built as part of the Ultra Mega projects, are expected to open the way for wider use of SC units in both India and other countries that rely on high-ash coals for power generation, such as Bulgaria, regions of China, Poland, Romania and South Africa (Burnard and Bhattacharya, 2011).

#### *2.2.2.2 Fluidised bed combustion technology*

There are two major categories of fluidised bed combustion units: those operating with bubblingfluidised bed combustion (BFBC) and those with circulating fluidised bed combustion (CFBC).Almost all of the recent plant additions have been CFBC units. CFBC

units can tolerate a widevariety of coals and particle sizes and, because of their low operating temperatures and stagedcombustion, produce low levels of $NO_x$ relative to PC boilers. The lower operating temperature isalso ideally suitable for the in situ capture of sulphur dioxide ($SO_2$). The combustion temperature in a CFBC boiler (800–900ºC) is significantly lower than in a PCC boiler (1300–1700ºC), which results in considerably reduced NOx formation compared to PCC. The majority of the sulphur in the coal is captured by limestone that is injected into the furnace; about 90–95% $SO_2$ reduction can be achieved. The lower combustion temperature also limits ash fouling and corrosion of heat transfer surfaces allowing the CFBC to handle fuels that are difficult to burn in a PCC boiler. Even though the combustion temperature of a CFBC boiler is low, the circulation of hot particles provides efficient heat transfer to the furnace walls and allows a longer residence time for combustion and desulphurisation reaction. This results in good combustion efficiencies, comparable to PCC boilers (IEA Clean Coal Center, 2013).

The efficiency of CFBC units issimilar to that of PC units. With around 20 GW operating worldwide, CFBC units can demonstrate significant operating experience. They have the ability to accept a variety of fuels, including a range of coals: from lignites to anthracite, waste coal and biomass.The largest operating sub-critical CFBC unit is of 320 MWe at Jacksonville, Florida. Units of asimilar size also operate in China. Total CFBC plant capacity globally is around 20 GW, and isexpected to grow. Previously only available in sub-critical designs, CFBC technology has nowreached an economic scale for supercritical conditions. The first supercritical CFBC unit (460 MWe, 282 bar/563$^{o}$C/582$^{o}$C) was located at Lagisza (Poland). Designed by Foster Wheeler, this plant is operating and has a design efficiency of

43.3% (LHV, net) on Polish lignite. A second supercritical CFBC unit, a 330 MWe capacity, will be located at the Novocherkasskaya GRES facility in Russia. It is also encouraging to see that a major guideline in China's 11th five-year plan is to build large-scale CFBC units (Burnard and Bhattacharya, 2011).

#### *2.2.2.3 Integrated Gasification Combined Cycle (IGCC)*

Coal-based IGCC uses a combination of gas and steam turbines to produce electricity. The gasused to fire the gas turbine is first made by "gasifying" or partially oxidising the coal to produce a fuel gas, which is then followed by gas cleaning. At present, only six coal-based IGCC plants are in operation. Other plants are either planned or under construction in China and the United States. The net efficiency for existing coal-fired IGCC plants is around 42% (LHV, net). NUON's Shell coal gasification process-based IGCC plant at Buggenum (the Netherlands) achieved up to 43% (LHV) on bituminous coals, which is equivalent to 41% (HHV). Commissioning began in 1993, with a V94.2 gas turbine and a turbine inlet temperature for natural gas of around 1 060°C. In theory, and depending on the choice of gasifier, a modern, high temperature, F-class gas turbine should produce an efficiency of 46% to 47% (LHV, net) or 44% to 45% (HHV, net) using bituminous coals (Burnard and Bhattacharya, 2011).

Entrained flow gasifiers require fine particle sizes, are suitable for all types of coals and operate at temperatures above the melting point of ash. Normal gasifiers require large particle sizes for effective fluidisation and operate at around 900$^{o}$C, i.e. below the melting point of ash. They are particularly suitable for highly reactive, non-caking coals, such as

lignites. Transport gasifiers, developed by KBR, are a hybrid between entrained flow and gasifiers. They can handle both lignites and bituminous coals, and operate at slightly higher temperatures than fluidized bed gasifiers (Burnard and Bhattacharya, 2011).

## 2.3 Characterisation of Coal

The characterisation of coal is vital for the efficient operation of a power plant for electricity generation. Various methods are used for this purpose, e.g. proximate analysis, determining petrographic constituents and reflectance and thermal analysis. These analyses are also used for solving operational problems. Proximate and ultimate analyses are generally not adequate since they cannot be used to explain high amounts of unburned particles and petrographic effects (Kizgut *et al.*, 2003).

There is a wide range of testing and evaluation procedures used to evaluate the performance of coals for pulverized coal combustion. These procedures range in scale from:

(i) Standard laboratory analysis.

(ii) Bench-scale testing to simulate some aspect(s) of the coal's impact on power plant processes.

(iii) Pilot-scale simulation of power plant.

(iv) Testing in full-scale boilers.

However, standard laboratory analyses of coal are often unreliable predictors of power plant performance. Nevertheless, laboratory data may be valuable as an indicator of areas of the coal performance that may be suspect, requiring investigation by a larger-scale form of testing. It also gives a measure of the variability of the coal's quality over the mine. It is

difficult to justify the cost of pilot scale tests on samples that represent every quality. For these reasons, extensive use is made of laboratory analysis as a preliminary predictor (Apriani, 2009).

Since the majority of the standard tests for determining the properties of coal are empirical, the values obtained will depend on the conditions specified. The standard methods have also been criticised as the conditions for determining some of the properties do not reflect thoseoccurring in a power plant. For example, the final temperatures, heating rates and residence times given in the standards for determining the volatile-matter content of a coal differsignificantly from the conditions experienced in a pulverised coal fired boiler where final temperatures are over 1500°C, heating rates are 103–106 K/s and residence times of around 1sec occur. Thus, the total volatile yield in a boiler is higher than the standard volatile-matter determination (where it is determined at 900°C after a residence time of several minutes). Other techniques for evaluating coals at combustion conditions nearer those in power plants have been proposed. These include the use of thermal gravimetric analysers, drop-tube furnaces, heated wire grids and pyroprobes (Carpenter *et al.*, 2007).

In addition, the standard tests reflect the average composition of the coal. However, coal is a heterogeneous, complex material. During combustion the coal particles, which have varying organic and inorganic (mineral-matter) compositions, can behave in completely different ways.

It should be emphasised that a coal (or blend) being evaluated must truly represent the mass of material from which it was taken. Various national and international standards specify the

procedures for collecting samples for analysis; following these should minimise any bias. However, the question still remains as to whether the milligram- or gram-scale samples used in the standard procedures (or in bench-scale tests) can provide a truly representative sample of the tonnes of coal consumed in a boiler (Carpenter *et al.*, 2007).

There are over sixty analyses that are used to evaluate the physical, chemical and technological properties of coal. For combustion purposes however, the characterization of coal can be carried out in two levels: empirical and fundamental. The empirical level consists of threeimportant laboratory analyses, two of which are chemical analyses and one is a calorific value determination. The fundamental level, which is an investigation of the organic and inorganic constituents that are "building blocks" of coal, is referred to as the fundamental or petrographic analysis of coal, and is made with a microscope. Swelling Index is also a useful analysis. Of importance to further combustion test work are thermogravimetric analysis and drop-tube furnace tests. They are used to assess the rate of devolatilisation and carbon consumption of coals under various experimental conditions, each set to emulate boilers of different types.

In terms of technological importance, coal petrography, thermogravimetric analyses, and drop-tube furnace tests have now become recognized 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 (Falcon and Ham, 1988).

### 2.3.1 Proximate analysis

The proximate analysis of coal gives the relative amounts of the moisture, ash, volatile matter and fixed carbon as determined by a series of prescribed or standard test methods. It was developed as a simple means of determining the distribution of products obtained when the coal sample is heated under specified conditions. Moisture content, volatile matter (consisting of gases and vapours driven off during pyrolysis), and ash (the inorganic residue remaining after combustion) are all determined by subjecting the coal to prescribed temperature levels for prescribed time intervals. The losses of weight are, by stipulation, due to loss of moisture and, at higher temperature, loss of volatile matter. The residue remaining after ignition at the final temperature is called ash. Fixed carbon, the combustible solid left after volatile matter is distilled off is calculated by difference. Fixed carbon consists mostly of carbon but also contains hydrogen, oxygen, sulphur and nitrogen not driven off with the gases. Inherent moisture, volatile matter and ash content are all determined by ASTM D-3173, ASTM D-3175 and ASTM D-3174 test methods, respectively (Speight, 2005).

Moisture content increases heat loss due to evaporation and superheating of vapour helps, to a limit, in binding fines, aids radiation heat transfer,affects coal (and ash) handling and storage (coal flow properties, behaviour in frost, dust emissions), andpulveriser capacity. An increase in moisture content increases the flue gas volume flow rate and influences theexcess air requirements with consequent effect on fans, air preheater and pollution control equipment.Increased moisture lowers thermal efficiency of boiler and can influence burner design (United Nations Environment Programme, 2006).

Volatile matter proportionately increases flame length and helps in easier ignition of coal, sets minimum limit on the furnace height and volume, influences secondary air requirement and distribution aspects and influences secondary oil support. Ash content reduces handling and burning capacity, increases handling costs, affects combustion efficiency and boiler efficiency and causes clinkering and slagging.Fixed carbon gives a rough estimate of heating value of coal (United Nations Environment Programme, 2006).

### 2.3.2 Ultimate analysis

The ultimate analysis of coal involves determination of the weight percent carbon as well as sulphur, nitrogen and oxygen (usually estimated by difference). Trace elements such as chlorine, mercury and other elements that occur in coal are often included as part of this analysis. Carbon determination includes carbon present as organic carbon occurring in the coal substance and any carbon present as mineral carbonate. The hydrogen determination includes hydrogen present in the organic materials as well as hydrogen in all of the water associated with the coal. In the absence of evidence to the contrary, all of the nitrogen is assumed to occur within the organic matrix of the coal. On the other hand, sulphur occurs in three forms in coal: as organic sulphur compounds; as inorganic sulphides that are, for most part, primarily the iron sulphides pyrites and marcasite ($FeS_2$); and as inorganic sulphates (e.g. $Na_2SO_4$, $CaSO_4$).

### 2.3.3 Calorific value

Calorific (or heating) value is a measure of the amount of energy that a given quantity of coal will produce when burned, expressed in Joules/Kilogram (J/kg). Many methods for determining calorific value exist. However, a more recent test method is the ASTM D-5865.

For practical applications in a coal-burning facility, corrections are made to the gross calorific value to account for the water vapour. The net calorific value is thus defined as the heat produced by combustion of a unit quantity of coal at constant atmospheric pressure under conditions such that all water in the products of combustion remains in the form of vapour (Speight, 2005). Calorific value determines the quantity of coal per unit of output and coal mass flow. It also affects the capacity of the furnace,pulverisers, burners, feeding systems, fans, pollution control equipment, and coal and ash handlingsystems (Carpenter *et al.*, 2007).

### 2.3.4 Petrographic analyses

Petrographic analyses of a single coal provide information about the rank, the maceral and microlithotype compositions and the distribution of mineral matter in the coal. The conventional microscopical investigations are carried out in reflected light at a total magnification of between 250 and 500. The equipment required for use is an ore microscope, with photomultiplier, digital read-out, and where possible, a computer attachment for the processing of data. The type of coal is determined petrographically by group maceral analysis and/or microlithotype analysis; the rank is measured by means of vitrinite reflectance. The techniques used are those recommended by the International Committee for Coal and Organic Petrology as incorporated in International Organisation for Standardisation (ISO) 7404-4, Parts 1 to 5 (Falcon and Snyman, 1986).

To prepare the coal for statistical analysis, the sample is crushed to pass a 1mm sieve and then riffled to obtain a 15g sample as representative as that used in conventional proximate analyses. The finely ground sample is mixed with epoxy resin and moulded into a particulate

block, after which the surface of each block is ground and polished to the required level for petrographic analysis(Falcon and Snyman, 1986).

Maceral analyses are carried out under oil-immersion using 25x, 32x, 50x or even 60x oil immersion objectives and an automatic point counter at traverse spacings of 0.4mm and intervals between the traverses of 0.5mm. At least 500 points (excluding binding resin) are counted and depending on the purpose of the analysis, visible minerals may be ignored, counted collectively or individually(Falcon and Snyman, 1986).

The percentage of monochromatic green light with a wavelength of 546 nm which isreflected from an area of well polished particulate block is compared with that reflected under the same conditions from a standard known reflectance. 100 readings are usually taken on different vitrinite particles evenly distributed over the polished surface of the block. The results are expressed as a mean reflectance value and also in the form of a reflectogram which shows the vitrinite-class distribution. The reflectance distribution can provide valuable information about the rank of the coal. Coal having a mean random vitrinite (huminite) reflectance less than 0.40% is lignite or brown coal while a reflectance equal to or greater than 0.40% but less than 0.50% indicates sub-bituminous coal(Falcon and Snyman, 1986).
Coal petrography affects grindability (pulveriser performance), combustion behaviour and efficiency (reactivity, burnout) andburner settings (Carpenter *et al.*, 2007).

#### *2.3.4.1 Macerals*

Three maceral groups form the foundation of petrography namely: vitrinite, exinite and inertinite. Each of these groups can be subdivided into more finely defined sub-macerals, all

of which share similar chemical and physical properties within each group. Vitrinites are subdivided into three subgroups and include textinite, ulminite, collotelinite, attrinite, gelinite, etc. Inertinites include fusinite, semifusinite, macrinite, micrinite, etc. Exinites (liptinites) include sporinite, cutinite, bituminite, alginate, etc.

In addition, based on reactivity, macerals are broadly divided into reactive and inert macerals. The reactive group consists of vitrinite, exinite (liptinite) and reactive semifusinite (RSF); while the inerts include inert semifusinite (ISF), fusinite,micrinite and minerals.

**Vitrinite** (also referred to as ***huminite*** in brown coals) is formed from cell wall material and cell fillings of wood plant tissue (leaves, roots, branches and trunks). Vitrinite does not have a defined structure due to the process of gelification. Vitrinite particles are dark to light grey in colour and can be almost white in antharacite.

***Inertinites*** are formed from the same material as vitrinite but in this case little or no gelification took place and the peat was strongly altered by oxidising conditions. The most obvious reactive behaviour of inertinite is during combustion where it burns readily. Inertinite rich particles may have a longer burn out time compared with vitrinite but much of the difference appears to be due to the tendency of inertinite to occur as larger fragments. ***Fusinites*** are easily identified by their high reflectance, almost gold in colour. ***Micrinites*** are identified by their small grained "sugar like" texture and are white to yellow in colour. Inertinite has a much wider variety of macro and micro structures than vitrinite. It can range from very well structured porous forms to an almost undefined nonporous gelified structure closely resembling vitrinite. This undefined structure is called ***semi fusinite*** and a part of this

is termed semi-reactive fusinite which, if heated above $600^{O}C$ forms isotropic coke unlike the anisotropic coke formed by vitrinite. It is also responsible for the difficulties when coals containing significant amounts of this maceral group are used. Reactive semifusinite is identified by a pale grey colour and some of the original visible cell structure while inert semifusinite is identified by cell structure and colour which is white to yellow white (W. Swanepoel, personal communication, October 24, 2014).

The term ***exinite*** (now referred to as ***liptinite***) is used to describe a chemically distinct group of plant parts such as fossil algae, spores, cuticles and resins. This maceral group contains the highest amount of volatile matter of all the macerals. It produces waxes, fats and oils and is the darkest in colour when viewed through a petrographic microscope. Liptinite is identified by the thin grey, almost purple bands usually included within a particle. When viewed under alight flourescence, liptinites will reflect an orange colour (Swanepoel, personal communication, October 24, 2014).

Table 2.2 summarises the major characteristics of the three maceral groups.

**Table 2.2: Summary of Major Characteristics of the Three Maceral Groups in Hard Coal**

| | | Reflectance | | | Chemical Properties | | |
|---|---|---|---|---|---|---|---|
| **Maceral group** | **Plant origin** | **Description** | **Rank** | **Reflected light %** | **Characteristic element** | **Typical products on heating** | **Technological characteristics** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| VITRINITE | Woody trunks, branches, twigs, stems, stalks, bark, leaf tissue, shoots | Dark to medium grey | High vol. to medium volatile Bituminous | 0.5 to 1.1 1.1 to 1.6 | Oxygen-rich | Light hydrocarbons | Decreasing amounts of volatiles | • Combusts rapidly<br>• Pyrolysis<br>• Hydrogenation/liquefaction<br>• Coking |
| | | Pale grey | Low volatile Bituminous | 1.6 to 2.0 | | | | • Combusts with little smoke |
| | | White | Anthracite | 2.0 to 10.0 | | | | • Combusts with no smoke |
| EXINITE | Cuticles, spores, resin bodies, algae | Black-brown | High vol. | -0.0 to 0.5 | Hydrogen-rich | Early methane gas | | • Combusts very rapidly |
| | | Dark grey | Bituminous | -0.5 to 1.1 | | Oil | | • Pyrolysis |
| | | Pale grey | Med. Vol. Bituminous | -1.1 to 1.6 | | Condensates Wet gases (decreasing) | | • Hydrogenation / liquefaction<br>• For bitumen production |
| | | Pale grey ( = vitrinite) to white shadows | Low vol. Bituminous to anthracite | -1.6 to 10.0 | | | | |
| INERTINITE | As for vitrinite, and oxidized detrital organic humus | Medium grey | High vol. Bituminous All bituminous coals and anthracite | 0.7 to 1.6 | Carbon-rich | | | • Combusts slowly<br>• Maintains flame<br>• Relatively inert in coking hydrogenation liquefaction pyrolysis |
| | | Pale grey | | | | | | |
| | | White | | 1.6 to 10.0 | | | | |
| | | Yellow white | | | | | | |

Source: Falcon and Ham, 1988

Plates I, II, III, IV and V depict micrographs showing some of the features of macerals.

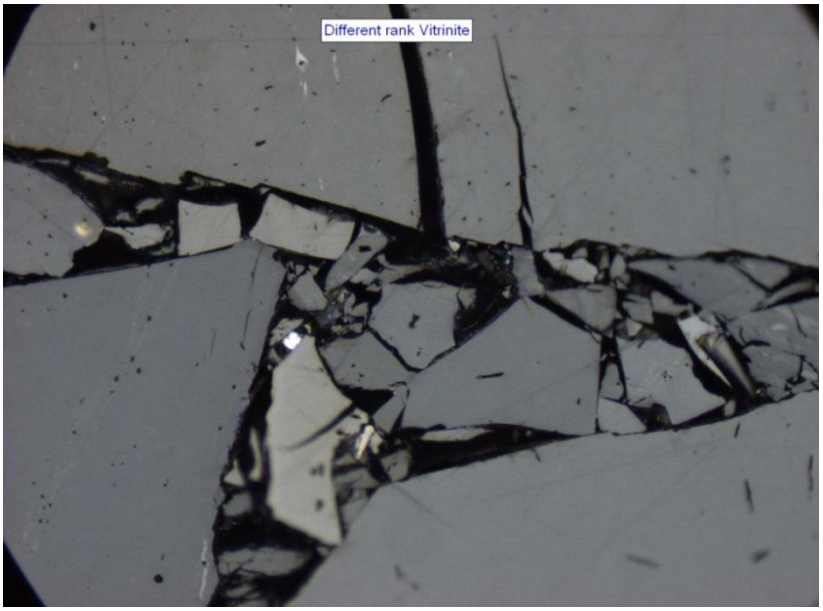



**Plate I: Micrograph of Vitrinite(50X) (W. Swanepoel, personal photograph, October 10, 2014).**

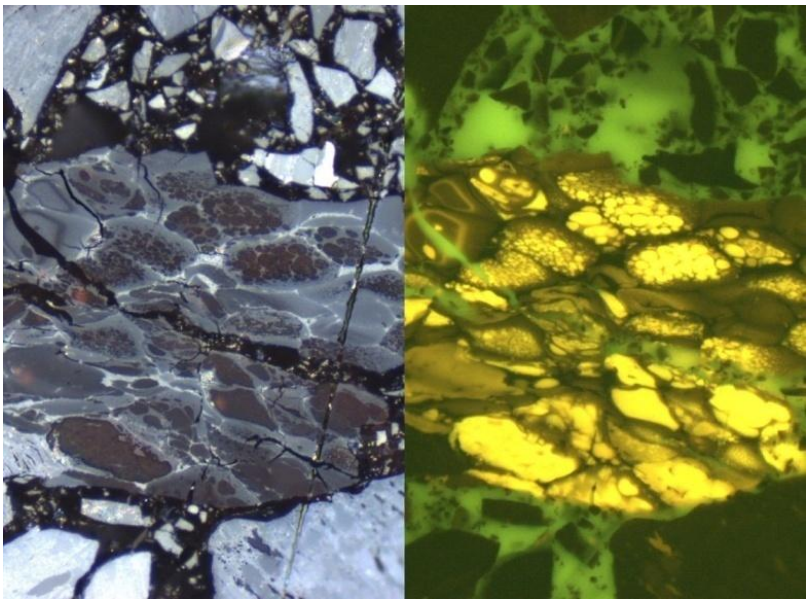


**Plate II: Micrograph of Exinite (Liptinite)(50X) (W. Swanepoel, personal photograph, October 10, 2014).**




**Plate III: Micrograph of Fusinite (50X)(W. Swanepoel, personal photograph, October 10, 2014).**

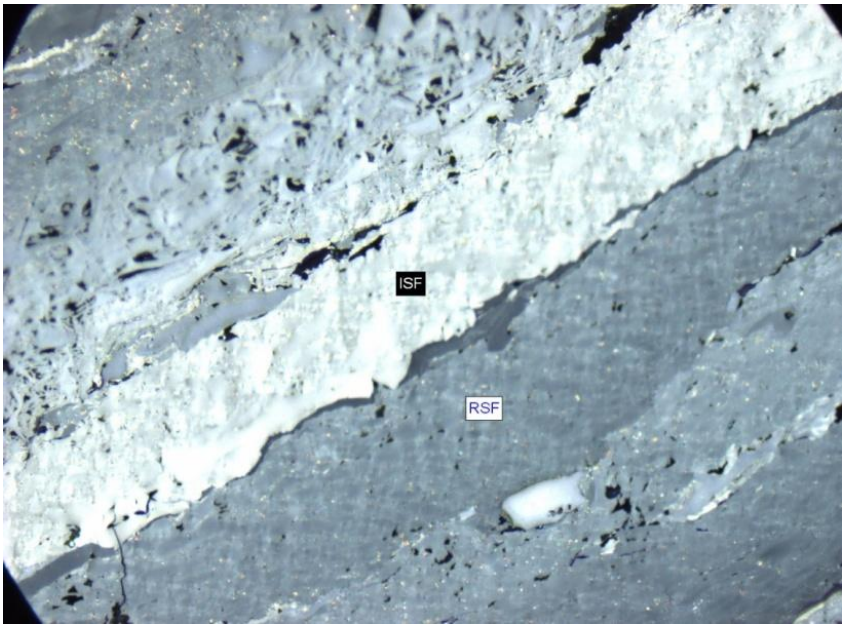



**Plate IV: Micrograph of Inert Semifusiniteand Reactive Semifusinite(50X)**
**(W. Swanepoel, personal photograph, October 10, 2014).**

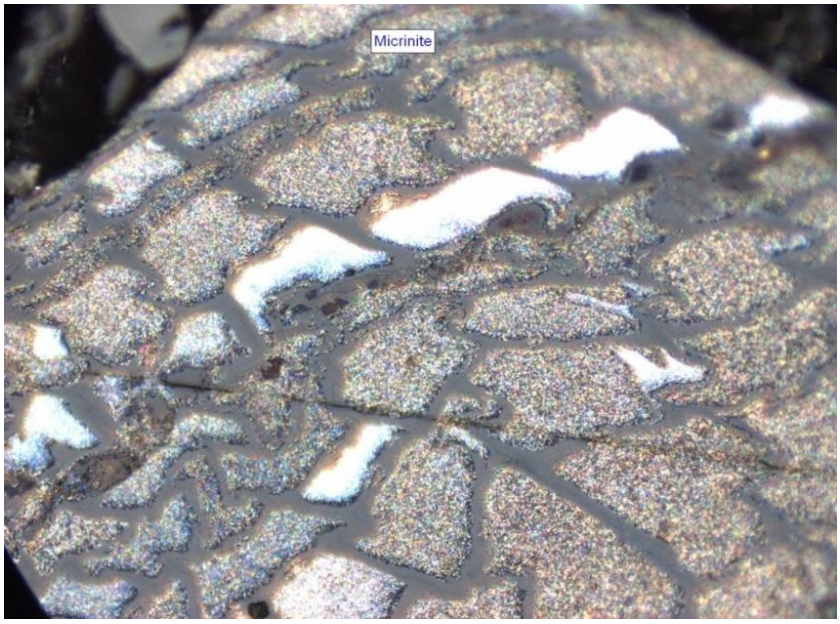



**Plate V: Micrograph of Micrinite(50X)(W. Swanepoel, personal photograph, October 10, 2014).**

### 2.3.5 Thermogravimetric analysis

Thermogravimetric analysis (TGA) is an analytical technique used to determine a material's stability and its fraction of volatile components by monitoring the weight change that occurs as a specimen is heated. In most cases, TGA is performed in an oxidative atmosphere (air or oxygen and inert gas mixtures) with a linear temperature ramp. The maximum temperature is selected so that the specimen weight is stable at the end of the experiment, implying that all chemical reactions are completed (i.e all the moisture content and volatiles are burnt off, leaving behind an ash residue). In cases where various weight losses are not completely discrete, use of the Derivative Thermogravimetric curve (DTG) is recommended. In DTG the rate of weight loss of the sample is recorded as a function of temperature. The DTG curve consists of a series of peaks, corresponding to the various steps in the decomposition of the sample. The area under each peak is proportional to the weight loss (Aguado, 2013).

TGA and DTG studies are useful tools for the determination of combustion characterisitics e.g. peak temperature, burnout temperature and activation energy of coals and chars and other combustible materials (Kizgut *et al.*, 2003).Peak temperature ofmaximum weight loss rate ($T_p$) is usuallyconsidered as the most important feature of DTG profiles. Coalswith lower peak maxima temperatures generally can be ignitedand burned easier (Marinov *et al.*, 2009).

In addition to weight changes, some instruments also record the temperature difference between the specimen and one or more reference pans (Differential Thermal Analysis, DTA) or the heat flow into the specimen pan compared to that of the reference pan (Differential Scanning Calorimetry, DSC). Differential Scanning Calorimetry is used to measure the heat of combustion. TGA is also used as fast method for proximate analysis.

### 2.3.6 Bases for reporting coal analysis

Because moisture and mineral matter (or ash) are extraneous to the coal substance, analytical data can be expressed on several different bases to reflect the composition of different coals.

***As-received (ar)***is data expressed as percentages of the coal with the moisture. This category is also sometimes referred to *as-fired* and is commonly used to monitor operations and for performing calculations as it is the whole coal that is being utilized.

***Dry-basis (db)*** is data expressed as percentages of the coal after the moisture has been removed.

***Dry, ash-free (daf)*** is data expressed as percentages of the coal with the moisture and ash removed.

***Dry, mineral-matter free (dmmf)*** is data expressed with the assumption that the coal sample is free of both moisture and mineral matter, and data are a measure of only the organic portion of the coal.

***Moist ash-free (maf)*** is data expressed with the assumption that the coal sample is free of ash but still contains moisture.

***Moist, mineral-matter-free (mmmf)*** is data expressed with the assumption that the coal sample is free of mineral matter but still contains moisture.

## 2.4 Fundamentals of Coal Combustion

During combustion, coal particles undergo four well-defined steps shown in Figure 2.1: drying, devolatilisation, volatile combustion and char burning. Drying starts once a coal particle enters the furnace and is a heat transfer-limited process influenced by furnace temperature, particle size, moisture content and porosity of the coal. On completion of drying, the particle is further heated to the pyrolysis temperature. As a result of drying and heating, the particle shrinks, with a volume reduction relative to initial moisture content and type of coal. Reduction in pore size, internal cracking or particle breakup may also result from this process.

Devolatilisation of coal starts typically at 450 – 500$^{o}$C. It produces non-condensible light gases, tar and residual char. The tar is subsequently converted to soot particles. Volatile yield increases with decreasing coal rank and with increasing temperature, soak time and heating rate. Generally, bituminous coals yield comparatively larger amounts of tar than other coals, while lower rank coals release less tar but larger amounts of light gases.As soon as they are released from the coal particle, the volatiles react with oxygen in the air surrounding the particle, producing carbon dioxide ($CO_2$) and water ($H_2O$). The reaction is rapid and, therefore, has a negligible effect on the overall combustion time (Carpenter *et al.*, 2007).

Char oxidation is a slow process, thus dominating the total burning time of a coal particle. This involves the oxidation of carbon to carbon monoxide (CO) or carbon dioxide ($CO_2$) at the particle surface. While oxidation to $CO_2$ dominates at low temperatures, oxidation to CO becomes important at high temperatures, and the direct formation of $CO_2$ at the char surface is negligible. Hence, the main carbon oxidation becomes a two-step reaction, with the CO being subsequently oxidized to $CO_2$ away from the char particle. Char fragmentation may occur during combustion. This reduces the initial particle mass, thus increasing the total external particle surface area and hence the char reaction rate (Carpenter *et al.*, 2007).

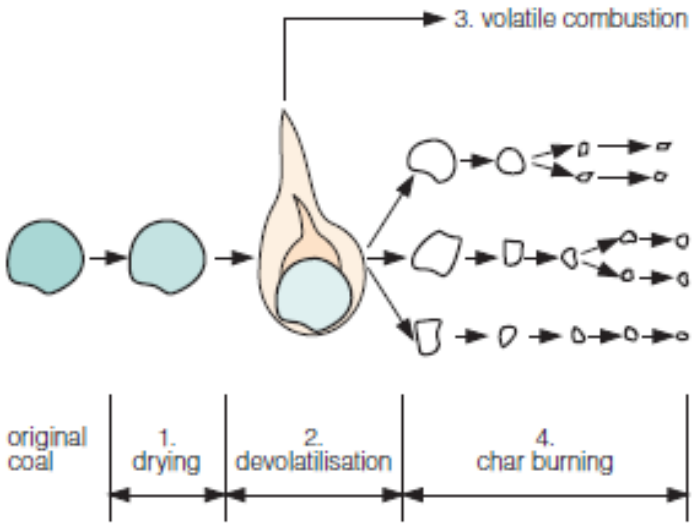



**Figure 2.1: Coal Combustion Processes. (Carpenter *et al.*, 2007)**

### 2.4.1 The effect of coal macerals on combustion

An attempt to establish the optimum operating conditions in a pulverised-coal boiler and reasons for the varying performance of two coals from the Kuznetsk region in Russiaconcluded that calorific value and volatile matter content do not assist in the prediction of the burnout characteristics of coals. On the other hand, the petrographic characteristics affect the processes of ignition, combustion and the efficiency of combustion; and variations in the percentage of volatiles in the flue gases. An increase from 45-57% reactive macerals caused a decrease in the char, a decrease in the unburnt carbon by 1.6-2.2% in the flue gases, and an increase in boiler efficiency in certain load ranges from 1.7-2% (Falcon and Ham, 1988).

Pilot-scale pulverised-coal combustion experiments conducted on two West Canadian and one United States coal concluded that the combustion performance of coal is inversely

related to the inert contents of the coals, i.e. coals rich in inert macerals produce fly ash with higher levels of unburnt carbon because these macerals persist through the flame in a partially reacted form. Coals rich in inert macerals 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 content of reactive macerals. Higher combustion air temperature, longer residence time and finer particles would achieve the same results without higher excess air (Falcon and Ham, 1988).

The ignition temperatures of maceral groups increase in order of liptinite (exinite) – vitrinite – inertinite. Petrographic analysis is important in explaining the inefficient combustion of coals and the optimisation of combustion (Kizgut *et al.*, 2003).

### 2.4.2 Reactivity index (RI)

While the general trend showed fuels with lower VM content were more difficult to burn than fuels with a higher VM content, there appeared to be a relatively large difference in burning characteristics for fuels of the same VM. Further investigation into the ignition content of coals and petroleum cokes resulted in the establishment of a Reactivity Index (RI). The Reactivity Index is the temperature (in degree celsius) at which a sample being heated in a special oxygen-supplied, adiabatic furnace achieves a $15^{o}$C per minute temperature rise rate. This index indicates the temperature at which devolatilisation and self-sustaining combustion of the fuel takes place. Therefore, the lower the RI, the easier it is to ignite the fuel. A reactivity index of greater than $275^{o}$C typically requires an arch-fired boiler to ensure stable combustion without support fuel through a reasonable load range (Goidich, 2006).

## 2.5 Influenceof Coal PropertiesonPower Plant Design

The intrinsic or inherent factors that influence the efficient combustion of coal include 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 external factors include 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 combustion particles in the furnace (Falcon and Ham, 1988).

The calorific value is normally the basic item specified in contracts for coal to be used in steam plants. Drying, pulverising, dust-proofing and the general handling of coal all depend on surface moisture data since wet coal is very difficult, and in some instances, almost impossible to pulverise. In combustion, high ash content reduces the amount of heat obtainable from a given quantity of coal and also leads to the problem of handling and disposing of larger amounts of ash produced during combustion. The composition of coal ash is considered in the amount of clinkering and boiler tube slagging that may occur in a boiler. The design of most boilers is such that only coals with a specified range of ash content may be used in the efficient operation of the boiler.

Volatile matter values are important in choosing the best match between a specific type of coal-burning equipment and the coal to use with the equipment. Such values are valuable in

setting up and maintaining proper burning rates.The fixed carbon value is one of the values used in determining the efficiency of coal-burning equipment. Coal nitrogen values are also useful in predicting the amount of nitrogen in the products of coal liquefaction and gasification processes. In calculating heat balances for boiler efficiency studies, it is important that an accurate value of the combustible material in coal be obtained. Thus, a correction for the oxygen content of the organic matter of coal should be made. In general, coals with high oxygen content are unsuitable for coking but may be more reactive and thus easier to gasify or liquefy (Speight, 2005).

The selection of the proper steam generator technology is a critical step in the basic design of a new power project. The fuel to be fired and the steam cycle to be adopted dictates the type of steam generator needed to satisfy the requirements of the project. For easy to burn fuels such as bituminous coals, suspension firing of the pulverized fuel in horizontal, wall-mounted burners is the configuration of choice. For low volatile, low reactivity fuels, such as anthracites and petroleum cokes, the down-fired arch furnace has been applied to provide the proper combustion environment (Goidich, 2006).

One of the most important fuel constituents is the volatile matter (VM)content. This constituent has a very large impact on the ignitability and burnout characteristics of solid fuels.The ignition temperature of coal increases with decreasing volatile matter content (Kizgut *et al.*, 2003). Fixed carbon (FC)is the other constituent in solid fuels that burns. Fixed carbon is more difficult to ignite and burns more slowly than volatile matter.As the volatile matter decreases, the ratio of the fixed carbon to volatile matter increases. A fuel with a higher FC/VMratio (or fuel ratio) is more difficult to burn than a fuel with a lower

ratio.Volatile matter content is often used as an indication of the ease of combustion of solid fuels. It is Foster Wheeler's experience that the transition from "easy to burn" to "hard to burn" occurs at approximately 18 – 20% volatile matter on an as-received basis (Goidich, 2006).

Boiler design is not an exact science, and operators tend to establish optimum coal characteristics and operating conditions based on operational experience. It is usual to have an allowable range for the most important coal properties, within which it is expected that full load may be produced, although possibly at reduced efficiencies. However, substantial deviation in one or more of the properties may result in impaired plant performance or evenseriousoperating and maintenance problems. Specification values derived from both the literature and a survey of power-plant operators are shown in Table 2.3 (Carpenter *et al.*, 2007).

**Table 2.3: Some Typical Bituminous Coal Quality Requirements for Pulverised Coal-Fired Plants (Carpenter *et al*., 2007).**

| Parameter | Desired Values | Typical Limits * |
|---|---|---|
| Heating value, MJ/kg ar | High | min 24 – 25 (23) |
| Moisture, % ar | 4 – 8 | max 12 |
| Volatile matter, % mf | 20 – 35 | min 20 (side-fired furnaces) |
| | 15 – 20 | max 20 (down-fired furnaces) |
| Ash, % mf | low | max 15 – 20 (max 30) |
| Sulphur, % daf | low | dependent on local pollution regulations |
| Nitrogen, % daf | low | (0.8 – 1.1), dependent on local pollution regulations |
| Chlorine | low | max 0.1 – 0.3 (max 0.5) |
| HGI | high | min 50 – 55 (min 39) |
| Ash analysis, wt % ash | | |
| Silicon dioxide | | (45 – 75) |
| Aluminium oxide | | (15 – 35) |
| Titanium oxide | | (0.4 – 2.2) |
| Ferric oxide | | (1 – 12) |
| Calcium oxide | | (0.1 – 2.3) |
| Magnesium oxide | | (0.2 – 1.4) |
| Sodium oxide | | (0.1 – 0.9) |
| Potassium oxide | | (0.8 – 2.6) |
| Sulphite | | (0.1 – 1.6) |
| Phosphorus pentoxide | | (0.1 – 1.5) |
| Ash fusion temperatures, $^{o}$C | | |
| Initial deformation | High | (>1075) |
| Softening | High | (>1150) |
| Hemispherical | high | (>1180) |
| Fluid | High | (>1225) |
| Maceral Analysis, % | | |
| Vitrinite | | 55 – 80 |
| Exinite | | 5 – 15 |
| Inertinite | | 10 – 25 |

***** Typical limits refer to those commonly quoted; those in brackets indicate outer limits acceptable in some cases.

In China, the expanded use of low-reactivity bituminous coals for pulverised-fuel firing is an important strategy for modernisation. In 1983, more than 10% of the coal used by power stations had more than 40% 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' (Falcon

and Ham, 1988). Resultsin 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 increasedfrom 9 to 13 degrees in order to increase the quantityof internally recirculated flame gases;

(2) the cone position in a cone-stabilized burner waschanged to increase the coal-exit area (decrease theprimary air velocity); and

(3) the swirl in the primary air-coal pipe on an annularburner was eliminated to delay mixing of the coal withsecondary air.

These modifications have improved the combustion performancein many Chinese pulverized-fuel boilers (Falcon and Ham, 1988).

Figure 2.2 gives an indication of which combustion process will be selected based on fuel quality. Good quality bituminous, sub-bituminous and lignite coals with relatively high heating values and high volatile contents will be wall-fired. Low volatile, low reactivity anthracites and petroleum cokes will be arch-fired. The entire range of high and low quality fuels can be fired with the Circulating Fluidized Bed (CFB) process (Goidich, 2006).

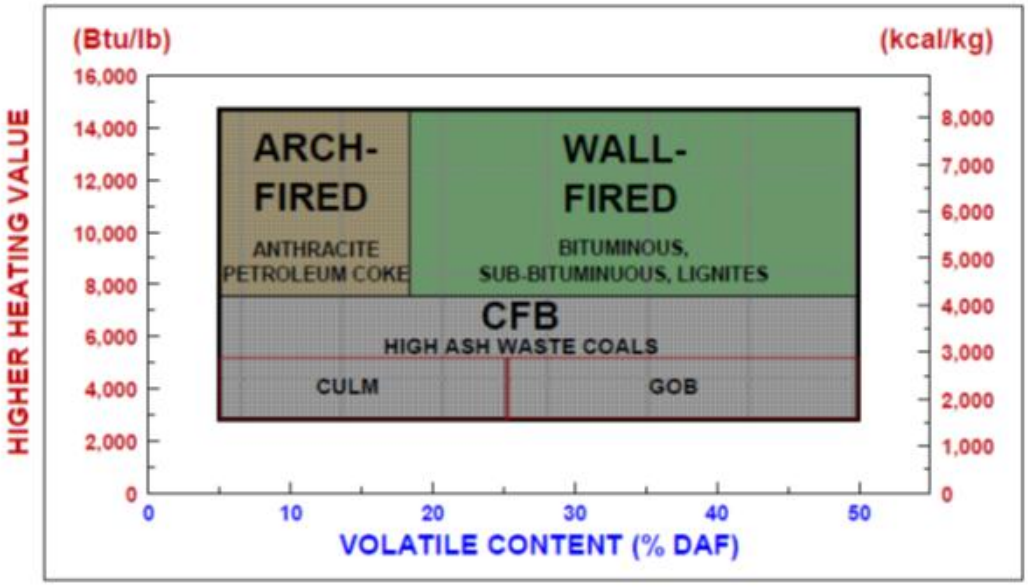



**Figure 2.2: Combustion Process based on Fuel Quality (Goidich, 2006)**

## 2.6 Power Generation from Low GradeCoals

Though Table 2.3 specifies the ideal qualities of coals typically required for bituminous pulverized-coal power generation, low grade coals (of high ash, high sulphur and high moisture contents) are successfully being used for power generation.However,the usual practice in most countries is to trade high quality coals internationally, while the lower quality coals are used domestically for power generation and other uses.

In Australia, while bituminous coals are exported on the international market, brown coals (Australia's terminology for lignites) are used domestically for pulverized-coal power generation (Commonwealth of Australia, 2010).In the state of Victoria, South Australia, for example, brown coal mostly from the Latrobe valley is the principal source of energy, providing 90% of the state's electricity from six power stations with a total output of 6,755

MWe. Table 2.4 shows the typical characteristics of Victorian brown coals, displaying a high moisture content (Minerals Council of Australia-Victoria Division, 2011).

**Table 2.4: Typical Characteristics of Victorian Brown Coals.**

| Properties | Values |
|---|---|
| Gross Calorific Value | 25 – 29 MJ/kg |
| Moisture Content | 48 – 70% |
| Carbon | 65 – 70% |
| Oxygen | 25 – 30% |
| Hydrogen | 4 – 5.5% |
| Ash | <4% |
| Nitrogen | <1% |
| Sulphur | <1% |

Source: Minerals Council of Australia-Victoria Division, 2011

Table 2.5 summarises the characteristics of low grade, high ash coals used by some recently constructed pulverised-coal fired plants located in different geographical locations in the world. This was extracted from the results of case studies of recently constructed coal- and gas-fired power plants carried out by the International Energy Agency and published in 2007.

**Table 2.5: Characteristics of Low Grade Thermal Coals used by some Power Stations.**

| Parameters | Power Stations | | | |
|---|---|---|---|---|
| | ***Niederausseum K*** | ***Genesee Phase 3*** | ***Suratgarh Unit 5*** | ***Majuba*** |
| Location | Germany | Canada | India | South Africa |
| Coal type | Lignite | Sub-bituminous | Bituminous Blend | Bituminous |
| Gross Calorific Value, MJ/kg | 12.24 | 17.9 | 14.7* | 21.8 |
| Ash, % | 2 – 12* | 19.4 | 30(45*) | 18.6 – 39.8 |
| Moisture, % | 51 – 58* | 20 | 10* | 1.7 – 4.4 |
| Sulphur, % | 0.2 | 0.2 | 0.5* | 0.7 – 1.7 |
| Gross Power Output at MCR, MWe | 1012 | 495 | 250 | Units 1-3: 657<br>Units 4-6: 713 |

Source: International Energy Agency, 2007.
NOTE: All values as received. MCR: Maximum Continuous Rating *: Design value/range

## 2.7 Coal Beneficiation

Coal beneficiation (otherwise known as coal cleaning or coal washing) is the process of improving coal quality to the extent possible and economically feasible. All coals contain inorganic materials, such as sodium, chlorine, and sulphur. During the combustion process, the inorganic materials form ash that is deposited in a dry (called fouling) or wet (called slagging) state in the boiler's combustion chamber. Removing these inorganic compounds by the application of mineral additives to the coal prior to its combustion or by washing the coal at either the mine mouth or at the coal plant itself improves the quality of coal (James and Gerhard, 2013)..

Beneficiation improves the calorific value of coal since the ash content of coal is inversely proportional to its calorific value. Reducing ash content makes the coal less abrasive and lowers transportation costs, as more carbon and less ash is transported. In addition, by reducing the amount of ash accumulation, operators can reduce the amount of scheduled and unscheduled maintenance required to remove the ash accumulation.Applying mineral additives containing aluminum can reduce ash fouling and slagging in pulverized coal boilers by up to 78%. Wet pretreatment can reduce the amount of ash that adheres to boiler tubes, thus reducing fouling.Reducing the abrasiveness of the ash and sulphur deposits on plant duct work can reduce corrosion that shortens the plant's expected life.Reducing sulphur in the fuel combusted also will reduce sulfate formation and fine particulate emissions (James and Gerhard, 2013).

Coal beneficiation is in principle possible for most bituminous coals and anthracite, which accounts for about two-thirds of worldwide coal production. About one-third of this potential

amount is presently washed. Lignites and sub-bituminous coals pose a different set of problems. While they are often low in ash and sulphur, they tend to contain a high percentage of moisture, ranging from 20 – 60%. This will cause a range of problems in a coal-fired boiler, requiringmore energy and causing higher mill, coal pipe and burner maintenance requirements. Beneficiation techniques involve drying these coals as efficiently and cost-effectively as possible (Burnard and Bhattacharya, 2011).

## 2.8 Research Gap

Most research work on Nigerian coals is focused on their usefulness in the metallurgical industry. The few research work carried out on Nigerian coals as regards power generation have not comprehensively characterised Nigerian coals based on the contemporary requirements of power plant designers and operators. The usual tests such as proximate analysis, ultimate analysis, calorific value determination and ash analysis have extensively been carried out. However, contemporary tests required for a comprehensive characterization of Nigerian coals for power generation such as thermogravimetric analysis, petrographic analysis and drop tube furnace tests have rarely been carried out.

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Coal Samples

Coal samples, each weighing 5kg,were obtained through the Nigerian Coal Corporation, Enugu, for five different deposits in Nigeria,which include Odagbo (Kogi State), Owukpa (Benue State), Ezimo (Enugu State), Amansiodo (Enugu State) and Inyi (Enugu State). The samples were stored in appropriately labeled air-tight containers to retain their as-received conditions.

600g of representative sample ofcoal from each site wasused at the laboratory of Advanced Coal Technology (now Bureau Veritas Testing and Inspections South Africa, BV-TISA), Icon Industrial Park, Sunderland Ridge, Pretoria, South Africa for proximate analyses, ultimate analyses, determination of gross calorific values, ash composition, ash fusion temperatures (in oxidizing and reducing atmospheres) and petrographic analysis. Thermogravimetric analysis was carried out at the Institute of Applied Materials of the University of Pretoria.

Results are reported as the average of duplicate tests as long as the results are within the repeatability limits set out in each ISO method.

## 3.2 General Sample Preparation

The principle of mixing and then dividing, using either mechanical or manual methods as described in ISO 13909-4:2001 was used to generate a representative pulverised sample of each coal, and then preparing each sample to the desired analytical specifications using an

array of sample preparation equipment. Crushing of the samples from a top-size of 150mm to a suitable size distribution range of 12.5 – 50.0mmwas carried out using an Osborn 10x6 inch jaw crusher shown in PlateVI. A double roller crusher, shown in PlateVII, was used to crush samples from a maximum top-size of 25mm to a size distribution of range of 1 – 6mm. A Retsch ZM200 ultra centrifugal mill, shown in PlateVIII, was then used to prepare samples from a top size of 6mm down to a suitable size distribution range of 150 – 212µm.

An automatic sieve shaker, shown in PlateIX, was used for sieving the samples to the desired size distribution required for each test while a hand rifler, shown in PlateX, was used to split the samples into representative sub-samples.



**PlateVI: Osborn 10x6 inch Jaw Crusher.**



**PlateVII: Double Roller Crusher.**



**PlateVIII: Retsch ZM200 Ultra Centrifugal Mill.**



**PlateIX: Automatic Sieve Shaker.**



**Plate X: Hand Rifler.**

## 3.3 Proximate Analysis

### 3.3.1 Moisture content.

The air-oven method based on the South African National Standards (SANS) 5925:2007 was used to analyse for moisture content.Coal samples passing a 212 µm test sieve were stored in the proximate analysis room for at least 30 minutes before the start of the test. Crucibles with lids were heated for a minimum time of 1.5 hours before the start of the test. The crucibles and lids were cooled for 10 minutes and then put in a desiccator cabinet for a minimum period of 10 minutes. An electronic balance was then used to weigh the crucibles before uniformly spreading 1.000g of conditioned sample and recording the mass of the crucibles and contents. The crucibles and contents were then loaded into theair oven (manufactured by LABCON) at a temperature of 105$^{o}$Cto 110$^{o}$C for at least 1.5 hours, and such that the atmosphere or flow within the oven is changed at a rate of at least five times per hour. The crucibles with dried samples were removed from the oven, the lids replaced and allowed to cool for 10 minutes, and then placed in the desiccator cabinet for another minimum period of 10 minutes before being weighed. The moisture content of the coal was calculated from the loss in mass.

### 3.3.2 Volatile matter.

ISO 562:1998 was the method used to analyse for volatile matter content. Coal samples passing a test sieve with an aperture of 212µm were stored in the proximate analysis room for at least 30 minutes before commencement of the test. Crucibles and lids (crucibles uncovered) were placed in the volatile furnace manufactured by Ultra Furn SA (Pty) Ltd. When the furnace attained a temperature of 895 – 905$^{o}$C, the crucible and lids were removed and allowed to cool for at least 60 minutes to room temperature. 1.000 – 1.0100g of coal

samples were put into each crucible. Each crucible was lightly tapped on a clean hard surface a few times to form an even layer on the bottom. The crucibles were loaded into the furnace with temperature maintained between 900 – 910$^{o}$C and timing with a stopwatch immediately commenced. A calibrated type-K thermocouple was used to verify the temperature range and was positioned in the middle of the samples. After 7 minutes (±5 secs), the crucibles were removed from the furnace and placed on an asbestos sheet and allowed to cool for about 60 minutes to attain room temperature. Each crucible was then weighed and the difference calculated to determine volatile matter.

### 3.3.3 Ash Content.

The method specified by ISO 1171:1997 was used to analyse for ash content. Coal samples passing a test sieve with an aperture of 212µm was stored in the proximate analysis room for at least 30 minutes before the test commenced. After the crucibles and lids were conditioned in the furnace and allowed to cool to room temperature, 1.000 – 1.0100g of coal samples was put into each crucible. The crucibles were loaded into the furnace equipped with a pre-programmed temperature controller manufactured by LENTON. The furnace temperature was ramped to 500±10$^{o}$C over a period of 60minutes; held at 500±10$^{o}$C for 30minutes; ramped to 815±10$^{o}$C over a period of 60minutes; and held at 815±10$^{o}$C for 60minutes. The temperature was verified with an external type-K thermocouple when the furnace stabilised at 815$^{o}$C. Once this cycle was completed, the crucibles were removed and placed on an asbestos slab to cool down for 10minutes. At the end of 10minutes, the crucibles were transferred to a desiccator cabinet and allowed to further cool down for 10minutes. After this period, the crucibles were removed and weighed, with difference calculated to determine ash content.

### 3.3.4 Fixed Carbon

*Fixed carbon* was calculated through the formula:

$$\%\text{Fixed Carbon} = 100 - (\%\text{Moisture} + \%\text{Ash} + \%\text{Volatile Matter}) \quad (3.1)$$

## 3.4 Ultimate Analysis

Coal passing through a sieve having an aperture of 212µm was used for this analysis. Ultimate analysis was carried out making use of the TRUSPEC CHN Elemental Determinator manufactured by LECO Corporation shown in PlatesXI and XII. The equipment is supplied with a reference material with known elemental composition. This reference material (Prox-Plus) was used to determine the accuracy of the CHN Elemental Determinator (Plate XI) before commencing the tests. 1.0g of sample was loaded into porous crucibles and subjected to combustion in an oxygen-rich environment. Typical run duration is about 7 – 10 minutes. The system converts the coal catalytically to Nitrogen, $CO_2$ and water, which are separated with a gas chromatographic column and detected through a sensor. The results were displayed on the computer monitor in terms of percentage carbon, hydrogen and nitrogen on an air dried basis. This was based on ISO 12902 – CHN instrumental method.

Oxygen was calculated by difference on an air-dried basis as follows:

$$\text{Oxygen (\%)} = 100 - (\text{Carbon} + \text{Hydrogen} + \text{Nitrogen} + \text{Ash} + \text{Moisture}) \quad (3.2)$$




**Plate XI: CHN Elemental Determinator (Main Unit).**

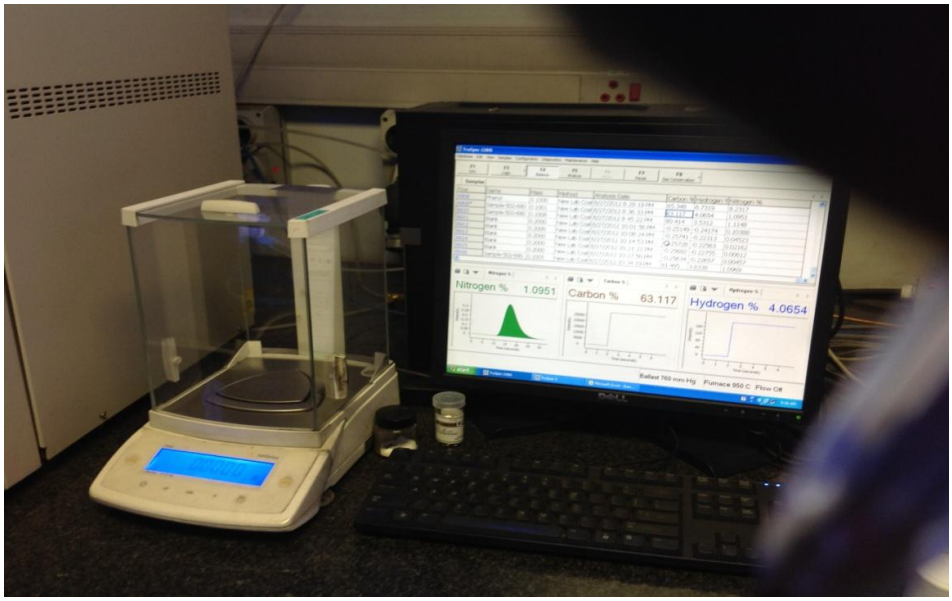



**Plate XII: CHN Elemental Determinator (Display Monitor).**

### 3.5 Determination of Calorific Value

ISO 1928:1995 specification was used to determine gross calorific value. Coal samples passing a sieve with an aperture of 212µm were used for this analysis. The calorific value of the samples was determined by combustion in a controlled environment. The heat released is proportional to the calorific value of the substance. The equipment used was the Parr 6400Isoperibol Calorimeter shown in Plate XIII. Certified benzoic acid tablet was used to calibrate the calorimeter before start of the test. 1.0g of coal sample in a nickel-chromium crucible wasplaced in a high pressure atmospheric environment called a Combustion Vessel, which is surrounded by water. The sample wasthen ignited. The calorimeter jacket was held at a constant temperature by modulating the fan speed while the heat generated by the burning sample caused the bomb and bucket temperature to rise. The temperature of the water was measured by an electronic thermometer with a resolution of 1/10000 of a degree. Any minute heat flow between the jacket and the surrounding during the test was continuously monitored by a microprocessor and necessary corrections of any heat leak applied automatically. Heat released is proportional to the gross calorific value (air-dried basis) of the sample and displayed automatically by the instrument. Duration of each run was 10 minutes.




**Plate XIII: Parr 6400 Isoperibol Calorimeter.**

## 3.6 Determination of Total Sulphur Content

Total sulphur was determined using infra-red (IR) spectroscopy method as specified by ISO 19579. Coal samples passing through a test sieve with an aperture of 212µm were used for determination of total sulphur content. Samples were then conditioned in a dry oven at a temperature of 105±5$^{o}$C for 60 minutes, transferred into a dessicator cabinet and allowed to cool for approximately 30 minutes. A LECO S-144 Dual Range Sulphur detector, shown in Plate XIV, was used for the test. 0.35g of coal sample was placed in a combustion system to burn in a stream of pure oxygen at a maximum operating temperature of 1350$^{o}$C. This oxidises the sulphur content and breaks down sulphur-bearing compounds to form $SO_2$. Anhydrous magnesium perchlorate removes all moisture, and the $SO_2$ flows to the infra-red detection cells where sulphur is measured by infra-red absorption detectors. $SO_2$ absorbs infra-red energy at a precise wavelength within the infra-red spectrum.Average run time

was3 – 5 minutes. Results were displayed automatically on the computer monitor in percentage sulphur on an air-dried basis.




**Plate XIV: LECO S-144 Dual Range Sulphur Detector.**

## 3.7 Petrographic Analysis

The method used is that recommended by the International Committee for Coal and Organic Petrology (ICCP) as published in ISO 7404 handbooks. Coal samples passing a sieve of 850µm, each weighing 15g, were used for the petrographic analysis. 30mm diameter particulate blocks shown in Plate XVwere produced using M Resin (epoxy resin)mixed with HY 956 modifed polyamide hardener in a ratio of 5:1, after which the pulverised coal sample was mixed in. The entire mix was put into pre-waxed moulds and compacted in a hydraulic press, after which they were left to cure for 24 hours to form cylindrical blocks. The blocks were ground and polished in a SAPHIR 520 (Plate XVI) grinder with the aid of abrasive

cloth and colloidal silica liquid. The quality of the polished surface is critical to the validity of the analysis. The highly polished particulate block representing a sample was coated with non-drying immersion oil and placed under an Ortholux 32X lens microscope shown in Plate XVII. An automatic point counter (Plate XVIII) moves the microscope crosshairs over the polished surface of the particulate block at traverse spacings of 0.4mm and intervals between the traverses of 0.5mm. A point is an observation of a portion of the particulate block under the crosshair. At least 500 points (excluding binding resin and visible minerals) were counted by tapping on the counter key allotted to each maceral spotted. At the end of 500 counts, the total count obtained for each maceral was used to obtain the percentage maceral composition of each coal sample.



**Plate XV: Particulate Blocks.**



**Plate XVI: SAPHIR 520 Grinder.**




**Plate XVII: Ortholux 32X Lens Microscope.**




**Plate XVIII: Point Counter.**

## 3.8 Thermogravimetric Analysis

The combustion in air method was used for this analysis. The instrument used for this analysis was an SDT Q600 simultaneous DSC/TGA instrument shown in Plate XIX. This is capable of performing both differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) simultaneously. Coal samples passing through a test sieve with an aperture of 212µm were used for this test. 25mg of the coal sample was carefully weighed and loaded into the instrument's lidless alumina crucible with a volume of 90µl. The sample was heated in air from 25$^{o}$C to 1000$^{o}$C at a heating rate of 10$^{o}$C/min and an air flow rate of 50ml/min. The change in weight of the sample was automatically recorded until there was no further change in weight. The residue in the crucible represents the ash content of the sample.Typical run time of the test was about 3.5 hours.

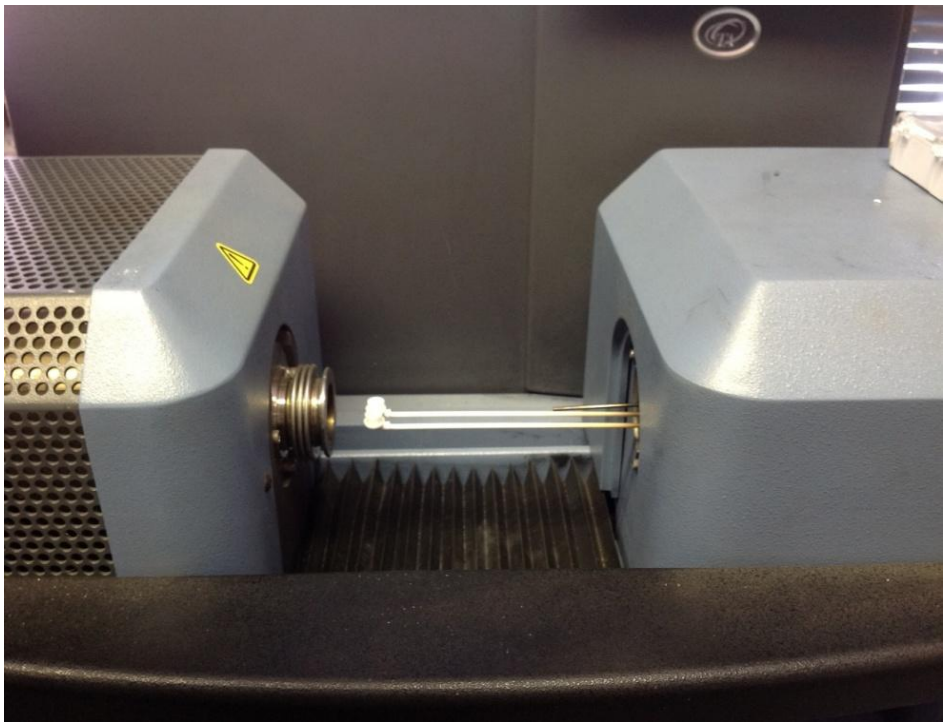


**Plate XIX: SDT Q600 Simultaneous DSC/TGA Instrument.**

## 3.9 Ash Composition Analysis

Ash composition analysis was carried out using the ASTM D-4326 x-ray fluorescence method. Coal to be analysed was heated to about 815$^{o}$C to a constant weight understandard conditions to form ash, a process referred to as “bulk ashing”, using the LENTON Ash Furnace. The ash was fused withlithium tetraborate ($Li_2B_4O_7$) and pressedinto a pellet. The pellet was irradiated byan x-ray beam of short wavelength. The characteristic x-rays ofthe atom that were emitted or fluoresced upon absorption of the primary or incident x-rays were dispersed and intensities at selected wavelengths were measuredby sensitive detectors. Detector output is related to concentration by calibration curves or by computerized data-handling equipment. All of the elementswere determined as the element and reported as the

oxide and included silicon,aluminum, iron, calcium, magnesium, sodium, potassium, phosphorus, titanium,manganese, strontium and barium.

### 3.10 Ash Fusion Temperature Analysis

This was based on the gradual thermal deformation of a pyramid-shaped ash sample in a reducing atmosphere and then an oxidising atmosphere. The test was carried out using ISO 540:2008 specifications. Bulk ashing was used to generate the ash samples as in Ash Composition Analysis. The coal ash was then manually compacted in a mould to form pyramids, which were heated in a CARBOLITE CAF Digital Furnace with a maximum operating temperature of 1550$^{o}$C. Plate XX shows the preparation of ash samples before being loaded into the furnace. Carbon dioxide gas was used for the oxidizing atmosphere while a combination of carbon dioxide and hydrogen gases was used for the reducing atmosphere. Four temperatures were obtained during the test.

The initial deformation temperature was one at which the tip of the pyramid began to show evidence of deformation; softening or fusion temperature was the temperature at which the ash sample fused and the height equaled the width; hemispherical temperature was the temperature at which the sample fused into a hemispherical shape for which height equals half of the width at the base; andfluid temperature was the temperature at which the sample fused down into a nearly flat layer. Typical run time was 3 – 4 hours.



**Plate XX: Preparation of Pyramid-Shaped Ash Samples for Ash-Fusion Temperature Analysis.**

### 3.11 Correlation Coefficient between some Properties and Calorific Value of Coal

Equation 3.3 was used to investigate the correlation of the results obtained for some of the properties of the coals sampled. Results for fixed carbon, volatile matter, carbon and hydrogen were correlated against calorific value.

$$r = \frac{n\sum(xy)-(\sum x)(\sum y)^2}{\sqrt{\{[n(\sum x^2)-(\sum x^2)][n(\sum y^2)-(\sum y^2)]\}}} \quad 3.3$$

where r = correlation coefficient

n = number of samples

x and y = variables (properties) investigated

# CHAPTER FOUR

# RESULTSAND DISCUSSION

## 4.1 Proximate Analysis

The results obtained from proximate analyses ofthe five coal samples are graphically depicted in Figure 4.1(raw data are shown in Appendix A) on an air-dried basis while the calculated fuel ratio of each sample is shown in Figure 4.2.Fixed Carbon was calculated by difference using equation (3.1).

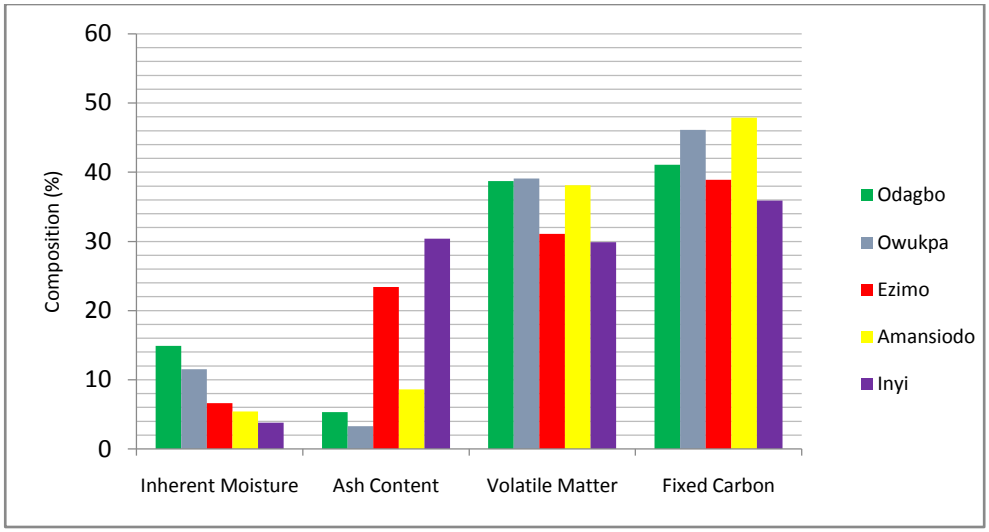



**Figure 4.1:Proximate Analyses ofthe Five Coal Samples**

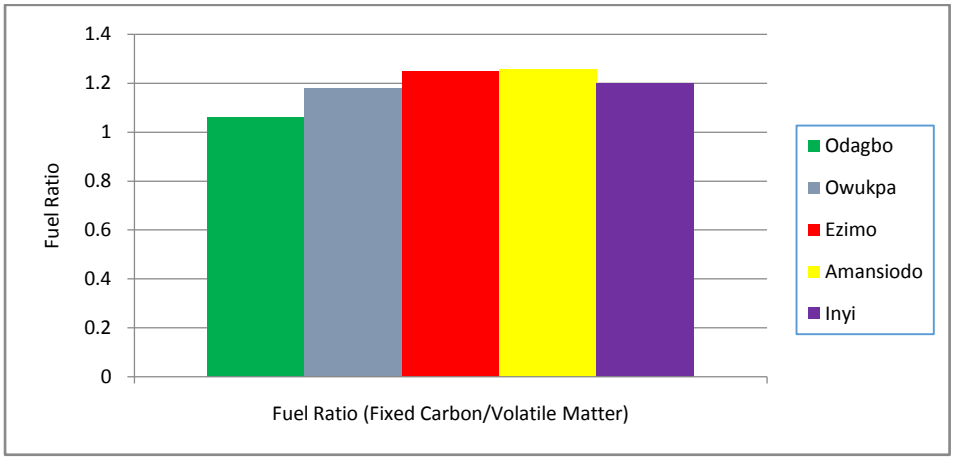



**Figure 4.2:Fuel Ratio ofthe Five Coal Samples**

## 4.2 Ultimate Analysis

The results obtained from the ultimate analysis carried out on the five coal samples are graphically depicted in Figure 4.3 (raw data are shown in Appendix B)on an air-dried basis. Oxygen was calculated by difference on an air-dried basis using equation (3.2).

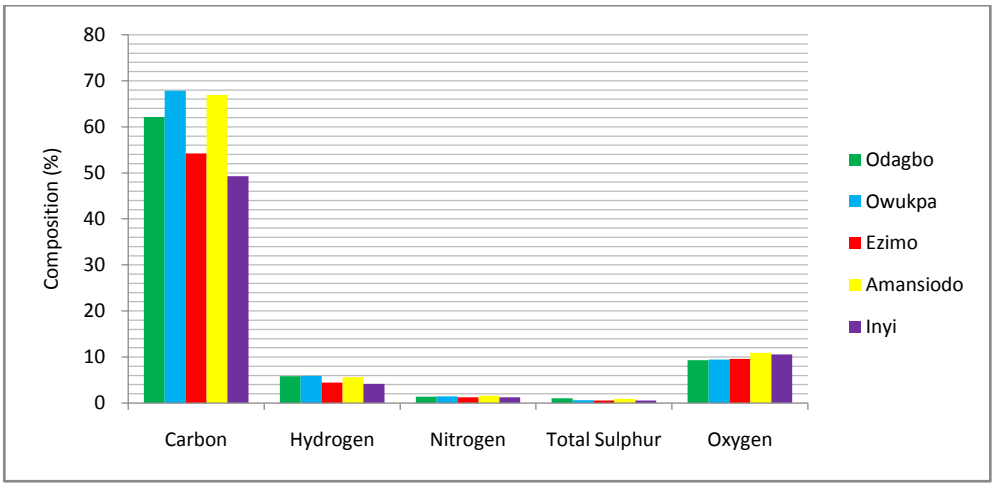



**Figure 4.3: Ultimate Analyses of theFive Coal Samples.**

## 4.3 Calorific Value

The results obtained from the gross calorific value determination carried out on the five coal samples are shown inFigure 4.4. Raw data are shown in Appendix C.

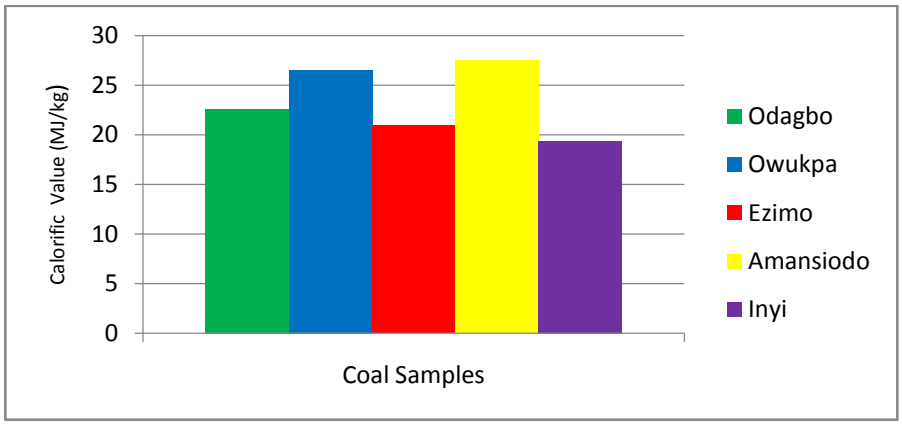



**Figure 4.4: Calorific Value of theFive Coal Samples.**

## 4.4 Ash Analyses

The results obtained from the ash composition test of the five coals samples using the x-ray fluorescence (XRF) technique are listed in Table 4.1.

**Table 4.1: Results ofAsh Composition Tests ofthe Five Coal Samples.**

| **Constituents** | **Samples** | | | | |
|---|---|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Amansiodo*** | ***Inyi*** |
| $Al_2O_3$ (%) | 25.78 | 27.60 | 20.76 | 29.13 | 19.02 |
| CaO (%) | 2.15 | 0.95 | 0.60 | 0.34 | 0.05 |
| $Cr_2O_3$ (%) | 0.03 | 0.03 | 0.02 | 0.04 | 0.01 |
| $Fe_2O_3$ (%) | 7.98 | 4.48 | 2.93 | 6.90 | 1.70 |
| $K_2O$ (%) | 0.31 | 0.06 | 1.13 | 1.32 | 0.36 |
| MgO (%) | 1.31 | 0.04 | 0.16 | 0.35 | 0.06 |
| MnO (%) | 0.41 | 0.03 | 0.04 | 0.05 | - |
| $Na_2O$ (%) | 0.07 | 0.02 | 0.03 | 0.06 | 0.01 |
| $P_2O_5$(%) | 0.06 | 0.77 | 0.21 | 0.22 | 0.06 |
| $SiO_2$(%) | 56.81 | 61.64 | 70.92 | 58.94 | 75.92 |
| $TiO_2$(%) | 1.98 | 2.98 | 2.29 | 2.13 | 2.29 |
| $V_2O_5$(%) | 0.09 | 0.03 | 0.02 | 0.04 | 0.02 |
| $ZrO_2$(%) | 0.10 | 0.13 | 0.11 | 0.07 | 0.15 |
| Ba (%) | 0.20 | 0.17 | 0.08 | 0.06 | 0.02 |
| Sr (%) | 0.04 | 0.13 | 0.04 | 0.05 | 0.01 |
| $SO_3$(%) | 1.74 | - | 0.28 | - | - |

The results obtained from the ash fusion temperature test(in oxidising atmosphere) of the five coals samples are listed in Table 4.2.

**Table 4.2: Results of Ash Fusion Temperature Test (in Oxidising Atmosphere) ofthe Five Coal Samples.**

| Temperatures | Samples | | | | |
|---|---|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Amansiodo*** | ***Inyi*** |
| Initial Deformation ($^{o}$C) | 1461 | >1550 | >1550 | >1550 | >1550 |
| Softening ($^{o}$C) | 1489 | >1550 | >1550 | >1550 | >1550 |
| Hemispherical ($^{o}$C) | 1518 | >1550 | >1550 | >1550 | >1550 |
| Fluid ($^{o}$C) | >1550 | >1550 | >1550 | >1550 | >1550 |

The results obtained from the ash fusion temperature tests (in reducing atmosphere) of the five coals samples are listed in Table 4.3.

**Table 4.3: Results of Ash Fusion Temperature Test (in Reducing Atmosphere) ofthe Five Coal Samples.**

| Temperature | Samples | | | | |
|---|---|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Amansiodo*** | ***Inyi*** |
| Initial Deformation ($^{o}$C) | 1519 | >1550 | >1550 | >1550 | >1550 |
| Softening ($^{o}$C) | 1528 | >1550 | >1550 | >1550 | >1550 |
| Hemispherical ($^{o}$C) | 1540 | >1550 | >1550 | >1550 | >1550 |
| Fluid ($^{o}$C) | >1550 | >1550 | >1550 | >1550 | >1550 |

## 4.5 Petrographic Analysis

The results obtained from the petrographic analysis giving the maceral composition of the coal samples are graphically depicted inFigure 4.5. Raw data are shown in Appendix D.

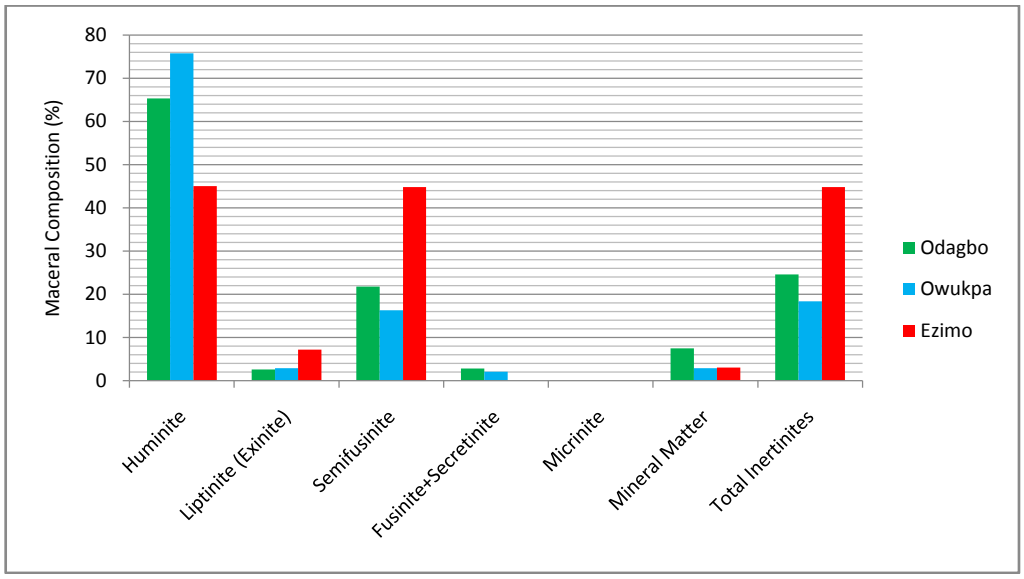



**Figure4.5: Petrographic Analyses**

## 4.6 Thermogravimetric Analysis

The results of the thermogravimetric analyses (TGA) carried out on the coal samples are shown on Table 4.4.

**Table 4.4: Thermogravimetric Analysis Results.**

| **Parameters** | **Samples** | | |
|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** |
| Weight Loss (%) for Temperature Range 25 - 150$^{o}$C | 20.16 | 14.90 | 8.76 |
| Weight Gain (%) for Temperature Range 150 - 250$^{o}$C | No Weight Gain | No Weight Gain | 0.43 |
| Weight Loss (%) for Temperature Range 300 - 1000$^{o}$C | 70.36 | 80.85 | 86.45 |
| Ash (%) | 9.47 | 4.08 | 5.17 |

The combustion profiles obtained for Odagbo, Owukpa and Ezimo coal samples were used to derive characteristic temperatures.The characteristic temperatures were designated as follows (Kizgut et al., 2003):

$T_i$= initial (or ignition) temperature where mass loss reaches a rate of 1% per minute,

$T_p$= peak temperature at the maximum weight loss rate, indicating coal combustibility,

$T_{1/2}$ = temperature at which 50% burn off (weight, ash free basis) occurs,

$T_b$= burnout temperature where DTG profile reaches a 1% combustion rate at the tail-end of the profile, indicating the completion of sample oxidation.

The characteristic temperatures obtained for the coal samples are shown in Figure 4.6. Raw data are shown in Appendix E.

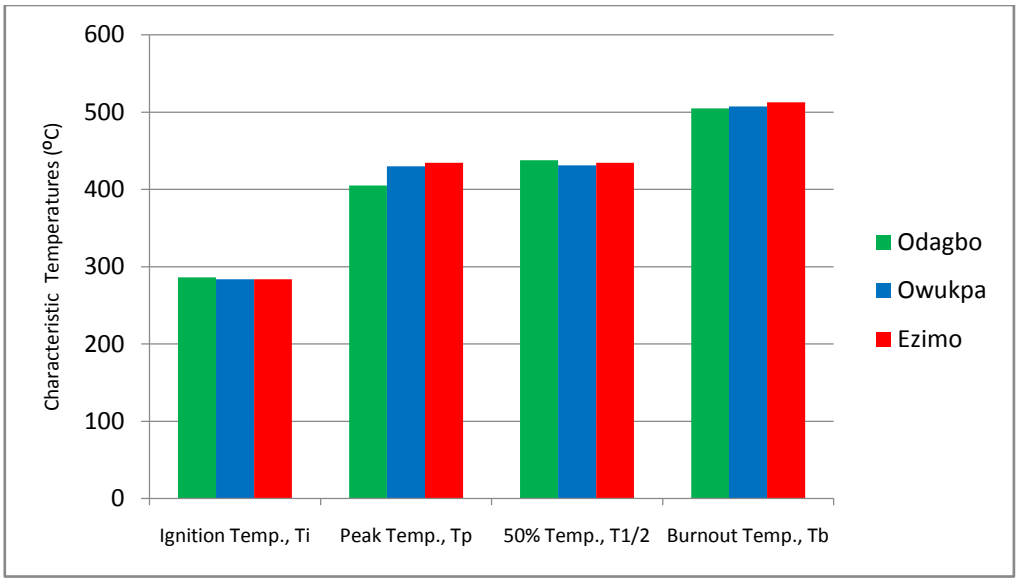



**Figure4.6: Characteristic Temperatures of the Coal Samples.**

Figures 4.7 through 4.9 show the thermograms for the thermogravimetric analysis (TGA)and the derivative thermogravimetric (DTG) curves for Odagbo, Owukpa and Ezimo coals respectively. Figure 4.10 shows a comparison of the curves.

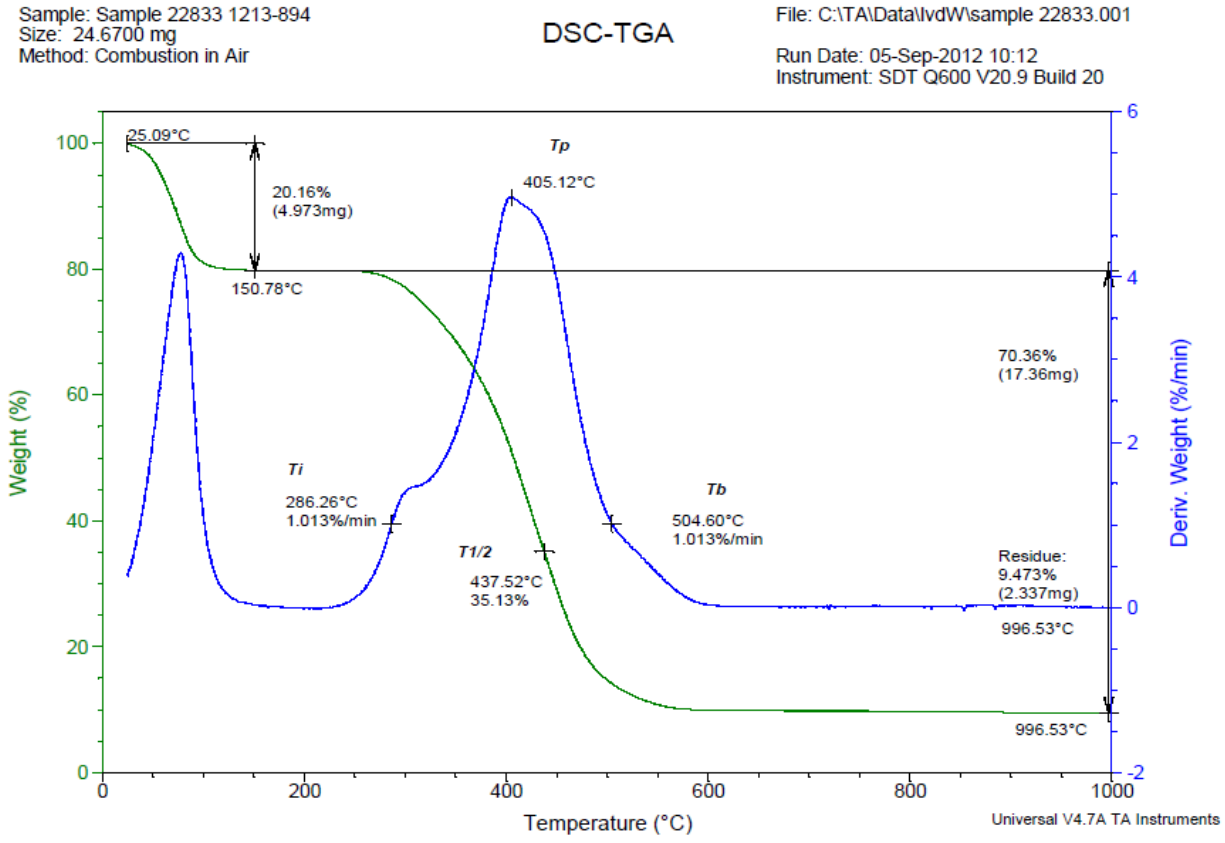



**Figure 4.7: TGA (green line)/DTG (blue line) Combustion Thermogram for Odagbo Coal.**

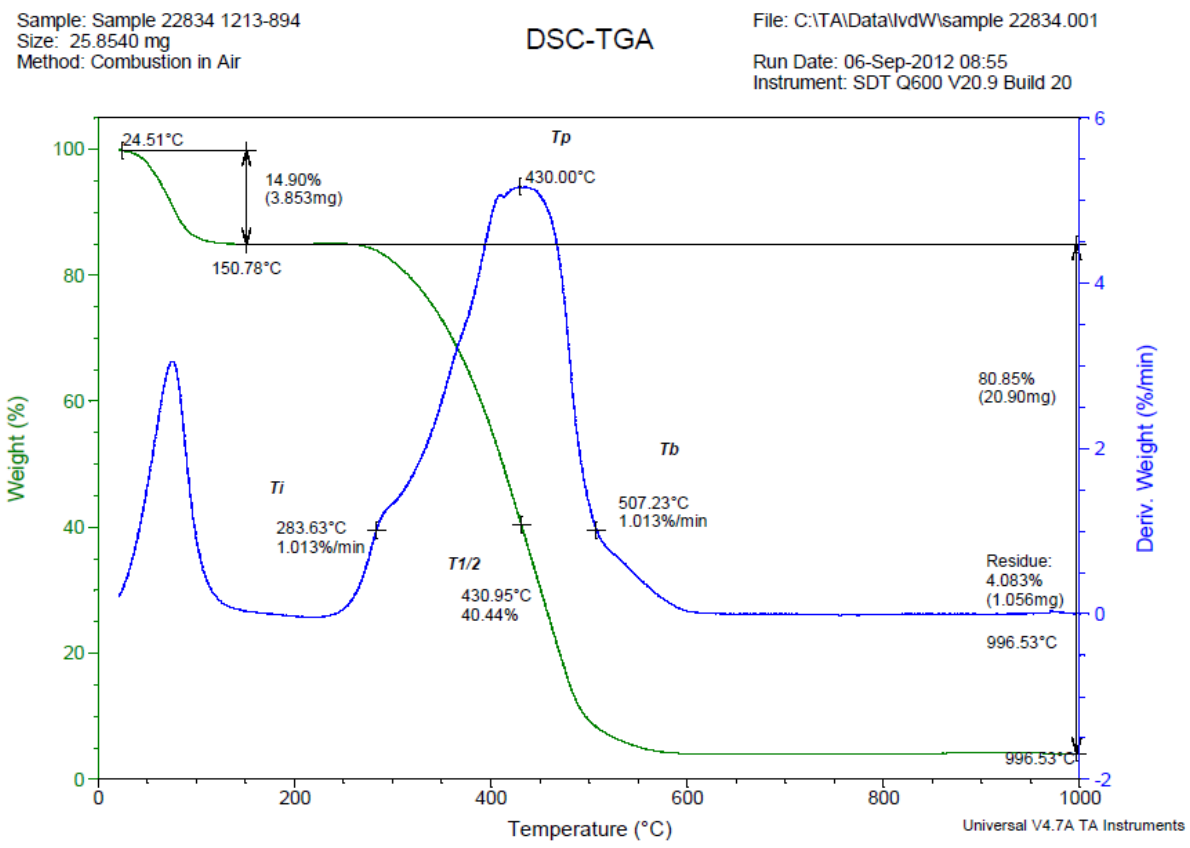



**Figure 4.8: TGA (green line)/DTG (blue line) Combustion Thermogram for Owukpa Coal.**

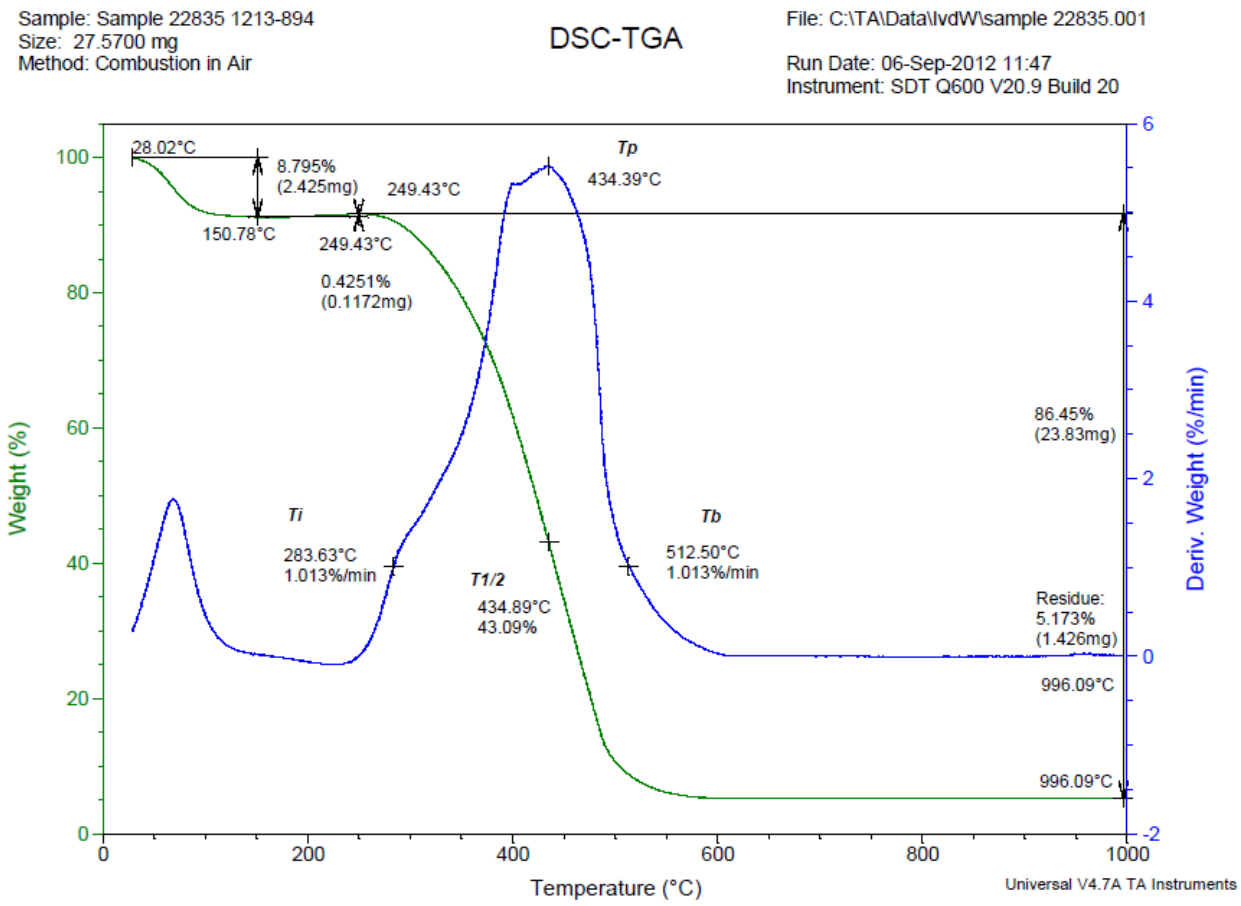



**Figure 4.9: TGA (green line)/DTG (blue line) Combustion Thermogram for Ezimo Coal.**

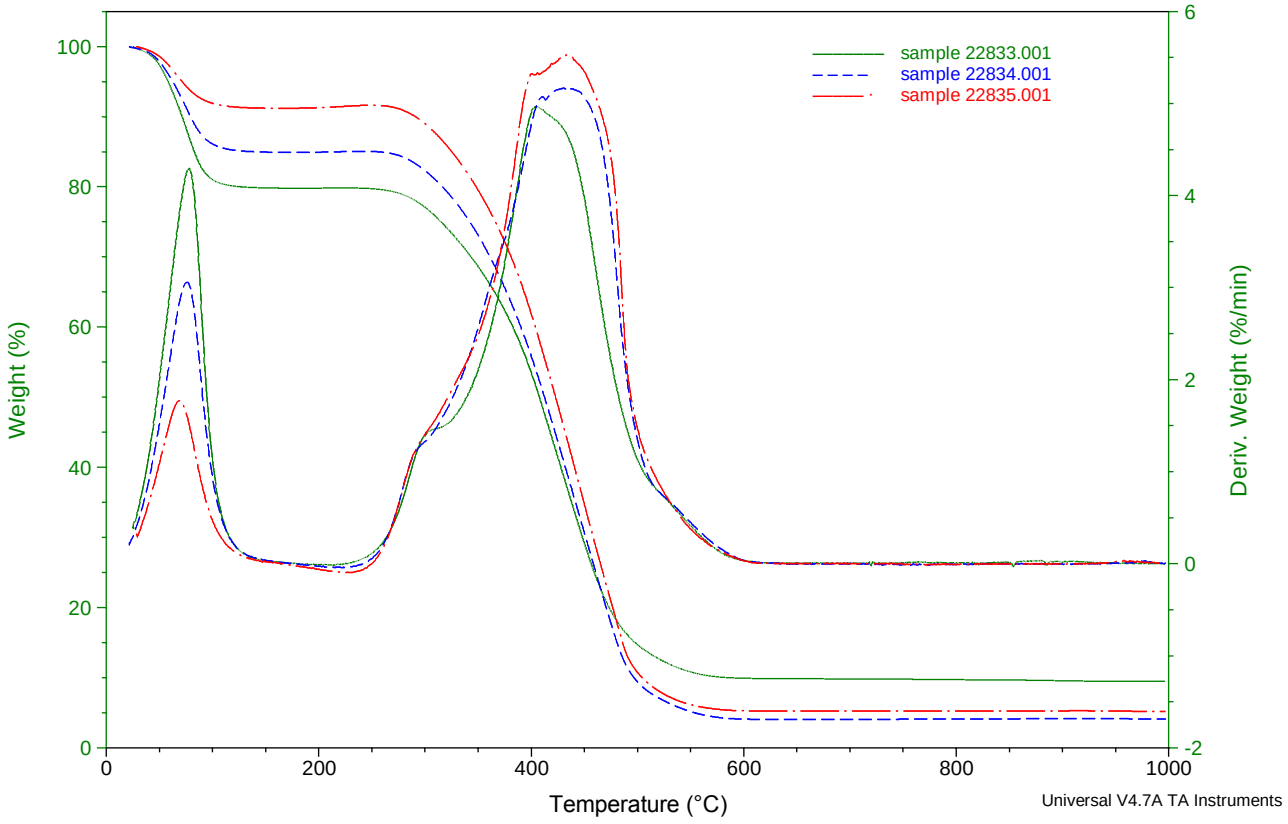



**Figure 4.10: TGA/DTG Comparative Thermograms for Odagbo (green line), Owukpa (blueline) and Ezimo(red line) Coals.**

## 4.7 Correlation of Some Properties and the Calorific Value of the Sampled Coals

Using Equation (3.3), correlation coefficient (r) between some of the properties and Gross Calorific values were obtained for the five (5) coal samples and the results are as shown in Table 4.5.

**Table 4.5: Correlation between Some Coal Properties and Calorific Value**

| Coal Property | Correlation Coefficient, r |
|---|---|
| Fixed Carbon | 0.998 |
| Volatile Matter | 0.834 |
| Carbon | 0.949 |
| Hydrogen | 0.801 |

## 4.8 Discussion of Results

### 4.8.1 Proximate analysis

The inherent moisture contents range from 3.80% to 14.9%. The Odagbo coal sample had the highest moisture content of 14.9%, followed by Owukpa, Ezimo, Amansiodo and then Inyi coal samples with 11.5%, 6.6% 5.4% and 3.8%, respectively. There is no much difference between the volatile matter contents of Odagbo, Owukpa and Amansiodo coal samples. The Inyi coal sample had the lowest volatile matter content (29.90%). The highest fixed carbon content of 47.9% was recorded in the Amansiodo coal sample, followed by Owukpa, Odagbo, Ezimo and Inyi coal samples with values of 46.1%, 41.1%, 38.9% and 35.9%, respectively. The Amansiodo coal sample had the highest gross calorific value of 27.48MJ/kg, followed by the Owukpa coal sample with 26.51MJ/kg, the Odagbo coal sample 22.60MJ/kg, the Ezimo coal sample 20.96MJ/kg and then the Inyi coal sample with 19.39MJ/kg.

Moisture content affects coal (and ash) handling and storage (coal flow properties, behaviour in frost, dust emissions), andpulveriser capacity. An increase in moisture increases the flue gas volume flow rate and influences theexcess air requirements with consequent effect on fans, air preheater and pollution control equipment.Increased moisture lowers thermal efficiency of boiler and can influence burner design (Carpenter *et al.*, 2007). Inyi coal sample with the lowest inherent moisture content (3.8%) would be the easiest to handle and store followed by Amansiodo (5.4%), Ezimo (6.6%), Owukpa (11.5%) and then Odagbo (14.9%) coal samples.

Ash content affects coal and ash handling systems, pulverisers (abrasion), furnace, superheater, reheater, economiser,sootblowing intervals (slagging and fouling propensity, erosion, corrosion), pollution control equipment andunburnt carbon in ash (Carpenter *et al.*, 2007). Owukpa coal sample with the lowest ash content (3.3%) would cost less in terms of investment in ash handling equipment and pulveriser abrasion followed by Odagbo (5.3%), Amansiodo (8.6%), Ezimo (23.4%) and Inyi (30.4%) coal samples.

The volatile matter content of coal affects storage behaviour (oxidation, danger of spontaneous combustion, loss of heating value), pulveriseroutlet temperature and required fineness for pulverisation, burner settings, furnace, combustion behavior and efficiency (ignition, flame shape and stability, burnout and carbon content of fly ash) (Carpenter *et al.*, 2007). Inyi coal sample with the lowest volatile matter (29.9%) would have the least danger of spontaneous combustion. This is followed by Ezimo (31.1%), Amansiodo (38.1%), Owukpa (39.1%) and Odagbo (38.7%) samples.

The calorific value gives the heating value or the heat of combustion of a substance. It has been suggested that the calorific value of power plant coals are in the range of 9.5 MJ/kg to 27 MJ/kg (Zactruba, 2009). Thus, all the coal samples would be suitable for power generation. The Amansiodo coal sample, with the highest heating value of 27.48MJ/kg, would be the best for heating and power generation.

### 4.8.2 Ultimate analysis

The elemental composition of carbon, hydrogen, nitrogen, sulphur and oxygen in the coal samples are shown in Figure 4.3. The percentages of the elemental carbon of Odagbo, Owukpa, Ezimo, Amansiodo, and Inyi Coal samples were as follows: 62.16%, 67.82%; 54.21%, 66.95%; and 49.27%, and hydrogen 5.87%, 5.88%, 4.42%, 5.62% and 4.19%. Ezimo and Inyi coal samples had low total sulphur contents of 0.56% each respectively, while Odagbo sample had the highest value of 1.07%. The oxygen contents of the coal samples fall between 9.34% and 10.93%. The Odagbo coal sample had the lowest oxygen content of 9.34%, followed by Owukpa, Ezimo, Inyi and Amansiodo coal samples with 9.47%, 9.59%, 10.53% and 10.93%, respectively. The Amansiodo coal sample had the highest nitrogen content of 1.58%, followed by the Owukpa coal sample with 1.43%, the Odagbo coal sample follows with 1.37%, Inyi coal sample 1.24%, while the Ezimo had the lowest value of 1.22%.

Carbon and hydrogen are the major combustible constituents of coal, and both of them are high in the coal samples. The higher the carbon content, the higher the calorific value and the better the quality of the coal for power generation.

### 4.8.3 Petrographic (PGA) and thermogravimetric (TGA) analyses

Based on the conclusion of Goidich (2006) that a fuel with a higher fuel ratio is more difficult to burn than a fuel with a lower fuel ratio, based on Figure 4.2, the ease of combustion of the coal samples in decreasing order is Odagbo (1.062), Owukpa (1.179), Inyi

(1.201), Ezimo (1.250) and Amansiodo (1.257). This is in agreement with the findings of Marinov *et al.* (2009) that coals with lower peak maxima temperatures ($T_p$) can generally be ignited and burned easier. The peak temperatures at maximum weight loss rate ($T_p$) obtained during thermogravimetric analysis of three (3) of the coal samples shown in Figure 4.6 was Odagbo (405$^o$C), Owukpa (430$^o$C) and Ezimo (434$^o$C) in increasing order, which is also a decreasing order of ease of combustion.

The percentage weight loss from 25 – 120$^o$C recorded during the thermogravimetric analysis is due to loss of moisture, where a high percentage weight loss is indicative of a high moisture content and vice-versa. The percentage weight loss in decreasing order has Odagbo coal (20.16%), Owukpa coal (14.90%) and Ezimo coal (8.96%). This agrees with results of proximate analysis in Figure 4.1, which has, in decreasing order of moisture content, Odagbo coal (14.9%), Owukpa coal (11.5%) and Ezimo coal (6.6%).

Ignition temperature ($T_i$) values obtained during thermogravimetric analyses (Figure 4.6) and Volatile Matter values obtained during proximate analyses (Figure 4.1) for Odagbo and Owukpa coals agree with the conclusions of Kizgut *et al.* (2003) that the ignition temperature of coal increases with decreasing volatile matter content. However, this conclusion is negated by the value for Ezimo coal, which ought to have the highest ignition temperature value since it possesses the lowest Volatile Matter content (31.1%) of the three samples analysed. This anomaly would be due to its relatively high liptinite content (7.2%) as compared to Odagbo (2.6%) and Owukpa coals (2.9%) as shown in Figure 4.5. This conclusion is based on findings by Kizgut *et al.* (2003) that the ignition temperatures of maceral groups increase in order of liptinite (exinite) – vitrinite – inertinite. In addition,

Falcon and Ham (1988) also summarised that research anddevelopment conducted over the past five years have indicated that organic matter (macerals) significantly influence combustion behaviour, ignition, andflame stability.

Crelling *et al.* (1992) found out during TGA studies that, of the three maceral groups, exinite (liptinite) has the highest burnout temperature. This is confirmed by the results of petrographic analysis showing Liptinite content of the samples as Odagbo (2.6%), Owukpa (2.9%) and Ezimo (7.2%) and TGA results showing burnout temperature, $T_b$, results as Odagbo (504.60$^o$C), Owukpa (507.23$^o$C) and Ezimo (512.50$^o$C). Liptinites are responsible for carbon emissions from boilers.

### 4.8.4 Correlation of properties

From Table 4.5, for the coal samples analysed, the correlation between fixed carbon content and calorific value of coal is the strongest. This means that the fixed carbon content of the coal samples contributes the strongest to the calorific value of the coals. This is followed by carbon, volatile matter and hydrogen contents in decreasing order.

### 4.8.5 Ranking of analysed coal samples using ASTM classification criteria

Using Table 2.1, results of proximate analyses in Figure 4.1 and calorific values in Figure 4.4, Table 4.6was obtained, showing the classification of the five (5) coal samples based on ASTM D388 specifications. Based on the results above, the Fixed Carbon (<69%) and Volatile Matter (>31%) values obtained imply that the coals may only be ranked using the Heating Value (Btu/lb) parameter.

**Table 4.6: Ranking of Five Coal Samples using the ASTM Classification.**

| Coal Rank | Heating Value Criteria (Btu/lb) (Miller, 2005) | Coal Samples (Heating Value, Btu/lb) | | | | |
|---|---|---|---|---|---|---|
| | | Odagbo (9,715.74) | Owukpa (11,396.65) | Ezimo (9,010.70) | Amansiodo (11,813.65) | Inyi (8,335.76) |
| Bituminous high-volatile B | 13,000 – 14,000 | | | | | |
| Bituminous high-volatile C | 10,500 – 13,000 | | | | ✓ | |
| Subbituminous A | 10,500 – 11,500 | | ✓ | | | |
| Subbituminous B | 9,500 – 10,500 | ✓ | | | | |
| Subbituminous C | 8,300 – 9,500 | | | ✓ | | ✓ |
| Lignite A | 6,300 – 8,300 | | | | | |
| Lignite B | <6,300 | | | | | |

Table 4.6shows that Amansiodo coal is a Bituminous high-volatile C coal and Owukpa coal, a Sub-bituminous A coal. Odagbo coal is a Sub-bituminous B coal while Ezimo and Inyi are both Sub-bituminous C coals. This classification agrees with published data shown in Table 1.5.

### 4.8.6 Ash and sulphur classification of analysed coal samples

From results of proximate and ultimate analyses shown in Figures 4.1and 4.3 respectively, Table 4.7was obtained, showing the ash and sulphur classifications of the coal samples.

**Table 4.7: Ash and Sulphur Classification ofthe Five Coal Samples.**

| *Classification | *Composition Range a.r. (%) | Coal Samples (Heating Value, Btu/lb) | | | | |
|---|---|---|---|---|---|---|
| | | Odagbo | Owukpa | Ezimo | Amansiodo | Inyi |
| Ash Content | | | | | | |
| High Ash | > 15.0 | | | ✓ | | ✓ |
| Medium Ash | 8.0 – 15.0 | | | | ✓ | |
| Low Ash | < 8.0 | ✓ | ✓ | | | |
| Sulphur Content | | | | | | |
| High Sulphur | > 3.0 | | | | | |
| Medium Sulphur | 1.0 – 3.0 | ✓ | | | | |
| Low Sulphur | < 1.0 | | ✓ | ✓ | ✓ | ✓ |

***Source: Tavoulareas *et al.*, 1995**

Table 4.7 shows that Ezimo and Inyi coals are both high-ash coals. Amansiodo coal is a medium-ash coal while Odagbo and Owukpa coals are low-ash coals. Odagbo coal is a medium-sulphur coal while Owukpa, Ezimo, Amansiodo and Inyi coals are all low-sulphur coals.

### 4.8.7 Suitability of analysed coal samples for pulverised coal-fired power generation

Pulverised Coal Combustion is the most commonly used method in coal-fired power plants.This technology is well developed, and there are thousands of units around the world, accounting for well over 90% of coal-fired capacity. Pulverised Coal Combustion can be used to fire a wide variety of coals, although it is not always appropriate for those with a high ash content(IEA, 2010). Results of the analysis of the coal samples were benchmarked with requirements of existing pulverised coal combustion plants from around the world.

Table 4.6 shows that Amansiodo coal is the only bituminous coal among the coals analysed. As a result of this, Table 4.8 compares all test results obtained for Amansiodo coal with the requirements in Table 2.3 (arising from both literature and a survey of requirements of actual PC power plant operators) to determine its suitability with typically published requirements for pulverised bituminous coal-fired power generation. This comparison clearly shows that the tested properties of Amansiodo coal, while meeting most of the requirements, exceed or fall below the benchmark in volatile matter content (slightly higher), nitrogen (higher) and sodium oxide in its ash (lower). Chlorine content, hardgrove grindability index (HGI), sulphite in ash and petrographic analysis were not carried out on this coal and so no comparison is provided.

**Table 4.8: Comparison of Properties of Amansiodo Coal with Published Bituminous Coal Quality Requirements for Pulverised Coal-Fired Plants (Based on Table 2.3)**

| Parameter | Desired Values | Typical Limits □ | Amansiodo Coal |
|---|---|---|---|
| Heating value, MJ/kg ar | High | min 24 – 25 (23) | 27.48 |
| Moisture, % ar | 4 – 8 | max 12 | 5.4 |
| Volatile matter, % mf | 20 – 35 | min 20 (side-fired furnaces) | 38.1 |
| | 15 – 20 | max 20 (down-fired furnaces) | 38.1 |
| Ash, % mf | low | max 15 – 20 (max 30) | 8.6 |
| Sulphur, % daf | Low (<1%) | dependent on local pollution regulations | 0.92 |
| Nitrogen, % daf | low | (0.8 – 1.1), dependent on local pollution regulations | 1.58 |
| Chlorine | low | max 0.1 – 0.3 (max 0.5) | Not analysed |
| HGI | high | min 50 – 55 (min 39) | Not analysed |
| Ash analysis, wt % ash | | | |
| Silicon dioxide | | (45 – 75) | 58.94 |
| Aluminium oxide | | (15 – 35) | 29.13 |
| Titanium oxide | | (0.4 – 2.2) | 2.13 |
| Ferric oxide | | (1 – 12) | 6.90 |
| Calcium oxide | | (0.1 – 2.3) | 0.34 |
| Magnesium oxide | | (0.2 – 1.4) | 0.35 |
| Sodium oxide | | (0.1 – 0.9) | 0.06 |
| Potassium oxide | | (0.8 – 2.6) | 1.32 |
| Sulphite | | (0.1 – 1.6) | Not analysed |
| Phosphorus pentoxide | | (0.1 – 1.5) | 0.22 |
| Ash fusion temperatures, $^{o}$C | | | |
| Initial deformation | High | (>1075) | >1550 |
| Softening | High | (>1150) | >1550 |
| Hemispherical | high | (>1180) | >1550 |
| Fluid | High | (>1225) | >1550 |
| Maceral analysis, % | | | |
| Vitrinite | | 55 – 80 | Not analysed |
| Exinite | | 5 – 15 | Not analysed |
| Inertinite | | 10 – 25 | Not analysed |

***** Typical limits refer to those commonly quoted; those in brackets indicate outer limits acceptable in some cases.
Legend: Acceptable Allowable Not Acceptable

Further still, Table 4.9 compares the characteristics of the sub-bituminous coal used by the Genesee 3 Phase power station in Canada (extracted from Table 2.5) with the remaining four samples which have been confirmed to be sub-bituminous coals. This comparison is only limited to the properties listed in Table 2.5.

**Table 4.9: Comparison of Four Coal Samples with Characteristics of Sub-bituminous Coal used by the Genessee Phase 3 Power Station in Canada.**

| Parameters | *Genesee Phase 3, Canada* | Coal Samples | | | |
|---|---|---|---|---|---|
| | | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Inyi*** |
| Coal type | Sub-bituminous | Sub-bituminous | Sub-bituminous | Sub-bituminous | Sub-bituminous |
| Gross Calorific Value, MJ/kg | 17.9 | 22.60 | 26.51 | 20.96 | 19.39 |
| Ash, % | 19.4 | 5.3 | 3.3 | 23.4 | 30.4 |
| Moisture, % | 20 | 14.9 | 11.5 | 6.6 | 3.8 |
| Sulphur, % | 0.2 | 1.07 | 0.60 | 0.56 | 0.56 |

Legend: able able

Table 4.9 shows that the sulphur contents of Odagbo, Owukpa, Ezimo and Inyi coals exceed the benchmark while the ash contents of Ezimo and Inyi coals also exceed the benchmark.

Table 2.5 shows that modern pulverised-coal combustion power stations have been designed to make use of low grade coals with ash contents as high as 45%, sulphur contents as high as 1.7% and moisture contents as high as 58%. Environmental regulations have been the only limiting factor in the actual use of these low grade coals (IEA, 2007). However, irrespective of the deficiencies noted, corrections may be effected through beneficiation or blending with other appropriate coals.

### 4.8.8 Suitability of analysed coal samples for circulating fluidised bed combustion (CFBC) powergeneration

Circulating Fluidised Bed Combustion (CFBC) units can tolerate a widevariety of coals and particle sizes and, because of their low operating temperatures and stagedcombustion, produce low levels of $NO_x$ relative to PC boilers. The lower operating temperature isalso ideally suitable for the in situ capture of sulphur dioxide ($SO_2$). The efficiency of CFBC units issimilar to that of PC units (Burnard and Bhattacharya, 2011). This is further reinforced by

Figure 2.2 and from the conclusion of Goidich (2006) that circulating fluidised bed technology can be used to fire the entire range of high and low quality coals. Thus, all the five (5) coal samples can be utilised for power generation using this technology.

CFBC technology was developed to burn low grade and/or difficult-to-burn fuels. Many existing CFBC units are fired with waste coal and serve to clean up waste piles left over from mining activities. CFBC technology has been employed for power generation for over 25 years and the technology is still evolving. The poorer economy of scale and lower efficiency of the CFBC plantsresult in higher plant costs and has limited its deployment (IEA Clean Coal Center, 2013).

# CHAPTER FIVE

# SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Summary

Five coal samples from Odagbo (Benue State), Owukpa (Benue State), Ezimo (Enugu), Amansiodo (Enugu State) and Inyi (Enugu State) have been characterised to determine their suitability for power generation. Specifically, tests carried out on the coal samples include proximate, ultimate, ash composition, petrographic and thermogravimetric analyses. Calorific value and ash fusion temperatures were also determined. Results obtained were compared with requirements published by pulverised coal power plant operators around the world. Amansiodo coal sample had the highest gross calorific value of 27.48MJ/kg, followed by Owukpa, Odagbo, Ezimo and Inyi coal samples with 26.51MJ/kg,22.60MJ/kg, 20.96MJ/kg and19.39MJ/kg, respectively. Results of proximate analysis show that Owukpa coal had the highest volatile matter content of 39.1% while Inyi coal sample had the lowest moisture content of 3.8%.The highest fixed carbon content of 47.9% was recorded in Amansiodo coal. Elemental carbon was highest in Odagbo coal (67.82%).

Petrographic analysis results show that Owukpa coal had the highest huminite content of 75.8%, followed by Odagbo and Ezimo coals with 65.3% and 45.0%, respectively. Ezimo coal had the highest liptinite content (7.2%). Thermogravimetric analysis results show that Owukpa and Ezimo jointly recorded the lowest ignition temperature (283.63$^{o}$C) while the lowest peak temperature at maximum weight loss rate was recorded in Odagbo coal (405.12$^{o}$C). Odagbo coal also had the lowest burnout temperature of 504.60$^{o}$C. The lowest ash fusion temperature recorded from analysis of all the samples was in the oxidising atmosphere with Odagbo coal (1461$^{o}$C).

## 5.2 Conclusions

Based on analysis of tests carried out, the coals have been classified in termsof rank, grade and type. Amansiodo coal is a bituminous, low sulphur and medium ash coal; while Owukpa coal is a sub-bituminous A, low sulphur, low ash coal rich in huminites. In addition, Odagbo coal is a sub-bituminous B, medium sulphur, low ash coal rich in huminites; Ezimo coal is a sub-bituminous C, low sulphur, high ash coal; while Inyi coal is asub-bituminous C, low sulphur, high ash coal.

The ease of combustion of the coal samples in decreasing order is Odagbo, Owukpa, Inyi, Ezimo and Amansiodo. While the ignition temperatures of the coals increase with decreasing volatile matter content, their calorific values are strongly correlated with the fixed carbon, elemental carbon, volatile matter and hydrogen contents in decreasing order.

Benchmarking the properties of the five (5) coal samples against requirements of existing PC plants from around the world shows that these coals meet most requirements. Pulverised Coal (PC) Combustion is the most commonly used technology in coal-fired power plants and is a well developed technology that accounts for well over 90% of coal-fired capacity worldwide. Deficiencies observed may be corrected through beneficiation and/or blending with other appropriate coals.

Finally, the five (5) coal samples analysed can be used for power generation using circulating fluidised bed combustion (CFBC) technology. CFBCtechnology was developed to burn low

grade and/or difficult-to-burn fuelsand can therefore tolerate a widevariety of coals and particle sizes.

## 5.3 Recommendations

From the conclusion of the International Energy Agency that developing economies have a particularly strong dependency on coal for power production, electricity generation from coal is the most feasible solution to the power supply problem bedeviling Nigeria. In keeping with its published Roadmap for Power Sector Reform, it is needful for the government to aggressively exploit Nigeria's abundant coal reserves for this purpose. Both pulverised coal combustion and fluidized bed combustion technologies may be deployed to ensure that Nigerian coals are used for generation of much-needed electricity.

Petrographic analysis of Amansiodo and Inyi coals, hardgrove grindability index and drop tube furnace tests of the five coal samples are recommended to complete the range of tests required for the characterization of these coals. In addition, a study of the characteristics of different ratios of blends of these coals with a superior bituminous coal is also recommended.

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# APPENDICES

**Appendix A: Results of Proximate Analyses ofthe Five Coal Samples.**

| Properties | Samples | | | | |
|---|---|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Amansiodo*** | ***Inyi*** |
| Inherent Moisture (%) | 14.9 | 11.5 | 6.6 | 5.4 | 3.8 |
| Ash Content (%) | 5.3 | 3.3 | 23.4 | 8.6 | 30.4 |
| Volatile Matter, VM (%) | 38.7 | 39.1 | 31.1 | 38.1 | 29.9 |
| Fixed Carbon, FC (%) | 41.1 | 46.1 | 38.9 | 47.9 | 35.9 |
| Fuel Ratio (FC/VM) | 1.062 | 1.179 | 1.250 | 1.257 | 1.201 |

**Appendix B: Results of Ultimate Analyses of theFive Coal Samples.**

| Elements | Samples | | | | |
|---|---|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Amansiodo*** | ***Inyi*** |
| Carbon (%) | 62.16 | 67.82 | 54.21 | 66.95 | 49.27 |
| Hydrogen (%) | 5.87 | 5.88 | 4.42 | 5.62 | 4.19 |
| Nitrogen (%) | 1.37 | 1.43 | 1.22 | 1.58 | 1.24 |
| Total Sulphur (%) | 1.07 | 0.60 | 0.56 | 0.92 | 0.56 |
| Oxygen (%) | 9.34 | 9.47 | 9.59 | 10.93 | 10.53 |

**Appendix C: Results of Calorific Value Determination ofthe Five Coal Samples.**

| Gross Calorific Value | Samples | | | | |
|---|---|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** | ***Amansiodo*** | ***Inyi*** |
| MJ/kg | 22.60 | 26.51 | 20.96 | 27.48 | 19.39 |
| Btu/lb (1MJ/kg=429.9Btu/lb) | 9,715.74 | 11,396.65 | 9,010.70 | 11,813.65 | 8,335.76 |

**Appendix D: Results of Petrographic Analyses**

| Macerals | Samples | | |
|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** |
| Huminite (%) | 65.3 | 75.8 | 45.0 |
| Liptinite (Exinite) (%) | 2.6 | 2.9 | 7.2 |
| Semifusinite (%) | 21.8 | 16.3 | 44.8 |
| Fusinite + Secretinite (%) | 2.8 | 2.1 | 0.0 |
| Micrinite (%) | 0.0 | 0.0 | 0.0 |
| Total Inertinites (%) | 24.6 | 18.4 | 44.8 |
| Mineral Matter (%) | 7.5 | 2.9 | 3.0 |

**Appendix E: Characteristic Temperatures of the Coal Samples.**

| Temperatures | ***Samples*** | | |
|---|---|---|---|
| | ***Odagbo*** | ***Owukpa*** | ***Ezimo*** |
| $T_i$ ($^oC$) | 286.26 | 283.63 | 283.63 |
| $T_p$ ($^oC$) | 405.12 | 430.00 | 434.39 |
| $T_{1/2}$ ($^oC$) | 437.52 | 430.95 | 434.39 |
| $T_b$($^oC$) | 504.60 | 507.23 | 512.50 |