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The Impact of Coal Quality and Technical Operating Conditions on the Efficiency of a Spreader Stoker Boiler

Rets'elisitsoe Lehlohonolo Taole

A Research Report submitted to the Faculty of Engineering and the Built Environment, in partial fulfilment of the requirements for the degree of Master of Science in Engineering,

University of the Witwatersrand,

Johannesburg, 2014.

DECLARATION

I, Rets'elisitsoe Lehlohonolo Taole, declare that this research report titled "**The Impact of Coal Quality and Technical Operating Conditions on the Efficiency of a Spreader Stoker Boiler**" is my own unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

Candidate Signature: .RL Taole.....

Date: 26/08/2014.

ABSTRACT

In South Africa a considerable number of small and large scale industrial consumers use coal for power generation and production of process heat, and for many years combustion efficiency was assured through the acquisition of high grade steam coals. This is not the case any longer as coal qualities on the inland market have deteriorated and such scenarios have led to unusual and often poor combustion performance and major plant stoppages. In-depth research and new technologies have been necessary to establish the cause of these unusual events.

This research study looks at the combustion behaviour of four different types of coal (coal A, B, C and D) in one particular spreader stoker boiler. Combustion conditions remained constant for all coals. The main focus of the investigation is based on thermographic flame temperature analysis of each coal and the interpreted results together with the physical and chemical properties of the coals. In deciding the best performing coal, factors considered include the steam output, the flame temperature recorded, the combustion efficiency determined and the amount of unburnt carbon registered in the fly and bottom ash samples. Interpretation of the results also included checking possible correlations of the above factors to determine the specific parameters that may have influenced the observed combustion behaviours. Implications and applications of the achieved results are made with regards to the efficiency, safety and environmental conditions of the plant and possible recommendations as to the best coal of choice for the boiler under investigation are presented.

Results obtained indicate that there was a strong correlation between the petrographic properties of the coals and steam output, combustion efficiency, amount of unburnt carbon and thermographic data, particularly the flame shape. On the other hand, association was not established between these parameters and the proximate analyses, calorific values and ash contents of the coals. In terms of combustion efficiencies, all coals yielded relatively high amounts of unburnt carbon in the fly ash (about 36.90 % on average for the four samples). Such magnitudes of unburnt material necessitate improvements on post combustion materials management, i.e. enhanced fly ash reinjection as one of the several options. The thermographic results led to the conclusion that South African low grade Gondwana coals undergo delayed ignition and burn at unusually high temperatures. Generally the coals were found to burn at temperatures between 1500 – 1800°C. Temperatures of this scale are in excess of those projected by fuel technologists, and are often not taken into account by boiler manufacturers whose belief is that combustion temperatures are normally anticipated to be around 1400°C. It is such conditions that now pose serious risk to boiler equipment.

Based on these results it is recommended that a design review be conducted to evaluate the suitability of the existing materials in boiler construction in order to address the high temperatures recorded when burning South African domestic coals. This would allow for equipment retrofitting that guarantee an extended lifespan as well as improved operational efficiencies of currently installed equipment or the acquisition of a more suitable plant in future.

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NOMENCLATURE

ABMA: American Boiler Manufacture Association

AFT: Ash Fusion Temperature

AI: Abrasion Index

COx: Oxides of Carbon (CO, CO_2)

CSN: Crucible Swelling Index

CV: Calorific Value

DCS: Distributed Control System

DMR: Department of Mineral Resources

EPA: Environmental Protection Agency

ESP: Electro-static Precipitator

ERM: Effective Reactive Macerals is arbitrarily defined as: vitrinite + liptinite + [reactive inertinite (semifusinite) + reactive inertodetrinite (part of inertinite)]/2

FBC: Fluidised Bed Combustion boilers

% FC: Percentage Fixed Carbon

FR: Fuel Ratio: $\mathrm{FR} = \frac{\%\ \mathrm{FC}}{\%\ \mathrm{VM}}$

HAZOP: Hazard and Operability Study

HGI: Hard Grove Index

ICP- OES: Inductively Coupled Optical Emission Spectrometry

ISO: International Organisation for Standardisation

LOI: Loss on Ignition

MCR: Maximum Continuous Rating

MOC: Materials of Construction

Nm^3/hr: Normal cubic meter per hour

NOx: Oxides of Nitrogen (NO, N_2O, NO_2)

PFB: Pulverised Fuel Boiler

PLC: Programmable Logic Controller

PM_{10}: Particulate Matter in the range of 10 micrometers (µm)

PPE: Personal Protective Equipment

NOMENCLATURE

PSD: Particle Size Distribution

QEMSCAN: Quantitative Evaluation of Minerals by Scanning Electron Microscopy

SABS: South African Bureau of Standards

SANAS: South African National Accreditation System

SCDA: Supervisory Control and Data Acquisition system

SEM: Scanning Electron Microscopy

SOx: Oxides of Sulphur (SO, SO_2 , SO_3)

UBC: Unburnt Carbon

% VM: Percentage Volatile Matter content

XRF: X-ray Fluorescence

XRD: X-ray Diffraction

ε : Combustion efficiency

µm: Micrometer

ppm: Part per million

^{o}C: Degrees Celsius

h^{-1}: per hour

V: Volts

Hz: Hertz

MJ/kg: Megajoule per kilogram

MW_t: Megawatts thermal

l/h: Litres per hour

barg: bar gauge pressure

kPa: kilo Pascal

δ: Standard Deviation

Rr: Random Reflectance

% mmf: Percentage by volume, mineral matter free basis

% AD: Percent by volume, air-dry basis

1": One inch ≡ 25.4 mm

CHAPTER 1

This chapter will highlight the motivation behind the initiation of the study and familiarise the reader with the project objectives and the approach that will be taken to achieve the objectives, as well as the scope of work. An introduction to the general problems facing the operation of spreader stoker boilers is also discussed.

1.1 Background and Study Motivation

Technical operational conditions, rather than the inherent characteristics of coal, were traditionally considered to be the core reasons for performance problems encountered in coal-fired boilers. As a result, industry's approach in resolving the operational problems was initially inclined towards the invention of new and sophisticated types of boilers. However, the challenges still persist and this now imposes the need to intensively scrutinise the nature of feed coals and to consider their properties as significant contributors to operational inefficiencies. The focal point of this research is on spreader stoker type boilers which, along with the complementary chain grate stokers, are regarded as not being very efficient combustors of coal due to their archaic designs (Lindsay and Pilkington, 1953).

Stoker-fired boilers were among the first types of boilers to be built. According to Giaier and Loviska (1997), travelling grate spreader stokers were first developed in the United States of America around 1938. During this era the primary concern for manufacturers was plant reliability and not much thought was put into designing equipment for efficient operation.

It is because of increasing environmental concerns and the condition of the aging equipment that some in industry have come to believe that stoker boilers should simply be abolished (Bogaard and Bergman, 1985). This view may be true for cases where applications are small or where the economics warrant replacement. On the other hand, there are factors in favour of keeping existing boilers. Firstly, the equipment and the infrastructure are already in place. Secondly, noticeable improvements can be achieved on the thermal efficiency and emission levels at significantly lower costs than that of the proposed replacements. Thus, industry today realises that the use of any advanced technology does not necessarily change the basic principles of combustion, but merely involves the use of a different type of equipment. It has now been acknowledged that a wealth of information can still be gathered from reassessing these 'old' technologies (Giaier and Loviska, 1997). Falcon (2010) estimated that there are about 6,000 industrial scale boilers in South African industries today, all using lower grade coals than they were initially designed for.

It must be emphasised that the discussion here is not on whether or not coal qualities actually influence boiler performance; past research has reasonably shown that they do. The reality, nonetheless, is that studies in this respect have not been exhaustively conducted and therefore not much information is accessible especially for stoker type of boilers. More work still needs to be done to adequately respond to the question to what extent do coal qualities affect boiler efficiency. Furthermore, there is virtually no published information which clearly draws the relationship between coal quality, technical operational conditions, and the boiler efficiency of spreader stokers for South African coals. Most of the information on related studies resides with boiler manufactures who rarely publish their results and findings. In addition, the bulk of this restricted investigational work was formerly based on laboratory and pilot-scale operating conditions. This absence of information suggests the need to further explore combustion performance of coal under full-scale operation.

In summary poor boiler efficiency is a source of concern for three main reasons: increased utilisation of raw materials to gain a given heat or steam output, higher maintenance costs, and elevated pollution levels. The research has the potential to successfully address these concerns and offer industry cost-saving options in terms of reduced overheads for coal used per tonne of steam generated. To be precise, once information on how coal quality impacts boiler efficiency is well understood and documented for this type of boiler, the proven methods can then be applied to make significant improvements in the performance and reduction of stack emissions on the existing plants.

The findings of this study will also be of importance to both private and governmental organisations that deal with environmental regulations, especially when considering South Africa's fast depleting and increasingly poor grades of coal reserves and increasing concerns regarding emissions leading to the climatic change. To the academic world, the benefit of this investigation lies in availing useful information that establishes ground theories for enhanced research into new technologies such as biomass co-firing. The competitiveness of travelling grate stoker boilers in firing a wide range of fuels is affirmed in Yin et al. (2008) cited by Lin et al. (2009) and by Oland (2002).

1.2 Problem Statement

Despite having been in use since the beginning of the twentieth century, coal-fired spreader stoker technology still presents challenges concerning inefficient combustion of coal (Lin et al., 2009). Boiler inefficiencies were traditionally associated more with inappropriate operating conditions. As a result, not much research was undertaken to investigate variations in coal quality as a credible contributor to these inadequacies. This dilemma has not only led to lack of accessible technical information relating to this subject, but has in the wider context, caused serious concerns in the utility and power generation industries due to cost implications associated with inefficient operation. High consumption rates of feed materials, increased maintenance schedules and elevated stack emissions are normally encountered with reduced efficiencies. It is for these reasons that the current research was undertaken.

1.3 Research Questions

The primary question posed by this research is, “what are the causes of reduced efficiencies in travelling grate stokers”? Consequently this raises the following sub-questions:

- To what extent does the quality of coal influence boiler efficiency in travelling grate spreader stokers?

- How can the existing inefficiencies in travelling grate spreader stoker-fired boilers be minimised for specific types of coal?

1.4 Study Objectives

The main objectives of this research are to refine the current understanding on the effect of varying coal qualities and operating conditions on boiler efficiency in one travelling grate spreader stoker boiler. The focus will be on studying flame characteristics in the boiler furnace when combusting South African coals of differing qualities. Four different coal samples, coals A, B, C and D, were tested to investigate their impact on the boiler efficiency. All feed coal types will be of consistent ‘pea’ size which represents particles size range of 6.25 x 25 mm.

It is expected that completion of the above objectives will allow for the combustion behavior of the four coal types to be better understood. The study will highlight the importance of interpreting results obtained from advanced analytical techniques, such as thermography and petrography, as well as conventional physical and chemical properties of coal (proximate and ultimate analyses), in order to fully comprehend the observed behavioral patterns of particular coals during combustion.

1.5 Report Structure

This report describes the impact of coal quality on the efficiency of a spreader stoker boiler through studying the flame characteristics of the different coals and highlights the significance and implications of the observed results. The report is divided into six chapters which are structured as follows:

CHAPTER 1: INTRODUCTION

This chapter introduces the study topic and summarises the research objectives. It outlines how the objectives will be achieved and provides a breakdown of the report structure, clearly setting out the scope of the work to be conducted.

CHAPTER 2: LITERATURE REVIEW

This section of the report provides an overview of the research topic, reviewing technical details in similar studies that have been conducted. This includes a review of the design specifics for the spreader stoker boilers and historical background on the nature of the problems encountered when operating this type of equipment. The review also establishes theoretical guidelines for the research study.

CHAPTER 3: EXPERIMENTAL METHOD

Describes the methods used in executing the study and provides details on how the sampling and testing techniques were performed. It also discusses the approach adopted in executing the work as well as identifying and summarising the various alternative scenarios that will be considered as part of the project scope and development.

CHAPTER 4: RESULTS

This section provides details of the main results of the tests work conducted. Two main categories of the results are discussed, i.e. Analytical Results and Operational Results. Interpretation of the results is presented in the Discussion section.

CHAPTER 5: DISCUSSION

This chapter provides detailed interpretation of the research findings. Results are first discussed individually and then comparisons are drawn between the different results achieved for the respective coals tested. Hypotheses are then developed around the observations made to provide essential meaning and implications.

CONCLUSIONS AND RECOMMENDATIONS

This section provides an overall summary of the report based on the observations made. The research findings and their possible implications are discussed. The proposed solutions to the operational challenges for the type of equipment and coal feedstock are highlighted and recommendations for improvement in operation and mitigation of challenges are presented.

CHAPTER 2

The literature review gives a background on theory for similar works conducted elsewhere in recent times and highlights the basis on which the study is structured from theoretical and fundamental points of view. The review then surveys the operating and design characters of stoker boilers.

2.1 Introduction

Travelling grate spreader stokers are one of the oldest technologies (Giaier and Loviska, 1997). They were developed to burn coal for small scale industrial steam generation and since that period there have been advancements into other technologies, such as pulverised fuel boilers (PFB), fluidised bed combustion (FBC), and circulating fluidised bed (CFB). However, conventional stokers are still widely used today in South African industries including the pulp and paper, sugar, and many other manufacturing industries requiring steam generation. Extensive use of chain grate boilers is also found in Asian countries such as India and China (Liu et al., 2008).

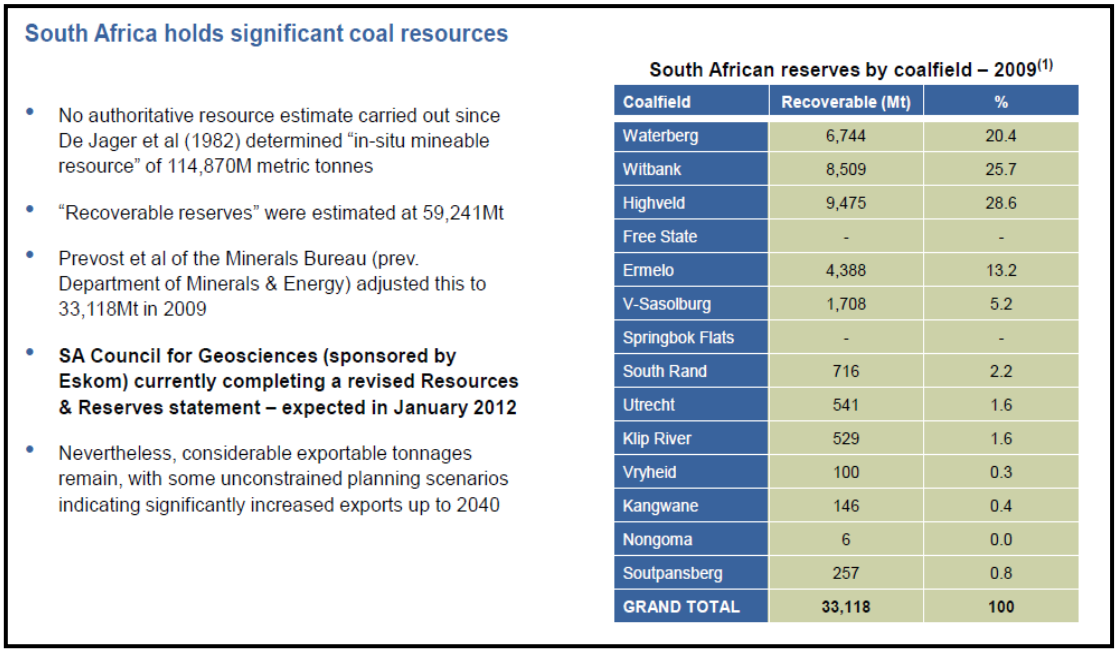
Stoker fired boilers were initially built for plant reliability rather than efficiency (Scaroni, 1984). Sustaining superior boiler efficiencies means that operators today have to adopt a holistic approach in their tackling of performance problems experienced in industry. There needs to be a shift from the traditional view that operational conditions are more important than the properties of coal! This realisation suggests that categorisation of coals should also be well understood if retrofitting of existing equipment is to be successful (Falcon and Ham, 1988). It is important that this standpoint be fully embraced especially in the South African context because majority of the old boilers were designed by overseas manufacturers (mostly American and British), using their own types of coal and not local coals. This implies that original designs of the old boilers did not necessarily match South African coal types. De Villiers (1994), cited in Thorne (1995), estimates that for South African industries, boiler efficiencies could be improved by 3 - 5 % on average with a payback time of one year or less.

2.2 General Information on South African Coal Reserves and Resources

Coal plays a very strategic role in the South African energy and industrial sectors, both locally and through the export markets. The challenge however is that the country's reserves are fairly limited and this implies that efficient utilisation of coal is crucial in ensuring that resources last for a reasonable period into the future. Prevost (2004), in Jeffrey (2005:95), estimated that South Africa's coal reserves were approximately 33 billion tonnes and such quantities could last up to the year 2050 based on the current production rates. Such a capacity of reserves can hugely boost and sustain the economy for many years if appropriately exploited. On average the production of marketable coal in South Africa is approximately 224 million tonnes per annum.

About 25% of this production is exported mainly as high grade steam coal and this makes the country a major competitor in the global coal trade (Falcon et al., 2009).

A similar figure was cited during the 2011 discussions of the South African Coal Road Map presentations (Hall, 2011).



South Africa holds significant coal resources

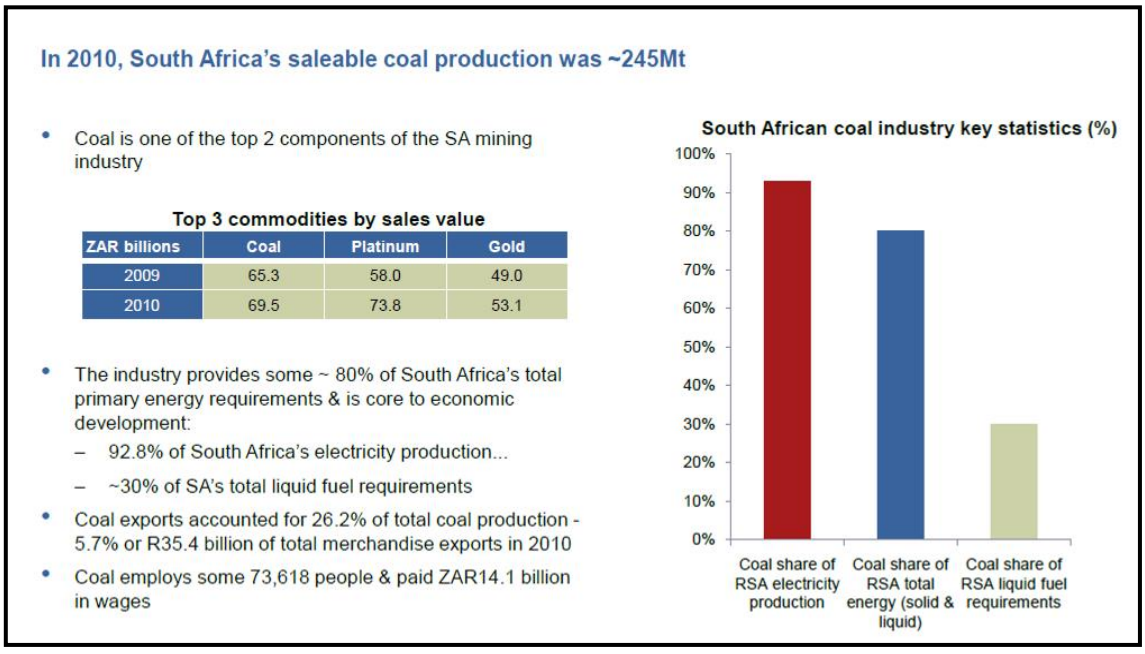
- No authoritative resource estimate carried out since De Jager et al (1982) determined "in-situ mineable resource" of 114,870M metric tonnes
- "Recoverable reserves" were estimated at 59,241Mt
- Prevost et al of the Minerals Bureau (prev. Department of Minerals & Energy) adjusted this to 33,118Mt in 2009
- **SA Council for Geosciences (sponsored by Eskom) currently completing a revised Resources & Reserves statement – expected in January 2012**
- Nevertheless, considerable exportable tonnages remain, with some unconstrained planning scenarios indicating significantly increased exports up to 2040

South African reserves by coalfield – 2009(1)

Coalfield	Recoverable (Mt)	%
Waterberg	6,744	20.4
Witbank	8,509	25.7
Highveld	9,475	28.6
Free State	-	-
Ermelo	4,388	13.2
V-Sasolburg	1,708	5.2
Springbok Flats	-	-
South Rand	716	2.2
Utrecht	541	1.6
Klip River	529	1.6
Vryheid	100	0.3
Kangwane	146	0.4
Nongoma	6	0.0
Soutpansberg	257	0.8
GRAND TOTAL	**33,118**	**100**

Figure 2.*1:* *South Africa coal resources [Hall, 2011].*

Locally, coal accounts for 95% of South Africa's energy production. However the economic prospects brought by the coal sector will not be realised if utilisation is not effective (Creamer Media, 2011). Increasing environmental concerns and operating costs mean that end-users today do not have the liberty to ignore inadequacies. Further details of the usable coal reserves and various end-users are illustrated in Figure 2.1 above and Figure 2.2 below.



In 2010, South Africa's saleable coal production was ~245Mt

- Coal is one of the top 2 components of the SA mining industry

Top 3 commodities by sales value

ZAR billions	Coal	Platinum	Gold
2009	65.3	58.0	49.0
2010	69.5	73.8	53.1

- The industry provides some ~ 80% of South Africa's total primary energy requirements & is core to economic development:
  - 92.8% of South Africa's electricity production...
  - ~30% of SA's total liquid fuel requirements
- Coal exports accounted for 26.2% of total coal production - 5.7% or R35.4 billion of total merchandise exports in 2010
- Coal employs some 73,618 people & paid ZAR14.1 billion in wages

South African coal industry key statistics (%)

Figure 2.2*: South Africa saleable coal production in 2011 [Hall, 2011].*

During the South African Coal Road Map presentations in October 2011, it was estimated that "just over two thirds (by mass) of domestic coal consumption is used for electricity generation by Eskom, the national power utility. Coal-to-liquid-fuel (CTL) plants, operated by Sasol, account for another fifth of coal consumption. Small merchants, who supply mainly residential use and small businesses, account for about two per-cent metallurgical industries about three percent and cement, chemical and other industries consume the remaining five percent" (Hall, 2011). Proportions of coal utilisation for various local end-users, i.e. excluding exports, is summarised in Figure 2.2 above as was projected by Prevost (2010) cited in Hall (2011).

Coal plays a vital role in South Africa's energy economy; it accounts for 70 % of primary energy consumption, 93 % of electricity generation and 30 % of petroleum liquid fuels (Van der Riet et al., 2009). However, coal production and use also results in a number of serious environmental impacts. In addition to greenhouse gas emissions and climate change being major areas of concern with respect to environmental impacts, a number of other coal mining related problems are also emerging. Perhaps the most serious immediate environmental problem is that of acid mine drainage (England et al., 2002).

In terms of availability of suitable coal qualities for the South African coal market, very little good quality coal remains as much of the coal has been mined out. Where such desired qualities are available they are sold at export parity prices on the local market. This leaves little option for local industrial consumers in terms of acquisition of lower grade coals for boilers originally designed for higher grades.

2.3 Coal Characterisation and Analysis

Coal quality is defined by various traits and some of the essential terminologies are clarified by Falcon and Ham (1988). Coal **grade** refers to the amount of impurities or the composition of mineral matter, in the coal, that results in ash content. **Rank** is the degree of maturation or metamorphism of coal and it is determined by temperature, pressure and time duration. **Type** signifies the organic composition of coal or the original vegetal matter; it is an indication of coal reactivity. **Condition** refers to the extent of weathering or abnormality including oxidised coal, coal heated by spontaneous combustion, coal distorted by rock or ground movements. Hence the expression 'quality' is used to refer to a combination of all the terms as mentioned above which may be used in various given applications. For instance, coal considered to be of poor quality in the metallurgical industry (coking coal) may be deemed to be good for steam coal and vice-versa. The work by Falcon and Ham (1988) concentrated predominantly on pulverised fuel boilers in power stations and did not address specific small scale industrial boilers of the stoker type.

The reliability of any study depends on ensuring that both the sampling and analytical techniques are adequately and precisely performed. Techniques for coal analysis can be considered as consisting of two major groups, those that determine the empirical properties and those that focus on the fundamental composition of coal. Empirical properties are verified using chemical and physical analyses methods. The most common conventional analyses are summarised on in Table 2.1 below (Falcon and Ham, 1988; Johns and Harris, 2009).

Table2.1*: Conventional analyses*.

Proximate (%)	**Ultimate (%)**	**Ash Composition (%) major minerals**	**Others**
Moisture	Carbon (C)	Quartz (SiO_2)	Calorific Value (MJ/kg)
Volatile Matter	Hydrogen (H)	Pyrite (FeS_2)	Swelling Index (CSN)
Ash Content	Oxygen (O) Nitrogen (N)	Calcite ($CaCO_3$)	Hard Grove Index (HI)
Fixed Carbon	Sulphur (S) Phosphorus (P)	Dolomite (MgO) Kaolinte (Al_2O_3)	Ash Fusion Temperature (AFT,^oC)

The proximate and ultimate analyses and those indicted as 'Others' in Table 2.1 above, are significant in characterising coal prior to combustion; and they involve the more common laboratory methods such as x-ray, spectroscopy, and atomic absorption. Analysis of ash composition reveals the proportion of minerals such as pyrite, clay, quartz, and carbonates, and this gives the end-user a glimpse on the coal's propensity to form clinkers when combusted.

While conventional methods allow one to have a quick assessment of coal qualities, on the other hand these yield limited information concerning the actual performance of coal in some cases. That is, alone they may not correctly predict and classify the vital aspects of combustion such as flame stability, rate of combustion, temperature distribution in furnace, burn-out characteristics, blending compatibility, and condition of coal. (Van der Riet et al., 2010). As a result, additional analyses that involve the more fundamental constitution of coal are required in order to fully understand the behaviour of different coals using methods such as the petrographic techniques. According to Falcon and Snyman (1986) and Magasiner et al. (2001), coal petrography can broadly be described as the microscopic determination of the organic and inorganic constituents of coal and the degree of metamorphosis, or rank, which the coal has obtained. Vitrinite reflectance is widely used as the main parameter for accurate judgment of rank and a standardised system for categorisation is used; the ISO classification published in 2005. Table 2.2 below provides a category for description of coal.

Table 2.2: *Summary of petrographic composition and ash yield categories.*

Vitrinite (Vol %, mf)	*Category*	*Ash Yield (%db)*	*Category*
<40	Low vitrinite	< 5	Very low ash
≥ 40 and < 60	Medium vitrinite	≥ 5 and <10	Low ash
≥ 60 and < 80	Moderately high vitrinite	≥10 and < 20	Medium ash
≥ 80	High vitrinite	≥20 and <30 ≥30 and <50	Moderately high ash High ash

Data Source: Adopted from 3rd ICCP training manual [Cook and Diessel, 2011].

Other advanced analytical techniques available for in-depth study of coal include scanning electron microscopy (SEM) and quantitative analysis of minerals by scanning (QEMSCAN). These are employed to identify mineralogical differences in coal qualities from differing regions and even within single seams. Further laboratory scale testing of combustion performance to establish the rate of devolatilisation and combustion reactivity is possible by using thermo-gravimetric analyses (TGA) and drop-tube furnace (DTF) techniques, as confirmed by Van Alphen (2007).

2.4 Factors Influencing Combustion

The combustion of coal is governed by several factors which can be classified as intrinsic and external. Both of these factors must be adequately understood, and appropriately adjusted during operation, to suitably complement each if efficient operation of boiler equipment is to be realised (Kural, 1994).

2.4.1 Intrinsic Factors

Intrinsic factors are essentially the inherent aspects of coal, its characteristics and nature (Falcon and Ham, 1988). The intrinsic factors of coal that influence combustion are the organic and inorganic composition of the coal, its rank, porosity, exposed surface area, moisture content, particle size, initial ignition temperature, proximate and ultimate analyses, and calorific value. These include additional analyses such as hardgrove index, abrasive index, reactivity, degree of weathering and state of oxidation, among many others.

2.4.2 External Factors

Operating conditions are considered to be external factors that influence combustion. These include, among others, particle size distribution, throughput or loading, temperature and velocity of the combustion air, the ratio of mixing fuel and air, the design and spacing of furnace, and the residence time of the combustible particles in the furnace (Van der Riet et al., 2010). Kitto and Stulz (2005) suggest that in order to minimize wear, the speed of a travelling grate should be kept below 12.2 m/hr. However this may limit its use in some high ash fuel applications.

One of the most important parameters to consider when evaluating the capacity of stoker-fired boilers, or when designing for new equipment, is the effective area of firing. The effective area is defined as the width of the stoker measured at the grate level multiplied by the distance from the centre-line of the rear wall tubes to the centre-line of the stoker front-shaft. For coal-fired boilers stoker rating is defined as the mass of fuel burned per unit of time per unit of effective stoker area (kg/m^2h) (Magasiner et al., 2001).

A typical layout of the spreader stoker boiler is shown in Figures 2.3A and 2.3B below. Figure 2.3A illustrates a picture of the actual boiler equipment used for the study (Impala Platinum boiler unit No.5).



Figure 2.3A: *Picture of Impala spreader stoker boiler unit No.5 showing furnace layout [photograph courtesy of Impala boiler archives]*

NB: Further details on the actual boiler design data including equipment dimensions is provided in Table G2B, Appendix G.

Figure 2.3B below indicates a similar layout of what the actual furnace would look like internally. With a width of 4m and an effective length of 4.8 m depicting the actual boiler dimensions, the furnace would have an effective grate area of 19.2 m^2.

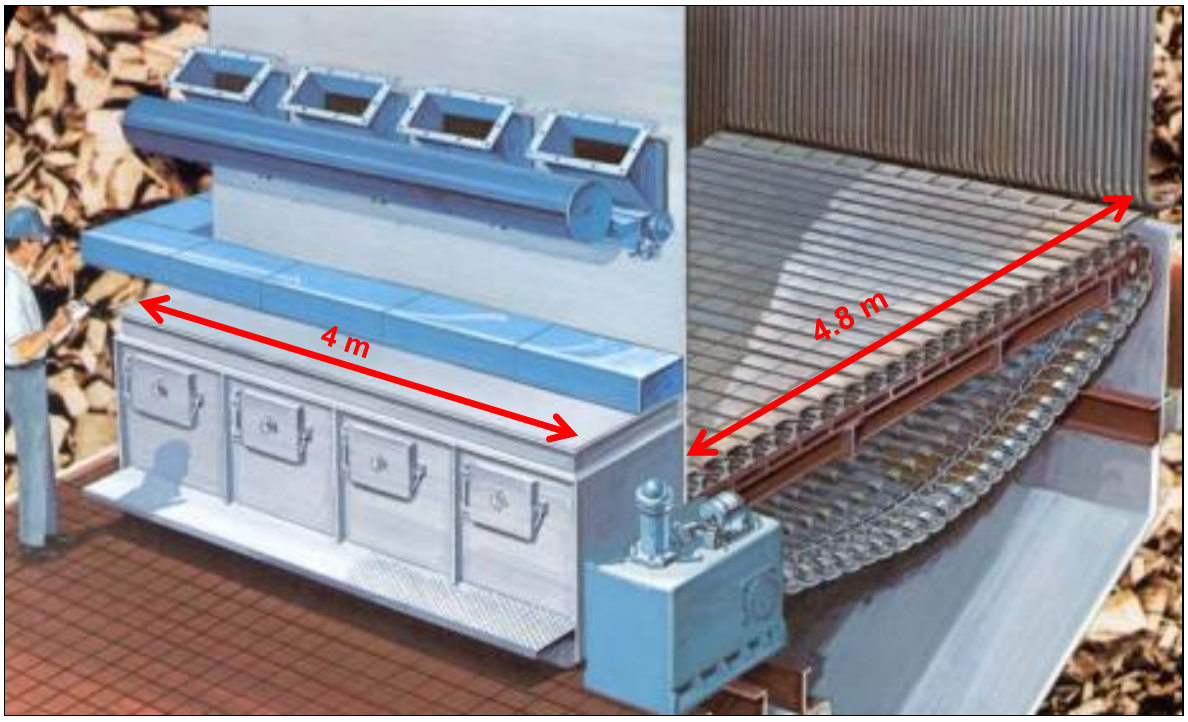


Figure 2.4B: *Picture of spreader stoker boiler showing furnace internal layout [excerpts from Keystone Energy, spreader stoker brochure, 1980]*

Investigational work that examines the relationship between different coal types and stoker rating was conducted by Magasiner et al. (2001) as shown in Figure 2.4 below.

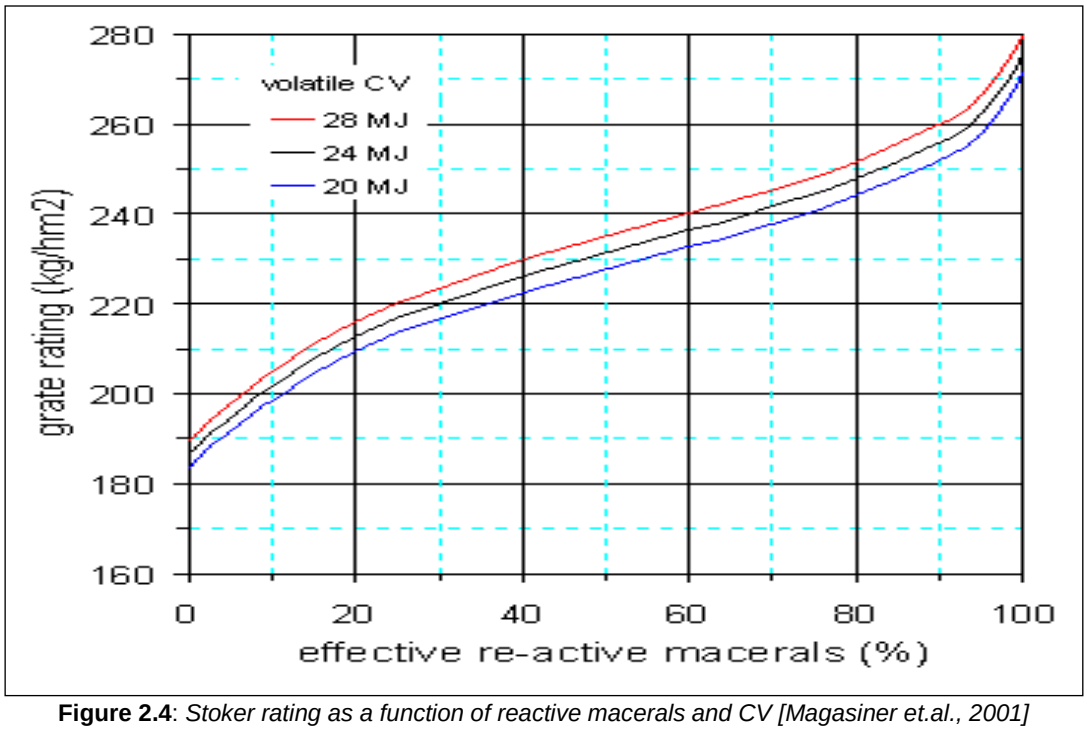


Figure 2.4: *Stoker rating as a function of reactive macerals and CV [Magasiner et.al., 2001]*

The model developed by Magasiner et al. (2001) postulates that the stoker rating increases almost linearly with the reactivity of coal. Conversely, this implies that the amount of coal burned per unit time, over a specific area, should decrease as coal quality becomes poorer, since ignition difficulties may be experienced.

Using this basis to rate a boiler suits the combustion of high ash content and low reactivity coals very well, as is the case with the majority of South African coals which have more than 10% ash. Coals with high ash content and low reactivity need a longer time to burn out. In order to have sufficient time for such coals to be burned out, lower gas up-flow velocities are needed and the stoker rating must be lower than for highly reactive coals (Marlow and Stokes, 1993; Green and Waite, 2004).

Typical heat release rates for stoker systems are presented in Table 2.3 below, with particular interest on data for coal fired travelling spreader stokers. Depending on the type of coal combusted, Kitto and Stulz (2005) indicate that typical heat release rate for spreader stokers is about 2.37 MW_t /m^2, with steaming capacity of up to 49.10 kg/s. Higher inputs tend to increase slagging potential and may cause excessive fuel entrainment or carryover. The width of the grate is the main variable in providing sufficient total grate area. Sufficient width is also required to install enough feeders and to keep the heat input per width to below 13.0 MW_t /m^2 (Kitto and Stulz, 2005).

Table 2.3: *Overview of stoker system.*

Stoker Type	Grate Type	Fuel	Typical Release Rate* 1000 Btu/h ft^2 (MW_t/m^2)		Steam Capacity 1000 lb/h (kg/s)	
Underfeed:						
Single retort	—	Coal	425	(1.34)	25	(3.15)
Double retort	—	Coal	425	(1.34)	30	(3.78)
Multiple retort	—	Coal	600	(1.89)	500	(63.0)
Overfeed:						
Mass	Vibrating: water-cooled	Coal	400	(1.26)	125	(15.8)
	Vibrating: water-cooled	Straw	500	(1.58)	320	(40.3)
	Traveling chain	Coal	500	(1.58)	310	(39.1)
	Reciprocating	MSW**	300	(0.95)	350	(44.1)
Spreader	Vibrating:					
	air-cooled	Coal	650	(2.05)	150	(18.9)
		Wood	1100	(3.47)	900	(113.4)
	water-cooled	Wood	1100	(3.47)	900	(113.4)
	Traveling	Coal	750	(2.37)	390	(49.1)
		Wood	1100	(3.47)	550	(69.3)
		RDF***	750	(2.37)	400	(50.4)

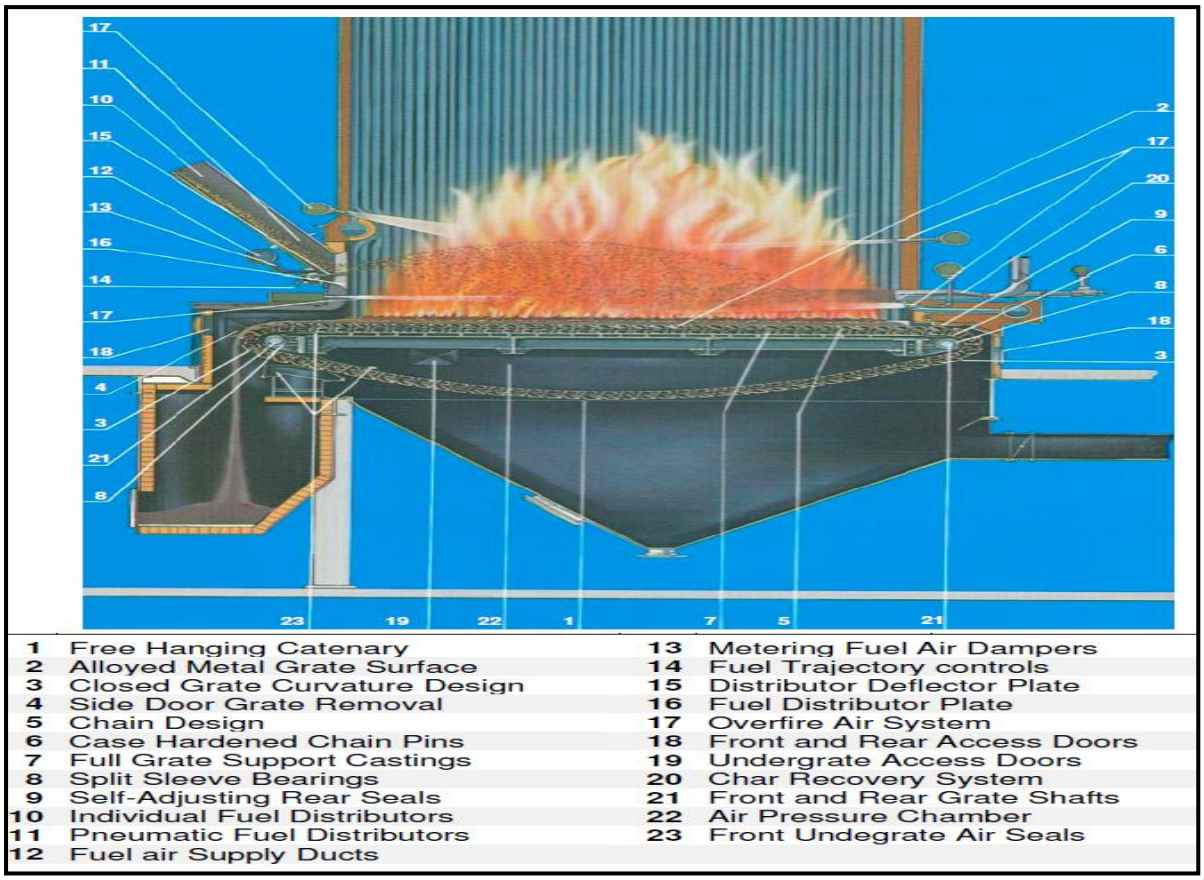
* Specific fuel characteristics and firing arrangements may allow higher heat release rates.
** Municipal solid waste
*** Refuse-derived fuel

Data Source: [Kitto and Stulz, 2005].

NB: When comparing data shown in Figure 2.4 for stoker rating (kg/hm^2) with that depicted in Table 2.3 for heat release rates (MW_t/m^2), the following conversion may be used:

Heat release rate (MW_t/m^2) = [Stoker rating (kg/hm^2)] x [Calorific value (MJ/kg)] x [1h/3600s]**.....Equation (2.1)**

A sectional view of a spreader stoker boiler is provided in Figure 2.5 below outlining the different parts of the boiler, how coal is introduced into the boiler furnace during combustion, the associated air supply and ash disposal systems. Typically, the combustion air in spreader stoker boilers is supplied in two forms; the primary air supply, or under-grate air (UGA), supplied by the forced draft (FD) fan and the secondary air, or over-fire air (OFA), supplied for the secondary air (SA) fan.



1	Free Hanging Catenary	13	Metering Fuel Air Dampers
2	Alloyed Metal Grate Surface	14	Fuel Trajectory controls
3	Closed Grate Curvature Design	15	Distributor Deflector Plate
4	Side Door Grate Removal	16	Fuel Distributor Plate
5	Chain Design	17	Overfire Air System
6	Case Hardened Chain Pins	18	Front and Rear Access Doors
7	Full Grate Support Castings	19	Undergrate Access Doors
8	Split Sleeve Bearings	20	Char Recovery System
9	Self-Adjusting Rear Seals	21	Front and Rear Grate Shafts
10	Individual Fuel Distributors	22	Air Pressure Chamber
11	Pneumatic Fuel Distributors	23	Front Undegrate Air Seals
12	Fuel air Supply Ducts		

Figure 2.5: *Cross sectional schematic of spreader stoker boiler [excerpts from CIBO, Johnson, 2002]*

Green and Waite (2004) suggest that a certain percentage of ash in travelling grate stokers, for example more than 5 %, is required as it forms a protective layer over the grate during combustion. As much of the coal as possible must be burned on the grate rather than in suspension in order to maximise the combustion phase. Otherwise most of the carbon-rich particulates will be carried over by the up-flowing air, leaving the combustion chamber partially oxidised (Hatt, 1990). Therefore the particle size distribution of low reactivity coals must be more uniform and coarser than that of highly reactive coals in order to ensure that an optimum number of particles land on the grate (Seibold and Bessette, 1978).

Coals too coarse will not burn at the high rate required for optimum spreader operation and coals too fine can cause operational as well as emission problems without proper design and operating procedures. As a guideline, the American Boiler Manufacturers Association (ABMA) prepared a curved distribution of recommended limits of coal sizes for spreader stokers as shown in Figure 2.6 below.

The desired theoretical size is equal proportions of 3/4" to 1/2" (19.05 mm to 12.7 mm), 1/2" to 1/4" (12.7 mm to 6.35 mm) and 1/4" to 0 (6.35 mm to 0 mm). The spreader feeder should have the ability to compensate for variations in fuel size (Wolfgang, 2012).

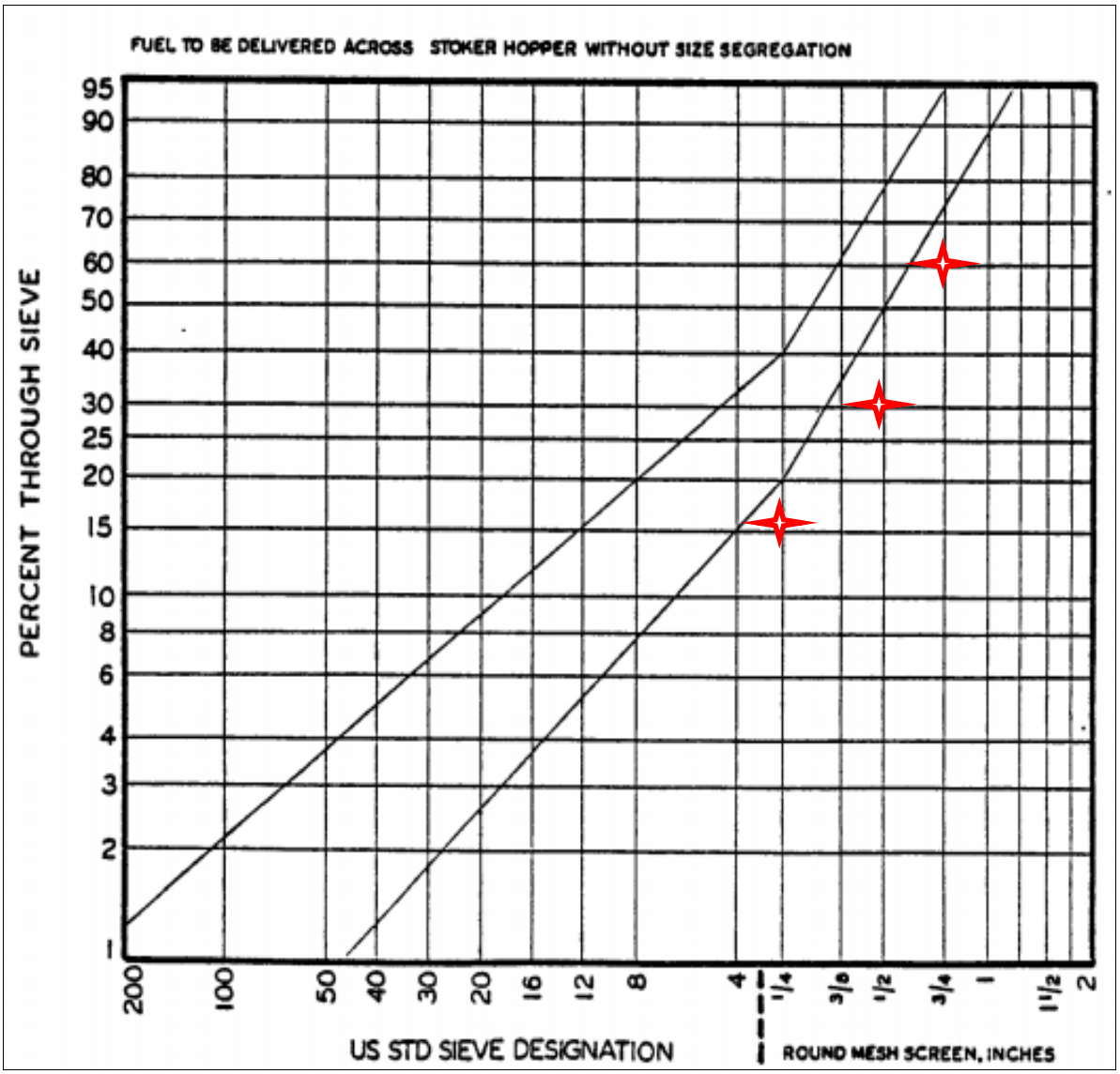


Figure 2.6: *Recommended limits of coal sizing for spreader stokers [excerpts from EPA report, EPA-600/8-81-016, May 1981]*

Recommended sizing is indicated in the region outlined in dark lines, while the red dots indicate the specifications as provided by Babcock and Wilcox (1973) for Impala Platinum boilers ordered in the 1970s. It can be seen from the Babcock and Wilcox specification (the red dots in Figure 2.6 above) that the fuel particle size distribution was coarser than what is advised by ABMA. It is possible to effectively burn coals having sizing outside the range shown on the ABMA curve. However, it is better to err on the fine side than on the coarse side (Wolfgang, 2012).

2.5 Boiler Efficiency and Heat Losses

According to Zeitz (1997), the Council of Industrial Boiler Owners (CIBO) manual, coal-fired stoker boilers are on average between 65 to 85 % thermally efficient and ways should be improvised to reduce energy losses. While it is acknowledged that there are certain cases in which losses are unavoidable, it is also possible to recover some of the energy and improve efficiencies by a further 15 - 20 %. Such improvements can only happen if the source of losses is fully understood. Boiler efficiency is an indicator of the proportion of chemical energy stored in coal that is converted into thermal energy. It therefore should be noted that concept of boiler efficiency is a twofold phenomenon; efficient combustion of fuel and efficient transfer of heat released from the 'fuel mass' to the heating surfaces that converts water into steam. Determining the ratio of steam produced per amount of coal used is simply indicative of the true boiler efficiency. The most accurate way of calculating boiler efficiency is the heat loss method (Zeitz, 1997). Continuous operation at peak efficiency is often impractical because of seasonal demands and load variations, but operation at steady load and avoidance of cyclic or on-off operation can improve efficiency. However, on-off operation can and will reduce overall energy usage, depending on the output requirements. While every boiler and burner arrangement will perform somewhat differently, it is possible to project variations in efficiency based on boiler load. It is important to understand that efficiency loss can vary as much as 10% when operations change from the maximum continuous rating (MCR) to reduced boiler output (30 to 40% of capacity) (Kitto and Stulz, 2005). The key to increased efficiency involves minimizing all forms of combustion and boiler heat losses (Johns and Harris, 2009).

The latter method entails measuring the individual heat losses, expressed as a percent of heat input, and subtracting them from hundred percent. The biggest energy loss for conventional coal fired boilers takes place through the stack. It is estimated that stack losses amount to as much as 30% of the fuel input (Johnson, 2002). Stack heat losses can be minimised in the following ways: minimising excess air, keeping heat transfer surfaces clean, and adding flue gas heat recovery equipment where necessary. With lower excess air, stack gas velocities and temperatures are reduced allowing the gas to spend more time in the furnace where the heat can be absorbed. Carbon monoxide is the most common gas that serves as an indicator of energy losses emanating from deficient combustion (Hatt, 1990). It forms when excess air is too low in some areas of the grate, or when the flame strikes a cold water tube wall tube. A carbon monoxide concentration of 400 ppm (0.4%) represents a 2% heat loss, and this is what boiler operators should aim at not exceeding (Wienese, 2001).

Significant heat loss is also perceptible in the form of unburned carbon in both the bottom and fly ashes. Unburned carbon is also referred to as carbon in ash. Carbon in the bottom ash comes from unburned coal discharged from the combustion chamber into the ash gutter. This can be controlled by properly adjusting the grate speed, under-grate air flow, and position of coal feeders. In the fly-ash, the unburned carbon loss is due to particles that are carried over by the gas flow before they settle on the grate (Kitto and Stultz, 2005).

Several measures can be undertaken to address this problem, i.e. increasing the over-fire or secondary air, reducing excess under-grate air or primary air supply, and using coal with fewer fines. The amount of unburned carbon in the bottom ash is usually less than 5 % for spreader stoker boilers and quite higher for chain grate stokers (Zeitz, 1997). When it comes to unburned carbon in the fly-ash, it is interesting to note that in this case chain grate stokers have lower unburned carbon, less than 2 %, whereas this value can be as high as 10 % for spreader stokers (Lindsay and Pilkington, 1953).

2.6 Environmental Legal Concerns

South Africa's air quality limits are more moderate than the international standards. However, changes in the global climatic conditions have already started impacting several sectors of the South African society. Apart from the environmental alarm, the other major reason why boiler emissions should be seriously scrutinised is for their potential risk to human health and animal life.

The risk depends on the nature, concentration, and dispersal mechanism of the emissions to the environment. It is widely accepted that trace elements such as Mercury, Arsenic, Lead, and Cadmium are associated with diseases like neural damage, anaemia, and cardiovascular effects, among others. Particulate matter less than ten microns (PM_{10}) causes respiratory diseases because it can easily be inhaled and dissolved through the lungs (WHO, 2005). Fine PM includes dust, smoke, and soot, which typically measure 10 um in diameter or less. The Principal sources of acidic compounds, including acid rain, involve emissions of SO_2 and NOx (Langsjoen et al., 1981).

Recently updated emission standards as shown in Table 2.4 below illustrate that boiler emission limits are becoming stricter and it is now up to industry to act proactively to reduce air pollution and avoid penalties or even being shut-down for environmental non-compliance.

Table 2. 4: *Minimum Emission Standards*

Description:	Solid fuels (excluding biomass) combustion installations used primarily for steam raising or electricity generation.		
Application:	All installations with design capacity equal to or greater than 50 MW heat input per unit, based on the lower calorific value of the fuel used.		
Substance or mixture of substances		**Plant status**	**mg/Nm^3 under normal conditions of 10% O_2, 273 Kelvin and 101.3 kPa.**
Common name	**Chemical symbol**		
Total Particulate matter	N/A	New	50
		Existing	100
Sulphur dioxide	$S0_2$	New	500
		Existing	3500
Oxides of nitrogen	NOx expressed as NO_2	New	750
		Existing	1100

Data Source: Adopted from *National Environmental Management: Air Quality act 39 of 2004 - National Ambient Air Quality Standards*, Government Acts

In addition, the overall system efficiency can be improved with attention to the application and uses of the steam and hot water produced by the boiler. Improving system efficiency means that less fuel is used to run the entire process, which in turn leads to lower overall emissions (Oland, 2002).

2.7 Summary and Conclusion

Much of the research and investigational work previously undertaken in the field of industrial stoker-fired boilers, including spreader stokers, has been primarily in Europe and America. The only published results that can be found locally using South African coals is limited to investigations conducted mostly by the sugar, pulp and paper industries. Even then, such studies focused mainly on the aspects of operating conditions on boiler performance and not specifically on the impact of coal quality. On the basis of the reviewed work there are many gaps in understanding compatibility between coal and stoker fired boilers. It is this fact that the current research seeks to address. The purpose of the current exercise therefore is to fill that gap by investigating the relationship between intrinsic and extrinsic factors in a little more detail.

CHAPTER 3

This chapter discusses the origins of the feed coals that were tested and explains the overall procedures followed in conducting the research. It gives a description of the test equipment used, detailing how each of test was performed and categorises the different types of analyses carried out.

3.1 Overview of Feed Coal Samples

The research essentially focuses on testing four coal samples labelled as Coal A, B, C, and D. A fifth coal type, referred to as Coal E, was partially tested and is used mainly as a reference for comparing the temperature profiles involved. The feed coals tested were sourced from separate mines in the Witbank area, except for Coals A and D which were both obtained from the same source, Stuart Mining, but supplied within five weeks of each other. Sample preparation and analyses were conducted at the ALS-Witlab and Petrographics SA facilities. Table 3.1 below gives details of the different coal sources and a summary of the analyses performed.

Table 3.1: *Summary of analyses and testing procedures*

Date (Year 2011)	Coal ID	Coal Source (Collieries)	Tests Conducted
25 & 26 May	**A**	Stuart	▪ Proximate & Ultimate ▪ Thermography; Petrography
01 & 02 June	**B**	Homelands	▪ Proximate & Ultimate ▪ Thermography; Petrography
09 & 0 June	**C**	Inyanda	▪ Proximate & Ultimate ▪ Thermography; Petrography
15 & 17 June	**D**	Stuart	▪ Proximate & Ultimate ▪ Thermography; Petrography
14 June	**E**	Brickor	▪ Proximate & Ultimate ▪ Thermography

Data Source: [Impala records, 2011]

NB:

Coals A and D, as referred to in Table 3.1 above, were both obtained from Stuart Coal mine and presumably from the same coal seam but supplied at different times of five weeks apart. Analyses and combustion testing of the each coal type was performed separately.

3.2 Equipment Set-up

The test work was undertaken at Impala Platinum Refining facilities at Springs, East Rand. The study was performed using a water-tube spreader stoker type boiler, Boiler unit No.5, built by Babcock and Wilcox. The boiler has a steam generation capacity of 45 tonnes per hour producing saturated steam at 31 bar gauge pressure (31 barg) and was installed in 1973. The boiler consisted of a negative pressure furnace house, an economizer and Electrostatic Precipitator (ESP) for capturing of particulates. A layout of the sampling areas considered during the trials is shown in Figure 3.1 below. To guarantee accuracy of readings and minimise errors, all required measurement instruments were calibrated prior to performing the trials.

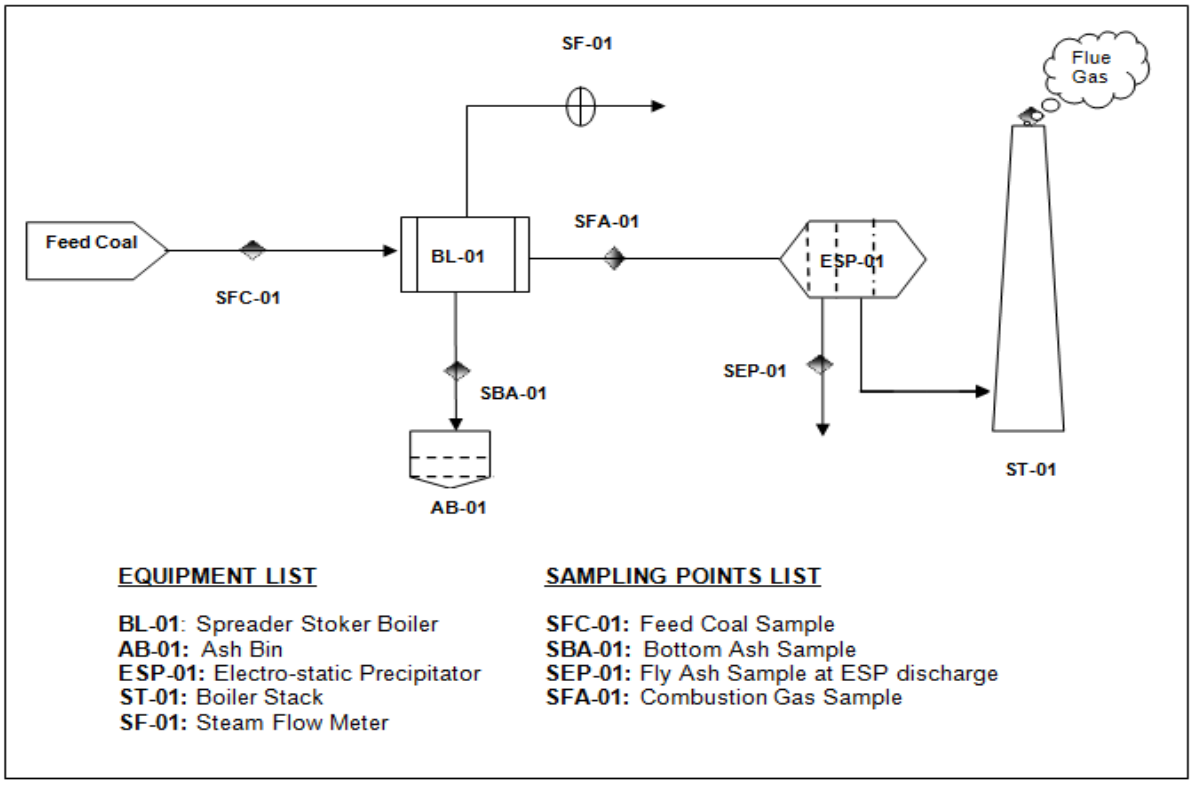


Figure 3.1: *Coal, ash and flue gas flow diagram showing sampling points*

Primary parts of a spreader stoker boiler consists of the following features: a fuel feeding system or coal feeder; a moving grate assembly to support the burning mass of fuel and to discharge resultant ash; primary air or under-grate air (UGA) system to convey primary combustion air to the overlying coal bed ; a secondary air or over-fire air (OFA) systems for supplying secondary combustion air; and an induced draft (ID) fan for extraction of flue gases from the combustion chamber to the exhaust stack. The remaining ash falling off the grate is removed using an ash discharge system. The different features of the boiler are further illustrated in Figure 3.2 below as follows: UGA as equipment FF 1003E; OFA as equipment FF 1004E; ID ducting as equipment BP1026; and ash discharge system as equipment AP1023E. Figure 3.2 also shows how boiler performance monitored during the tests using the Supervisory Control and Data Acquisition (SCADA) system and real-time data captured.

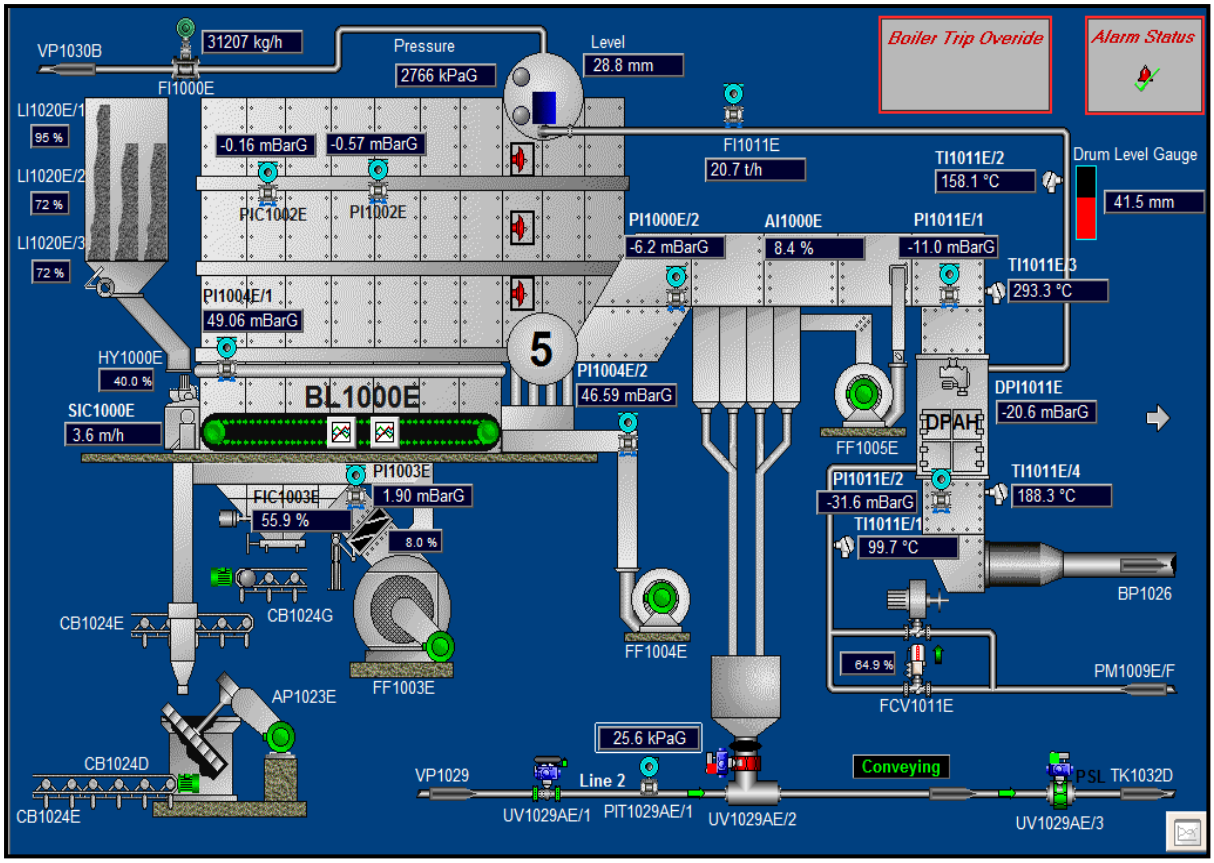


Figure 3.2: *Schematic of Spreader stoker from SCADA system installed at Impala [2011]*

The way the boiler operates is that coal is introduced at the front of the furnace through coal feeders (or flingers). Lighter coal particles burn in suspension and the heavier ones fall on the grate, burning on it while it runs from the back of the furnace towards the front where the ash is discharged. Any remaining portion of the finer particles entrained in the flue-gas is captured by the ESP. The boiler operates under negative pressure (below atmospheric) introduced by the induced ID Fan which extracts flue-gas from the furnace towards the stack. A balanced draft is maintained between the UGA, OFA and ID drafts to ensure efficient combustion of coal inside the furnace. The main control parameters on the master controller of the boiler are the Air to fuel ration (Air/Fuel), which is adjusted to allow for the right mixture of coal and air in the furnace, the boiler drum pressure and the feed water flow. The coal bed thickness is determined by the grate speed and the rotational speed of coal feeders. A summary of the boiler furnace design data for Boiler unit No.5 is shown in Table 3.2 below. The data represent original boiler manufacturer information.

Table 3.2*: Boiler equipment design data.*

Furnace design Data	**Parameter Value**
Heating surface (m^2)	169.5
Volume (m^3)	191
Mean height (m)	9.98
Width (m)	4
Effective length (m)	4.8
Grate area (m^2)	19.3
Number of coal feeders	3

Data Source: [Babcock and Wilcox, 1973]

3.3 Sampling and Testing Procedure

The feed coals were delivered by road trucks to the testing facilities at Impala Platinum Refineries in Springs and fed to the boilers in their "as-received" condition from the mine. In order to minimise contamination of the feed, a single stockpile of each coal type was kept separately for a whole week and the next lot from a different coal source supplied only the following week and once the previous supply had been consumed. All sampling procedures were conducted under the supervision of expert consultants, ALS Group - Witlab (Pty) Ltd, in accordance with the South African National Accreditation System (SANAS). Sample analyses were also carried out by accredited laboratories: ALS Group - Witlab and Petrographics SA. Thermographic analysis of the coals during combustion was performed by OEN Enterprises (Pty) Ltd. The sampling process for each coal type was conducted at intervals of 30 minutes over a period of three hours to constitute a single day's composite sample batch. This exercise was repeated over two days period for each coal quality type and the two samples analysed separately. Designated sampling locations are shown in Figure 3.1 above.

Dependable information was obtained by employing standard methods when evaluating the samples and measurements taken. The feed coals and ash products sampled were analysed using conventional and advanced analytical techniques. Characterisation tests performed on the different samples as well as analyses of key interest are shown in Figure 3.3 below.

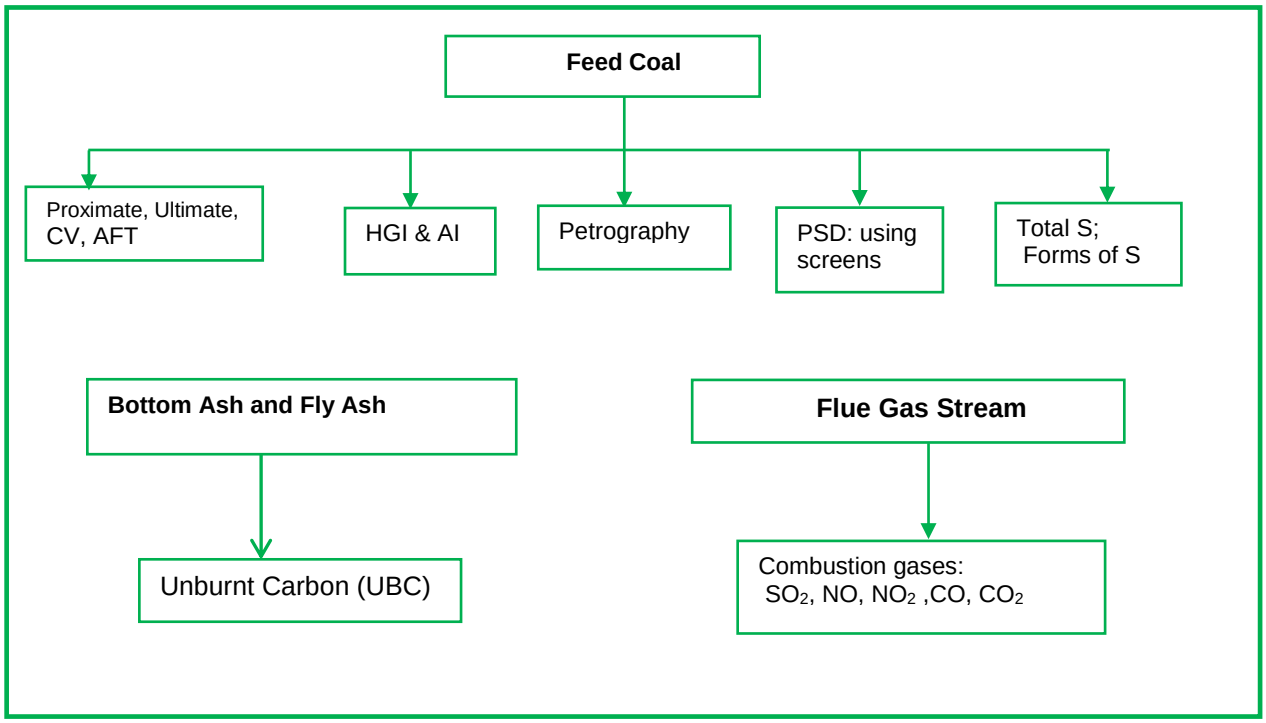


Figure 3.3: *Characterisation of samples (Feed coal, Ash, and Flue gas streams).*

For the feed coal, proximate analysis was conducted to determine the: Total Moisture (ISO 589: 2008); Inherent Moisture (SABS 925:1978); Volatile Matter (ISO 562: 1998); Ash content (ISO 1171: 1997); and Fixed Carbon (by difference) content. The ultimate analysis (ASTM D 5373) and calorific value (ISO 1928: 1995) were also determined. Petrography of the feed coals was also determined in accordance with ISO standard procedures (7404-2:1985).

The mechanism of calculating fuel ratio (FR) will also be included in assessing the quality of the coals for combustion performance. Fuel ratio (FR) is the ratio of quantities of fixed carbon (% FC) and volatile matter content (%VM).

The formula used is: $\mathbf{FR} = \frac{\%\ \mathbf{FC}}{\%\ \mathbf{VM}}$ **.....Equation (3.1)**

Other important analyses performed on the feed coal samples are the following: Ash Fusion Temperature (ISO 540); Crucible Swelling Index (ISO 501); Hardgrove Grindability Index (ASTM D3402); Abrasive Index (Eskom standards); Total Sulphur (ASTM D4239:1997); and Forms of Sulphur (ISO 157). Both the bottom ash and fly-ash samples were analysed for the amount of unburnt carbon (UBC) using the standard ASTM D4239:199 to determine the total carbon concentration. For comparison purposes with the UBC, percentage loss on ignition (LOI) was also determined. LOI is a quicker method for evaluating organic carbon content but has limited precision.

% LOI = $[(W_1-W_2) / (W1- W_C)] X100$ **%.....Equation (3.2)**

Where:

W_1 is the first weight recorded at 110^oC

W_2 is the second weight recorded at 1000^oC

W_C is weight of the crucible

3.3.1 Feed Coals

Each coal quality type was combusted for a full week. The actual testing and sampling campaign for the specific type of coal was only performed two days after introducing the coal to the boiler. This was done to minimise chances of contamination with a different feedstock during the trials. On the day of the testing, the boiler was kept steady for at least three hours before testing and sampling commenced. Feed coal samples were captured at closest point of entry into the boiler furnace, the coal feeders as shown in Figure 3.4 below. To constitute a single day's sampling batch, samples were taken from each of the three feeders to and fro to make a single sampling run. This was repeated every 30 minutes over a period of three hours to make a composite batch for the day. In order to enhance reliability of results, sampling was conducted for two days and each batch analysed separately.

The sampling procedure was performed under the supervision of expert consultants from ALS-Witlab, using the ISO 18283:2006(E) guidelines. The advantage of sampling at the coal feeders is that it offered the most representative coal fed into the boiler furnace, as opposed to sampling at the stockpile.

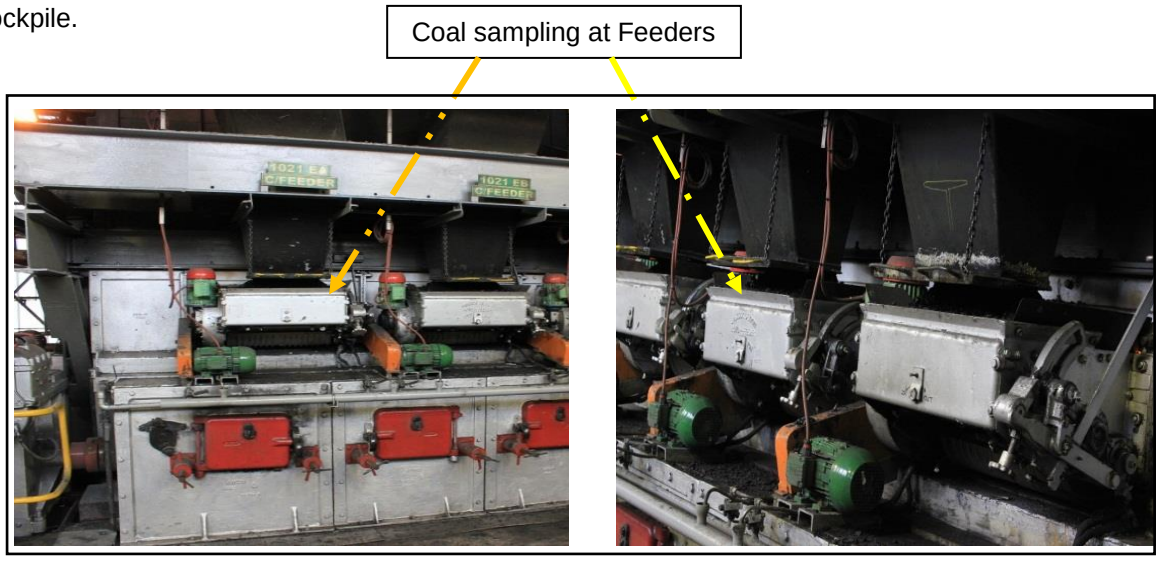


Figure 3.4: *Coal Feeders showing coal sampling points*

Figures 3.4 above indicate coal feeders at the closest point of coal entry into the boiler furnace where the sampling was conducted.

3.3.2 Bottom Ash

The extraction system for the bottom-ash, sometimes referred to as slag or clinker ash, is shown in Figure 3.5 below. As the bottom-ash falls off the grate and collects into water trough beneath for quenching before the ash paddles discharges it into a conveyor belt. Sampling was performed periodically at intervals similar to that undertaken for the coal samples. The key parameter for analysis for this sample was the amount of unburned carbon or carbon in ash content.

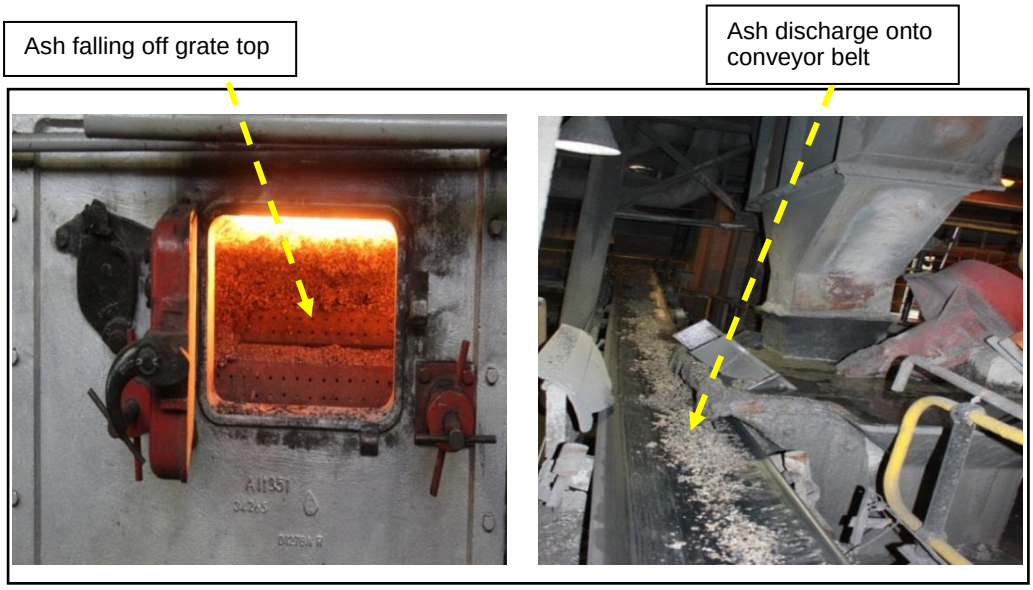


Figure 3.5*: Bottom Ash falling from the grate and onto the under-grate chute*

As shown in figure 3.5 above, ash falls off from the top of the travelling grate, through a chute and onto the water trough laying below for cooling off before being discharged onto a coal conveyor. The most important parameter analysed for the bottom ash samples was the unburnt carbon (UBC). This was then compared to the loss on ignition values (LOI) in all ash samples.

3.3.3 Fly Ash

The sample was a combination of both granular portions, referred to as “grits”, and finer particles from the flue gas stream trapped by the cyclone separators immediately at boiler furnace exit, as well as those trapped by the Electrostatic Precipitator (ESP). A dust extractor fan located at the furnace’s flue-exit ducting induces suction, discharging the coarser particles trapped by a cyclone overhead; this coarser form ash that is entrained in the flue-gas is normally referred to as ‘grits’. Thus grits generally represent relatively denser particles (normally above 100 µm size rating) which are retainable from the flue-gas stream by means of a cyclone while the actual fly-ash proceeds towards the stack.

However, analysis of such samples can be considered as reasonably indicative of constituents of the actual fly-ash samples, when one considers the proportions of unburned carbon or carbon in ash. In analysing these samples both the LOI and UBC values were determined and found to be consistent with one another.

3.3.4 Combustion Gases

Combustion gases were captured on site and monitored using an Orsat apparatus. The flue gases monitored instantly on-site included carbon dioxide (CO_2), carbon monoxide (CO) and oxygen in the flue gas (O_2). The samples were captured in gas pipettes and Tedlar bags for further analyses using Gas Chromatography (GC) analysis at the Witbank laboratory. Combustion gas testing is an important part for determination of boiler efficiency. The samples were securely stored in sealed bottles and delivered to the laboratory on the same day after sampling to avoid deterioration of gas sample constituents; that is, samples were dispatched to the laboratory within 12 hours of capturing. Figure 3.6 below shows a typical diagram of an Orsat apparatus. A similar apparatus was placed at the boiler economiser exit and used for sampling and testing of combustion gases.

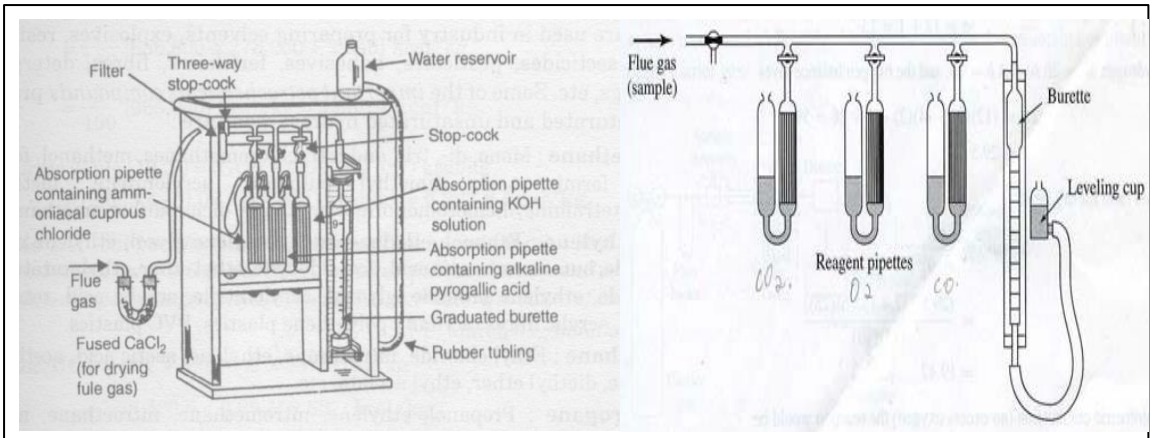


Figure 3.6: *Schematic of Orsat's Apparatus [excerpts from Xu et al., 1994].*

Certain precautions must be followed when using an Orsat appartus. Xu et.al (1994) emphasises that it is necessary to follow the order of absorbing gases when using the Orsat apparatus: Carbon dioxide (CO_2) first, Oxygen (O_2) second, and carbon monoxide (CO) last. This is because the absorbent used for O_2 , such as alkaline pyrogallic acid, can absorb only some CO_2 and the percentage CO_2 left would be less while the percentage of O_2 detected would be more. The absorbent used for CO_2, however, does not absorb O_2 or CO_2.

3.3.5 Petrography

Petrography was conducted to identify the fundamental constituents of the coal samples and their related proportions under the microscope. Sample blocks of each coal were prepared by South African Bureau of Standards (SABS), Pretoria, following the ISO Standard 7404-2 of 1985. The microscopic characterisation was performed by Petrographics SA laboratory. Maceral analysis and random reflectance measurements were carried out to determine the petrographic composition and rank of the coal, respectively. Mineral groups (Pyrite, Carbonates, Quartz, Clays) and conditional analyses of the feed coals were also performed. Finally the organic and inorganic association was determined by analysing the microlithotypes, including the carbominerites and minerites analyses.

Reflectances of vitrinite values were determined as random values. The values obtained using this method therefore ranges between the true maximum and minimum. Several formulae can be used to estimate the maximum reflectance from random values observed.

Cook and Diessel (2011) quoted two formulae as follows in Equations (2) and (3) below:

$\%R_{max} = 1.106\%R_{rand} - 0.024$ Neavel et al (1981)**.....Equation (3.3)**

$\%R_{max} = 1.07\%R_{rand} - 0.01$ Diessel and McHugh (1986) **.....Equation (3.4)**

NB:

Due to budget constraints full petrographic analyses could not be performed on chars in fly and bottom ash samples. However, it is believed that the available results obtained from the feed coal samples will be adequate to provide meaningful insight into the characteristics of the tested coals and the associated combustion behaviours.

3.3.6 Thermography with Furnace Camera

Thermographic investigation formed the core of the research study. This included investigation into behavioural characteristics of the different coals during combustion. Real time analysis of furnace conditions during coal combustion was performed using a video camera, DURAG type D-VTA 100-10 series. The video and thermography system allows for analysis of the flame temperature profiles and visualisation of flames in real-time. The camera uses Infrared to acquire and analyse thermal information using non-contact thermal imaging device. An abridged version of the technical data for the furnace camera used during the tests is shown in Table 3.3 below. Furnace temperature profiles and flame morphology were studied to comprehend the behaviour of the different coals during combustion.

Table 3.3: *Summarised technical data for video and thermographic camera D-VTA100-10.*

Parameter	Degree
Video System	PAL, picture elements: 752(H) x 582(V), fixed focus
Thermography from total radiation	Temperature range: 1,000 -1,800oC
Optical field of view	Sensor 0°: horizontal 72°, vertical 54°, diagonal 90°;
Auxiliary energy	230 V / 50 Hz, 500 VA
Gas temperature in combustion chamber	Water-cooled sensor <1,800°C
Space requirements for sensor/retraction device	1450 x 500 x 800 mm (LxWxH)
Field cabinet	600 x 380 x 210 mm (HxWxD)
Cooling water volume	350 l/h, 1.5 - 8 barg
Compressed air volume	max. 25 Nm3/h

Data Source: Adopted from DURAG manuals [2010]

Generally, in addition to the video system, the camera provides for temperature determinations at individual points; such as thermal analysis of local temperature distribution, classification of temperature definable measuring windows and lines referred to as Regions of Interest (ROI).

Figure 3.7 below indicates a typical arrangement of the thermographic system for data capturing in the boiler furnace and conveyance to a Programmable Logic Controller (PLC) system for operator control and monitoring. When performing thermographic tests for furnace temperature profiling, it is important to define the orientation of the video camera so as to provide reference to the extent of data captured and the extent of the optical field viewed. The camera was placed about one metre above the boiler grate level and one metre from the furnace arch where the coal was being fed into the boiler. This arrangement allowed for coverage of almost the entire furnace area of interest to the tests.

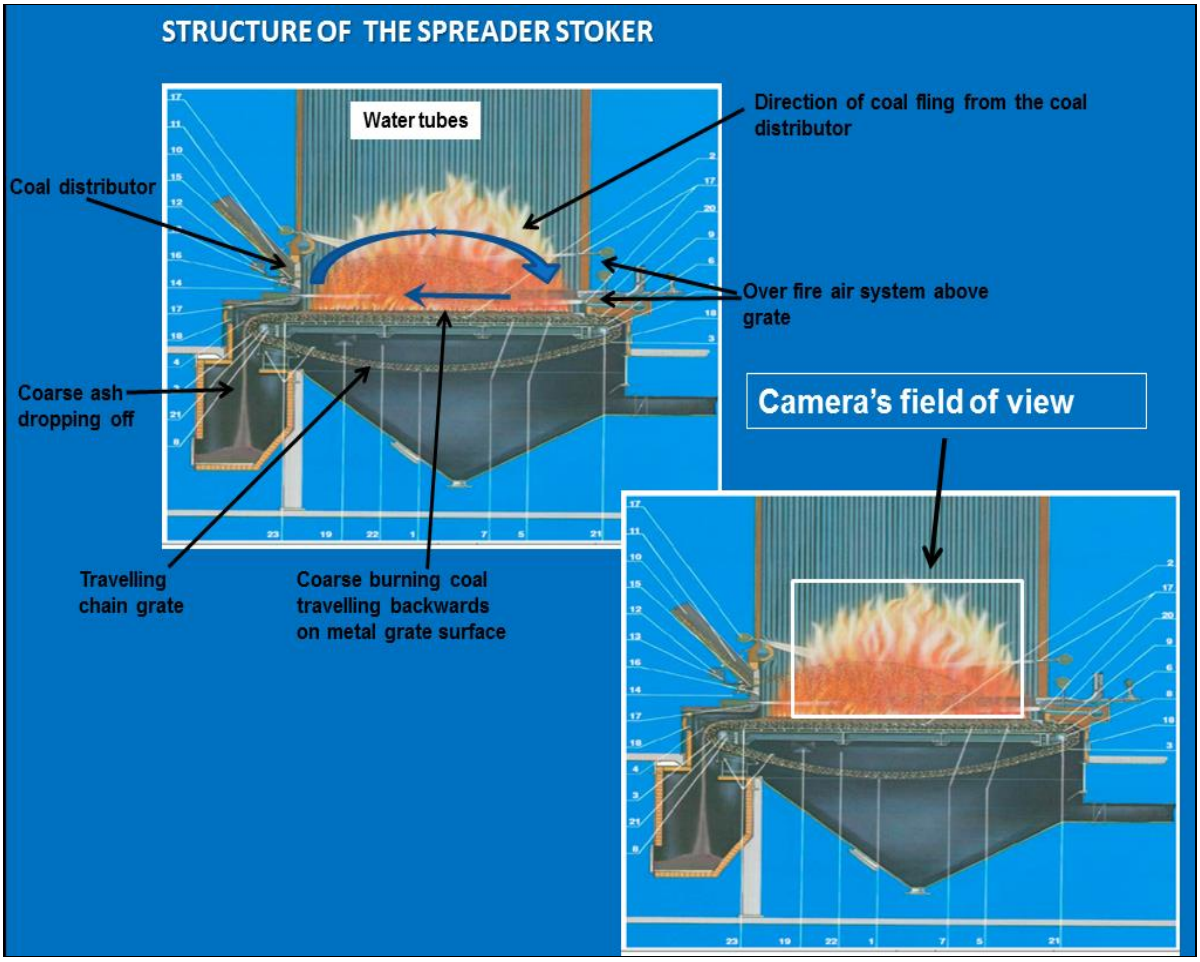


Figure 3.7: *Location of thermal camera with reference to boiler furnace.*

The lower diagram in Figure 3.7 above shows, in the white rectangle, the area of view of the camera. While the upper diagram indicates the trajectory and direction of coal particles when flung into the boiler as well as the direction of the travelling grate (Taole et al., 2012).

A perspective of the furnace coverage with camera and link to computer is illustrated in Figures 3.7 above and 3.8 below, based on an optical field of view of 72° (as described in Section 3.3.6, Table 3.3).

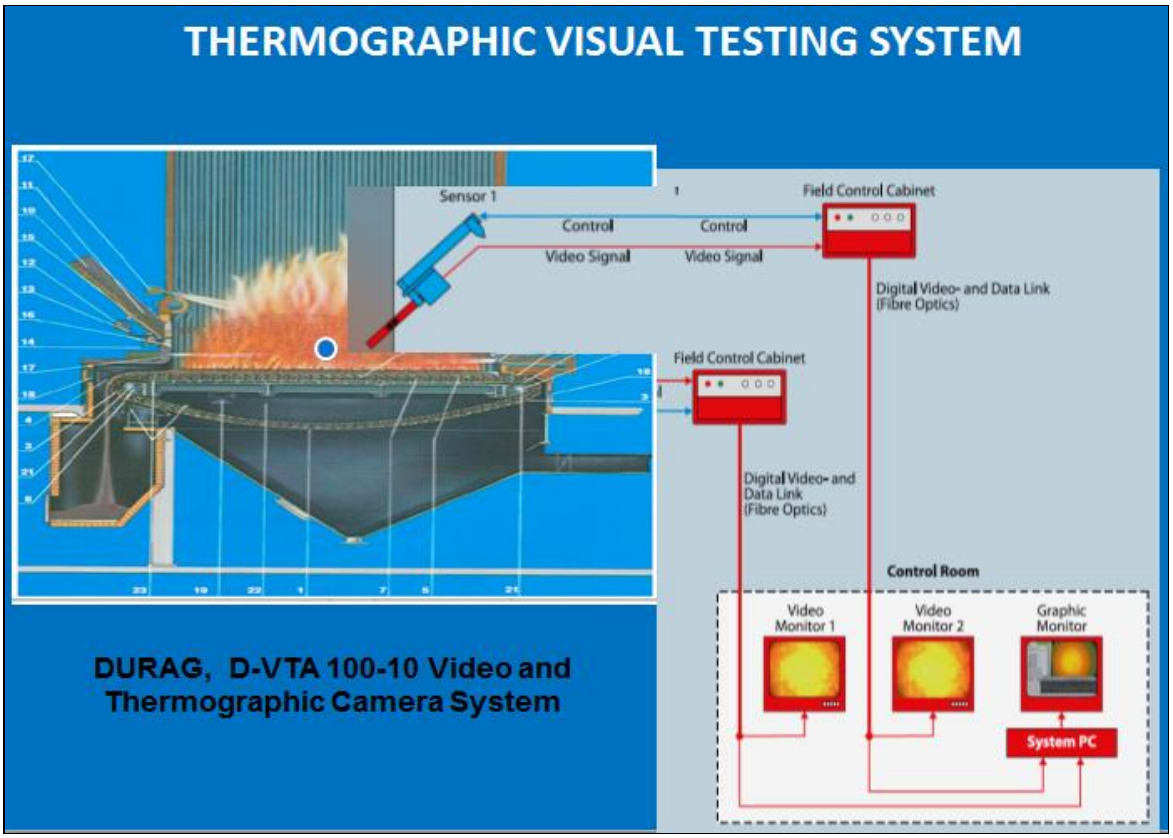


Figure 3.8: *Location of thermal camera in Boiler furnace showing connection to computer [excerpts from DURAG manuals, 2010]*

3.4 Operational Test Procedures

The boiler was operated under as steady load conditions as was possible during the test period, i.e. operations were allowed to stabilise at least an hour prior to commencement of the tests. In order to exclusively establish the impact of coal quality on combustion performance, all boiler operating conditions were kept constant during the trials. The grate speed, coal-feeder stroke rate, and UGA remained fairly steady during the testing period. Since the trials were performed under full scale operation, and thus the boiler was under normal production demands, occasional fluctuations in operating conditions were experienced. Despite the restricted variations, mostly on the grate speed, the tests can be considered to have occurred under fairly constant conditions most of the time.

In order to mitigate potential 'outliers' caused by fluctuations in operating conditions as described above, data was collected repeatedly over two days testing period and the two sets of results averaged. The boiler steam output rate, the grate speed and the percentage oxygen in flue-gas were the operational parameters monitored using the supervisory control and data acquisition (SCADA) system.

3.5 Data Processing and Analysis

Data was classified into two main sub-groups: analytical and operational results. Analytical results comprise of the solid and gas sample as analysed from the laboratories; these were interpreted in contrast with the boiler operating conditions on the day. Operational results characterise real-time data obtained during the combustion tests. This set of data was extracted from the plant SCADA system and exported to Microsoft Excel Spread Sheet files for calculations and graphical analysis of the different parameters.

The key factors which were taken into account and analysed for the purpose of the research can be categorised into two sets.

- Consistent factors: grate speed, primary and secondary air supply and coal-bed thickness.
- Variable factors: steam output, coal feed rate, furnace and flue-gas temperatures, percentage oxygen in the flue gas and combustion gases content.

Main results are presented in graphical and tabular format within the report text, while the raw and full data details are contained in the Appendices section of the report (Appendices A to F).

3.6 Conclusion to Test work

It is important to note the following points regarding the test procedures and consequent results obtained:

- For each coal type, sampling and testing was performed for a two day period to constitute two separate sample batches for the same coal in order to allow for repeatability of the results. Proximate and ultimate analyses were conducted in duplicate while the petrographic and thermographic analyses were only performed on a single day's sample due to financial constraints.
- Having proven repeatability all results and discussions in the successive chapters will refer to samples taken on one specific day per coal and all results (conventional analysis, petrographic results, combustibility tests and thermographic results) will be based on those particular coals for those particular days.

CHAPTER 4

This chapter presents the main results of the test-work conducted as discussed in Chapter 3 above.

The first section describes the results obtained from experimental analyses .The Analytical Results considers the conventional and petrographic results. Data attained from actual testing of the different coals and calculations performed were classified as Operational Results. This included information on boiler efficiencies and observed thermographic temperature profiles. Full details of the results are presented in the Appendices section of the report (Appendices A and C).

The second part of the chapter provides discussions of the results, explains the observations made, and draws comparisons between the different tests. This section concludes with a summary of all the observations made.

4.1 Analytical Results

All the coals tested were obtained from the Mpumalanga Witbank area as indicated in Table 4.1 above; they were all determined to be of medium rank C bituminous coals. In discussing these results a comparison is drawn between the results obtained for the various type of coals combusted on the specific days, and the respective temperature profiles as captured in the furnace and combustion efficiency determined. Conclusive interpretation of results for this research is based on the testing of four coals, i.e. Coal A, B, C and D. Five coals were initially available for testing, but testing of the fifth type of coal, coal E, was abandoned due to flame out during full-scale plant operation and continued testing would have affected normal productivity. Thus, meaningful results could not be obtained for coal E hence this sample does not form part of the main research findings. Some aspects are merely used for reference purposes.

4.1.1 Conventional Analyses

The following tables, Table 4.1, 4.2 and 4.3, presents analytical results of the four main coals under review. For the purposes of this research, conventional analyses include the proximate and ultimate analyses, calorific value (CV), ash fusion temperature (AFT), hardgrove and abrasive indices (HI and AI), the different forms of Sulphur, as well as petrography. All the results presented in Tables 4.1 to 4.2 below are reported on an Air-Dry Basis (% ad).

NB:

Full details of the repeatable conventional analyses, i.e. for the two consecutive days' samples for all of the coals are reported in Appendix A, Table A1. The results show extremely close repeatability. The results reported in this chapter are taken from the day one for which petrographic analyses and thermographic tests were undertaken.

Table 4.1: *Summary of proximate analyses and other physical properties of the coals.*

	Coal Identity (ID)				
	Coal A	**Coal B**	**Coal C**	**Coal D**	**Coal E**
Proximate:					
%Fixed Carbon	50.40	54.50	58.10	48.60	46.90
%Moisture	4.8 (9.55)	3.4 (7.32)	3.7 (9.10)	4.5 (5.90)	5.1 (6.20)
%Volatile Matter	29.20	24.60	23.50	30.20	24.90
%Ash	15.60	17.30	14.70	16.70	23.10
CV (MJ/Kg)	26.13	26.42	26.99	25.54	22.19
HGI	52	61	59	70	54
AI	246	149	99	94	54
AFT ($T^{o}C$)					
Deformation	>1500	1351	>1500	1320	1500
Flow	>1500	1403	>1500	1400	1500
Sulphur Forms:					
%Mineral	0.78	0.13	0.15	0.71	0.24
%Organic	0.66	0.24	0.34	0.51	0.24
%Sulphate	0.02	0.01	0.02	0.01	0.01
Unburnt Carbon (UBC):					
%Bottom Ash	16.97 (17.30)	22.70 (24.10)	21.62 (22.60)	16.26 (17.20)	23.53 (24.70)
%Fly-Ash	30.13 (30.50)	42.76 (44.10)	42.81 (45.90)	31.90 (33.10)	27.56 (29.10)
% Coal Particles					
< 6.3 mm	29.62	26.60	21.87	16.47	20.84
< 3.5 mm	18.06	15.92	13.09	8.97	

Data Source: ALS Witbank-Coal Division report No. 534/11-1 [2011]

In Table 4.1 above, the figures shown in brackets on the section labeled of "Proximate" represent total moisture, while the adjacent data indicates the inherent moisture content. On the section labeled "Unburnt Carbon" the numbers in brackets symbolise carbon content determined by the loss-on-ignition method, while the adjacent figures are for total carbon concentration obtained using analytical methods. In order to boost reliability of the research results obtained, testing for the same coal type was performed over two separate days under similar operating conditions.

A comparison of the properties of the coals tested against the specification of the original boiler manufacture is presented in Table 4.2 below. The data shows that the particular boiler used for the study was initially designed to burn grade A coal, based on calorific value. However, currently the frequently used coal quality has depreciated to mostly C and D grades coals.

Table 4.2: *Proximate analyses of Coals A to E compared to original manufacturer specification.*

Coal ID	Proximate Analysis (% ad)					Commercial Grades of coal sold on CV values
	VM	Ash	H_2O	Tot S	CV (MJ/kg)	
MANUFACTURER SPECIFICATIONS	25.0	14.0	2.4	-	28.0	A
A	29.2	15.6	4.8 (9.55)	1.46	26.13	C
B	24.6	17.3	3.4 (7.32)	0.46	26.42	C
C	23.5	14.7	3.7 (9.1)	0.51	26.99	B
D	30.2	16.7	4.5 (5.9)	1.23	25.54	D
*E *No further tests due to flame-out	24.9	23.1	5.1 (6.2)	0.49	22.19	DIII

As described in section 4.1 above (Analytical Results), further data for coal E sample does not feature in the succeeding chapters as part of the main results presentation and discussions.

Ultimate analyses of the four coals that were initially available for testing are shown in Table 4.3 below.

Table 4.3: *Summary of ultimate analysis.*

Element	Coal ID			
	Coal A	Coal B	Coal C	Coal D
Ultimate: %Carbon	65.86	65.13	67.36	61.58
%Hydrogen	3.97	3.61	3.44	3.68
%Nitrogen	1.66	1.62	1.66	1.59
%Oxygen	6.65	8.56	8.63	8.76

Data Source: ALS Witbank-Coal Division report No. 534/11-1 [2011].

4.1.2 Description of Coal and Conventional Analyses

In terms of coal qualities, the four coals may be described as follows. The calorific values (CV) of the coals range from 25.91 to 27.26 MJ/kg, with coal C having the highest CV and coal D the lowest. All the four coal samples are considered to be of reasonably low ash ranging from 14.4 to 18.7 %. The volatile matter content varies between 23.4 to 29.6 %. It is of interest to note that coal C with the highest CV value and lowest ash content of 14.4 % has the lowest volatile matter content of 23.4 %.

With regards to prospective emission levels of oxides of sulphur in the flue-gas post combustion, different forms of sulphur contained in the parent coals were determined. Of the three sulphur forms determined (shown in Table 4.1), sulphate sulphur was generally low at below 0.02 % for all the coals. The mineral sulphur, normally pyritic in nature, is observed to be in higher proportions in coals A and D compared to coals B and C; the quantity was determined to be highest in coal A at 0.78 % and lowest in coal B at 0.13 %. The highest fraction of organic sulphur is also found in coal A at 0.66 %, while coal B again contained the lowest quantity of the particular form at 0.24 %. This would imply that coal A is likely to produce higher levels of SOx emissions. This, however, was not measured in this study.

Among the ultimate analyses results, the proportions of nitrogen content is of particular interest as it is suggestive of the potential emission levels of oxides of nitrogen during combustion. These are commonly referred to as NOx, and mainly include nitrogen monoxide (NO), nitrogen dioxide (NO_2), and sometimes nitrous oxide (N_2O). The fraction of nitrogen for the four coals tested was fairly similar, with the lowest value being 1.59 % for coal D and the highest value being 1.66 % for both coals A and C. This would imply that coals A and C are likely to produce higher proportions of fuel NOx contributing to the total NOx emissions. It must be noted, however, that atmospheric nitrogen significantly contributes to total NOx emissions through thermal NOx during combustion at elevated temperatures and optimal quantities of oxygen. In this specific research, NOx formation was not considered for the current scope of work.

Assessment of hardgrove and abrasive indices (HGI and AI) is important in ascertaining the grindability and milling efficiency for the given coal. Generally, HGI values below 45 are considered as hard coals and those above 50 as soft coal. Eskom considers coals with AI less than 100 as acceptable for efficient utilisation in the milling of their power stations. The HGI values for the coals in this study range from 52 to 70, while the AI values vary from 54 to 246. Coal A is the hardest sample with HGI of 52 and AI of 246, while coal sample D is the softest coal with HGI value of 70 and AI value of 54.

It is interesting to note that, while the low HGI value of 59 for coal C is considered to be fairly comparable to that of coal A at a value of 52, the AI values of the two coals differ disproportionately. The AI value of coal C at 99 is significantly lower than that of coal A at 246. These results imply variable physical properties of coal in terms of breakage, particle size and the degree of weathering in coal D which is indicated to be soft and easily grindable. The impact of such weathered material is likely to lead to thermal shattering in the free-board of the spreader stoker furnace. Whereas, weathered hard coals are likely to lead to concentrated combustion on the grate.

The magnitude of ash fusion temperature is an important indicator of the potential for slagging and clinker formation on the grate and furnace heat transfer equipment during coal burning. The flow ash fusion temperatures (AFT) for the four coals tested ranged from 1400°C to 1500°C. The highest readings were recorded for coals A and C, both at 1500°C, while the lower fusion temperatures were detected in coals B and D at around 1400°C.

When considering the particle size distribution within the research context, and based on the design coal specification for the particular spreader stoker boilers, fine particles are considered to be those smaller than a screen size of 6.25 mm, one quarter of an inch (1/4”). The coal specification for the one boiler equipment is 6.25 x 25 mm (1/4“ x 1“) screen size. A summary of the particle size distribution (PSD) presented in Table 4.1 indicates that, of the four samples, coal D contained the lowest proportion of finer particles at 16.47 % of the feed coal sample below 6.25 mm size, while coal A contained the highest amount of finer particles at 29.62 % below 6.25 mm size. The proportion of fine particles below 6.25mm size for coals B and C were at 26.60 and 21.87 %, respectively.

4.1.3 Petrographic Analyses

Petrographic results of the four coals are presented in Tables 4.4 and 4.5 below. The main petrographic analyses conducted were maceral composition, mineral groups, conditional analysis and rank.

Table 4.4 *Petrographic results of Coals A to D.*

Analysis	Coal ID			
	Coal A	**Coal B**	**Coal C**	**Coal D**
Maceral Analysis (%mmf)				
%Total Vitrinites	47	28	24	44
%Total Liptinites	4	4	5	9
%Total Reactive Inertinites	12	24	25	11
%Total Reactive Macerals	63	56	54	64
%Total Inertinites	49	68	70	47
%Total Inert Macerals	37	44	45	36

- Total Reactive Macerals = Vtr + R SMF + R Intd + Lipt
- Total Reactive Inertinite = R SMF + R Intd
- Total Inert Macerals = Total Intertinite - Total Reactive Inertinite
- Vtr ≡ Vitrinite; Lipt ≡ Liptinite; R SMF ≡ Reactive Semi-Fusinite; R Intd ≡ Reactive Inertodetrinite;

Mineral Group Analysis (% particles examined):				
%Total Quartz and Clays	17	18	21	25
%Total Carbonates	4	5	3	4
%Total Pyrite	7	4	2	6
%Total Clean Coal	72	73	74	65
Conditional Analysis (%):				
%Total Abnormal	14	19	22	25
% Cracked	11	16	16	20
%Heat Affected	0	0	1	0
Rank:				
%Random Reflectance (Rr)	0.61	0.70	0.76	0.63
-Standard Deviation (δ)	0.066	0.075	0.099	0.064

Data Source: Petrographics SA report No. 2011-221 [2011].

Maceral composition of the four coals is presented in Table 4.5 below, including coal rank and conditional analyses.

Table 4.5: *Selected results of petrographic analyses and coal rank for Coals A to D.*

COALS	PETROGRAPHIC ANALYSES (% mmf)					
	TOTAL VITRINITE (%)	TOTAL REACTIVES	TOTAL INERTINITE (%)	Micro-Lithotype Inertite (%)	ABNORMAL CONDITION Weathered (%)	RANK RoVr%
A	47	63	49	24	14	0.61
B	28	56	68	33	19	0.70
C	24	54	70	40	22	0.76
D	44	64	47	20	25	0.63

4.1.1.4 Summary of Petrographic Description of the Coals

Data presented in Tables 4.4 and 4.5 above provides an overview of the petrographic results for the four coals tested. It will be noted that coals A and D possess relatively high vitrinite contents (47 to 44 %, respectively). Whereas coals B and C have significantly high proportions of inertinite (68 to 70 %, respectively). Total reactive macerals for the four coals range from 54 to 64 %. Coal D has the highest proportion of total reactive macerals at 64 % while coal C shows the lowest fraction at 54 %. Microlithotypes reflect these values.

In terms of abnormal conditions, Coal D appears to have a slightly higher proportion than the other three coals (25 % relative to 14 – 22 %). The lowest quantity of abnormal particles (at 14 %) was observed in coal A. This means that of the four coals, coal D has a condition in which the organic components are more extensively cracked, weathered and oxidised than has been found in the other three coals.
The mean random reflectance values (Rr %) for the four coals ranges between 0.61 to 0.76 %. In terms of ranks all coals are the bituminous C in range, with coal A and D slightly lower in maturity.

Looking at mineral group analysis shown in Table 4.4 above, coal C and D samples contained higher proportions of clay and quartz components than those recognised in coals A and B. Coal D consists of the highest proportion of clay and quartz at 25 % volume of the particles examined while coal A contained the lowest fraction of at 17 %.

Coal C comprised of the highest quantity of total clean coal particles at 74 % while coal D sample consisted of the lowest amount at 65 %.

4.2 Operational Results

Section 4.2 presents results obtained from the performance of the test equipment in the form of the rates of steam output and combustion efficiencies of the coals. Summaries of the related results are shown in Tables 4.6 to 4.8 and Figures 4.1 to 4.2 below. Throughout the testing period the boiler loading, or operating steam output, varied between 60 – 90 % of the maximum continuous rating (MCR). This variation could have potentially biased boiler performance to a certain extent. However, for specific testing periods, the boiler steadied for about three hours before any sampling was performed to ensure the fluctuations referred to do not significantly affect the results obtained and operational data collected.

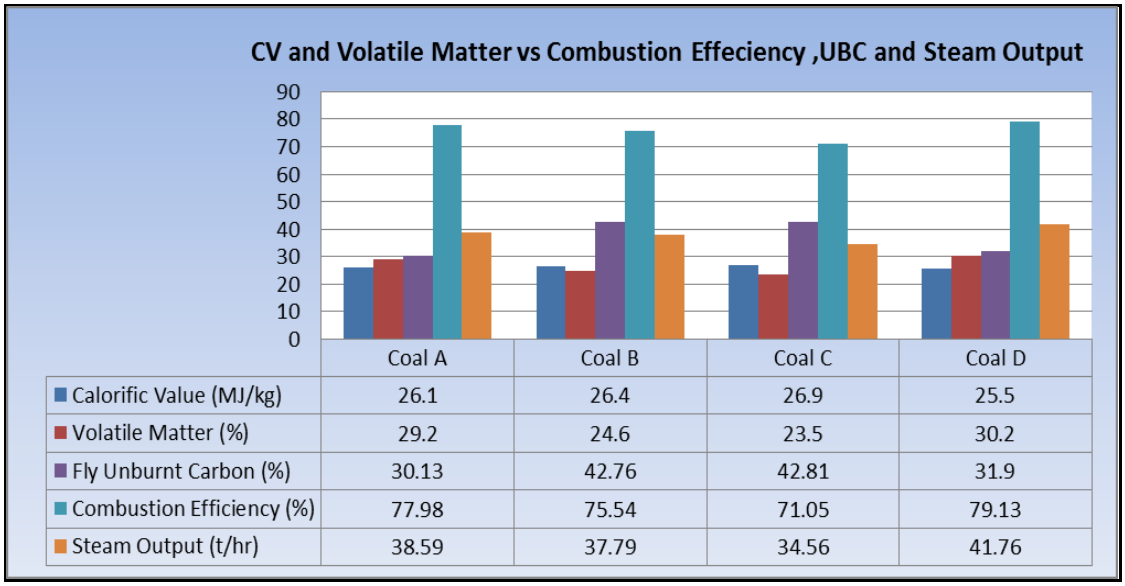
Table 4.6: *Boiler exit flue-gas temperatures, steam outputs and oxygen content in flue-gas (averages).*

Parameter	Coal ID			
	Coal A	**Coal B**	**Coal C**	**Coal D**
Flue-gas Temperature at Furnace exit/ Economiser inlet (^{o}C)	300.06	306.42	295.64	306.03
Flue-gas Temperature at Economiser outlet (^{o}C)	181.06	179.74	177.98	176.16
Steam output (t/hr)	38.59	37.79	34.56	41.76
Flue-gas O_2 content at Furnace exit (%) (Orsat analyser readings)	10.9	10.5	11.7	9.5
Flue-gas CO_2 content at Furnace exit (%) (Orsat analyser readings)	10.0	11.1	8.8	11.6
Unburnt Carbon (UBC) in Fly-ash (in Bottom ash) (%)	30.13 (16.97)	42.76 (22.70)	42.81 (21.62)	31.90 (16.26)
Calculated heat loss corresponding to total % UBC detected (%)	4.92	8.92	12.04	6.70

Data presented in Table 4.6 above provides an insight into the conditions of flue-gas exiting the boiler furnace and before entering the economiser section, in terms of exit temperatures and combustion gases. The readings recorded indicate averaged values over the four hour testing period for each coal sample. The indications are that coals C, with the highest O_2 content and lowest CO_2 fraction in the flue-gas, exhibits poor combustion looking at the relatively high amounts of unburnt carbon (UBC) in ash yielded. While coal D, with the lowest O_2 content and highest proportion of CO_2 in the flue-gas, displays improved combustion considering its comparatively low amount of UBC in ash.

4.2.1 Boiler Performance

The results presented include information on the boiler operating conditions, boiler performance and determinations of boiler efficiency. Information obtained from the chemical and physical properties, as well as combustion gases, makes it possible to determine boiler efficiency. The heat loss method was employed to determine the combustion efficiency using the British Standards, BS 845-1:1987: Methods for Assessing Thermal Performance of boilers for steam, hot water and high temperature heat transfer fluids. The boiler performance during each coal type combusted was determined by monitoring the proportion of UBC in the fly-ash as well as the amount of steam output. In this section, the unburnt carbon depicted in Figures 4.1 and 4.2 represents carbon loss in the fly ash.



	Coal A	Coal B	Coal C	Coal D
Calorific Value (MJ/kg)	26.1	26.4	26.9	25.5
Volatile Matter (%)	29.2	24.6	23.5	30.2
Fly Unburnt Carbon (%)	30.13	42.76	42.81	31.9
Combustion Efficiency (%)	77.98	75.54	71.05	79.13
Steam Output (t/hr)	38.59	37.79	34.56	41.76

Figure 4.1: *Influence of physical and chemical characteristics on coal combustion*.

The above illustration in Figure 4.1 depicts how the physical and chemical properties of coal, namely the calorific value and volatile matter content, possibly affected the coals during combustion. The graph maps the characteristics of coal with the coal performance indicators such as the proportion of UBC in fly ash, the determined combustion efficiency based on actual sampled combustion gases, and the boiler steaming rate at the time of testing.

Table 4.7: *Combustion efficiencies compared with proximate analyses and calorific values.*

Coal ID	Proximate Analysis (% ad)					Overall Efficiency	
	VM	Ash	H_2O Inherent (Total)	Tot S	CV -Grade (MJ/kg)	ε (%) Comb efficiency	(%) UBC Fly-ash (Bottom)
D (15/06)	30.2	16.7	4.5 (5.9)	1.23	25.5 D	79.13	31.90 (16.26)
A (26/05)	29.2	15.6	4.8 (9.6)	1.46	26.1 C	77.98	30.13 (16.97)
B (02/06)	24.6	17.3	3.4 (7.3)	0.46	26.4 C	75.54	42.76 (22.70)
C (09/06)	23.5	14.7	3.7 (9.1)	0.51	26.9 B	71.05	42.81 (21.62)
*E (14/06) *No further tests due to flame-out	24.9 ↑	23.1	5.1 (6.2)	0.49	22.1 DII	65.00 ↑	27.56 (23.53) ↓

A more detailed demonstration of how the physical and chemical properties of coal influence the performance of the different coals under combustion is displayed in Table 4.7 above. The Table compares calorific values and proximate analyses to the observed combustion efficiencies of the coals. It will be noted that combustion efficiency increases with decreasing amounts of unburnt carbon in the fly ash, but does not appear to correlate with the calorific value and ash values.

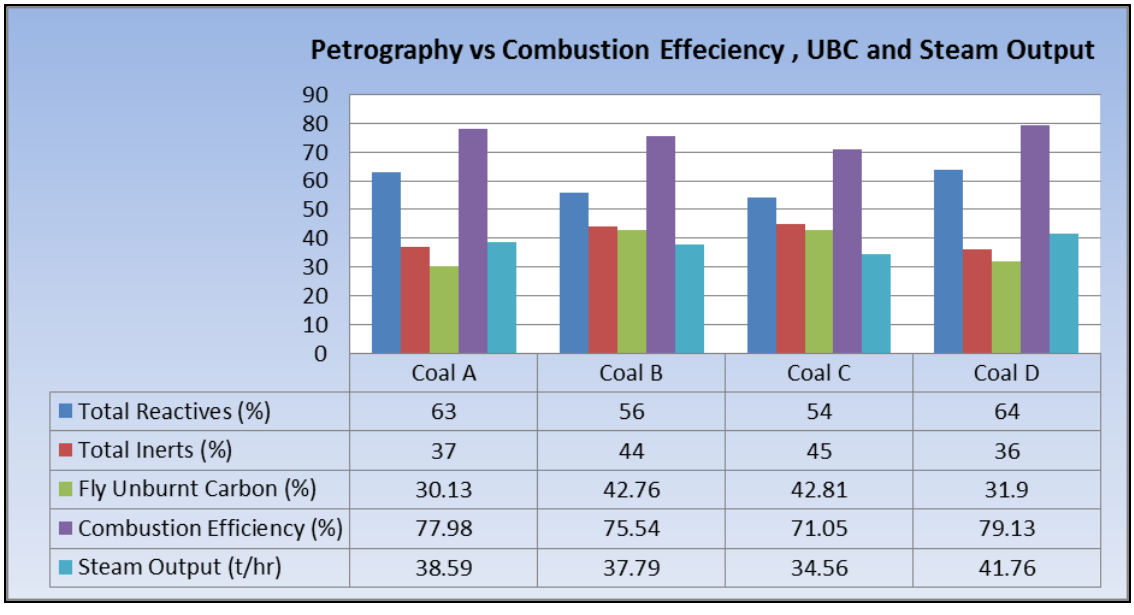


Figure 4.2: *Influence of petrographic characteristics on coal combustion*

Petrographic analysis provides vital information for the holistic understanding of the combustion behaviour of coal. The analyses and associated combustion profiles of the four coals are illustrated in Figure 4.2 above and Table 4.8 below.

Results indicate that higher combustion efficiency correlated to higher vitrinite content and total reactive macerals. Whereas higher amounts of unburnt carbon corresponded with higher quantities of inertinite.

Table 4.8: *Combustion efficiency compared with petrographic composition.*

COAL	Petrographic Analyses (% mmf)						Combustion Efficiency and % Unburnt Carbon (UBC)	
	TOTAL VITRINITE (%)	TOTAL REACTIVES (%)	TOTAL INERTINITE (%)	Micro-Lithotype Inertite (%)	ABNORMAL CONDITION Weathered (%)	RANK RoVr%	ε (%) Comb efficiency	(%) UBC Fly-ash (Bottom)
D	44	64	47	20	25	0.63	79.13	31.90 (16.26)
A	47	63	49	24	14	0.61	77.98	30.13 (16.97)
B	28+	56	68	33	19	0.70	75.54	42.76 (22.70)
C	24	54	70	40	22	0.76	71.05	42.81 (21.60)

The sets of information illustrated with 'circles' in Table 4.8 above and Tables 4.9 and 4.10 in the subsequent section together highlight the core differentiating results which were compared.

4.2.2 Summary of Boiler Performance

In terms of boiler performance, combustion efficiencies for the coals ranged from 71.05 to 79.13 %, while steam outputs ranged from 34.56 to 41.76 t/hr. Of the four coals, coal A and D samples yielded higher combustion efficiencies and higher steam outputs. Coal D produced the highest steam output at 41.76 t/hr and highest combustion efficiency at 79.13 %. Coal C yielded the lowest steam output and lowest combustion efficiency at 34.56 t/hr and 71.05 %, respectively as shown in Figure 4.2 and Table 4.8. The reduced boiler performance noted when burning coals B and C is further highlighted when considering the increased quantities of unburnt carbon in the fly ash samples for the two coals, i.e. 42.76 % UBC for coal B and 42.81 % UBC for coal C. This corresponds with the lower steam output for the two coals at 37.79 t/hr for coal B and 34.56 t/hr for coal C. The high amounts of unburnt carbon observed in coals B and C have also been calculated to indicate higher losses of heat equivalent to 8.92 and 12.04 %, respectively for the two coals (as shown in Table 4.6 section 4.2).

Correlation between petrographic properties of the coals and their combustion effectiveness is highlighted in in Figure 4.2 and Table 4.8 above. The highest combustion efficiencies were achieved when burning coals which generally contained the lowest fraction of inert macerals, and the highest quantities of total vitrinite content and total reactive macerals. Coals A and D display higher ratios of total reactive to inert macerals and this is matched by superior combustion efficiencies as shown Figures 4.1 to 4.2 and Tables 4.7 to 4.8 above. Similarly, coals B and C, exhibiting lowest total reactive to inert macerals ratios, registered relatively poorer combustion efficiencies. Relatively smaller quantities of UBC in the fly ash and coarse ash samples are observed for coals A and D. These two coals also have lower proportions of inert macerals and higher fraction of total reactive macerals.

4.3 Thermography

4.3.1 Thermographic Results relative to Conventional analyses

In this section thermographic results are interpreted in the context of the chemical and physical analyses, as well as the petrographic characteristics of the coals. Thermography constitutes the focal point of the research investigation into the thermal behaviour of the different coal qualities tested by showing maximum combustion temperature and characteristics of the flames. The thermographic results are presented in Tables 4.9 to 4.10 and Figures 4.3A to 4.6B below.

Table 4.9: *Thermographic results compared with proximate analyses, calorific values and combustion efficiencies.*

Coal ID	Proximate Analysis (% ad)					Combustion Efficiency , % Unburnt Carbon and Thermographic flame temperatures			
	VM	Ash	H_2O Inherent (Total)	Tot S	CV (MJ/kg)	ε (%) Comb efficiency	(%) UBC Fly-ash (Bottom)	Flame T°C lowest	Flame T°C Highest
D	30.2	16.7	4.5 (5.9)	1.23	25.5 D	79.13	31.90 (16.26)	1771	1793
A	29.2	15.6	4.8 (9.6)	1.46	26.1 C	77.98	30.13 (16.97)	1509	1549
B	24.6	17.3	3.4 (7.3)	0.46	26.4 C	75.54	42.76 (22.70)	1709	1779
C	23.5 ↑	14.7	3.7 (9.1)	0.51	26.9 B	71.05 ↑	42.81 (21.62) ↓	1616	1722

In Table 4.9 above, thermographic flame temperatures are compared to the physical and chemical properties of the coal. Thermography temperature profiles, combustion efficiency and unburnt carbon contents show little or no relationship with physical and chemical characteristics of coal. There is a minor trend indicated with increasing volatile matter and increasing combustion efficiency.

4.3.2 Thermographic Results Relative to Petrographic Results

Table 4.10 below reflects thermographic flame temperatures within the context of the petrographic characteristics of the coals.

Table 4.10: *Thermographic results compared with petrographic composition.*

COALS	Petrographic Analyses (% mmf)						Combustion Efficiency, % Unburnt Carbon and Thermographic flame temperatures			
	TOTAL VITRINITE (%)	TOTAL REACTIVES	TOTAL INERTINITE (%)	Micro-Lithotype Inertite (%)	ABNORMAL CONDITION Weathered (%)	RANK RoVr%	E (%) Comb efficiency	(%) UBC Fly-ash (Bottom)	Flame T°C lowest	Flame T°C Highest
D	44	64	47	20	25	0.63	79.13	31.90 (16.26)	1771	1793
A	47	63	49	24	14	0.61	77.98	30.13 (16.97)	1509	1549
B	28	56	68	33	19	0.70	75.54	42.76 (22.70)	1709	1779
C	24	54	70	40	22	0.76	71.05	42.81 (21.62)	1616	1722

It will be noted that the high flame temperatures encountered both at the highest and lowest ranges for each coal related to the different factors:

a. Temperatures in the range 1616 – 1779 ^{o}C in coals B and C correlate with high inertinite maceral contents and inertite microlithotypes. Minor correlations also exist with lower carbon effeciencies and higher unburnt carbons contents. (Falcon, pers.comm)

b. Temperatures in the range 1771 – 1793 ^{o}C for coal D correlate with the relatively high proportions of oxidised and weathered materials. (Falcon, pers.comm)

4.3.3 Photographs of Thermographic Results for Coals A to D

Thermographic data in the form of photographs, histograms and graphs for each type of coal illustrating combustion behaviour is presented in Figures 4.3A to 4.6B below. For each coal two thermal camera photographs are presented to show the boiler flame in grey and in coloured images. Temperature profiles are depicted in the form of a histogram below the flame images. For the purpose of the current research, the aggregate temperature distribution within the furnace is recorded at three main regions, i.e. just above the grate at a region referred to as ROI 5, in the middle and fireball zone referred to as ROI 3, and in the top parts of the freeboard denoted as ROI 3 (towards the boiler heat exchangers or steam drum). In addition four snapshots at different time intervals for each coal are included. The purpose of these is to illustrate the consistent nature of the flame for each coal at different time intervals. The histrograms and graphs are not legible due to the nature of the computer printouts. However, key parameters, i.e. temperature readings, are illustrated on the diagrams presented.

Thermographic data for coal A is represented by Figures 4.3A and 4.3B below. Majority of the snapshots captured at various time intervals indicate evenly distributed flames within the furnace area. In terms of commercial grades sold on calorific values, coal A with calorific value of 26.13 MJ/kg can be classified as Grade C. Coal A was determined to contain high contents of volatile matter and vitrinite.

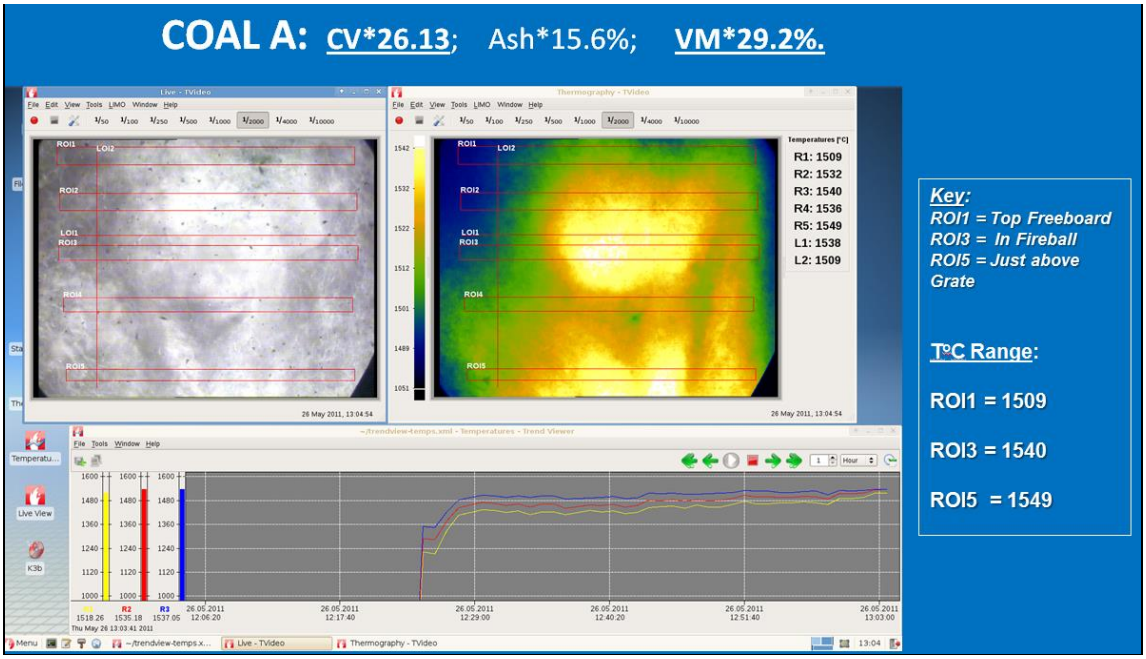


Figure 4.3 A: *Overall thermography profiles for Coal A.*

The data shows good ignition and combustion on the grate and fire-ball zones of the furnace. Of the four coals, coal A registered the lowest flame temperature of ROI5 = 1549 ^{o}C.

All the four snapshots captured show that the highest flame temperatures were around the lower parts of the boiler at ROI5, just above the grate. Temperatures tended to lower slightly towards the upper parts of the furnace, at regions depicted as ROI1 on the thermographic data, where the boiler heat exchangers are situated.

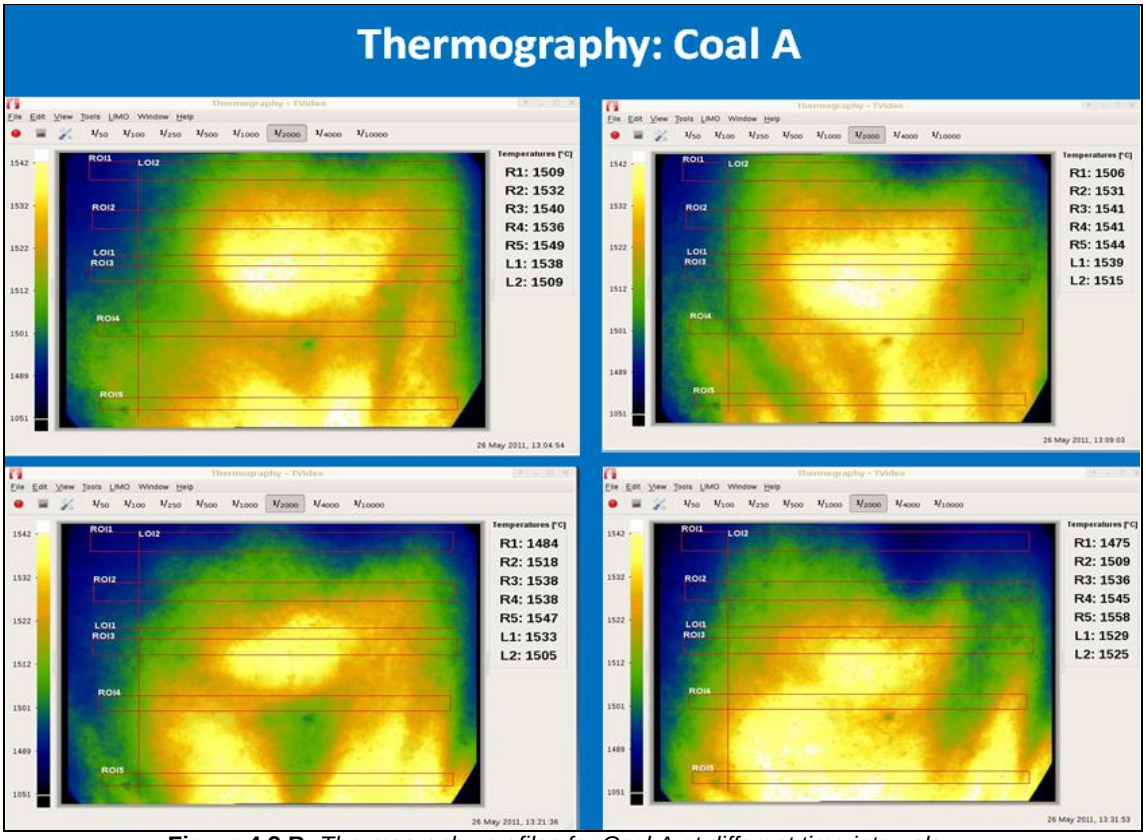


Figure 4.3 B: *Thermography profiles for Coal A at different time intervals.*

Corresponding thermographic data for coal B is represented by Figures 4.4A and 4.4B below. The snapshots show irregular and segregated flame distribution within the furnace. Based on commercial grades sold on CV standards, coal B with calorific value of 26.42 MJ/kg can be classified as Grade C. The sample is composed of low volatile matter content and high quantities of inertinite macerals.

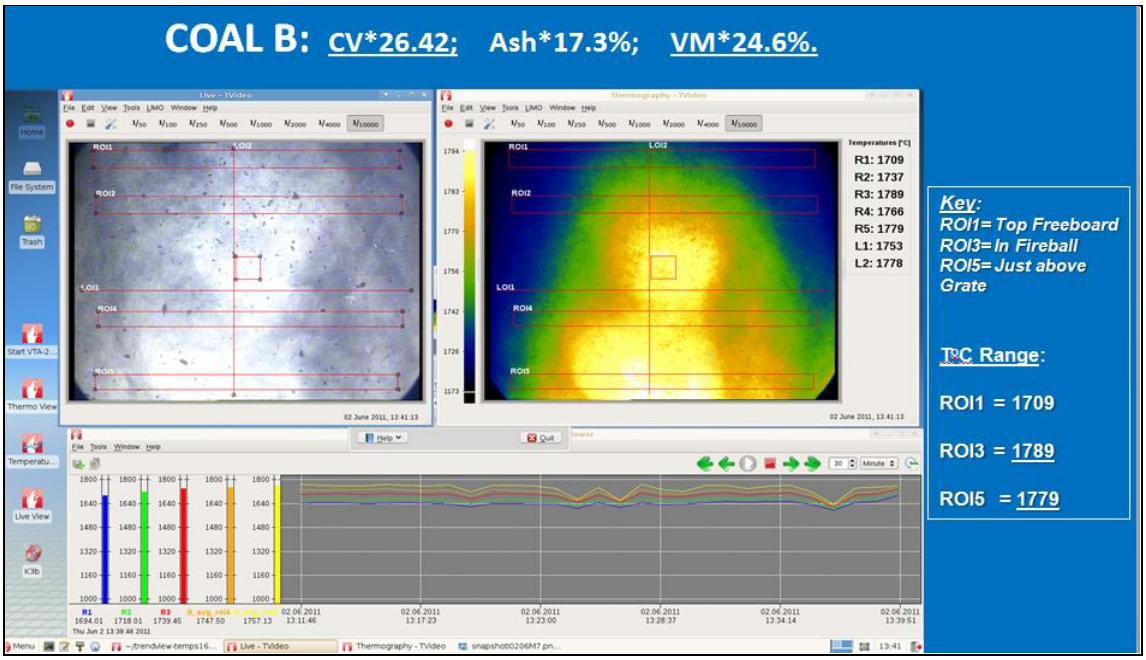


Figure 4.4 A: *Overall thermography profiles for Coal B.*

The thermographic pictures are illustrative of moderate to poor ignition and combustion on the segregated on the grate and fire-ball zones of the furnace. Coal B recorded the second highest temperature amongst the four coals of ROI3 = 1789 ^{o}C , at the region around the fire-ball area of the furnace. In some of the snapshots for coal B, flames were concentrated in the lower parts of the boiler at region ROI5 just above the grate, while during other time intervals combustion seemed to be occurring mostly in the fireball zones of the furnace at region ROI3.

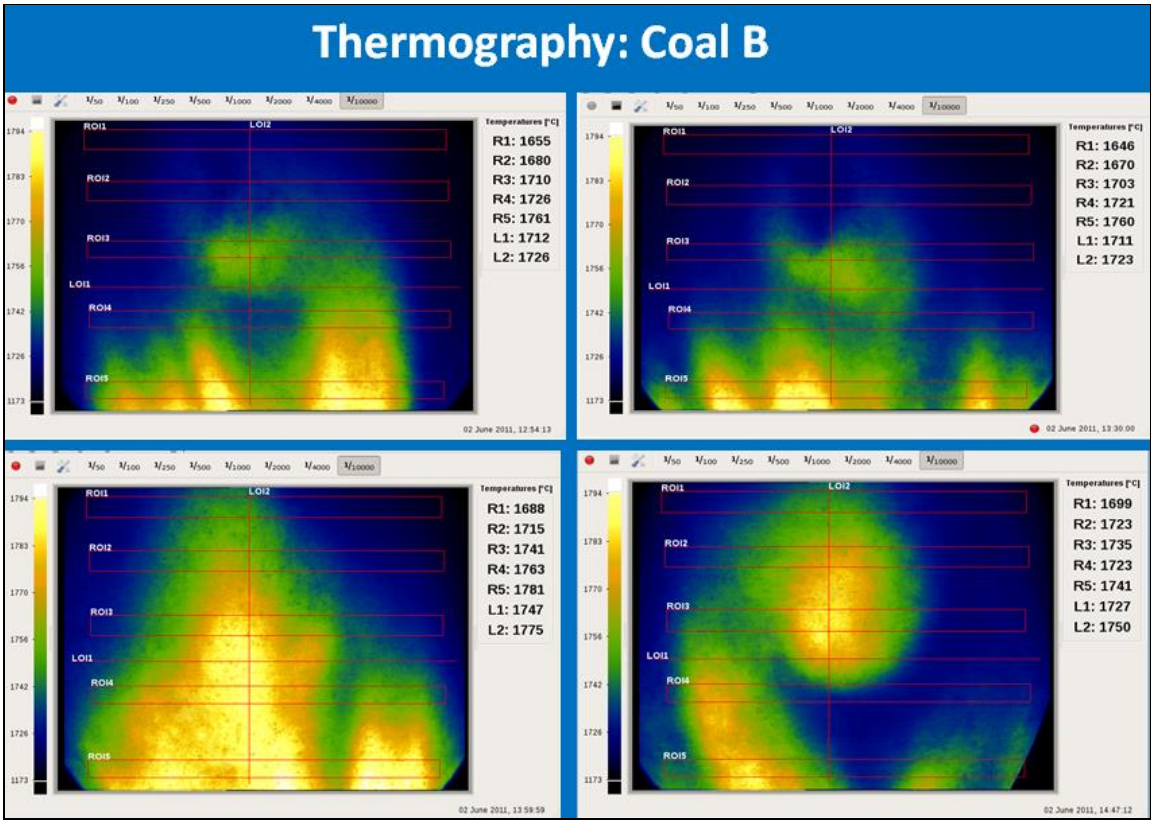


Figure 4.4 B: *Thermography profiles for Coal B at different time intervals.*

Figures 4.5A and 4.5B below represents the thermographic data for coal C. The snapshots show erratic flames distribution mainly on the grate area of the furnace. With a calorific value of 26.99 MJ/kg, coal C can be classified as Grade B. The sample is of low volatile matter content and high content of inert macerals.

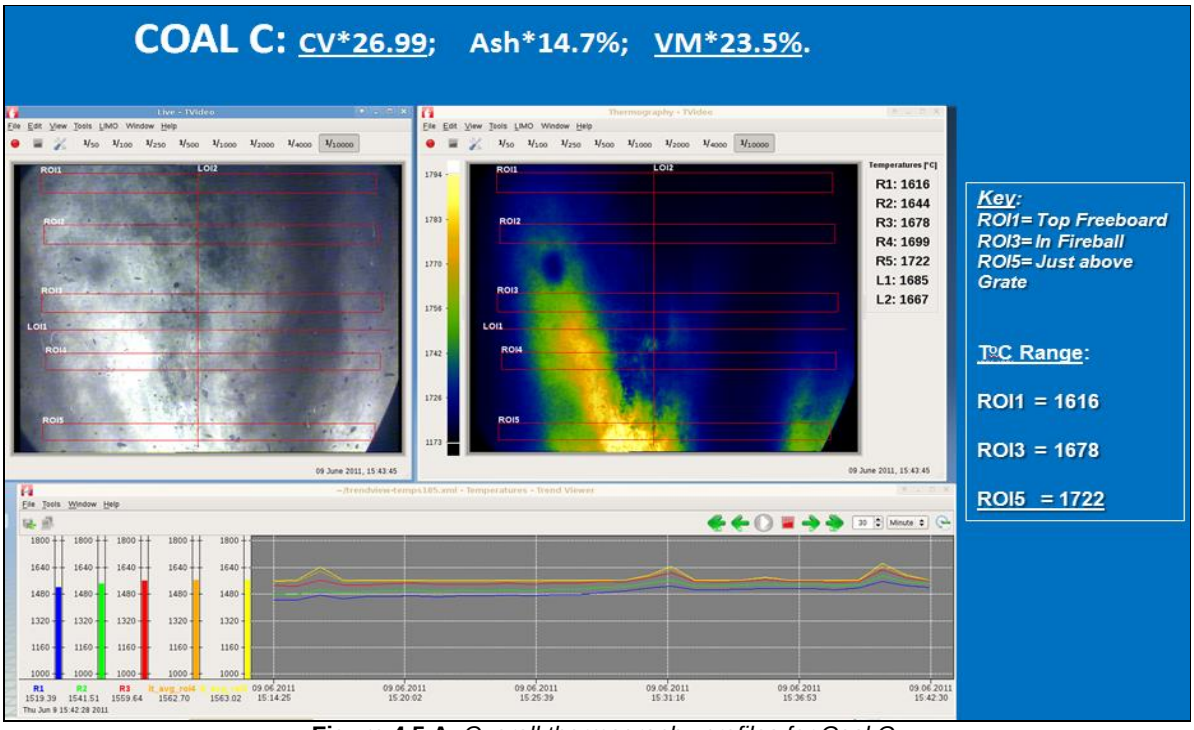


Figure 4.5 A: *Overall thermography profiles for Coal C.*

The thermographic pictures are illustrative of poor ignition and delayed combustion restricted entirely to the grate zones. Coal C burnt at relatively high flame temperatures around the grate area with ROI5 = 1722 ^{o}C.

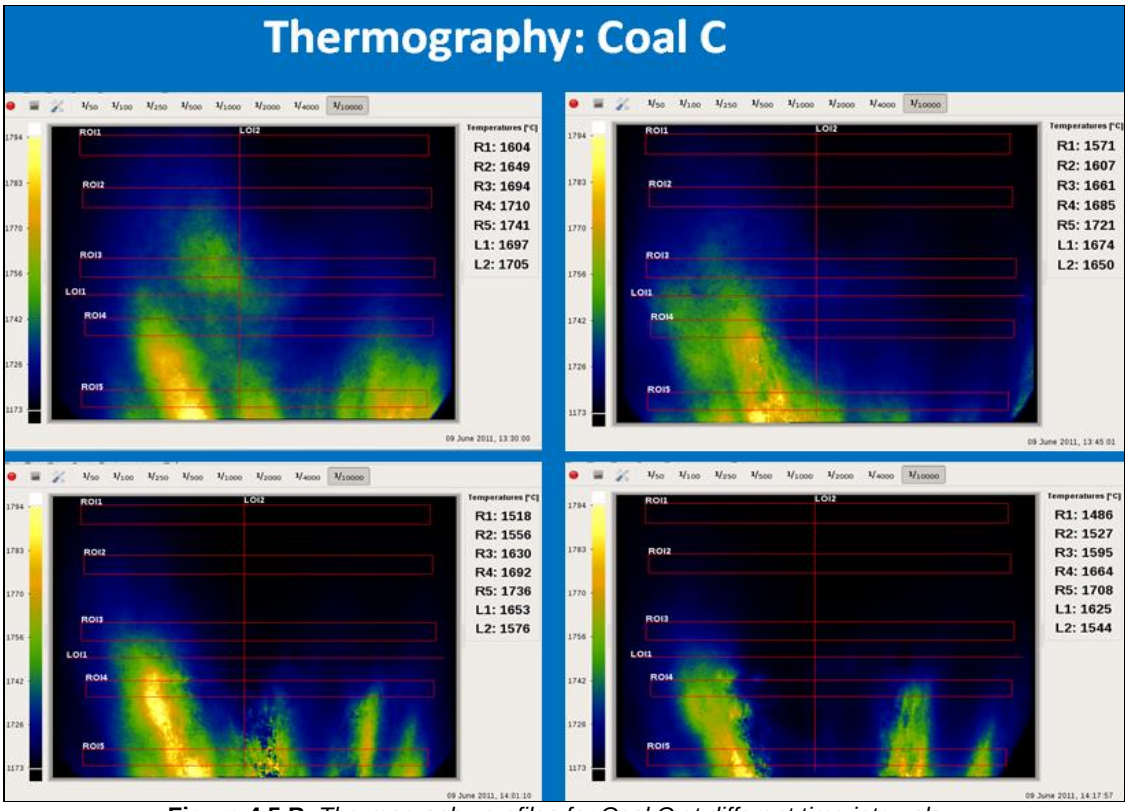


Figure 4.5 B: *Thermography profiles for Coal C at different time intervals.*

This combustion performance correlates with increased concentration of O_2 in flue-gas at the backend of the boiler as recorded in Table 4.6. This in turn indicates lack of combustion and therefore results in excess O_2 in the flue gas exiting the furnace.

The pictures shown in Figures 4.6A and 4.6B below represent thermographic data for coal D. All snapshots exhibited evenly distributed flames throughout the furnace. Based on a calorific value of 25.54 MJ/kg, coal D can be categorised as Grade DII. The sample consisted of high volatile matter content and high quantities of vitrinite macerals.

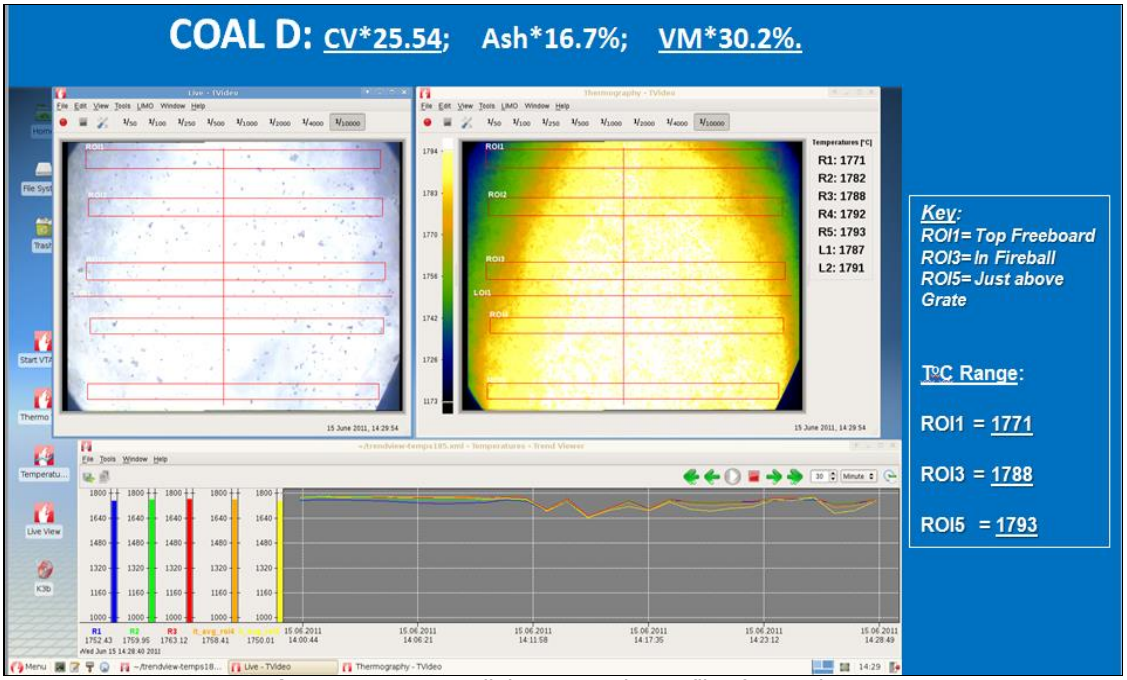


Figure 4.6 A: *Overall thermography profiles for Coal D.*

Based on the thermographic pictures illustrated below, coal D burnt with excellent ignition and massive combustion on the grate and fire-ball regions. Of the four coals, coal D registered the highest flame temperature of ROI5 = 1793 ^{o}C at the lowest section of the furnace just above the grate. But it must be noted that, in practice, these high temperatures could well damage equipment and be the cause of plant stoppages. Such conditions have been noted when burning some South African coals.

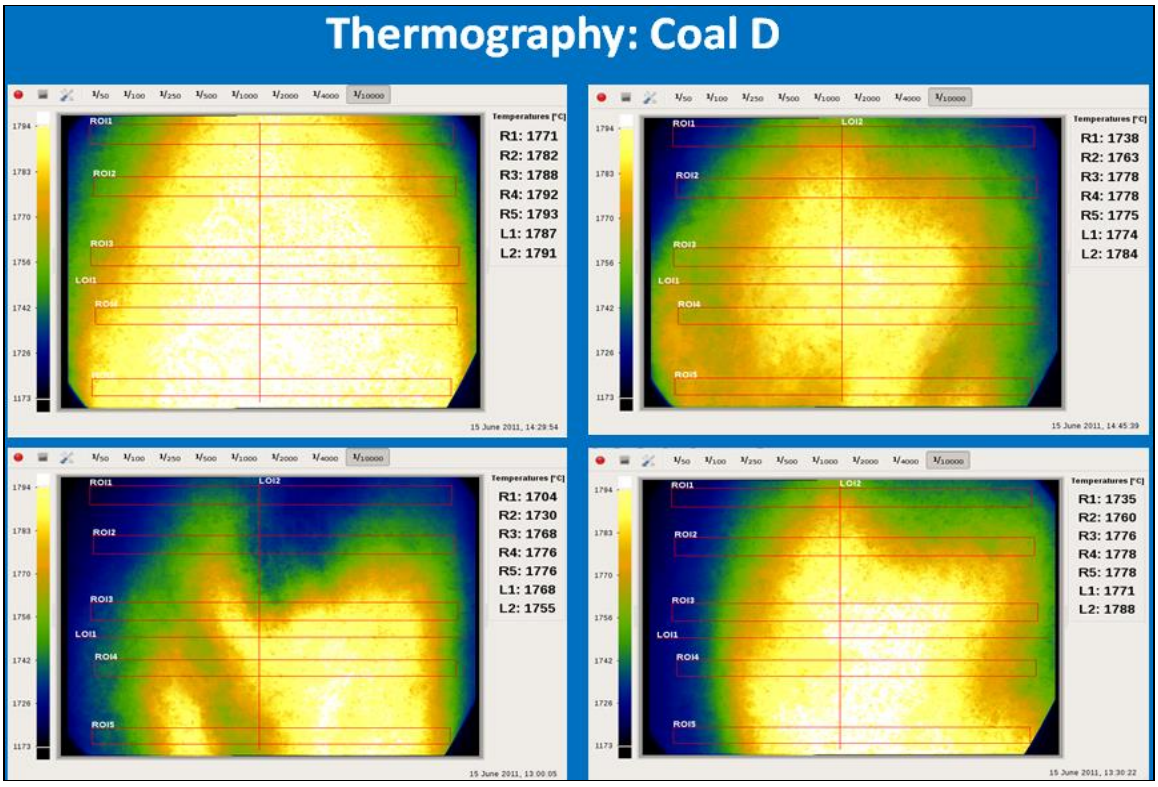


Figure 4.6 B: *Thermography profiles for Coal D at different time intervals.*

In terms of O_2 in the flue-gas when burning coal D as seen in Figures 4.6A and 4.6B above, in this case the O_2 was the lowest concentration, therefore indicating consistent combustion and utilisation of the oxygen. This is in direct contradiction to the combustion situation observed in coal C.

4.3.4 Summary of Thermographic Results

Despite the notably different flame characteristics of the four coals, generally all coals burnt at high temperatures of above 1500°C. Coals A and D demonstrated good ignition and combustion, with flames uniformly spread on the grate and fire-ball zones of the furnace. Coal D showed the highest temperature of all coals and the most extensive flame. On the other hand, the thermographic data of coals B and C contrast significantly different with that observed for coals A and D. Data for coals B and C are indicative of poor ignition and combustion with flames unevenly spread throughout the furnace area and explicitly segregated to points along the grate.

Coal A registered the lowest flame temperature amongst the four tested coals (at ROI5 = 1549 ^{o}C). The highest flame temperature of all four coals (at ROI5 = 1793 ^{o}C) was recorded in coal D. Coal B registered the second highest flame temperature (at ROI3 = 1789 ^{o}C) that was detected in the fire-ball area of the furnace. The highest temperature recorded for coal C was observed to be in the range of ROI5 = 1709 – 1779 ^{o}C. Such peculiarities in the location of maximum temperatures focussed to lower sections of the furnace are likely to significantly obstruct optimal heat distribution and consequently the rate of steam output.

CHAPTER 5

The primary objective of this research was to establish the combustion characteristics and efficiencies of four coals and their impact on the performance of one specific spreader stoker boiler. In seeking to postulate conceivable reasons for the attained variable experimental results, a detailed investigation involving the following determinations was conducted:

a. boiler operational conditions associated with physical and chemical characteristics of the coals,
b. petrographic properties, and
c. finally thermographic data as observed in the boiler.

This consequently sought to answer the question of what parameters were dominant in influencing good or poor combustion efficiency and boiler performance. Combined results of the research are presented in Tables 5.1 to 5.2 and Figure 5.1 below.

5.1 Boiler Performance Related to Proximate Analysis and Calorific Values

Looking at Figure 5.1 below, it is noticeable that coals B and C with the highest calorific values and lowest volatile matter contents yielded the lowest steam outputs and combustion efficiencies. In contrast, coals A and D with the lowest calorific values and highest volatile matter contents produced higher steam outputs and combustion efficiencies. Even for coals with closest similarities in physical and chemical properties, such as coals A and D, there were noteworthy differences in boiler performance when burning the two coals, seemingly under matching operating conditions, as marked by varying steam outputs and combustion efficiencies.

Table 5.1: *Combination of combustion efficiencies, proximate analyses, flame temperatures and boiler performance.*

COAL	Proximate Analyses Fuel Ratio				Boiler Efficiency		Thermography Flame T°C		BOILER OUTPUT
	CV MJ/kg	Volatile matter ad %	Fixed Carbon Ad%	FUEL RATIO	ε (%) Comb efficiency	(%) UBC Fly-ash (Bottom)	Flame T°C Lowest RO1	Flame T°C Highest RO5	Average Steam Output (O_2 in flue gas %)
D	25,5	30.2	48,6	1,61	79.13	31.90 (16.26)	1771	1793	41,76 (10,27)
A	26,1	29.2	50,4	1,73	77.98	30.13 (16.97)	1509	1549	38,59 (11,5)
B	26,4	24.6	54,7	2,22	75.54	42.76 (22.70)	1709	1779	37,79 (11,4)
C	26,9	23.5	58,1	2,47	71.05	42.81 (21.62)	1616	1722	34,56 (11,7)

The enhanced performance observed when burning coals A and D, as compared to coals B and C may partly be attributed to higher volatile matter contents as this would imply the coals were easier to ignite. In terms of boiler performance based on proximate analyses, the highest steam output at 41.76 t/hr and highest combustion efficiency at 79.13 % were observed in Coal D which showed the highest volatile matter content and lowest fuel ratio (FR) value. On the contrary, the lowest steam output at 34.56 t/hr and lowest combustion efficiency at 71.05 % were displayed by Coal C with the lowest volatile matter content and highest FR value. At this stage, without expansive consideration of the analogous petrographic properties of the coals, it cannot be projected as to what extent the quantity of volatile matter could have influenced boiler performance. However, generally the high steam output correlated with high volatile matter and high combustion efficiency, but correlated inversely with fuel ratio and unburnt carbon, as shown in Figure 5.1 above.

5.2 Boiler Performance Related to Petrographic Composition

Results in this study as summarised in Table 5.2 below indicate that increasing combustion efficiency correlates with increasing vitrinite content. Conversely, high combustion efficiency proves to be inversely proportional to the amount of unburnt carbon and total inertinite. This relationship can alternatively be viewed as that of low combustion efficiencies and high unburnt carbon correlating with high inertinite coals.

Table 5.2: *Combination of petrography, flame temperatures and boiler performance.*

COALS	Petrographic Analyses (% mmf)						Overall Efficiency		Thermograph Flame T°C		BOILER OUTPUT
	TOTAL VITRINITE (%)	TOTAL REACTIVES (%) (Liptinites)	TOTAL INERTINITE (%)	Micro-Lithotype Inertite (%)	ABNORMAL CONDITION Weathered (%)	RANK RoVr%	ε (%) Comb efficiency	(%) UBC Fly-ash (Bottom)	Flame T°C Lowest RO1	Flame T°C Highest RO5	Average Steam Output (O_2 in flue gas %)
D	44	64 (9)	47	20	25	0.63	79.13	31.90 (16.26)	1771	1793	41,76 (10,27)
A	47	63 (4)	49	24	14	0.61	77.98	30.13 (16.97)	1509	1549	38,59 (11,5)
B	28	56 (4)	68	33	19	0.70	75.54	42.76 (22.70)	1709	1779	37,79 (11,4)
C	24	54 (5)	70	40	22	0.76	71.05	42.81 (21.62)	1616	1722	34,56 (11,7)

With regards steam production, the highest steam outputs correlate with high vitrinite content, highest combustion efficiency and lowest unburnt carbon. Coal D with the second highest vintrinite content at 44 % mmf and lowest inertinite content at 47 % mmf produced the highest amount of steam at 41.76 t/hr. The association between steam output and petrographic composition was also observed to be consistent on all the other three coals, coals B, C and D, which yielded steam outputs paralleling their respective petrographic compositions in terms of total reactive and inert maceral contents.

Consequently the impact of petrographic characteristics is crucial in understanding the combustion behaviour of coal as indicated in the current results. It can further be asserted that for combustion behaviour of any particular coal sample to be wholly known there has to be equally comprehensive study of the petrographic characteristics of the coal

5.3 Comparison of Thermographic Characteristics of the four Coals

The focal point of the investigation into the combustion behaviour of the four coals tested was based on thermographic analysis and temperature profiling of the furnace during combustion. A summary of the thermography temperature profiles is presented in Figure 5.1 below and the behaviour of each coal is illustrated in terms of flame characteristics and associated temperature readings.

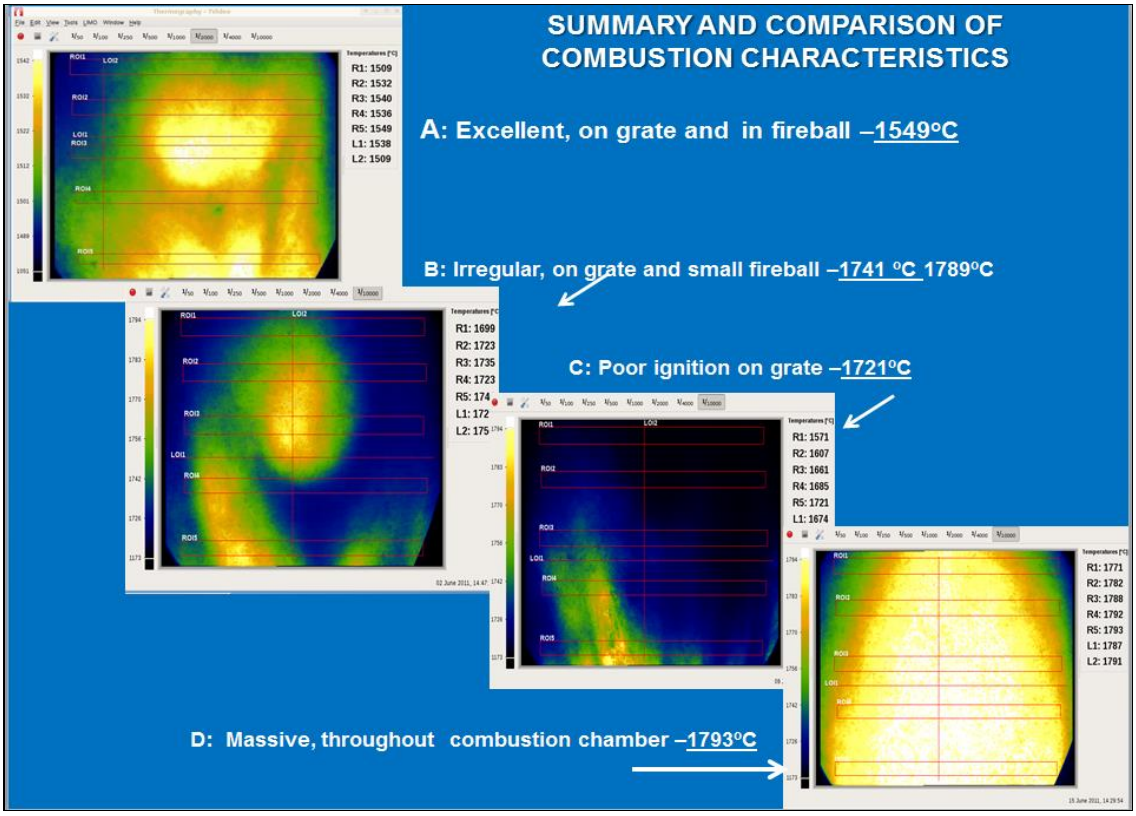


Figure 5.1: *Summary of thermography profiles for the four coals.*

All the four coals under review showed significantly different combustion characteristics despite having similar calorific values, volatile matter content, and ash contents. On the other hand, the results indicate that there is a strong correlation between thermographic data (combustion behaviour and maximum flame temperatures) and petrographic composition of the coals. This association is not reflected in calorific values and proximate analyses of the coals. The different thermographic trends observed in coals A and D from the same colliery provide a typical illustration that verifies the view that there was no clear correlation between flame temperature, calorific value, combustion efficiency, ash and volatile matter content. In spite of having fairly similar proximate analyses and calorific values, the two coals burnt at notably different flame temperatures under similar operating conditions. Coal A burnt with the lowest flame temperature of all the four coals at ROI5 = 1549 ^{o}C while coal D recorded the highest flame temperature amongst the four coals at ROI5 = 1793 ^{o}C (full thermographic data is presented in Appendix D, Figure D1). It is relevant to note that coal D was characterised by 25 % of weathered coals which on entering the boiler may well have thermally shattered (unlike for normally fresh coals) when being introduced into the combustion chamber. Weathered coal is known to burn at considerably higher temperatures due to its reduced volatile matter content and its condition. Coal A on the other hand has similar petrographic properties but is relatively unweathered. The latter coal will burn in the normal condition.

The second highest temperature at ROI5 = 1741 ^{o}C was detected in coal B which had the highest calorific value but yet its flame characteristics did not exhibit good combustion or ignition as the flame burnt irregularly and were also segregated to discrete parts of the furnace. This observation further confirms that interpretation that there is no correlation between flame temperature and calorific value and proximate analyses. With the exception of coal B, which produced highest temperature in the middle of the furnace (the desirable combustion zone), all other coal samples tend to yield highest flame temperatures both on the grate and in the upper fire-ball zones of the furnace where the boiler heat-exchangers (steam drum) are located. This indicates signs of delayed combustion at the back end of the boiler. Such conditions are undesirable as they imply loss of efficiency due to combustion happening in regions outside of the furnace heat transfer zones, leading also to fouling of the heat exchange surfaces and blocking of convective passes by ash deposits. High flame temperatures pose a greater risk of soot formation due to volatile matter components of the coal, especially tar, undergoing secondary reactions at high temperature (Fletcher et al., 1997).

As described on section 4.1 (Analytical Results), further testing of the fifth type of coal, coal E, had to be abandoned due to flame out. However, even with the limited thermographic data captured, coal E clearly showed poorest ignition and combustion with flames concentrated entirely in the fire-ball zone with hardly any burning on the grate. This combustion pattern compares reasonably close to the analytical data of the coal (Appendix A, Table A1) which showed the highest ash content (23.10 %), lowest calorific value (22.19 %), highest oxygen content (9.22 %), and lowest abrasive index (54). These properties indicate that the coal sample was oxidised and weathered possibly originating from shallow seams or due to stockpiling for long periods.

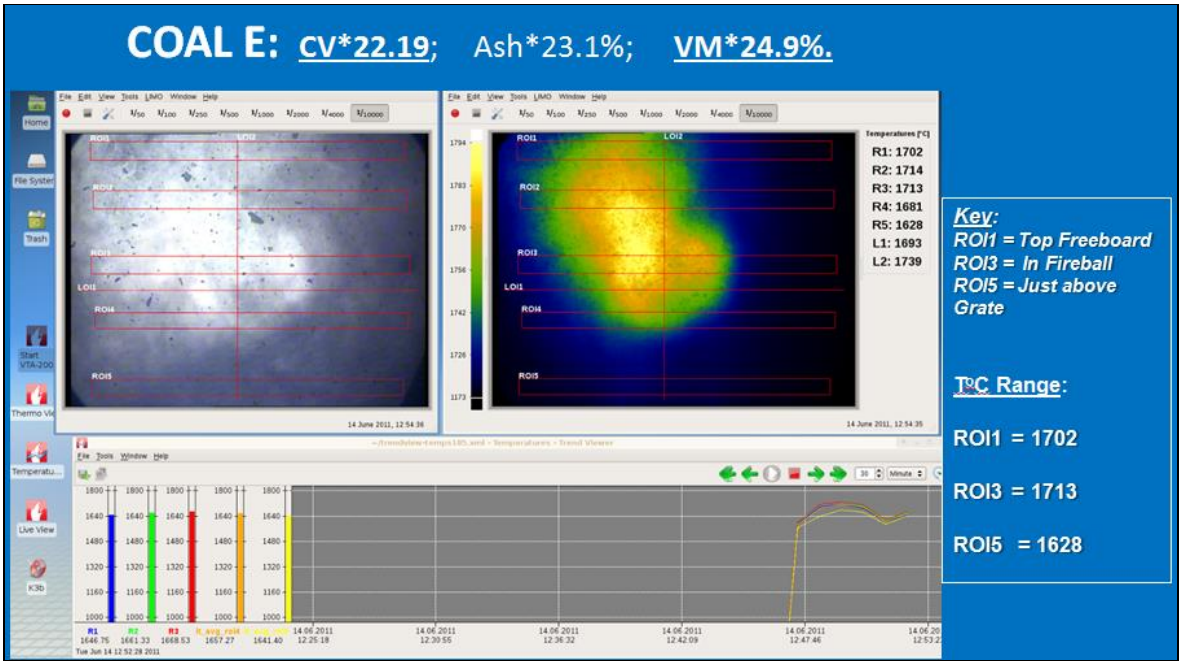


Figure 5.2: *Temperature profile for Coal E showing characteristic fireball and delayed combustion.*

The flame pictures as depicted in Figure 5.2 above also indicate clear signs of delayed combustion. Such deprived combustion behaviour could be anticipated from the inferior coal properties; low calorific value, low volatile matter content and high ash content. Despite difficulties with ignition, the sample remarkably yielded the lowest unburnt carbon in fly ash of all the four main coals tested at 27.56 %. Full thermographic data for the sample is presented in Appendix D**.** It is therefore likely that such coal thermally shattered on impact on entering the spreader stoker furnace. Thereby combusting as fine sizes almost exclusively in the fire ball space.

5.4 Summary of Discussions

In summary, the best performing coals were found to be coals A and D, while the poorest performing coals were coals B and C. When it comes to the single choice of coal, coal A would be the best choice due to the following reasons. The sample generated high steam outputs, high combustion efficiency and lowest unburnt carbon at much lower flame temperature than any other coal. While coal D produced the highest amount of steam, this was however at very high temperatures which could threaten the life span of materials of construction. Furthermore, bearing in mind the commercial prices of coal based on calorific value, it could be argued that coal A being of higher quality than coal D should not be the best option as it would be more expensive. However, it is considered that the risk of damage to equipment due to exposure to higher temperatures when burning coal D is not worth the limited savings that may be realised on the cost per tonnage alone. With regards to the coal type of least choice, coal B, this sample initially looked to be of the highest grade amongst the four coals based on calorific value alone, but actually performed the poorest in terms of lowered steam outputs, reduced combustion efficiencies, higher quantities of unburnt carbon in ash, and burning with one of the highest temperatures. The sample performed poorly as expected of a sample consisting the lowest volatile matter, lowest vitrinite content and highest inertinite content. The results achieved affirm the principle that anticipation of possible combustion performance for any coal sample relies more on its petrographic properties and to a lesser extent on the proximate analyses and calorific value.

Depending on plant operating procedures, even some of the strongest types of steel material will have shortened lifespans when exposed to high temperatures as high as about 1800°C as was detected in this study. With extended exposure materials tend to become more brittle and weak, eventually lead to complete failure over time. Thermography is thus instrumental in predicting possible combustion behaviours and the associated flame temperatures. When incorporated into conceptual design, such data will equip boiler designers and manufacturers with extra knowledge for constructing high tolerance equipment capable of burning any given type of feed coal or feed stock material.

This will allow for improved operation that minimises unplanned plant stoppages, reduces maintenance costs and boost safety of equipment operation.

The notable differences on the combustion patterns between coals A and D from the same colliery, with specific reference to the flame temperatures recorded, is of considerable interest when considering that the coal properties of the two samples were very similar; the samples apparently originated from the same mine source; and they were burnt under similar boiler operating conditions. To this juncture, nevertheless, the exact factors that influenced remarkable differences could not be established with certainty. Consequently several questions arise around the noted disparities:

a. Could the discrepancies observed when combusting the two coals be attributed largely to the higher proportion of weathered and oxidised particles found in coal D (25 %) when compared to that of coal A (14 %)?
b. Did the higher total moisture content noted in coal A (9.55 %), relative to that of coal D (5.9 %), contribute significantly to the observed diminished thermographic flame temperatures between the two coals?
c. Were the notable differences in combustion performance of the two coals influenced essentially by their greatly different ash constituents, i.e. coal D contained a higher fraction of clays and quartz (25 %) compared to that of coal A (17 %)?

The proportion of clean coal was also lowest for coal D (65 %). Beyond specific coal properties discrepancies, it is also possible that there may have been slight and unnoticed operating conditions that biased the impact of any existing determining factors. To provide answers to the above questions will require supplementary research to be conducted with particular focus on the assumed discriminating factors and coal properties.

CHAPTER 6

This chapter presents a summary of observations, interpretation of the results achieved and finally implications on the research undertaken. The association of combustion performance of the coals with particular reference to coal properties, especially petrography and thermography, was established. Such information provided genuine insight into the combustion behaviour encountered when burning the coals under investigation.

Based on the results obtained in this research the following conclusions are drawn:

1. ***The quality of coal proved to significantly influence the combustion performance*** in the stoker boiler under investigation. This was best reflected in the petrographic composition of the coals and the thermorgaphic results as indicated by flame temperatures and combustion flame characteristics. Calorific value and ash content bore no relation to such combustion performance.

2. The ***most relevant results*** were observed in the combustion performance of coals A and D, both from the same colliery. These coals had the same proximate analyses, calorific values and ash contents but differed significantly in combustion temperatures, flame shapes as well as petrographic compositions.

3. In terms of ***efficiency when combusting the four coals***, coal A produced the second highest combustion efficiency and steam output and achieved this by burning at the lowest flame temperatures of all four coals. Coal D, on the other hand, whilst producing the highest steam output and combustion efficiency, burnt at the highest flame temperatures of all four coals, with a massive flame that encompassed virtually the entire freeboard above the grate as well as on the grate. Under these conditions, such a coal may be expected to lead to extensive thermal damage of boiler plant equipment and to severe ash slagging in wide sectors of the boiler.

4. The ***difference in combustion performance between coal A and coal D*** was revealed in part by petrographic analyses, where it was observed that coal A was described as a fresh coal while coal D was composed to some extent (25%) of oxidised and weathered organic matter, all other petrographic factors being relatively consistent. This observation is supported by an unusually high hardgrove index (HGI, indicating a particularly low or soft grindability), a particularly low abrasion index (AI) and a lower than normal ash fusion temperature (AFT) relative to the values found in coal A.

5. The ***reason for the unusual massive fireball*** and the particularly high temperatures in the freeboard produced by coal D is interpreted to be due to the presence of friable weathered coal material which underwent intense thermal shattering as the particles entered the hot zone and were thrown across the boiler chamber. This would have led to an unusually high proportion of fine particles burning in suspension thus giving rise to the intense flame in the freeboard with only a limited number of larger lumps falling to the grate. The presence of high unburnt carbon in the fly ash appears to support this contention as does the high oxygen content and high HGI values of the feed coals.

6. The ***combustion characteristics of coals B and C*** were found to differ from that of coals A and D in producing limited ignition, reduced flames and poor burnout characteristics leading to higher unburnt carbon contents in the fly ash. These factors indicate reduced combustion efficiencies, all of which can be correlated to increased proportions of relatively inert forms of petrographic organic components (inertinite) in these coals.

7. ***In terms of selection as a feed coal for the boiler under investigation***, the coal of choice for this boiler application would be coal A. This is because of its lower propensity for ash fusion or slagging due to its high AFT, the second highest combustion efficiency and steam output, and the lowest flame temperatures of all four coals. This would ensure safe operation of boiler equipment when burning combusting such coals.

8. ***Specific areas of improvement in boiler efficiency***, as indicated by the test work in the stoker boiler under investigation, therefore included:
    a. reduction in the quantity of unburnt carbon (indicating more efficient burnout within the boiler chamber),
    b. enhanced steam output per ton of coal consumed, and
    c. optimum heat distribution and lower risk of thermal damage to equipment by lowered combustion flame temperatures with evenly distributed flames.

    Whilst even greater efficiencies could be achieved by acquiring better grades of feed coal, it should be noted that such better quality coals are seldom available on the inland market due to the lower qualities of coal now being mined in South Africa.

9. ***The impact of adopting a more advanced approach to combustion assessment*** and boiler operation could lead to:
    a. Improved selection of suitable feed coals using key parameters for better selection.

b. Improved design or retrofitting of main boiler and auxiliary equipment such as precipitators, or bag-house filters, in order to adapt to the lower grade coals currently being mined.
c. Extended boiler plant availability and reduced maintenance by minimising hot spots, boiler tube rupture, slagging and fouling, and chain-grate failure.
d. Enhanced combustion efficiency leading to greater cost effectiveness based on increased steaming rates per tonnage of coal combusted and decreased heat losses.
e. Reduced greenhouse emissions by using fewer tons of more suitable coal feed to reach an objective which would, in turn, lead to lower carbon dioxide emission. **NB**: the emissions of NOx and SOx have not been discussed as those topics fall outside the remit of this Research Report.

Notwithstanding the role played by the specific inherent coal properties encountered in the four coals under review and the boiler operating conditions, the overall observation from this research study is that all four coals burnt at much higher temperatures than expected and it is suspected that this could be the trend with most saleable South African coal products in grades lower than grade B in future.

As a consequence, when it comes to choosing the best performing type of coal, it is concluded that such decisions should be reached after broad consultation with as much information on the properties of the coals as possible, and the use of thermographic analyses when anomalous or unacceptable combustion performance is encountered.

In conclusion, it has been observed that, achieving the desired combustion condition, such as high steam outputs and combustion efficiencies, is not, in itself, adequate without also taking into account the inherent temperatures experienced in reaching the wanted boiler performance, because the gains in the short term may be offset by persistent losses in the long run, such as degradation of equipment and system integrity. For these reasons, a more comprehensive approach is required by coal-fired boiler users in future.

CHAPTER 7

The chapter presents suggestions for more advanced research to investigate the challenges encountered during the research so far undertaken. It is believed that the proposals presented will be helpful in overcoming shortfalls in the current study, consolidation of past hypotheses, and provision of practical solutions to the existing problems in the boiler industry.

On the basis of the observations, discussion and results obtained so far, the recommendations are as follows:

1. A design review needs to be conducted on:
    - The materials of construction to ensure that these are suitable for the high temperatures as recorded on the thermographic data. This will help guarantee the lifespan of boiler main and auxiliary equipment and maintain safe operation of pressure vessels. As thermography technology was not very advanced in the early 1900s when most spreader stoker boilers were manufacture, it is likely that the maximum attainable flame temperatures for the specific types of coal were underestimated during design phase of the equipment.
    - The grit return system to assess that the effectiveness of fly ash reinjection from a mechanical dust collector into the furnace. The system should be retrofitted to enable effective recovery of the currently high quantities unburnt carbon for introduction back into the furnace.

2. A mass and energy balance exercise needs to be performed on the boiler furnace and economiser in a comprehensive combustion testing campaign. This will enable the determination of true boiler efficiency, maximise heat recoveries and allow for better monitoring of the boiler performance. The setup of draft and coal feed systems will have to be reviewed to appropriately account for the amount of combustion air supplied to the boiler, the flow of combustion gases in the flue, and the flow of coal and ash streams into and out of the boiler unit.

3. Further research should be conducted on coals with wider margins of varying properties in order to establish the extreme best and worst case scenarios, that is of burning a high grade A coals compared to poor grade D coals. This would provide a much broader outlook into the combustion behaviours of South Africa coals in all categories.
4. In addition, the scope of the new study should include the pattern of emissions with regard to particulates, unburnt carbon and greenhouse gases (CO_2, SO_x and NO_x) for all tested coals and their associated environmental impacts.

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LIST OF APPENDICES

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- **Appendix C: Petrography Analysis**
- **Appendix D: Additional Thermography Data**
- **Appendix E: Combustion Efficiency Determination**
- **Appendix F: Boiler Operational Conditions**
- **Appendix G: Boiler Design Data**
- **Appendix H: Boiler Plant Layout**

Appendix A: Proximate and Ultimate Analyses

Table A1: *ALS - Witlab coal and ash samples general report.*

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Registration No. 2003 / 009138 / 07

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TO IMPALA PLATIINUM
JOB NO 534/11-1
DATE 2011/07/18

Test Report

Results reported on an Air-Dry Basis

			SABS 925:1978	ISO 1171: 1997	ISO 562: 1998	By Diff.	ISO 1928: 1995	ASTM D4239: 1997	ASTM D4239: 1997	ISO589 2008	ISO 501	Ash Fusion Temperature (*ISO 540)				Ultimates (*ASTM D 5373)			
		%	%	%	%	%	MJ/Kg	%	%	%	Index	°C Reducing Atmosphere				%	%	%	%
Lab No.	Sample Identity	LOI	H_2O	Ash	Volatile	F/Carbon	Cal Value	T Sulphur	T Carbon	T Moisture	CSN	Def	Soft	Hem	Flow	Carbon	Hydrogen	Nitrogen	Oxygen
528240	GRIT SAMPLE 25/05/11	33.2							32.45			1251	1272	1285	1307				
528241	ASH SAMPLE 25/05/11	15.7							15.20			1353	1384	1403	1423				
528242	COAL SAMPLE 25/05/11		4.8	16.3	29.6	49.3	25.91	1.64		9.66	1.0	>1500	>1500	>1500	>1500	64.39	3.94	1.64	7.29
528243	GRIT SAMPLE 26/05/11	30.5							30.13			1334	1343	1353	1368				
528244	ASH SAMPLE 26/05/11	17.3							16.97			1348	1378	1393	1411				
528245	COAL SAMPLE 26/05/11		4.8	15.6	29.2	50.4	26.13	1.46		9.55	1.0	>1500	>1500	>1500	>1500	65.86	3.97	1.66	6.65
532021	GRIT SAMPLE 01/06/11	37.5							36.96			1451	1481	>1484	>1484				
532016	ASH SAMPLE 01/06/11	19.6							18.55			1455	>1484	>1484	>1484				
532018	COAL SAMPLE 01/06/11		3.8	16.8	25.1	54.3	26.38	0.46		8.19	0.5	1353	1375	1383	1401	65.69	3.65	1.56	8.04
532020	GRIT SAMPLE 02/06/11	44.1							42.76			1430	1444	1464	1484				
532017	ASH SAMPLE 02/06/11	24.1							22.70			1451	1484	>1484	>1484				
532019	COAL SAMPLE 02/06/11		3.4	17.3	24.6	54.7	26.42	0.38		7.32	0.5	1351	1361	1374	1403	65.13	3.61	1.62	8.56
535312	GRIT SAMPLE 09/06/11	45.9							42.81			1373	1384	1395	1414				
535314	ASH SAMPLE 09/06/11	22.6							21.62			1458	1484	>1500	>1500				
535313	COAL SAMPLE 09/06/11		3.7	14.7	23.5	58.1	26.99	0.51		9.1	0.5	>1500	>1500	>1500	>1500	67.36	3.44	1.66	8.63
535316	GRIT SAMPLE 10/06/11	50.6							50.91			1481	>1500	>1500	>1500				
535456	ASH SAMPLE 10/06/11	24.6							23.77			>1500	>1500	>1500	>1500				
535315	COAL SAMPLE 10/06/11		3.5	14.4	23.4	58.7	27.26	0.50		8.9	0.5	>1500	>1500	>1500	>1500	68.41	3.58	1.68	7.93
537511	GRIT SAMPLE 14/06/11	29.1							27.56			1347	1371	1401	1448				
537512	ASH SAMPLE 14/06/11	24.7							23.53			1368	1384	1408	1450				
537513	COAL SAMPLE 14/06/11		5.1	23.1	24.9	46.9	22.19	0.49		6.2	0.0	>1500	>1500	>1500	>1500	57.32	3.35	1.42	9.22
537514	GRIT SAMPLE 15/06/11	33.1							31.90			1374	1384	1399	1426				
537515	ASH SAMPLE 15/06/11	17.2							16.26			1341	1346	1351	1383				
537516	COAL SAMPLE 15/06/11		4.5	16.7	30.2	48.6	25.54	1.23		5.9	1.0	1320	1340	1360	1400	63.54	3.97	1.60	8.46
537517	GRIT SAMPLE 17/06/11	35.0							33.88			1295	1305	1320	1360				
537518	ASH SAMPLE 17/06/11	19.0							17.96			1387	1390	1398	1414				
537519	COAL SAMPLE 17/06/11		5.0	18.7	27.8	48.5	24.57	0.69		8.4	0.5	1387	1402	1427	1453	61.58	3.68	1.59	8.76

			Ash Constituent Analyses (*ASTM D3682)											* ASTM D3402	* Eskom	Forms of sulphur (*ISO 157)			
			%	%	%	%	%	%	%	%		%	%	Index	Index	%	%	%	
Lab No.	Sample Identity		SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	Na_2O	K_2O	TiO_2		SO_3	P_2O_5	Hardgrove	Abrasion	Mineral	Sulphate	Organic	
528242	COAL SAMPLE 25/05/11													52	55	0.87	0.01	0.76	
528245	COAL SAMPLE 26/05/11													52	246	0.78	0.02	0.66	
532018	COAL SAMPLE 01/06/11													61	126	0.19	0.02	0.25	
532019	COAL SAMPLE 02/06/11													61	149	0.13	0.01	0.24	
535313	COAL SAMPLE 09/06/11													59	99	0.15	0.02	0.34	
535315	COAL SAMPLE 10/06/11													86	79	0.11	0.02	0.37	
537513	COAL SAMPLE 14/06/11													54	54	0.24	0.01	0.24	
537516	COAL SAMPLE 15/06/11													70	94	0.71	0.01	0.51	
537519	COAL SAMPLE 17/06/11													83	58	0.29	0.01	0.39	

Technical Signature

Note :- Analysis marked with * are excluded from the schedule of accreditation

T 0478

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6. ALS was not involved in sampling. The results are subject to the sample received only,and not necessarily that of the original source.
7. A summary of QC data is available upon request.

Appendix B: Particle Size Distribution

Table B1: *Particle size distribution for Coal A, 26 May 2011.*

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TEST REPORT

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IMPALA PLATIINUM
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1590

Tel.no. 011 731 9000 Fax.no.

Date 2011/07/18
Job No. 534/11-1

Lab Number	**528245**
Sample Name	**IMPALA PLATINUM JOB NO:534/11-1**
Description	**COAL SAMPLE 26/05/11**

Screen Size	Mass kg	Yield %
Original	33.05	
+25 mm	1.67	5.08
+20 mm	2.21	6.72
+16.0mm	2.96	9.00
+12.5 mm	5.29	16.09
+9.0mm	3.66	11.13
+6.3 mm	7.35	22.35
+3.5 mm	3.80	11.56
+1 mm	3.38	10.28
+0.5 mm	0.84	2.55
-0.5 mm	1.72	5.23

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Table B2: *Particle size distribution for Coal B, 02 June 2011*

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ALS Witbank - Coal division

Registration No. 2003 / 009138 / 07

TEST REPORT

Coal and Mineral Analysis

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e-mail : laboratory@witlab.co.za

IMPALA PLATIINUM
P.O.BOX 222
SPRINGS
1590

Tel.no. 011 731 9000 Fax.no.

Date 2011/07/18
Job No. 534/11-1

Lab Number	532019
Sample Name	IMPALA PLATINUM JOB NO:534/11-1
Description	COAL SAMPLE 02/06/11

Screen Size	Mass kg	Yield %
Original	28.16	
+25 mm	0.53	1.89
+20 mm	2.36	8.40
+16.0mm	3.80	13.53
+12.5 mm	6.04	21.50
+9.0mm	3.81	13.56
+6.3 mm	4.08	14.52
+3.5 mm	3.00	10.68
+1 mm	3.26	11.61
+0.5 mm	0.44	1.57
-0.5 mm	0.77	2.74

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Table B3: *Particle size distribution for Coal C, 09 June 2011.*

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ALS Witbank - Coal division
Registration No. 2003 / 009138 / 07

TEST REPORT

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Tel.no. 011 731 9000 Fax.no.

Date 2011/07/18
Job No. 534/11-1

Lab Number	**535313**
Sample Name	**IMPALA PLATINUM JOB NO:534/11-1**
Description	**COAL SAMPLE 09/06/11**

Screen Size	Mass kg	Yield %
Original	26.39	
+25 mm	0.93	3.55
+20 mm	3.03	11.56
+16.0mm	4.97	18.96
+12.5 mm	5.57	21.25
+9.0mm	2.55	9.73
+6.3 mm	3.43	13.09
+3.35 mm	2.30	8.78
+1 mm	1.80	6.87
+0.5 mm	0.55	2.10
-0.5 mm	1.08	4.12

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Table B4: *Particle size distribution for Coal D, 15 June 2011.*

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ALS Witbank - Coal division
Registration No. 2003 / 009138 / 07

TEST REPORT

Coal and Mineral Analysis

IMPALA PLATIINUM
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Date 2011/07/18
Job No. 534/11-1

Lab Number	537516
Sample Name	IMPALA PLATINUM JOB NO:534/11-1
Description	COAL SAMPLE 15/06/11

Screen Size	Mass kg	Yield %
Original	29.26	
+25 mm	1.47	5.03
+20 mm	2.83	9.69
+16.0mm	4.41	15.10
+12.5 mm	5.71	19.55
+9.0mm	4.14	14.17
+6.3 mm	5.84	19.99
+3.35 mm	2.19	7.50
+1 mm	1.42	4.86
+0.5 mm	0.37	1.27
-0.5 mm	0.83	2.84

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Appendix C: Petrographic Analysis

Five petrography analyses performed for the four coal samples are maceral composition and reflectance (**Table C1**), Microlithotype (**Table C2**), Carbominerite and Minerite Analysis (**Table C3**), Mineral groups (**Table C4**) and Conditional analysis (**Table C5**). The sample dates presented on the petrography results below corresponds to the tested coal samples as follows:

- Coal Sample 26/05/11: **Coal A**
- Coal Sample 02/06/11: **Coal B**
- Coal Sample 10/06/11: **Coal C**
- Coal Sample 15/06/11: **Coal D**

Coal Sample 17/06/11: additional sample for Coal D not included in the thermography tests.

Table C1: *Maceral composition of the coals.*

PETROGRAPHICS SA

COAL AND ORGANIC PETROLOGY

PETROGRAPHICS SA CONTRACT NO. : PSA 2011-221 — DATE : 18-08-2011

COMPANY NAME : WITLAB (PTY) LTD, PO BOX 1569, WITBANK 1035 — ATTN : MR. ETTIENE VAN DYK

ORDER NUMBER: # 92 — SAMPLES RECEIVED : 17-06-2011

SAMPLE CODES			MACERAL ANALYSIS (PERCENT BY VOLUME, MINERAL MATTER-FREE BASIS)															RANK RANDOM REFLECTANCE	
			VITRINITE			LIPTINITE			INERTINITE								TOTAL REACTIVES		
WITLAB NO.	COMPANY NO.	PSA NO. 2011	VIT %	PV %	TV %	S/R/C %	ALG %	TOT L %	RSF %	ISF %	FI SEC %	MIC %	R INT %	I INT %	TOT I %	HEAT ALTERED %	OTHER %	(mmf) %	_ Rr %	σ
528245 1	COAL SAMPLE 26/05/11	542	47	0	**47**	4	0	**4**	9	21	4	1	3	11	**49**	0	0	**63**	0.61	0.066
532019 2	COAL SAMPLE 02/06/11	544	27	1	**28**	4	0	**4**	17	21	6	1	7	16	**68**	< 1	0	**56**	0.70	0.075
535315 3	COAL SAMPLE 10/06/11	546	23	1	**24**	5	0	**5**	19	24	3	1	6	17	**70**	1	0	**54**	0.76	0.099
537516 1	COAL SAMPLE 15/06/11	557	43	1	**44**	9	0	**9**	7	19	7	1	4	9	**47**	0	0	**64**	0.63	0.064
537519 2	COAL SAMPLE 17/06/11	558	34	2	**36**	5	0	**5**	10	28	4	< 1	4	12	**58**	1	0	**55**	0.65	0.071

THESE RESULTS RELATE ONLY TO THE SAMPLES ANALYSED

Total Reactives = Vitrinite + Liptinite + Reactive Semifusinite + Reactive Inertodetrinite

Table C2: *Microlithotype analyses.*

PETROGRAPHICS SA
COAL AND ORGANIC PETROLOGY

				MICROLITHOTYPE ANALYSIS (PERCENT BY VOLUME, MINERAL MATTER BASIS)						
WITLAB NO.		COMPANY NO.	PSA NO. 2011	VITRITE %	LIPTITE %	INERTITE F/SF/S * %	INERTITE M/IN/M ** %	INTERMEDIATES %	CARBOMINERITE %	MINERITE %
528245	1	COAL SAMPLE 26/05/11	542	16	0	18	6	41	14	5
532019	2	COAL SAMPLE 02/06/11	544	10	0	25	8	37	14	6
535315	3	COAL SAMPLE 10/06/11	546	8	0	26	14	39	10	3
537516	1	COAL SAMPLE 15/06/11	557	18	0	17	3	45	12	5
537519	2	COAL SAMPLE 17/06/11	558	14	0	24	8	36	14	4

THESE RESULTS RELATE ONLY TO THE SAMPLES ANALYSED

* F/SF/S FUSITE / SEMIFUSITE / SECRETITE
** M/IN/M MACRITE / INERTODETRITE / MICRITE

Table C3: *Carbominerite and Minerite analyses.*

PETROGRAPHICS SA
COAL AND ORGANIC PETROLOGY

				CARBOMINERITE ANALYSIS				MINERITE ANALYSIS			
WITLAB NO.		COMPANY NO.	PSA NO. 2011	CARB-ARGILITE/SILICITE COAL MACERALS PLUS CLAYS/QUARTZ %	CARBO-PYRITE COAL MACERALS PLUS PYRITE %	CARB-ANKERITE COAL MACERALS PLUS CARBONATES %	TOTAL CARBO-MINERITE * TOTAL MACERAL/MINERAL ASSOCIATIONS %	CLAY/QUARTZ GROUPS MINERALS %	PYRITE MINERALS %	CARBONATE GROUP MINERALS %	TOTAL MINERITE MINERAL RICH PARTICLES %
528245	1	COAL SAMPLE 26/05/11	542	7	4	3	14	3	2	< 1	5
532019	2	COAL SAMPLE 02/06/11	544	11	1	2	14	4	1	1	6
535315	3	COAL SAMPLE 10/06/11	546	7	1	2	10	2	< 1	1	3
537516	1	COAL SAMPLE 15/06/11	557	6	4	2	12	3	1	1	5
537519	2	COAL SAMPLE 17/06/11	558	9	2	3	14	3	< 1	1	4

THESE RESULTS RELATE ONLY TO THE SAMPLES ANALYSED

* TOTAL ORGANIC/INORGANIC MICROLITHOTYPES

Table C4: *Mineral group analysis.*

PETROGRAPHICS SA

COAL AND ORGANIC PETROLOGY

MINERAL GROUP ANALYSIS (PERCENT OF PARTICLES EXAMINED)

WITLAB NO.	COMPANY NO.	PSA NO. 2011	QUARTZ AND CLAYS				PYRITE							CARBONATES							CLEAN COAL %
							SYN	EPI	SYN	EPI	SYN	EPI		SYN	EPI	SYN	EPI	SYN	EPI		
			< 25 %	25 - 50 %	> 50 %	TOTAL %	< 25 %		25 - 50 %		> 50 %		TOTAL %	< 25 %		25 - 50 %		> 50 %		TOTAL %	
528245 1	COAL SAMPLE 26/05/11	542	11	4	2	17	5		1			1	7	2			1		1	4	72
532019 2	COAL SAMPLE 02/06/11	544	12	4	2	18	3		1				4	2		1			2	5	73
535315 3	COAL SAMPLE 10/06/11	546	14	5	2	21	1		1				2	2		1			< 1	3	74
537516 1	COAL SAMPLE 15/06/11	557	16	7	2	25	5					1	6	2		1			1	4	65
537519 2	COAL SAMPLE 17/06/11	558	17	7	3	27	3						3	3		1	1		1	6	64

THESE RESULTS RELATE ONLY TO THE SAMPLES ANALYSED

SYN - Syngenetic minerals. These are intimately intergrown in the organic matrix and are normally formed in situ. However, some may have formed subsequent to the first stages of coal formation.

EPI - Epigenetic minerals. These are deposited in fissures, cleats and cavities and are coarsely intergrown. Replacement forms of pyrite have been included in the epigenetic groups.

Table C5: *Conditional analysis.*

COAL AND ORGANIC PETROLOGY													
SAMPLE CODES				Fresh coal particles	Pyrite		Particles with extensive cracks or fissures	Severely weathered particles	Shrinkage/ desiccation cracks	Particles with oxidized/thermally ffected rims or zone	Particles displaying low temperature devolatilization	Severely hea altered (coke/char)	Total abnormal particles
WITLAB NO.		COMPANY NO.	PSA NO. 2011	%	normal %	altered %	%	%	%	%	%	%	%
528245	1	COAL SAMPLE 26/05/11	542	83	3	0	11	2	1	0	0	0	14
532019	2	COAL SAMPLE 02/06/11	544	81	< 1	0	16	2	1	< 1	0	0	19
535315	3	COAL SAMPLE 10/06/11	546	78	< 1	0	16	3	2	0	0	1	22
537516	1	COAL SAMPLE 15/06/11	557	73	2	0	20	2	2	0	0	1	25
537519	2	COAL SAMPLE 17/06/11	558	69	1	0	24	3	2	0	0	1	30
THESE RESULTS RELATE ONLY TO THE SAMPLES ANALYSED													
NOTES :		Significant proportions of the particles examined displayed extensive cracks and micro-fissures. Some cracking probably occurred during handling and preparation due to the somewhat brittle nature of coal (particularly vitrinite) of this level of maturity.											
		The pyrite present appeared a "fresh" bright yellow colour throughout.											

Appendix D: Additional Thermography Data

The thermographic temperature profile of coal D with the highest recorded temperature of the four coals tested at ROI5 = 1793 ^{o}C is presented in Figure D1 below.

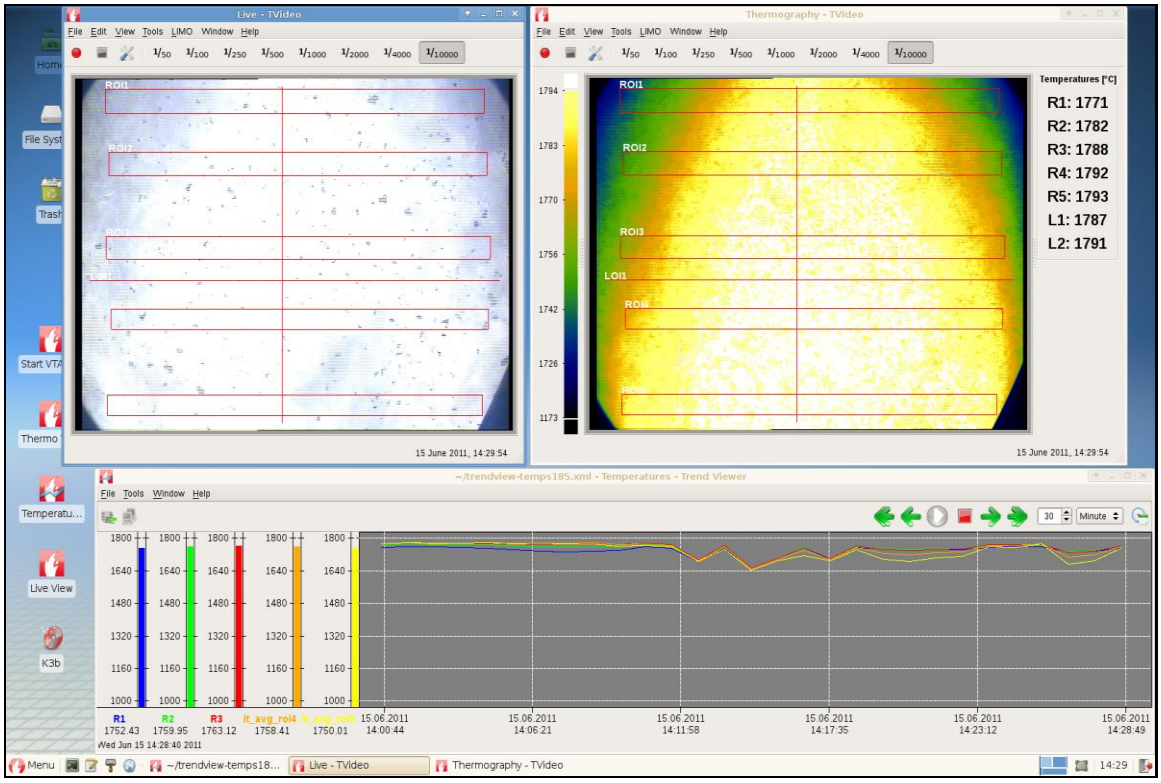


Figure D1: *Highest recorded temperature (Coal D)*.

The following thermography data represent limited testing conducted for coal E before further testing was abandoned due to difficulty with ignition and flame out. The flames focused predominantly on the fire-ball zone of the furnace.

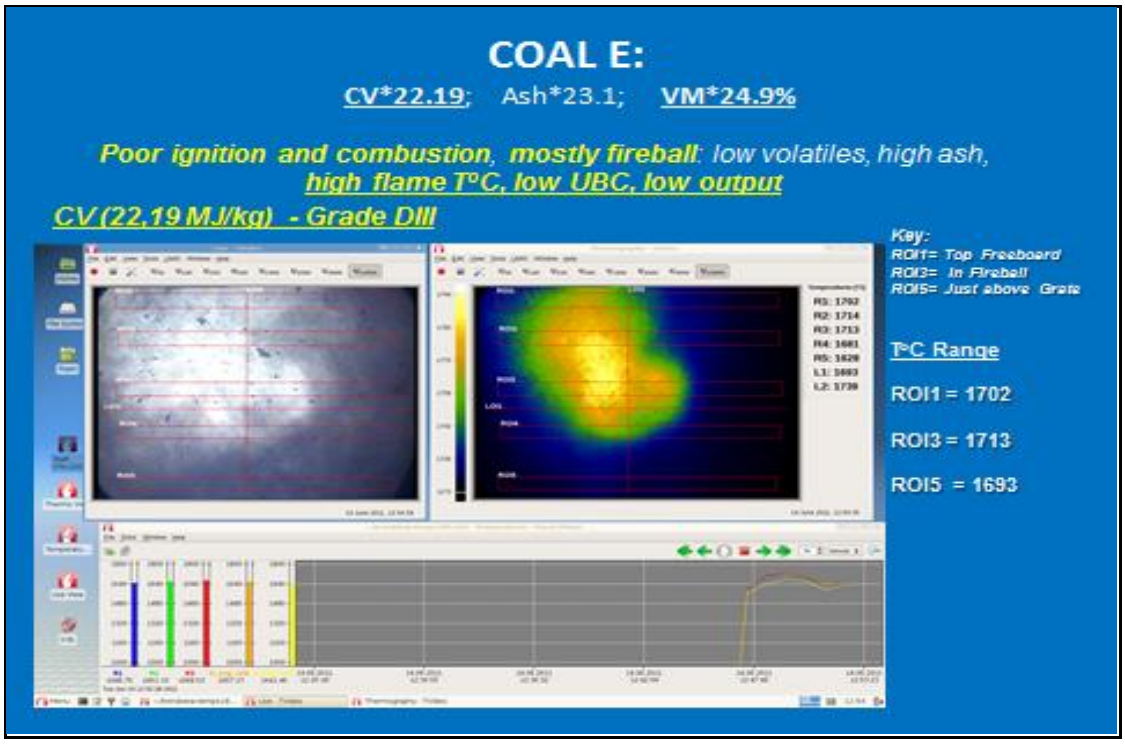


Figure D2A: *Overall temperature profile for Coal E showing characteristic fireball and delayed combustion.*

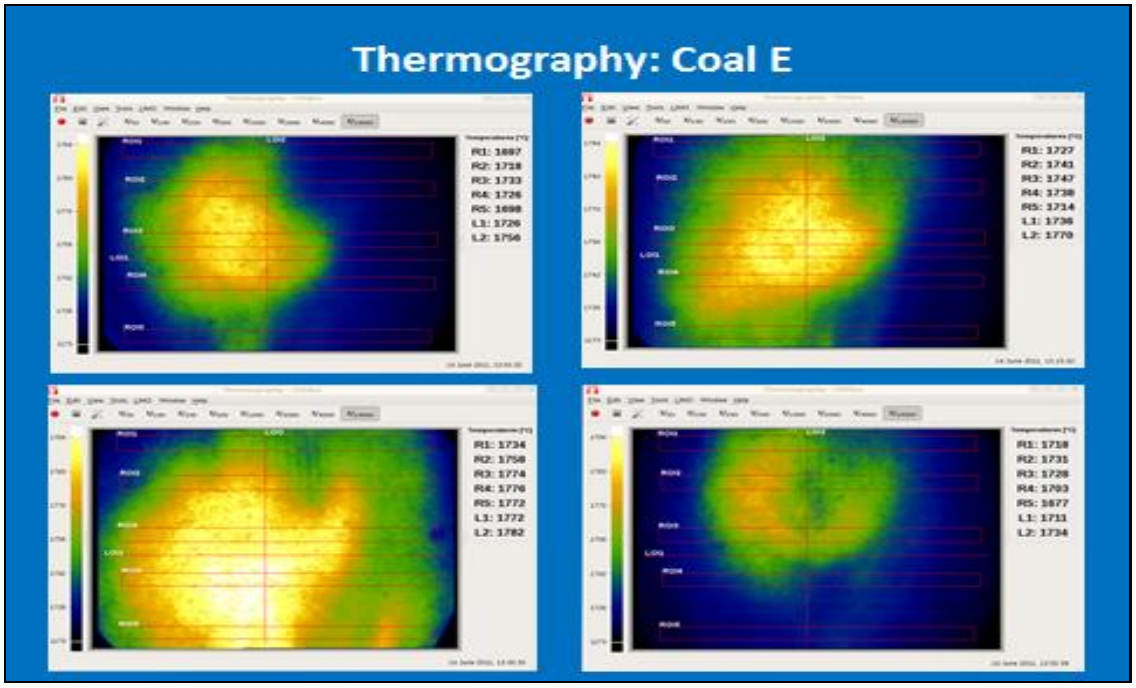


Figure D2B: *Temperature profile for Coal E at different time intervals.*

Appendix E: Combustion Efficiency Calculations

Table E1A: *Efficiency calculations for Coal A (raw data).*

Impala boiler test 2 26/05/11

Boiler efficiency test according to BS 845

Variable names and values used in equations

Coal type: A
Boiler load:

Primary Data

Variable	Description		Units	Value
Tm	Total moisture	(as fired)	%	9.55
Im	Moisture on the analytical sample	(air dried basis)	%	4.8
Cv	Gross Calorific value	(air dried basis)	MJ/kg	26.13
A	Ash content of coal	(air dried basis)	%	15.6
C	Total carbon in coal	(air dried basis)	%	65.86
H2	Hydrogen in coal	(air dried basis)	%	3.97
N	Nitrogen in coal	(air dried basis)	%	1.66
S	Total sulphur in coal	(air dried basis)	%	1.46
Ea	Enthalpy of steam at Temp Ta		kJ/kg	2769
En	Enthalpy of water at Temp T		kJ/kg	49
N2	Nitrogen in flue gas		%	80.4
SO2	Sulphur dioxide in flue gas		%	
CO2	Carbon dioxide in flue gas		%	10
O2	Oxygen in flue gas		%	10.9
CO	Carbon monoxide in flue gas		%	0
Ma	Mass of coarse ash collected		kg	3244
Mf	Mass of coal fired		kg	19720
De	Mass of dust collected		kg	0
Kg	Mass of grits		kg	566
Ca	Carbon content of coarse ash		%	17.3
Cg	Carbon content of grits		%	30.5
De	Carbon content of emitted dust		%	0
Tg	Temperature of ashes		deg C	52.9
T	Ambient temperature		deg C	12
Ta	Chimney gas temperature		deg C	172.6

Chemical molar masses

Mol C	Carbon	kg	12.011
Mol H2	Hydrogen	kg	2.0158
Mol S	Sulphur	kg	32.06
Mol O2	Oxygen	kg	31.998
Mol N2	Nitrogen	kg	28.014
Mol CO2	Carbon dioxide	kg	44.009
Mol H2O	Water	kg	18.015
Mol SO2	Sulphur dioxide	kg	64.058
Mol CO	Carbon monoxide	kg	28.01

Table E1B: *Efficiency calculations for Coal A.*

Equation 1	Conversion of gross CV from Mj/kg(a.d) to kj/kg(a.d)		kj/kg	26130
Equation 2	Conversion factor for analytical data from air dried to as fired basis		H2O Fac	0.9501
Equation 3	Heat loss due to moisture in fuel	(Loss 1)	%	1.0463
	Note: Enthalpy of steam - at stack gas temperature Enthalpy of water - at ambient temperature			
Equation 4	Heat loss due to water in flue gas formed from hydrogen in coal.	(Loss 2)	%	3.6932
Equation 5	Heat loss in dry flue gas	(Loss 3)	%	10.3438
5a	Mass of dry flue gas / mass of fuel			15.9104
5b	Enthalpy difference between flue gas at ambient and stack exit temperatures.		Kj/Kg	161.4030
Equation 6	Heat loss due to incomplete combustion of fuel resulting in carbon monoxide in flue gas	(Loss 4)	%	0.0000
Equation 7	Heat loss due to incomplete combustion of fuel resulting in unburnt carbon in residues	(Loss 5)	%	4.9165
Equation 8	Heat loss due to heat in residue	(Loss 6)	%	0.0205
	Assumed radiation loss	(Loss 7)	%	2.0

Sum of losses as % of as fired calorific value

(1) Loss due to moisture in fuel	1.0463
(2) Loss due to water formed from hydrogen in fuel	3.6932
(3) Loss due to heat in dry flue gas	10.3438
(4) Loss due to incomplete combustion - CO formation	0.0000
(5) Loss due to incomplete combustion - carbon in residue	4.9165
(6) Loss due to heat in residue	0.0205
(7) Loss due to radiation	2.0000
Total loss	22.02
Overall efficiency	77.98

Table E2A: *Efficiency calculations for Coal B (raw data).*

Impala boiler test 4 2/06/11

Boiler efficiency test according to BS 845

Variable names and values used in equations

Coal Type : B
Boiler load:

Primary Data

Variable	Description		Units	Value
Tm	Total moisture	(as fired)	%	7.32
Im	Moisture on the analytical sample	(air dried basis)	%	3.4
Cv	Gross Calorific value	(air dried basis)	MJ/kg	26.42
A	Ash content of coal	(air dried basis)	%	17.3
C	Total carbon in coal	(air dried basis)	%	65.13
H2	Hydrogen in coal	(air dried basis)	%	3.61
N	Nitrogen in coal	(air dried basis)	%	1.62
S	Total sulphur in coal	(air dried basis)	%	0.38
Ea	Enthalpy of steam at Temp Ta		kJ/kg	2787
En	Enthalpy of water at Temp T		kJ/kg	56
N2	Nitrogen in flue gas		%	80.1
SO2	Sulphur dioxide in flue gas		%	
CO2	Carbon dioxide in flue gas		%	11.1
O2	Oxygen in flue gas		%	10.5
CO	Carbon monoxide in flue gas		%	0
Ma	Mass of coarse ash collected		kg	4026
Mf	Mass of coal fired		kg	21332
De	Mass of dust collected		kg	0
Kg	Mass of grits		kg	1134
Ca	Carbon content of coarse ash		%	24.1
Cg	Carbon content of grits		%	44.1
Da	Carbon content of emitted dust		%	0
Tg	Temperature of ashes		deg C	88.8
T	Ambient temperature		deg C	13.5
Ta	Chimney gas temperature		deg C	193.4

Chemical molar masses

Mol C	Carbon	kg	12.011
Mol H2	Hydrogen	kg	2.0158
Mol S	Sulphur	kg	32.06
Mol O2	Oxygen	kg	31.998
Mol N2	Nitrogen	kg	28.014
Mol CO2	Carbon dioxide	kg	44.009
Mol H2O	Water	kg	18.015
Mol SO2	Sulphur dioxide	kg	64.058
Mol CO	Carbon monoxide	kg	28.01

Table E2B: *Efficiency calculations for Coal B.*

Equation 1	Conversion of gross CV from Mj/kg(a.d) to kj/kg(a.d)		kj/kg	26420
Equation 2	Conversion factor for analytical data from air dried to as fired basis		H2O Fac	0.9594
Equation 3	Heat loss due to moisture in fuel	(Loss 1)	%	0.7887
	Note: Enthalpy of steam - at stack gas temperature Enthalpy of water - at ambient temperature			
Equation 4	Heat loss due to water in flue gas formed from hydrogen in coal.	(Loss 2)	%	3.3349
Equation 5	Heat loss in dry flue gas	(Loss 3)	%	9.3761
5a	Mass of dry flue gas / mass of fuel			13.1452
5b	Enthalpy difference between flue gas at ambient and stack exit temperatures.		Kj/Kg	180.7995
Equation 6	Heat loss due to incomplete combustion of fuel resulting in carbon monoxide in flue gas	(Loss 4)	%	0.0000
Equation 7	Heat loss due to incomplete combustion of fuel resulting in unburnt carbon in residues	(Loss 5)	%	8.9192
Equation 8	Heat loss due to heat in residue	(Loss 6)	%	0.0414
	Assumed radiation loss	(Loss 7)	%	2.0

Sum of losses as % of as fired calorific value

(1) Loss due to moisture in fuel	0.7887
(2) Loss due to water formed from hydrogen in fuel	3.3349
(3) Loss due to heat in dry flue gas	9.3761
(4) Loss due to incomplete combustion - CO formation	0.0000
(5) Loss due to incomplete combustion - carbon in residue	8.9192
(6) Loss due to heat in residue	0.0414
(7) Loss due to radiation	2.0000
Total loss	24.46
Overall efficiency	75.54

Table E3A: *Efficiency calculations for Coal C (raw data).*

Impala boiler test 5 09/06/11

Boiler efficiency test according to BS 845

Variable names and values used in equations

Coal Type : **C**
Boiler load:

Primary Data

Variable	Description		Units	Value
Tm	Total moisture	(as fired)	%	9.1
Im	Moisture on the analytical sample	(air dried basis)	%	3.7
Cv	Gross Calorific value	(air dried basis)	MJ/kg	26.99
A	Ash content of coal	(air dried basis)	%	14.7
C	Total carbon in coal	(air dried basis)	%	67.36
H2	Hydrogen in coal	(air dried basis)	%	3.44
N	Nitrogen in coal	(air dried basis)	%	1.66
S	Total sulphur in coal	(air dried basis)	%	0.51
Ea	Enthalpy of steam at Temp Ta		kJ/kg	2781.8
En	Enthalpy of water at Temp T		kJ/kg	37.3
N2	Nitrogen in flue gas		%	80.1
SO2	Sulphur dioxide in flue gas		%	
CO2	Carbon dioxide in flue gas		%	8.8
O2	Oxygen in flue gas		%	11.7
CO	Carbon monoxide in flue gas		%	0
Ma	Mass of coarse ash collected		kg	479.6
Mf	Mass of coal fired		kg	6625
De	Mass of dust collected		kg	0
Kg	Mass of grits		kg	1114
Ca	Carbon content of coarse ash		%	22.6
Cg	Carbon content of grits		%	45.9
Da	Carbon content of emitted dust		%	0
Tg	Temperature of ashes		deg C	84.8
T	Ambient temperature		deg C	8.8
Ta	Chimney gas temperature		deg C	186.5

Chemical molar masses

Mol C	Carbon	kg	12.011
Mol H2	Hydrogen	kg	2.0158
Mol S	Sulphur	kg	32.06
Mol O2	Oxygen	kg	31.998
Mol N2	Nitrogen	kg	28.014
Mol CO2	Carbon dioxide	kg	44.009
Mol H2O	Water	kg	18.015
Mol SO2	Sulphur dioxide	kg	64.058
Mol CO	Carbon monoxide	kg	28.01

Table E3B: *Efficiency calculations for Coal C.*

Equation 1	Conversion of gross CV from Mj/kg(a.d) to kj/kg(a.d)		kj/kg	26990
Equation 2	Conversion factor for analytical data from air dried to as fired basis		H2O Fac	0.9439
Equation 3	Heat loss due to moisture in fuel	(Loss 1)	%	0.9803
	Note: Enthalpy of steam - at stack gas temperature Enthalpy of water - at ambient temperature			
Equation 4	Heat loss due to water in flue gas formed from hydrogen in coal.	(Loss 2)	%	3.1261
Equation 5	Heat loss in dry flue gas	(Loss 3)	%	10.7667
5a	Mass of dry flue gas / mass of fuel			15.3593
5b	Enthalpy difference between flue gas at ambient and stack exit temperatures.		Kj/Kg	178.5885
Equation 6	Heat loss due to incomplete combustion of fuel resulting in carbon monoxide in flue gas	(Loss 4)	%	0.0000
Equation 7	Heat loss due to incomplete combustion of fuel resulting in unburnt carbon in residues	(Loss 5)	%	12.0431
Equation 8	Heat loss due to heat in residue	(Loss 6)	%	0.0348
	Assumed radiation loss	(Loss 7)	%	2.0

Sum of losses as % of as fired calorific value

(1) Loss due to moisture in fuel	0.9803
(2) Loss due to water formed from hydrogen in fuel	3.1261
(3) Loss due to heat in dry flue gas	10.7667
(4) Loss due to incomplete combustion - CO formation	0.0000
(5) Loss due to incomplete combustion - carbon in residue	12.0431
(6) Loss due to heat in residue	0.0348
(7) Loss due to radiation	2.0000
Total loss	28.95
Overall efficiency	71.05

Table E 4A: *Efficiency calculations for Coal D (raw data).*

Impala boiler test 7 15/06/11

Boiler efficiency test according to BS 845

Variable names and values used in equations

Coal Type : **D**
Boiler load:

Primary Data

Variable	Description		Units	Value
Tm	Total moisture	(as fired)	%	5.9
Im	Moisture on the analytical sample	(air dried basis)	%	4.5
Cv	Gross Calorific value	(air dried basis)	MJ/kg	25.54
A	Ash content of coal	(air dried basis)	%	16.7
C	Total carbon in coal	(air dried basis)	%	63.54
H2	Hydrogen in coal	(air dried basis)	%	3.97
N	Nitrogen in coal	(air dried basis)	%	1.6
S	Total sulphur in coal	(air dried basis)	%	1.23
Ea	Enthalpy of steam at Temp Ta		kJ/kg	2771.3
En	Enthalpy of water at Temp T		kJ/kg	60.6
N2	Nitrogen in flue gas		%	80.6
SO2	Sulphur dioxide in flue gas		%	
CO2	Carbon dioxide in flue gas		%	11.6
O2	Oxygen in flue gas		%	9.5
CO	Carbon monoxide in flue gas		%	0
Ma	Mass of coarse ash collected		kg	2768
Mf	Mass of coal fired		kg	17023
De	Mass of dust collected		kg	0
Kg	Mass of grits		kg	823
Ca	Carbon content of coarse ash		%	17.2
Cg	Carbon content of grits		%	33.1
Da	Carbon content of emitted dust		%	0
Tg	Temperature of ashes		deg C	148.2
T	Ambient temperature		deg C	14.6
Ta	Chimney gas temperature		deg C	174.8

Chemical molar masses

Mol C	Carbon	kg	12.011
Mol H2	Hydrogen	kg	2.0158
Mol S	Sulphur	kg	32.06
Mol O2	Oxygen	kg	31.998
Mol N2	Nitrogen	kg	28.014
Mol CO2	Carbon dioxide	kg	44.009
Mol H2O	Water	kg	18.015
Mol SO2	Sulphur dioxide	kg	64.058
Mol CO	Carbon monoxide	kg	28.01

Table E4B: *Efficiency calculations for Coal D.*

Equation 1	Conversion of gross CV from Mj/kg(a.d) to kj/kg(a.d)		kj/kg	25540
Equation 2	Conversion factor for analytical data from air dried to as fired basis		H2O Fac	0.9853
Equation 3	Heat loss due to moisture in fuel	(Loss 1)	%	0.6355
	Note: Enthalpy of steam - at stack gas temperature Enthalpy of water - at ambient temperature			
Equation 4	Heat loss due to water in flue gas formed from hydrogen in coal.	(Loss 2)	%	3.7656
Equation 5	Heat loss in dry flue gas	(Loss 3)	%	8.6641
5a	Mass of dry flue gas / mass of fuel			13.5426
5b	Enthalpy difference between flue gas at ambient and stack exit temperatures.		Kj/Kg	161.0010
Equation 6	Heat loss due to incomplete combustion of fuel resulting in carbon monoxide in flue gas	(Loss 4)	%	0.0000
Equation 7	Heat loss due to incomplete combustion of fuel resulting in unburnt carbon in residues	(Loss 5)	%	5.7310
Equation 8	Heat loss due to heat in residue	(Loss 6)	%	0.0734
	Assumed radiation loss	(Loss 7)	%	2.0

Sum of losses as % of as fired calorific value

(1) Loss due to moisture in fuel	0.6355
(2) Loss due to water formed from hydrogen in fuel	3.7656
(3) Loss due to heat in dry flue gas	8.6641
(4) Loss due to incomplete combustion - CO formation	0.0000
(5) Loss due to incomplete combustion - carbon in residue	5.7310
(6) Loss due to heat in residue	0.0734
(7) Loss due to radiation	2.0000
Total loss	20.87
Overall efficiency	79.13

Appendix F: Boiler Operational Conditions

Table F1: *Raw data for steam, water and oxygen in flue-gas (SCADA readings from control room).*

		Feed Water PV (tons/hr)	Air Flow (%) Forced draft	Steam Flow (kg/hr)	Drum Level (%)	O2 Indication (%)	
DATE	TIME	BMR.BOI_FIC1011E_PV	BMR.BOI_FI1003E_PV	BMR.BOI_FI1000E_PV	BMR.BOI_LIC1000E_PV	BMR.BOI_AI1000E_PV	
26/05/2011	12:59:24 AM	38.03418	71.97407	37110.58203	4.98523	11.48947	
26/05/2011	2:35:06 AM	41.3287	75.37057	40825.25781	4.69614	10.75798	
26/05/2011	4:10:48 AM	40.06335	75.85869	39091.41797	5.13182	11.17365	
26/05/2011	5:46:30 AM	35.64348	72.22494	34499.87891	5.53571	12.03088	Coal A
26/05/2011	7:22:12 AM	37.89317	75.00842	37303.46875	4.80828	11.65061	
26/05/2011	8:57:54 AM	37.39799	75.39021	36473.90234	5.18146	11.94079	
26/05/2011	10:33:36 AM	38.73253	75.33678	38160.35938	4.78729	11.64398	
26/05/2011	12:09:18 PM	39.39799	75.42767	38591.07031	4.95421	11.77121	
26/05/2011	1:45:00 PM	37.48721	75.22597	37349.92578	5.52178	11.84242	
26/05/2011	3:20:42 PM	37.34382	74.88877	36905.82422	4.99383	11.9189	
26/05/2011	4:56:24 PM	38.45007	74.29675	38166.25	4.66525	11.41993	
26/05/2011	6:32:06 PM	45.88607	73.90013	45743.61719	4.86707	9.76581	
26/05/2011	8:07:48 PM	44.94968	74.61478	44357.72656	5.13063	10.06266	
26/05/2011	9:43:30 PM	46.23502	74.37862	45861.91016	4.44925	9.67435	
26/05/2011	11:19:12 PM	41.48535	74.24492	40741.94531	5.26598	10.85093	
02/06/2011	12:27:54 AM	36.5155	63.21476	35387.63281	0.00483	12.11829	
02/06/2011	2:03:36 AM	36.05186	61.21568	35094.71094	0.15801	12.06984	
02/06/2011	3:39:18 AM	35.33582	60.26597	34222.04688	-0.22526	12.08875	
02/06/2011	5:15:00 AM	34.10614	58.52585	32962.14453	-0.2394	12.14388	
02/06/2011	6:50:42 AM	33.25662	56.49851	32314.05469	0.24612	12.12637	
02/06/2011	8:26:24 AM	35.13585	61.67959	34272.70313	-0.06373	12.19094	
02/06/2011	10:02:06 AM	35.90171	61.36261	34881.80859	0.02705	12.03929	Coal B
02/06/2011	11:37:48 AM	44.06152	68.43312	43403.32031	-0.93916	11.08752	
02/06/2011	1:13:30 PM	42.4598	68.68117	41470.79688	0.42412	11.59439	
02/06/2011	2:49:12 PM	43.75116	68.1895	42870.625	-0.05135	11.39848	
02/06/2011	4:24:54 PM	42.21107	67.53218	41193.35938	0.31719	11.66335	
02/06/2011	6:00:36 PM	37.74553	63.15954	36708.83203	0.10877	11.97002	
02/06/2011	7:36:18 PM	38.17964	63.85278	37338.20703	0.14926	11.86167	
02/06/2011	9:12:00 PM	39.56594	64.68726	38255.43359	0.08661	11.77804	
02/06/2011	10:47:42 PM	34.35643	56.3954	33449.30078	0.63835	11.91717	
09/06/2011	1:32:06 AM	41.30935	72.7646	35013.29297	5.0782	10.75961	
09/06/2011	3:07:48 AM	40.21434	72.07803	33988.64844	4.97369	10.94647	
09/06/2011	4:43:30 AM	35.44357	64.57644	29135.57422	5.72247	11.53865	
09/06/2011	6:19:12 AM	38.179	70.95646	32139.43945	5.08647	11.22898	
09/06/2011	7:54:54 AM	39.00566	71.46391	32815.1875	5.00358	11.25877	
09/06/2011	9:30:36 AM	43.21312	71.86948	36497.09766	4.42714	10.59784	Coal C
09/06/2011	11:06:18 AM	38.02406	73.49892	31852.84375	5.6328	11.77344	
09/06/2011	12:42:00 PM	38.85799	73.55315	32897.66016	5.07221	11.42844	
09/06/2011	2:17:42 PM	34.29694	73.30664	32669.84961	6.17527	11.76325	
09/06/2011	3:53:24 PM	39.06476	72.8722	38356.75	4.99931	10.33299	
09/06/2011	5:29:06 PM	40.41806	72.14689	39278.55078	4.89873	10.2383	
09/06/2011	7:04:48 PM	39.80793	69.06836	38895.69141	4.99044	10.09125	
09/06/2011	8:40:30 PM	41.3747	71.92664	40218.87109	5.32417	10.10013	
09/06/2011	10:16:12 PM	41.09752	72.73093	40094.19922	4.68144	10.17216	
09/06/2011	11:51:54 PM	40.37627	72.15408	39221.55859	5.04974	10.367	
15/06/2011	1:05:06 AM	46.20865	72.15555	45353.03516	4.6863	9.78984	
15/06/2011	2:40:48 AM	40.49116	71.12276	39605.28516	5.53161	11.03186	
15/06/2011	4:16:30 AM	36.53759	68.09254	35767.09766	5.11165	11.6922	
15/06/2011	5:52:12 AM	37.27288	69.39005	36401.44531	5.05941	11.78467	
15/06/2011	7:27:54 AM	39.43682	70.83052	38786.92578	4.53863	11.21415	
15/06/2011	9:03:36 AM	39.71487	69.2485	39260.32813	5.40596	11.21877	
15/06/2011	10:39:18 AM	42.27309	69.56978	41921.46484	5.29882	10.61506	Coal D
15/06/2011	12:15:00 PM	43.84517	66.40885	43341.125	4.48078	10.25675	
15/06/2011	1:50:42 PM	47.85303	66.71967	47781.0625	5.01703	9.46538	
15/06/2011	3:26:24 PM	47.45538	68.49608	46865.23438	5.01123	9.48275	
15/06/2011	5:02:06 PM	44.94907	67.5808	44234.66016	5.57304	10.12377	
15/06/2011	6:37:48 PM	37.92893	67.49368	37245.68359	4.87104	11.4277	
15/06/2011	8:13:30 PM	42.98621	67.9472	42773.80469	4.29354	10.41463	
15/06/2011	9:49:12 PM	45.23806	70.37395	44748.26172	5.03731	10.04553	
15/06/2011	11:24:54 PM	45.70073	70.03646	45228.14844	5.12596	9.97154	

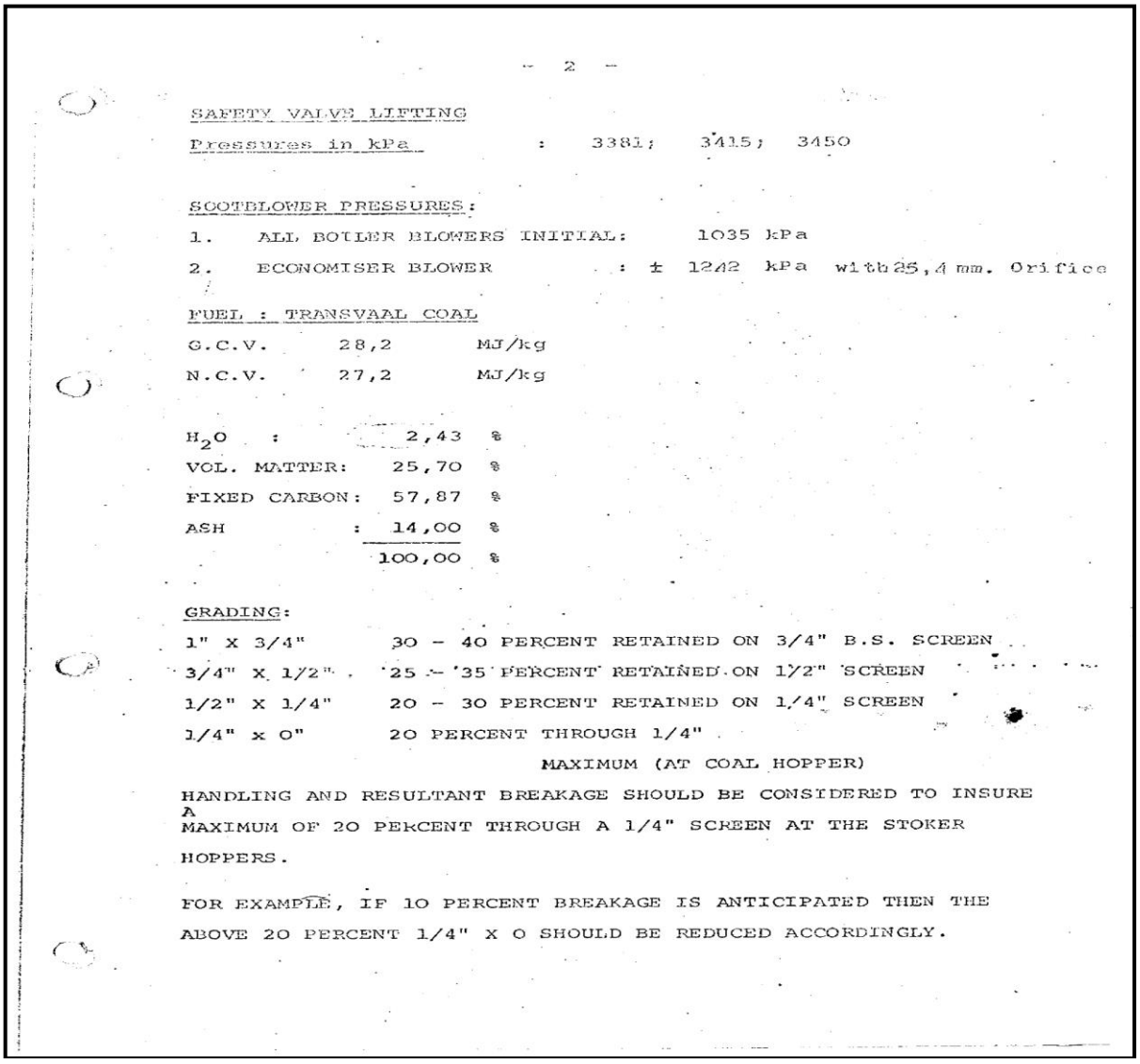
Table F2: *Raw Data for furnace pressures, flue-gas and water temperatures (SCADA readings from control room).*

		Front SA (mBarG)	Econo Inlet (mBarG)	Econo Outlet (mBarG)	exit O2 indicator (%)	Econo in Water T (oC)	Econo out Water Temp (oC)	Econ in Gas Temp (oC)	
DATE	TIME	BMR.BOI_PI1004E_1_PV	BMR.BOI_PI1011E_1_PV	BMR.BOI_PI1011E_2_PV	BMR.BOI_AI1000E_PV	BMR.BOI_TI1011E_1_PV	BMR.BOI_TI1011E_2_PV	BMR.BOI_TI1011E_3_PV	
26/05/2011	12:59:46 AM	56.24746	-13.47864	-29.23607	11.42021	84.87897	142.11501	301.54758	
26/05/2011	2:38:12 AM	56.39613	-13.86129	-30.09464	10.8051	83.07202	138.17513	305.60312	
26/05/2011	4:16:38 AM	56.34404	-13.85926	-30.13265	11.17197	84.87801	140.53554	305.14102	
26/05/2011	5:55:04 AM	56.36206	-13.30362	-28.99426	12.03028	89.00349	147.12659	297.90277	
26/05/2011	7:33:30 AM	56.62544	-13.72186	-29.8658	11.71026	86.8282	143.29189	300.25699	Coal A
26/05/2011	9:11:56 AM	56.89783	-13.88613	-30.18919	11.89537	84.12149	142.18671	300.04114	
26/05/2011	10:50:22 AM	56.88877	-13.9625	-30.29956	11.60705	83.96098	140.17291	302.5498	
26/05/2011	12:28:48 PM	56.75319	-14.1176	-0.00019	11.80724	75.19946	134.56808	298.86783	
26/05/2011	2:07:14 PM	56.71821	-14.36834	0	11.95556	60.63912	123.66339	298.79221	
26/05/2011	3:45:40 PM	56.17062	-14.31063	-0.0001	11.73089	59.47462	124.12976	300.04236	
26/05/2011	5:24:06 PM	55.55184	-14.16459	-14.598	11.00282	60.04093	122.06297	303.73001	
26/05/2011	7:02:32 PM	55.55838	-14.40869	-30.74153	9.84811	63.07281	119.023	311.29187	
26/05/2011	8:40:58 PM	55.79184	-14.35529	-30.72991	10.14698	63.5912	121.51292	310.06857	
26/05/2011	10:19:24 PM	56.06897	-14.16681	-30.45393	9.9008	70.73937	125.52934	310.53711	
26/05/2011	11:57:50 PM	56.40749	-14.01402	-30.41475	10.69349	81.26649	136.93829	309.20224	
02/06/2011	12:19:58 AM	57.19492	-12.42982	-26.98921	12.16486	99.19987	151.36247	298.93402	
02/06/2011	1:58:24 AM	57.56624	-11.93537	-25.8888	12.01471	99.12516	150.74477	297.13419	
02/06/2011	3:36:50 AM	57.82158	-11.84873	-25.75105	12.13706	99.11421	151.65752	296.4118	
02/06/2011	5:15:16 AM	57.92836	-11.40968	-24.77373	12.13997	99.00857	151.82932	294.00952	
02/06/2011	6:53:42 AM	57.87779	-11.12963	-24.16551	12.1232	98.91101	152.44417	292.65179	
02/06/2011	8:32:08 AM	58.21085	-12.05787	-26.17094	12.19585	98.78109	151.85025	295.93402	
02/06/2011	10:10:34 AM	58.34216	-11.93038	-25.91199	12.0107	98.90912	151.20297	297.3439	
02/06/2011	11:49:00 AM	57.43236	-13.32532	-12.0822	11.03988	99.06853	146.46225	308.81345	Coal B
02/06/2011	1:27:26 PM	56.6716	-13.23199	-0.00157	11.62075	99.2375	148.10001	308.83173	
02/06/2011	3:05:52 PM	56.05558	-13.39791	-0.00098	11.42663	99.58392	147.34454	310.68085	
02/06/2011	4:44:18 PM	55.58096	-12.92475	-15.26564	11.70273	99.50729	148.46764	307.96875	
02/06/2011	6:22:44 PM	55.34137	-12.30663	-26.66516	11.99752	99.69242	150.11421	301.13974	
02/06/2011	8:01:10 PM	55.46897	-12.24521	-26.58839	11.80366	99.71383	149.58408	302.02109	
02/06/2011	9:39:36 PM	56.27404	-12.12465	-26.37337	11.8348	99.59072	149.75128	301.43591	
02/06/2011	11:18:02 PM	56.6309	-10.87268	-23.73049	11.86415	99.5468	151.33058	293.54459	
09/06/2011	1:18:36 AM	56.42564	-12.79375	-27.67357	10.77292	78.19416	131.59407	300.99271	
09/06/2011	2:57:02 AM	56.41612	-12.68655	-27.43023	10.94077	76.61517	130.76555	300.51205	
09/06/2011	4:35:28 AM	56.24626	-11.6059	-25.30895	11.50034	81.20606	136.49001	293.21051	
09/06/2011	6:13:54 AM	56.52595	-12.30685	-26.73725	11.25117	80.46034	134.84201	294.7619	
09/06/2011	7:52:20 AM	56.6573	-12.5566	-27.30308	11.23905	86.52934	138.29268	296.14673	
09/06/2011	9:30:46 AM	56.525	-12.62822	-25.09614	10.59921	98.24378	144.12723	300.20377	
09/06/2011	11:09:12 AM	56.34917	-12.89353	-0.02868	11.7593	98.65212	148.94971	294.33691	Coal C
09/06/2011	12:47:38 PM	56.37982	-12.95676	-0.02525	11.44684	97.3263	146.55029	293.30664	
09/06/2011	2:26:04 PM	56.05685	-12.98683	-6.1329	11.75714	97.87119	153.23747	294.72336	
09/06/2011	4:04:30 PM	56.01935	-12.88074	-28.08617	10.21369	98.04346	148.05504	301.50095	
09/06/2011	5:42:56 PM	56.1625	-12.93366	-28.1803	10.24387	97.89689	147.56917	303.09186	
09/06/2011	7:21:22 PM	56.39467	-12.43418	-27.11923	10.01091	97.76269	147.08138	301.94543	
09/06/2011	8:59:48 PM	56.5565	-13.06429	-28.5302	10.17861	98.04576	147.61703	304.29672	
09/06/2011	10:38:14 PM	56.71865	-13.05257	-28.57732	10.17076	98.20336	147.7933	304.43622	
15/06/2011	12:02:18 AM	56.09496	-13.72076	-30.2089	9.95014	82.34981	134.39972	312.19849	
15/06/2011	1:40:44 AM	56.41935	-13.63052	-29.97985	10.05943	84.76761	136.19734	311.84247	
15/06/2011	3:19:10 AM	56.74473	-13.43147	-29.50571	11.37028	81.46637	139.06885	303.19846	
15/06/2011	4:57:36 AM	56.56612	-13.71053	-29.89378	11.72599	78.01761	138.20605	300.31219	
15/06/2011	6:36:02 AM	56.73496	-13.86548	-30.12671	11.7498	80.06012	139.27061	301.14786	
15/06/2011	8:14:28 AM	56.86586	-13.81796	-30.08677	11.15246	81.31932	138.03998	304.65799	
15/06/2011	9:52:54 AM	56.09886	-13.89413	-6.17557	10.86514	78.77237	134.05869	303.63864	Coal D
15/06/2011	11:31:20 AM	55.36646	-14.19279	-0.00118	10.40615	62.87899	120.93463	305.87183	
15/06/2011	1:09:46 PM	54.9889	-14.28474	-0.06897	9.96927	62.07678	117.28791	309.95511	
15/06/2011	2:48:12 PM	54.76032	-13.82529	-29.95189	9.06857	75.19183	125.14423	313.44376	
15/06/2011	4:26:38 PM	54.68166	-13.85647	-30.05698	9.85563	71.89578	125.1691	311.25998	
15/06/2011	6:05:04 PM	54.8769	-13.5513	-29.45863	11.04305	74.8401	131.8125	304.60947	
15/06/2011	7:43:30 PM	55.23357	-13.68014	-29.70432	11.03924	75.00571	132.80853	303.0495	
15/06/2011	9:21:56 PM	55.65178	-13.87529	-30.21564	9.99897	73.96922	127.20828	308.2381	
15/06/2011	11:00:22 PM	55.77736	-13.93791	-30.27809	9.98123	73.08673	126.23438	309.2186	

Appendix G: Boiler Design Data

Initial coal specification of the boiler showing proximate analysis, calorific value and desired particle size distribution as provided by Babcok and Wilcox [Impala Contract No.81269, 1973].

Table G1: *Original coal specification*



- 2 -

SAFETY VALVE LIFTING

Pressures in kPa : 3381; 3415; 3450

SOOTBLOWER PRESSURES:

1. ALL BOILER BLOWERS INITIAL: 1035 kPa
2. ECONOMISER BLOWER : ± 1242 kPa with 25,4 mm. Orifice

FUEL : TRANSVAAL COAL

G.C.V. 28,2 MJ/kg

N.C.V. 27,2 MJ/kg

H_2O :	2,43	%
VOL. MATTER:	25,70	%
FIXED CARBON:	57,87	%
ASH :	14,00	%
	100,00	%

GRADING:

1" X 3/4"	30 - 40 PERCENT RETAINED ON 3/4" B.S. SCREEN
3/4" X 1/2"	25 - 35 PERCENT RETAINED ON 1/2" SCREEN
1/2" X 1/4"	20 - 30 PERCENT RETAINED ON 1/4" SCREEN
1/4" x 0"	20 PERCENT THROUGH 1/4"

MAXIMUM (AT COAL HOPPER)

HANDLING AND RESULTANT BREAKAGE SHOULD BE CONSIDERED TO INSURE A MAXIMUM OF 20 PERCENT THROUGH A 1/4" SCREEN AT THE STOKER HOPPERS.

FOR EXAMPLE, IF 10 PERCENT BREAKAGE IS ANTICIPATED THEN THE ABOVE 20 PERCENT 1/4" X 0 SHOULD BE REDUCED ACCORDINGLY.

Boiler design data showing maximum steaming rate, design pressure, steam temperature and boiler full water capacity.

Table G2A: *Boiler design data (boiler capacity).*

IMPALA PLATINUM

B & W CONTRACT 81269

BOILER DESIGN DATA

NO. OF BOILERS IN CONTRACT: ONE

TYPE OF BOILER: CROSS FLOW BI-DRUM

EVAPORATION AT M.C.R.: 45351 kg/hr

WORKING PRESSURE: 3103 kPa

DESIGN PRESSURE : 3448 kPa

STEAM TEMPERATURE: Saturated

FEED TEMPERATURE : 102° C

AMBIENT TEMPERATURE: 27° C

SITE CONDITIONS:

ALTITUDE ABOVE S.L.: 1627 m

ELECTRIC SUPPLY: 500V; 3 PH; 50 C/S

WATER CONTENT

1. FOR HYDROSTATICTEST:

BOILER FULL:	32555	LITRES
ECONOMISER FULL:	1015	LITRES
TOTAL	33570	LITRES

2. FOR BOILING OUT:

BOILER FULL TO N.W.L.:	28301	LITRES
ECONOMISER FULL:	1015	LITRES
TOTAL	29316	LITRES

BOIL-OUT CHEMICALS REQUIRED: 64,5 kg ($Na_3 PO_4$)

Boiler design information dimensions and type of furnace material and firing equipment.

Table G2B: *Boiler design data (furnace and stoker dimensions)*

CONSTRUCTIONAL PARTICULARS

FURNACE	
TYPE	Water Cooled
HEATING SURFACE	169,5 m^2
VOLUME	191 m^3
FRONT WALL TUBES	27 X 76 mm O/D at 154 mm PITCH
REAR WALL TUBES	53 x 76 mm O/D at 77 mm PITCH
SIDEWALL TUBES 2 x	30 x 76 mm O/D at 152 mm. PITCH
MEAN HEIGHT	9,98 m
WIDTH ℄ TO℄ S.W.TUBES	4,23 m
SECONDARY AIR PORTS:	FRONT UPPER: 3 X 44mm FRONT LOWER: 8 X 28,6 mm REAR UPPER : 12 X 31,7 mm REAR LOWER : 6 X 25,4 mm
GRIT REFIRING NOZZLES:	3 X 19 mm
FIRING EQUIPMENT	
STOKER TYPE	ROTOGRATE
WIDTH	4 m.
EFFECTIVE LENGTH	4,8 m.
GRATE AREA	19,3 m^2.
FEEDERS TYPE	COAL
NO. PER BOILER	3
SIZE	685 mm (27")
STOKER DRIVE	HYDRAULIC
BOILER	
TYPE	Cross Flow Bi-Drum
NO. WIDE	35 + 2
HOR. PITCH	102/133 mm
DEEP	17 + 1
VERT. DRUM CRS	8,53 m.

Appendix H: Boiler Plant Layout

Feed coal samples were captured at the closest point of entry into the furnace, on each of the three coal feeders to constitute a single coal batch.

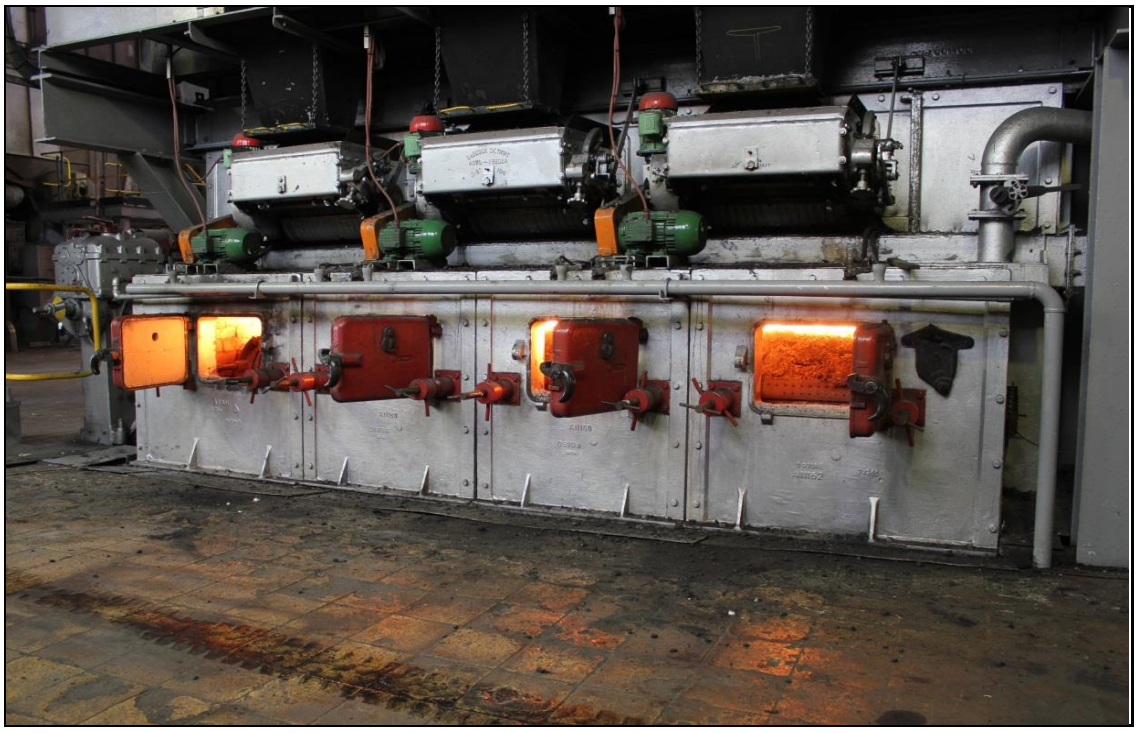


Figure H1: *Coal feeders where feed coal was sampled entering the furnace.*

Bottom ash samples were collected as the ash fell off the ash paddle and onto the conveyor belt.



Figure H2: *Bottom ash disposal System.*

Boiler auxiliary equipment: Economiser unit, ESP and Stack



Figure H3A: *Boiler ESP, ID fan and stack.*



Figure G12 below shows where the gas sampling of combustion gases was conducted, after the economiser and before the ESP unit.

Figure H3B: *Economiser unit.*

Coal is normally assembled into place towards underlying sink holes, after offloading by truck deliveries, using an overhead crane and front-end loader. The coal is then conveyed to the bucket elevator system for filling up the coal bunkers.



Figure H4: *Feed stock pile conveyed by front-end loader.*