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The application of pilot scale coal evaluation to full scale boilers

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2011-05-12
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THE APPLICATION OF PILOT SCALE COAL EVALUATION TO FULL SCALE BOILERS

Priven Rajoo

A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfillment of the requirements for the degree of Master of science in Engineering

DECLARATION

I declare that this dissertation entitled “Application of Pilot Scale Coal Evaluation to Full Scale Boilers” is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering to the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

……..

(Signature of candidate)

……day of ……..year……..

ABSTRACT

South Africa will continue to have a reliance on coal-fired power for the foreseeable future, given that coal is abundant, inexpensive and available. As much of the country's good quality coal becomes depleted, the qualities available for power generation is fast declining. Therefore, pilot scale tests will be crucial in the development of methodologies for predicting coal performance in specific power plants. The main objective of this research is to validate the coal combustion performance of the Pilot Scale Combustion Test Facility (PSCTF) against four utility boilers to determine it's scale up capabilities. Coal samples obtained from the operating feeders during each utility boiler test were evaluated at the PSCTF under conditions of similitude and at variations in excess air levels.

This dissertation details the comparison of pulverized fuel (pf) burnout and gaseous emissions between the pilot facility and four coal-fired boilers of different configurations. The pilot furnace was able to simulate the pf burnout for the three full-scale wall-fired and the tangentially fired boilers at elevated excess air levels and under conditions of similitude respectively. The pilot carbon monoxide (CO) and sulphur dioxide (SO_2) emission results were simulated under conditions similitude for all four boilers. The quantitative determination of the pulverized fuel burnout, CO and SO_2 was found to be dependant on the boiler configuration (boiler size, burner type and burner arrangement) of the full-scale boiler which indicated the setup conditions at the PSCTF. The pilot furnace produces higher flame temperatures than the utility boilers which results in thermal NO_x and inevitably significantly higher NO_x emissions.

The results emanating from this research has shown that the PSCTF is an effective tool for the evaluating and characterising coal combustion performance on a quantitative basis. Validation of more boilers is required to increase the degree of confidence in the PSCTF results and understanding the impact of the full-scale boiler configurations. All future validation tests should incorporate other pf combustion aspects. A quantitative methodology for the NO_x emission should be further investigated.

ACKNOWLEDGEMENTS

The author would like to express his thanks and gratitude to the following people for their invaluable encouragement and knowledge throughout this project

- The test team for their contribution and assistance at the utility boilers and the Pilot Scale Combustion Test Facility: Bonny Nyangwa, Gerson Neumaungwi, Lesigen Moodley and Koogendran Govender (thanks guys, without your help I would have not completed this research)

- The Chemical Laboratory team for their contribution and assistance, Willie Delport, Maria Kgaphola and Patrick Musie

- Brian Pitman for his guidance, help and inexhaustible knowledge on the topic and professionalism in all areas pertaining to the investigation

- Raymond Lopez and his team for conducting the pulverized fuel sampling at the full-scale boilers

- My wife Thanesha, daughter Mikayra and son Livaran for their continued support and inspiration (I love you guys)

- To my supervisor Prof Rosemary Falcon for her persistence and firm belief in me (thanks prof).

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NOMENCLATURE

- VM_{DTF} DTF – Volatile Matter
- E Activation Energy (J/mol)
- E_r Energy Ratio
- MW_e Mega Watts (electrical)
- MW_{th} Mega Watt (thermal)
- NO_x Oxides of Nitrogen
- ppm parts per million
- µm micron metre

ABBREVIATIONS/ACRONYMS

- ACTC Australian Combustion Technology Centre
- BS British Standards
- CF Coal Flow
- CM Combustible Matter
- CRIEPI Central Research Institute of Electric Power Industry
- CR Combustible Residue
- CRR Combustible Residue Ratio
- DTF Drop Tube Furnace
- ESKOM Electricity Supply Commission
- FFP Fabric Filter Plant
- H/C Hydrogen/Carbon Ratio
- HGI Hardgrove Index
- IFRF International Flame Research Foundation
- IM Inherent Moisture
- ISO International Organization for Standardization
- LWF Large Wall-Fired
- NM Not Measured
- PF Pulverized Fuel
- PSCTF Pilot Scale Combustion Test Facility
- SABS South Bureau of Standards
- SA/TA Secondary Air/Tertiary Air Ratio
- SWF Small Wall-Fired
- TF Tangentially-Fired
- VM/FC Volatile Matter/Fixed Carbon

1 INTRODUCTION

1.1 SOUTH AFRICA'S DEPENDENCY ON COAL

South Africa will continue to have a reliance on coal-fired power for the foreseeable future, given that coal is abundant, inexpensive and available. To date specific collieries have been tied by long term contracts to specific power stations, hence ensuring security of supply and relative consistency in quality. However many of these collieries have closed or cannot supply the quality required, resulting in a situation which has forced in the acquisition of coal from a wide variety of collieries. Such multi-sourced feedstocks have given rise to wide variations in quality which, in turn, has affected the operations and efficiencies of the boiler/power plants concerned. In addition, as much of the country's good quality coal becomes depleted, the qualities available for power generation is fast declining. This will place increasing pressure on each power plant to adjust to the changing feedstocks, or to select coals of specific quality. This can only be accomplished by the adequate understanding of coal qualities and the development of methodologies for predicting coal performance in specific power plants.

Further challenge facing coal usage in South Africa will be the increasing environmental pressures from both local and international quarters. These are the motivating factors that led to the proactive establishment of the Pilot Scale Combustion Test Facility (PSCTF) and the research.

1.2 STATUS OF PILOT SCALE FACILITIES

Coal contracts comprise the coal specifications according to the basic chemical analyses; i.e. ash content, volatile matter, gross calorific value, moisture, total sulphur, ash fusibility, Abrasiveness Index and Hardgrove Index. This is often supplemented by Drop Tube Furnace (DTF) tests for char burnout profiles at specified combustion temperatures and variable residence times. The DTF provides a screening procedure for coals, but does not allow for the evaluation of the combustion process in a dynamic environment. Due to these deficiencies, it is becoming common practice to conduct a coal combustion test as part of the coal characterisation and evaluation process.

The best indication of coal combustion behaviour in a particular boiler would be obtained from a full scale test burn in the plant itself, but this is impractical, costly, and risky to the plant. For the above reasons, pilot scale combustion test facilities are designed to simulate coal particle residence times and/or velocity simulation histories of those in a full-scale commercial plant. This offers a practical means of characterizing fuels under various

operating inlet conditions to determine its impact on combustion and emissions on a qualitative basis.

The current status of pilot scale facilities includes various designs, such as sizes and configurations; namely:

- Single or multiple burners – with different types of burners
- Tangentially, wall or down fired furnaces
- Thin ceramic lined walls with water jackets or thick ceramic lined walls without a water jacket
- Other features

Each of the Pilot Scale Facilities is design to incorporate the customer's need that replicates certain processes.

1.3 THE PROBLEM STATEMENT

Majority of the coal-fired boilers in ESKOM and South Africa have been designed by international suppliers. These boilers were designed on their knowledge and experience of their reactive low ash coals. Therefore, the majority of boilers are inadequately designed for the relatively inert high ash coals. This is due to limited information being available on coal combustion characteristics for South African coal sources. The coal combustion behaviour of coals in South African power station boilers depends on three factors:

- the coal's inherent reactivity
- the boiler design
- the boiler operating conditions

The gradual decline in coal quality and the depletion of the design coal has led to an ESKOM power plant having to decommission their top row burners due to longer pf burnout times. The reduction in the reserve margin of ESKOM's power generating capacity and the increase in demand for electricity in South Africa have led to increased boiler load factors that has resulted in higher coal consumption. This factor has led to purchasing additional quantities of coal from various suppliers.

In order to select the appropriate coal source for the relevant power plant, it will be required to determine coal combustion characteristics that can influence boiler performance and gaseous emissions. Hence the need for the PSCTF to quantitatively characterize a coal source and/or blend in order to determine the pf burnout and the gaseous emissions.

1.4 OVERALL PURPOSE OF THE STUDY

The majority of the internationally operated single burner pilot scale facilities deriavitives within the 1 MW_{th} size range utilise interface programs or scale up factors to predict pulverized fuel (pf) burnout and gaseous emission of full-scale boilers, as is the case with the ESKOM facility. This process does not always relate directly to the full scale operation.

The ESKOM's Pilot Scale Combustion Test Facility (PSCTF) is a 1 MW_{th} test furnace that incorporates the following design:

- Burner that is 1 MW_{th} with variable swirl and a low NO_x technology option
- Furnace that is refractory lined with the burner being down fired for high ash coals
- Overfire air facility for NO_x reduction strategies

The main objective of this research is to validate the pf burnout and gaseous emissions of Pilot Scale Combustion Test Facility against four full-scale boiler configurations to determine it's scale up capabilities. This will be achieved by

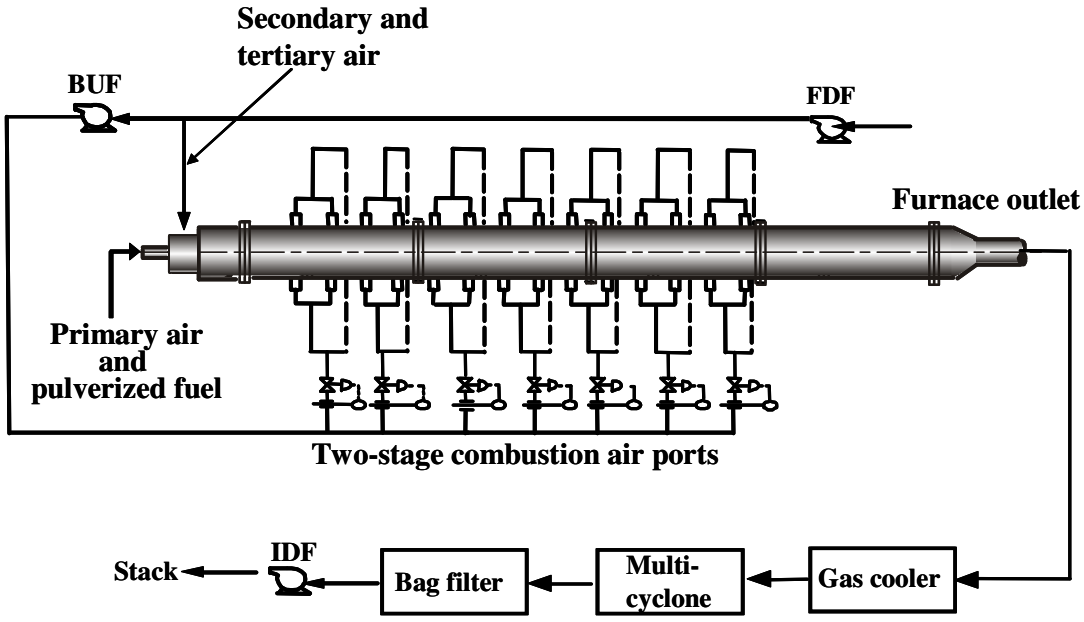
- Comparing the use of the DTF and the PSCTF relative to the utility boilers
- Evaluating the setup conditions of the plants
- Assessing the results as measures of the comparative performance of the plants under investigation.

2 BACKGROUND AND LITERATURE REVIEW

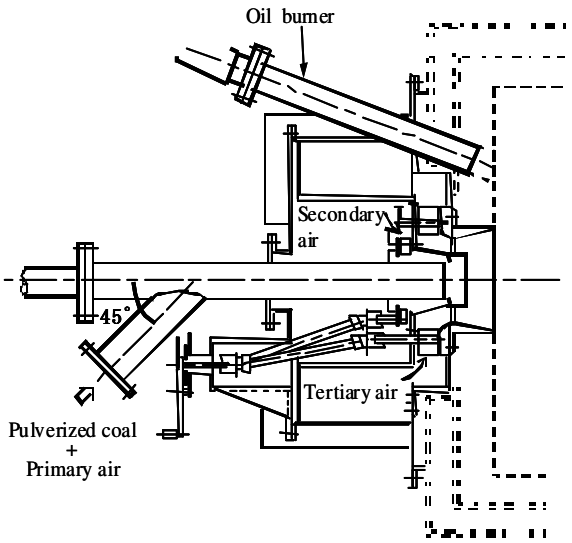
2.1 INFORMATION GAIN FROM VISITS TO OTHER RESEARCH FACILITIES

Central Research Institute of Electric Power Industry (CRIEPI), Japan

CRIEPI's test furnace is a water-cooled horizontal and cylindrical furnace made of steel. The inner diameter of this furnace is 0.85m and the length is 8m. Refractory materials are coated onto the inside wall of the furnace to a thickness of 0.075m. Fourteen ports are mounted on the furnace sidewall for two-stage combustion air injection. Thermocouples and gas sampling probes are inserted into the furnace through these ports.



The CI-α burner is designed to have a combustion capacity of approximately 100kg/h on bituminous coal. This burner was developed through co-operative research between CRIEPI and Ishikawajima-Harima Heavy Industries Co. Ltd. Combustion air, supplied by a forced draft fan, is injected into the furnace through the burner and the two-stage combustion air ports, and the air through the burner is divided into primary air, secondary air and tertiary air. The primary air carries the pulverized coal from the table feeders to the burner through a coal exhauster. The secondary and tertiary air is fed into the furnace via a wind box. The two-stage combustion air is divided before the wind box and injected through the side ports of the furnace.



CRIEPI performed a study on the "Scale-up Effect for Emission Characteristics of NO_x and Unburned Carbon in Fly Ash on Pulverized Coal Combustion". In their study three furnaces were utilised to determine the scale-up capability and these were the 0.1 t/hr test furnace (as described above), 1.5 t/hr large single burner test facility or a multi-burner system where each of the four burner's has a capability of 0.375 t/hr (owned by Ishikawajima-Harima Heavy Industries Co. Ltd) and full-scale boilers (700 MW and 1000 MW). The NO_x and unburned carbon emission characteristics of the furnace types including the small coal combustion test furnace, large-scale test furnace, and utility boilers when burning the same coal. These results were compared with the unburned carbon values for the three furnace types under conditions in which NO_x concentrations were similar whereas the unburned carbon in fly ash tended to decrease as the furnace capacity increased (Makino et al, 1996).

International Flame Research Foundation, The Netherlands

The International Flame Research Foundation (IFRF) obtained funding from the steel industry to develop a pulverized fuel test facility. The test facility replicated the kiln design and was of a similar design to that of the CRIEPI facility described above. Each test facility defined their own standard test procedure that had been gained from the individual experience and their emission legislation of that specific country. The IFRF had decommissioned their coal combustion test facility and was focusing on oxygen-enrichment for gas combustion.

Visits to the above two pilot facilities have indicated that no quantitative pf burnout test procedure has been achieved. Hence the need for research in this dissertation.

2.2 LITERATURE

Running experimental scale tests does not eliminate the desirability of a full-scale test burn; however, in some cases the experimental scale results may prove decisive, and in other cases a full-scale test burn is impossible or uneconomic. Sotter et al (1986) cites that along with the potential advantages of experimental scale testing, comes the responsibility of scaling up the results. This appears to be a very difficult problem. In some cases, such as the size distribution of the particles produced by the combustion process, one may hope that there is a one-to-one correspondence with full-scale results, and for other phenomena one may hope that there is a simple empirical correlation, or an accurate mathematical model. The first aspect that makes the scaling problem difficult is the fact that a single burner is used in most experimental scale tests, but the full-scale boiler has a multiplicity of burners, which operate under a variety of conditions. The second complication is due to the fact that the boiler wind box design itself is often a compromise, and the burners are competing for the air supply with varying degrees of success. There is also a maldistribution of the pf supply to the burners. This leads to non uniformity in combustion stoichiometry across burner banks. The result of this complication is that one can probably not expect to have a perfect prediction of how a new coal is going to behave in a particular boiler; but careful interpretation and cautious use of experimental scale results can be valuable in anticipating what problems will or will not occur if the coal is used in a large boiler. Predictions based on experimental scale tests not only aid in the selection of a coal, but can help to reduce the risk entailed in the first full-scale test burn. Initial operating conditions such as coal fineness, primary and secondary airflows, burner settings, and load limits can be set on the experimental scale results so there is less chance of an unexpected problem developing.

The Electric Power Research Institute (EPRI) conducted a survey on 11 utilities from the following countries; Australia, Canada, Germany, Japan and the United States that have used pilot scale testing of coals. The object of the survey was to evaluate the comparison between pilot scale coal performance results with full-scale coal behaviour (Johnson et al, 1988). The survey incorporated six aspects of coal behaviour which impact on boiler operation and availability, viz.:

- Milling Characteristics
- Combustion stability and burnout
- Pollutant formation (gaseous)
- Ash slagging, fouling and heat transfer
- Fireside erosion and corrosion
- Particulate removal (either electrostatic precipitator or fabric filter plant)

The survey revealed good qualitative agreement was found between the pilot-scale predictions and full-scale boiler test results, provided reasonable care was taken to simulate the essential features of the combustion process relevant to the aspect of coal behaviour of interest. Although, quantitative agreement was not achieved.

A study performed by (Juniper, 1995) to review the design criteria needed for correct simulation, and the problems associated with designing experimental furnaces to simulate two important aspects of combustion (pf burnout and slagging) concluded the following:

- to simulate pf burnout, it is necessary to design the experimental scale plant so that the flame and furnace gas temperatures are similar. Due to high rates of heat loss in these small furnaces, the wall temperature needs to be designed for temperatures above 1000℃.
- to simulate ash deposition, it is important that similarity of the deposit temperature between experimental scale and full-scale plants is maintained. This can be achieved by varying the deposit probe wall temperature, or by increasing the flame emissivity in the experimental scale plant by adding soot.

A study by (Smart et al, 1996) compared the effects of burner scale and scaling criteria on the performance of a generic swirl stabilized pulverized coal burner in the thermal input range 2.5 to 12 MW, operating under baseline high-NO_x operation and low-NO_x staged firing conditions. Throughout the study, the work was performed on the same coal and with the same particle size distribution. From the in-flame measurements performed, broad similarities in global flame structure were shown; but significant differences were seen in the detailed chemistry. It is suggested that the differences arise in the thermo-chemistry due to the flame aerodynamics which don't scale in accordance with the applied scaling rules. An important part is played by differences in coal particle dispersion in the near burner region, and the actual effect of scale on the turbulent mixing process in the near burner region. It was also suggested that there is a minimum scale at which representative full-scale information can be obtained when studies are made of reduced scale burners. This limit was not quantified. In conclusion, it was suggested that neither constant residence time nor constant velocity scaled flames can produce total similarity in flame structure and thermo chemical fields.

Australian Combustion Technology Centre (ACTC) undertook a study for ESKOM to correlate experimental and full-scale NO_X emissions of South African coals, making the task of estimating full-scale NO_x emissions easier, and making experimental scale NO_x testing more valuable (Holcombe, 1994). Experimental scale and full-scale results were correlated on the basis of the severity of mixing and temperature conditions. The results of the

experimental scale measurements were plotted versus the level of severity of conditions. This level has been termed a “mixing number”. The experimental and full-scale results for a particular coal enabled a mixing number to be assigned to the boiler, by locating the value of NO_x emission measured at the boiler on the plot of experimental scale NO_x versus mixing number for that coal. The mixing number used was more boiler and experimental furnace specific, and so may not be directly applicable to ESKOM’s pulverized fuel test facility.

Harding et al (1984) proved the feasibility of a 440 kW experimental furnace by determining if coal cleaning would improve combustion performance and reduce slagging. Results showed that cleaning did allow the coal to be burned at higher thermal inputs before slagging occurred. The experimental furnace incorporates the major features of a boiler viz. Ashpit, firebox, radiant and convection zones, nose and exhaust sections. The facility allows for wide variability in operating conditions including volumetric heat release rate, firing mode, firebox pressure, excess air levels, preheat temperatures and velocities. Video cameras captured both the convection and radiant/firebox sections. Samples collected during the tests include as received raw coal, pulverized coal, bottom ash, fly ash, slagging and fouling deposits. Exhaust gas samples are continuously collected, and an inert gas or water quenched sample probe is still available for sampling in the firebox and radiant sections. A triple-shield high velocity thermocouple is used for temperature mapping. Gas samples are analyzed with on-line instruments. Solid samples are extensively analyzed, including special analyses such as trace elements (17 species), sulphur forms, and ash fusion. Scanning electron microscopy photographs are taken on slagging and fouling deposits and fly ash. In situ ash resistivity is also available in the exhaust stream. Gas, thermal, and solid data permit complete mass and energy balances to be performed.

Padayachy (1996) indicated that International experimental furnaces have been successfully designed and operated to study the certain aspects of the combustion phenomena, such as flame stability, ash deposition rates, deposit heat transfer properties (emissivity and thermal conductivity), deposit removal characteristics, erosion, corrosion of radiant and combustion tube surfaces, baghouse collectability, gaseous emission formation (SO_2, NO_x, CO) and particulate emission (fly ash and trace elements)

The impact of coal quality on boiler operation and experienced gained from international experimental furnaces have led to ESKOM installing a $1MW_{th}$ Pilot Scale Combustion Test Facility in their research centre. Test work was then undertaken to establish whether agreements could be achieved between pilot and full-scale boilers when burning relatively inert high ash coals in South Africa.

3 METHODOLOGY

This chapter presents the method of sampling, analyses and test work carried out in this research.

3.1 SAMPLING

3.1.1 Raw Coal Sampling

Raw coal was sampled in accordance with ISO 1988:1975 Solid Fuel sampling. Raw coal samples for the four utilities were taken at 15 minutes intervals from all the coal feeders in service over the duration of the test period. A total quantity of approximately 8 tons of the raw coal was sampled over a 10 hour period. The bulk coal samples from each facility was coned and quartered to obtain representative samples prior to it undergoing the basic chemical analyses.

3.1.2 Coarse Ash Sample

Coarse ash was sampled in accordance with ISO 1988:1975 Solid Fuel sampling over the duration of the test period. A total quantity of approximately 300kg of coarse ash was collected and stored in plastic bags.

3.1.3 Fly Ash Sample

Fly ash was sampled in accordance with ISO 1988:1975 Solid Fuel sampling over the duration of the test period. A total quantity of approximately 300kg of fly ash was obtained from the conveyors and stored in metal containers to avoid contamination.

3.1.4 Pulverized Fuel Sampling

The Pulverized Fuel (pf) samples were extracted iso-kinetically according to ASME -1954 PTC 3.2 - Solid Fuels (Pulverized Fuel Sampling). The pf sampling results are within 10% accuracy. The particle size analysis was carried out under laboratory conditions by firstly drying the samples to evaporate the moisture content. The dry pf was then graded through test sieves of the following apertures: 300, 150, 106 and 75 microns. The results have been plotted on Rosin-Rammler graphs.

3.2 LABORATORY ANALYSES

All the coal samples were analysed at ESKOM's Research and Innovation Centre using the ESKOM Methods (see Appendix I). All the samples were prepared to less than <212µm, in accordance with South African Bureau of Standards (SABS) 0135 – Part II – 1977, for the various required chemical analyses discussed below.

3.2.1 Proximate Analysis

The proximate analysis of a coal describes its composition in terms of moisture, ash content, volatile matter and by difference the fixed carbon of the coal.

Description	Procedure	Sample	Reported Analysis
Moisture content	ESKOM Method 103 rev2	Variable	Weight %
Volatile Matter (VM)	ESKOM Method 102 rev1	1g	Weight %
Ash content	ESKOM Method 101 rev1	1g	Weight %
Fixed Carbon	ESKOM Method 128 rev1	Calculated	Weight %

The proximate analysis was determined by the gravimetric method. Surface moisture and inherent moisture was determined by air-drying to laboratory environment temperatures and oven drying at 105-110℃ respectively. The volatile matter was determined by oven drying at ±900℃ for 7 minutes in the absence of oxygen. The ash content was determined by oven drying at ±815℃ for at least 3 hours. For the detailed ESKOM methods refer to Appendix I.

3.2.2 Ultimate Analysis

The ultimate analysis describes the elemental composition of the coal in terms of Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S), and by difference the Oxygen (O_2).

Description	Procedure	Sample	Reported Analysis
Carbon	ESKOM Method 118 rev1	1g	Weight %
Hydrogen	ESKOM Method 118 rev1	1g	Weight %
Sulphur	ESKOM Method 104 rev1	1g	Weight %
Nitrogen	ESKOM Method 118 rev1	1g	Weight %
Oxygen	ESKOM Method 132 rev1	Calculated	Weight %

A pellet of coal was combusted at ±950℃ in an oxygen rich environment which produces oxides of carbon, water and oxides of nitrogen. A series of processes were conducted on the gases and thereafter the carbon, hydrogen, and nitrogen were calculated. For the detailed ESKOM methods refer to Appendix I.

3.2.3 Calorific Value

The Gross Calorific Value (GCV also named High Heating Value, HHV) of a coal sample is the total amount of energy that can be released by combustion of a unit mass of coal including the energy consumed to vaporise the moisture in the coal (latent heat of vaporisation). The Net Calorific Value (NCV also named Low Heating Value, LHV) was calculated by subtracting the energy liberated during condensation (LHV) from the GCV. A known mass of the sample of coal was combusted in an oxygen environment in a bomb calorimeter under standardised conditions. A high speed micro-processor performs the temperature measurement of the bomb and calculates the calorific value from the individual measurements taken (according to the ESKOM method 105 rev3 in Appendix I). The

proximate analysis, ultimate analysis, and calorific values can be reported on any of the following basis:

As received basis (includes total moisture), i.e. the coal as received in the laboratory and generally very close to the actual condition of the coal at the time of sampling. The measured moisture content on this basis is termed "Total Moisture"

Air dry basis (includes inherent moisture), i.e. the coal after having reached equilibrium with laboratory ambient environment. The measured moisture content on this basis is termed "Inherent Moisture" as majority of the surface moisture has evaporated

Dry basis (excludes all moisture), i.e. the coal after all the moisture has been removed by drying the coal in an oven at ±105℃

Dry, ash free basis (excludes all moisture and ash), which is predominantly concerned with measurement of the combustible part of the coal. Results are reported relative to there being no ash or moisture in the coal. In the current research, all chemical analyses were reported on a dry basis.

3.2.4 Ash analysis

Ash elemental analysis determines the amount of the main mineral compounds present in the ash expressed as simple oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, SO_3, MnO, P_2O_5, TiO_2. The ash elemental analysis was determined according to the ESKOM Method 121 rev3 (refer to Appendix I).

3.2.5 Hardgrove Grindability Index (HGI)

This is a laboratory-based test to determine the ease of grinding a coal relative to a standard (Maximum HGI value of 100). The smaller the HGI value, the more difficult the coal is to grind on a plant and this influences the quantity and quality of the pf produced. A low HGI tends to produce larger particle size which is more difficult to burn out completely, while conversely, a coal with a high HGI value will produce a finer grind size. The Hardgrove Grindability Index was determined according to the ESKOM Method 117 rev1 (refer to Appendix I).

3.2.6 Abrasiveness Index

The abrasiveness of a coal will affect the wear on the coal handling plant, i.e. the mill feeder chutes, grinding components, and the pulverized fuel pipe work. The main abrasive components in coal are quartz and to a lesser extent, pyrites. The Eskom Standard test simulates sliding wear such as that occurring in the mill, but is less representative of the type of impact wear (erosion) in the pulverized fuel pipe work. It should be noted that the index is derived by using an empirical method to index coal in a relative manner to other

coals. The Abrasiveness Index was determined according to the ESKOM Method 123 rev1 (refer to Appendix I).

3.3 COMBUSTION TEST EQUIPMENT

All the coal samples were evaluated at the Drop Tube Furnace, the Pilot Scale Combustion Test Facility and the Full-Scale Boilers.

3.3.1 Drop Tube Furnace (DTF)

Description

The Drop Tube Furnace (DTF) is a laboratory scale furnace that simulates the important conditions of temperature, residence time and oxidising environment within a pulverized fuel furnace. The DTF enables the evaluation of ignition and combustion performance of small representative samples (typically 1 kilogram) of coal. The small size of sample required allow, for instance, the use of geological survey boreholes, enabling combustion predictions of coal deposits that have yet to be mined. This test has been implemented as a routine requirement for all new coal feedstocks that is purchased.

The DTF data has also proven to be very useful in diagnosing ignition and combustion problems for operational plant, by confirming whether the root cause of the problem is coal related or not.

Finally, the DTF data can provide a prediction of combustion behaviour on a qualitative basis, and in combination with combustion modelling can provide quantitative data as well. The qualitative assessment is by means of comparison with the DTF combustion database which, includes

- Level 1 – Full Test (5 Temperatures @ 5 residence time positions with two size fractions to determine the combustion profile)
- Level 2 – Medium Test (3 Temperatures @ 5 residence time positions with one size fraction to determine the combustion profile.
- Level 3 – Fingerprint test (1 Temperature @ 5 residence time positions)

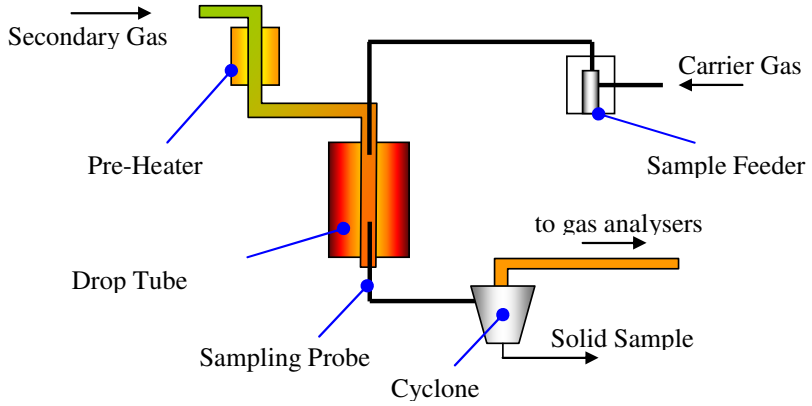


FIGURE 1: SCHEMATIC OF DROP TUBE FURNACE

Sample Preparation for DTF tests

The DTF enables the evaluation of ignition and combustion performance of small representative samples (typically 1 kilogram) of coal. The coal samples should be taken according to SABS sampling guidelines. For example, if coal is delivered with a top size of 25mm then 10 kilograms will be required. Each coal sample is crushed to -150µm and pyrolised in the DTF under a nitrogen atmosphere for 1.8 seconds to devolatilize it. The sample (before pyrolysis) and the char (after pyrolysis) are evaluated for proximate, ultimate and calorific value analyses. The volatile matter characteristic (quality and quantity) is quantified, giving an indication of energy available for the ignition process. The char is resized and ground to two size fractions (-38µm and 38 to -75µm) which are then combusted in the DTF at various temperatures.

The following laboratory analysis of each coal supply option is typically needed prior to the DTF tests:

- Proximate analysis
- Ultimate analysis
- Calorific Value
- Ash elemental analysis

The Table below details the Drop Tube Furnace Specifications

TABLE 1: DROP TUBE FURNACE SPECIFICATIONS

	Units	DTF
Maximum Temperature	℃	1500
Pressure	MPa	0.1
Heating Rate	℃/s	≈1000
Heated Zone	mm	ϕ70 x 1320
Residence Time	s	< 4
Coal Feed	g/hr	< 60

3.3.2 PILOT SCALE COMBUSTION TEST FACILITY (PSCTF)

The Pilot Scale Combustion Test Facility comprises of a coal handling plant as well as a test furnace.

Description of the Coal Handling Plant

Three coal storage silos have been included in the design. Each of these silos is large enough to provide coal to the system for a period of approximately 12 hours at 100% MCR; i.e. 250kg/hr. Each silo is equipped with level sensors and a volumetric feeder to control the rate of coal release. This system allows for blending of up to three different coals on a continuous basis. Additionally, a nitrogen blanketing system has been designed for the coal silos. This system is intended to reduce the hazards of ignition in the silos.

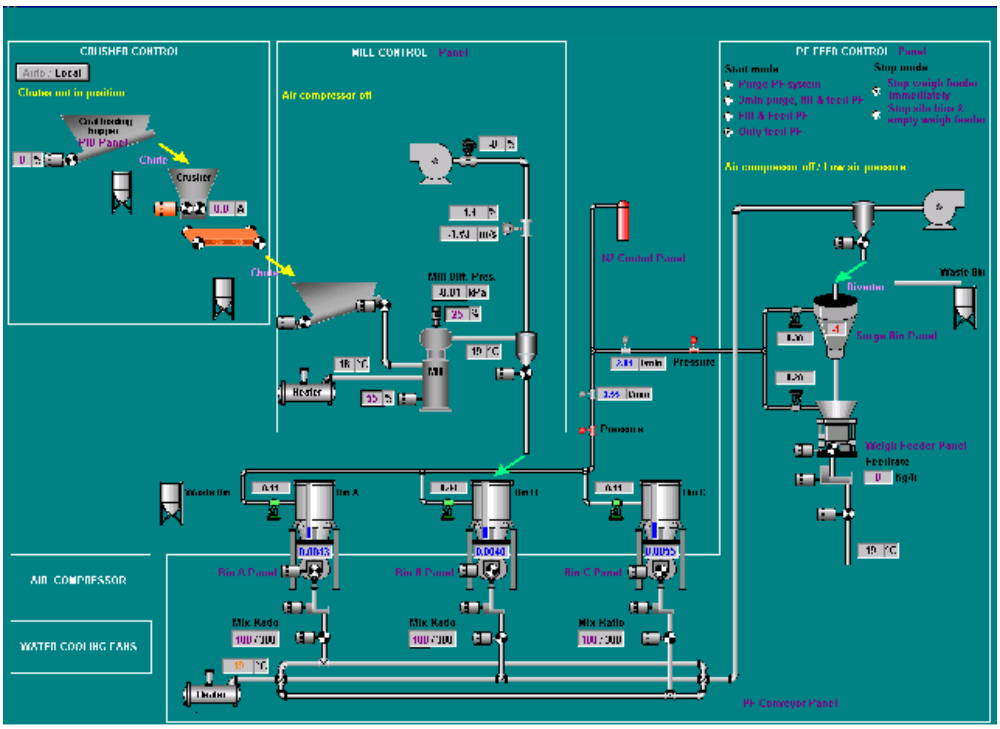


FIGURE 2: SCHEMATIC OF THE COAL HANDLING PLANT

Prior to the coal being tested in the test furnace, the coal sample received has to be prepared and pulverized to the required fineness in the coal handling plant. The Coal Handling Plant (CHP) consists of (see Figure 2):

- Crusher Hopper with screw feeder – loading and storage bin for the raw coal samples
- Crusher – crushes the raw coal sample to a top size of –10mm
- Conveyor – transports the crushed coal to the mill hopper
- Mill Hopper with screw feeder – storage and feed bin for crushed coal to be milled
- LM 3.6 Loesche Mill – table and tyres mill (design output of 550 kg/hr), operating under an induced draught, which is not typical of industrial milling plants, which

operate using a forced draught. The following items on the mill maybe controlled to achieve the desired fineness:

- Table speed – variable speed drive
- Classifier speed– variable speed drive
- Electrical air heater – regulation of the temperature of the air entering the mill
- Extraction fan with damper control of the air flow through the mill

Description of the Pilot Scale Combustion Test Facility

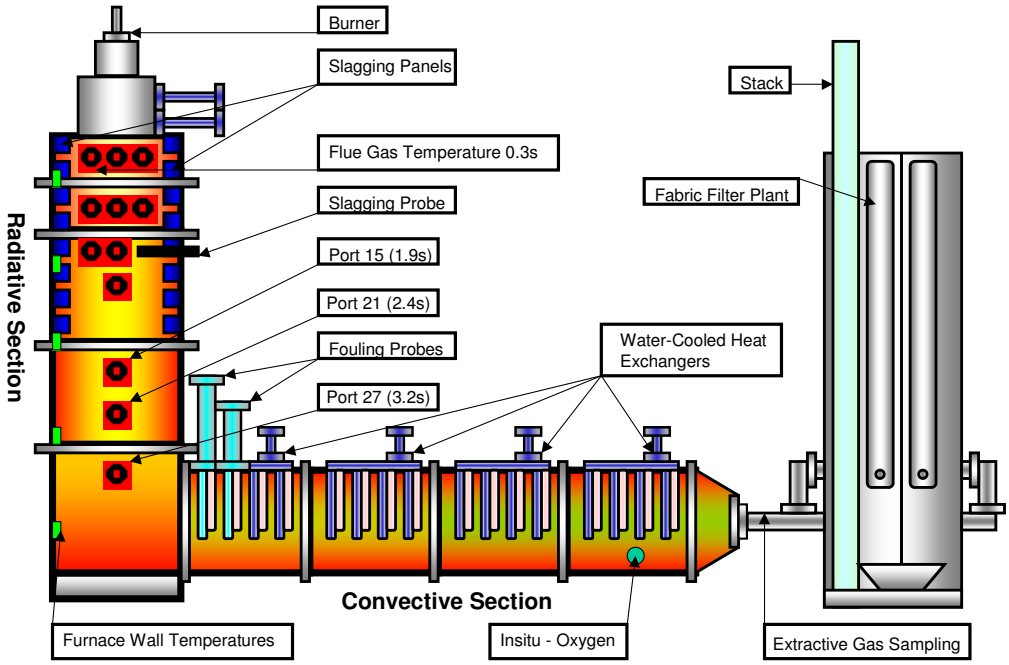


FIGURE 3: PILOT SCALE COMBUSTION TEST FACILITY DIAGRAM

The PSCTF is a flexible tool designed to cover a wide range of coal combustion characteristics and is located at the ESKOM research facility. It is designed to use diesel as a light-up fuel prior to firing the coal to be tested. The PSCTF has been designed using "residence time scaling". This concept states that a fuel particle entering the PSCTF will experience the same history of gas atmospheres and temperatures and particle residence times similar to that of the full-scale plant.

The combustion chamber and convective section of the PSCTF are both lined with refractory, whose properties have been chosen to replicate as closely as possible the temperature field of a (hypothetical) boiler furnace. Outside the refractory is a metal skin. At the exit of the main radiative combustion chamber (corresponding to furnace exit of a boiler), the combustion duct narrows to increase gas velocities to match those used in industry. This is important since the parameters, which are of interest in this zone (such ash deposition and erosion), are dependent not only on atmosphere and temperature, but also on absolute velocity. The convective pass turns through 90 degrees and passes over

two air-cooled U-shaped tubular ducts (fouling probes). The flue gas is gradually cooled down to approximately 750℃ before entering the water-cooled tube heat exchangers, which provides rapid cooling to reduce the temperature of the gas to 130℃, i.e. Fabric Filter Plant (FFP) inlet conditions. At the exit of the convective section, the gas passes through a FFP to the stack.

Performance specifications

The 1 MW_{th} (thermal) PSCTF has been designed with a number of features incorporated to aid in the evaluation of fuels for the use in full-scale and industrial boilers. The furnace is equipped with a single down-fired variable swirl burner.

The following features are included at the PSCTF:

- Variable Swirl Burner has the flexibility to vary the swirl between 0 swirl (jet burner) to 2 swirl (high swirl burner).
- Over fire air ports and a low NO_x burner is available for studies on NO_x reduction
- Water-cooled and refractory-lined radiant and convective sections that allow simulation of actual boiler temperatures
- Fourteen individual removable slagging panels in the radiative section
- An ash hopper with access for manual removal of ash
- Thirty six and thirty two (100 mm) sample ports on each of the two opposing furnace walls in the radiant and convective sections respectively
- Two individual removable fouling probes in the convective section
- Fourteen individual removal heater exchangers in the convective section
- Sixteen ash removal doors on each of the two opposing furnace walls in the convective section

Electrical air heaters at the PSCTF have been designed to allow control over a reasonable range of operating conditions for both the primary and secondary air systems. The primary air system is designed to operate between 35 and 105℃. The secondary air system is designed to operate between 35 and 400℃. These temperature ranges should allow simulation of reasonable plant operating conditions.

Conditions of Similitude

In order to obtain a combustion performance on the PSCTF that is most representative of the conditions in the full-scale plant, the following rules of similitude were maintained:

- Inlet conditions matched to full-scale plant
- Primary and Secondary air temperatures
- Secondary to Primary air flow ratio
- Excess air levels

- PSCTF pf Fineness
- Particle residence time in the combustion zone

Measurements and Observations

A typical test produced the following measurements and observations:

- A log of coal feed and air flow rates, temperatures and gas compositions, and other operational parameters
- Solid samples were drawn from either of the three Ports 9, 15, 21 and 27 (refer to Figure 3) in the radiant section for the four series of validation tests

The following equation is utilised to normalised the gaseous emissions of Carbon Monoxide (CO), Oxides of Nitrogen (NO_x) and Sulphur Dioxide (SO_2) to 6% oxygen concentration.

The measured oxygen concentration is converted by the following formula:

Gas emissions normalised to 6% O_2 = (1 + (6 – O_2) / (20.9 - 6)) x Gaseous Emission 1

Thereafter the NO_x and SO_2 were converted from ppm to mg/Nm by multiplying the normalized 6% O_2 concentration with gas density of 2.86kg/m^3 for SO_2 and 2.06kg/m^3 for NO_x respectively.

Combustion Efficiency Measurements (Burnout)

Combustion efficiency takes into account the total carbon loss from each coal. Utilizing combustible residue in ash to gauge combustion performance is a quick and accurate method when evaluating different boiler-set-up conditions with firing the same coal. However reporting on combustible residue in ash only can obscure the assessment of a coal when comparing different coals containing different ash content; i.e. a high ash coal with a low carbon in ash content can result in higher total carbon losses than a low ash coal with an equivalent or slightly higher combustible residue in ash content due to the larger volumes of ash produced by the higher ash coal. Therefore, the combustion efficiencies were calculated by determining mass flow of the combustible residue in ash divided by the inlet mass flow of carbon. The combustible residue of the flue dust, coal flow, total carbon and ash content in raw coal were utilised in equations 2 and 3 to calculate the combustion efficiencies for comparative purposes.

Combustion Efficiency (%) = 1 - (CM / (Coal Flow x Total Carbon%)) 2

Combustible Matter (CM) (kg/s) = (Coal Flow x CR% x Ash%) / (1-CR%) 3

The accuracy of the coal combustion efficiency calculation is as follows:

Total Carbon	=	within 0.3% (ESKOM Method 118 rev1)
Combustible Residue	=	within 0.3% (ESKOM Method 126 rev1)
Weigh feeder	=	within 0.1% (Intecont Plus FDW 0201-04 Schenck)
Sampling from flue gas	=	within 5%
TOTAL	=	within 5.7%

The PSCTF flue dust samples were extracted from the furnace at any of the three ports 9, 15, 21, 27 (refer to Figure 3). These samples were obtained by using suction pyrometers with cyclones attached to the outlet end. The particle residence times for the extracted flue dust samples at the PSCTF were determined by dividing the volume flow rate of the flue gas by the volume between the burner and the extraction point. The concentration of the gas species in the flue gas was measured by an online gas analyser. This flue gas was extracted from the exit of the convective pass of the experimental furnace.

Temperature Measurements

All the temperature measurements at the PSCTF were logged to an on-line database. Thermocouples are located in all the critical areas measuring air, gas and water inlet and outlet temperatures. The accuracy of the all the thermocouples and fluctuations in flue gas ducts are within 5℃ and 5% respectively.

Stoichiometric Air Calculation

The following formulae were utilised to calculate the stoichiometric air requirements for each coal sample. Thereafter, the total air requirements were determined by the excess air levels and setup accordingly. The primary and secondary air mass flows were adjusted to achieve a burner air ratio of approximately 2.5 to 3.5.

Stoichiometric Air = $\frac{100}{23.2} x((\frac{8}{3} xC + 8x(H - \frac{O_2}{8}) + Sx\frac{94}{100} + \frac{8}{7} xNx\frac{20}{100}))$ 4

Excess Air = $\frac{O_2 x100}{fx(20.9-O_2)}$ 5

Where: f = $\frac{(1+3xK)}{(1+2.37xK+0.09xN)}$ 6

Where: K = $\frac{(H-\frac{O_2}{8})}{(C+\frac{3}{8}xS)}$ 7

Where: N = $\frac{N}{(C+\frac{3}{8}xS)}$ 8

3.3.3 FULL-SCALE TESTING

The following four coal-fired utility boilers were selected to validate the Pilot Scale Combustion Test Facility.:

- Small Wall Fired Boiler (200MW_e with a vertical spindle milling system)
- Large Wall Fired Boiler A (600MW_e with a tube milling system)
- Tangentially Fired Boiler (700 MW_e with a tube milling system)
- Large Wall Fired Boiler B (600 MW_e with a vertical spindle milling system)

In order to validate the PSCTF the following measurements were performed at the full-scale plant:

- Raw coal was sampled from the coal feeders in service over the duration of the test
- Pulverized Fuel sampling had been performed on all the burner pipes from the mills in service
- Fly and coarse ashes were sampled from the relevant hoppers during the test period
- Boiler logs were setup to record all the boiler settings (where possible); namely primary and secondary air temperatures, pressures and airflows, optical pyrometer temperatures, excess oxygen percentages from the economizer outlet, coal flow, etc
- Water cooled suction pyrometers were situated at three different levels (when possible) in the furnace (one at the furnace exit) to extract the boiler flue dust for the determination of the extent of combustion

Site Visit

The following areas were inspected during the initial site visit:

- Suction pyrometer port sizes on the furnace of >80mm
- Pulverized Fuel sampling access points on the pf burner pipes
- Raw coal access points on the feeders
- Coarse ash sampling access points
- Fly ash sampling access points
- Access for manoeuvring water cooled suction pyrometer (probes) around furnace
- Distances of the air supply for the 3 selected traverse points – includes air manifold where necessary
- Distances between the main water supply, water manifold and the suction pyrometers
- Distances between water cooled suction pyrometers and outlet drains
- Hoisting/Rigging areas
- Scaffolding platforms if required
- Sample preparation – access to perform cone and quartering for:
  - Raw coal sampling
  - Coarse ash sampling
  - Fly ash as sampling

Information needed and requirements from power stations

- Safety and induction course
- Latest verification on inlet control instrumentations and the oxygen analyzers
- Availability of a rigger to hoist probes to the relevant levels
- A Test program and ESKOM's Plant and Safety Regulation
- Boiler logs

3.3.4 Full-Scale Boiler Test Program

The full-scale boilers are online power generators and are controlled by the national grid. Therefore, the full–scale test program had to be issued in advance to the respective power station for them to coordinate the necessary load requirements with the national control. An example of the test program is shown in Table 2 below.

TABLE 2: FULL-SCALE BOILER TEST PROGRAM

Full-scale Boiler Test Program

Preliminaries

1. The boiler had to be soot blown, the unit was isolated and on a steady steam flow on the day of the test
2. The Station Chemical laboratory was warned not to do any water sampling during test period
3. The Unit was off SCALD (System Control and Load Dispatching) and frequency control

Unit SET-UP

Load %	Economizer O_2	BUFFER	Mill combinations
97% (Boiler)	3%	Minimum 2% and Maximum 9%	Top mills

Test programme

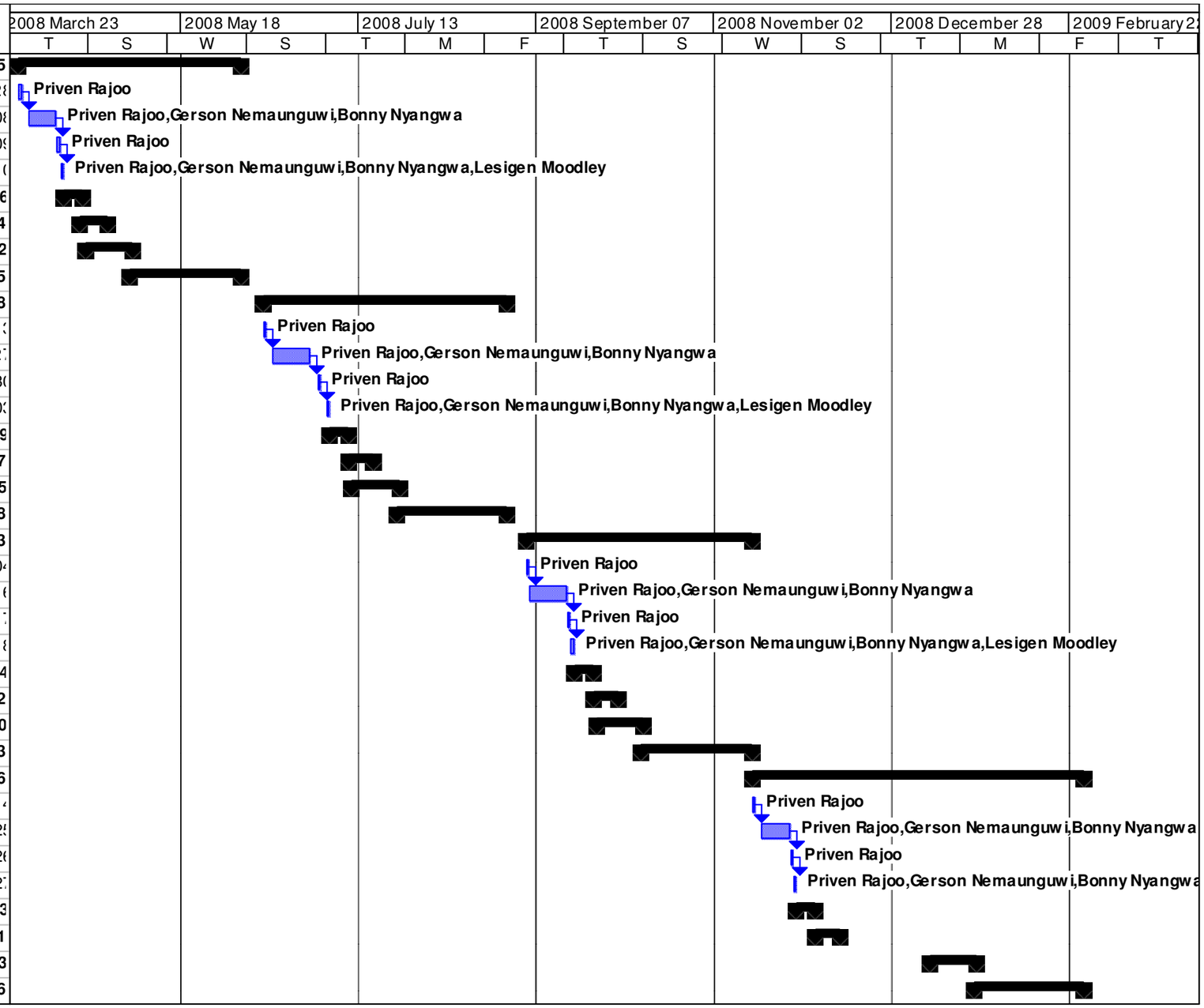
One or two excess air level test was performed for 10 hours under stable boiler conditions for each coal
Ashing and dusting were performed before the test

3.4 VALIDATION OF THE PILOT SCALE COMBUSTION TEST FACILITY

It must be noted that the author did not intend to attempt to replicate the exact firing conditions of the full-scale boilers in the PSCTF. Full-scale boilers vary in size and have different combustion configurations with multiple burners, whereas the PSCTF has a single wall-fired burner. It is clearly impossible to expect the latter to exactly replicate the coal combustion performance (Sotter et al,1986). The intention was to determine the PSCTF setup to achieve the combustion performance that most closely matches that of the full-scale boilers. The entire test schedule for this research is shown in the project schedule below.

3.5 TEST SCHEDULE

ID	Task Name	Start	Finish
1	**Small Wall Fired Boiler Validation**	**Fri 08/03/28**	**Thu 08/06/05**
2	Site Visit Meeting	Fri 08/03/2	Fri 08/03/2
3	Preparation for Site visit	Mon 08/03/3	Tue 08/04/0
4	Follow-up site meeting	Wed 08/04/0	Wed 08/04/0
5	Pack up equipment	Thu 08/04/1	Thu 08/04/1
6	**Commercial Boiler Test 1**	**Fri 08/04/11**	**Wed 08/04/16**
10	**Coal Preparation and Analyses**	**Wed 08/04/16**	**Thu 08/04/24**
13	**Pilot Facility Test 1**	**Fri 08/04/18**	**Fri 08/05/02**
19	**Report**	**Fri 08/05/02**	**Thu 08/06/05**
23	**Large Wall Fired Boiler Validation A**	**Fri 08/06/13**	**Thu 08/08/28**
24	Site Visit Meeting	Fri 08/06/1	Fri 08/06/1
25	Preparation for Site visit	Mon 08/06/1	Fri 08/06/2
26	Follow-up site meeting	Mon 08/06/3	Mon 08/06/3
27	Pack up equipment	Thu 08/07/0	Thu 08/07/0
28	**Commercial Boiler Test 2**	**Fri 08/07/04**	**Wed 08/07/09**
32	**Coal Preparation and Analyses**	**Thu 08/07/10**	**Thu 08/07/17**
35	**Pilot Facility Test 2**	**Fri 08/07/11**	**Fri 08/07/25**
41	**Report**	**Fri 08/07/25**	**Thu 08/08/28**
45	**Tangentially Fired Boiler Validation**	**Thu 08/09/04**	**Thu 08/11/13**
46	Site Visit Meeting	Thu 08/09/0	Thu 08/09/0
47	Preparation for Site visit	Fri 08/09/0	Tue 08/09/1
48	Follow-up site meeting	Wed 08/09/1	Wed 08/09/1
49	Pack up equipment	Thu 08/09/1	Thu 08/09/1
50	**Commercial Boiler Test 3**	**Fri 08/09/19**	**Wed 08/09/24**
54	**Coal Preparation and Analyses**	**Thu 08/09/25**	**Thu 08/10/02**
57	**Pilot Facility Test 3**	**Fri 08/09/26**	**Fri 08/10/10**
63	**Report**	**Fri 08/10/10**	**Thu 08/11/13**
67	**Large Wall Fired Boiler Validation B**	**Fri 08/11/14**	**Thu 09/02/26**
68	Site Visit Meeting	Fri 08/11/1	Fri 08/11/1
69	Preparation for Site visit	Mon 08/11/1	Tue 08/11/2
70	Follow-up site meeting	Wed 08/11/2	Wed 08/11/2
71	Pack up equipment	Thu 08/11/2	Thu 08/11/2
72	**Commercial Boiler Test 4**	**Fri 08/11/28**	**Wed 08/12/03**
76	**Coal Preparation and Analyses**	**Thu 08/12/04**	**Thu 08/12/11**
79	**Pilot Facility Test 4**	**Fri 09/01/09**	**Fri 09/01/23**
85	**Report**	**Fri 09/01/23**	**Thu 09/02/26**



4 RESULTS

This chapter presents the chemical analyses of the four coal samples and the comparison of the results from the Drop Tube Furnace (DTF) and Pilot Scale Combustion Test Facility (PSCTF) relative to the four utility boilers.

4.1 CHEMICAL ANALYSES FOR THE COAL FROM FULL-SCALE BOILERS

A summary of the basic chemical analyses for the SWF, LWF A, TF and LWF B validation coal samples are shown in Table 3. The four coals are variable and generally high in ash content ranging from 25% to 39.6% with corresponding calorific values ranging from 22.27 MJ/kg to 15.02 MJ/kg placing all coals in Grade D South African Bureau of Standards (SABS) classification. The volatile matter content also ranges from 19.2% to 22.1%. Total sulphur is relatively low in the SWF sample and high in the TF sample.

The Fuel Ratio is calculated as Fixed Carbon/Volatile Matter and is based on laboratory analysis results. This ratio is utilized to determine whether there is sufficient volatile matter content available to provide ignition for the carbon present. From previous experience, it has been shown that the typical fuel ratio value for low ash coal should be less than <2.2. The minimum volatile matter content is dependant on the design of the furnace and/or burner types and arrangement. Therefore, the fuel ratio is a guideline and values lower than 2 indicate better ignition properties for a coal. Based on the fuel ratio, the LWF A coal sample should possess the best ignition properties in comparison to the others.

The Hydrogen / Carbon Ratio is another calculation utilized as a guideline to determine a relative percentage of reactive macerals. Reactivity is defined as the propensity of the organic constituents of the coals to react to heating. Therefore, the higher percentage of reactive macerals in a coal, the better the ignition combustion performance is likely to be. From previous experience, it has been shown that the typical acceptable value for the Hydrogen/Carbon ratio is >0.05. Based on the Hydrogen/Carbon ratio the TF coal sample should possess the highest content of reactive macerals and therefore be easier to combust.

However, the TF coal sample has a significantly lower Hardgrove Index (HGI) value in comparison to the other coal samples. This implies that the TF coal sample will be more difficult to grind than the other coal samples in the test mill at the PSCTF. This implies that there will be a compromise between particle fineness and throughput.

TABLE 3: BASIC CHEMICAL ANALYSES FOR THE VALIDATION COAL SAMPLES OBTAINED FROM THE FULL-SCALE BOILERS

Component (air dried basis)	Units	Small Wall-Fired	Large Wall-Fired A	Tangentially-Fired	Large Wall-Fired B
Proximate					
Inherent Moisture	%	4.2	6.2	2.8	4.6
Ash	%	25.0	39.6	35.7	32.2
Volatile Matter – VM	%	22.1	19.2	21.4	22.1
Fixed Carbon – FC (by difference)	%	48.7	35.0	40.1	41.1
Fuel Ratio - FC/VM		2.20	1.82	1.87	1.86
Ultimate					
Carbon	%	56.73	41.62	47.90	49.45
Hydrogen	%	2.75	2.20	2.87	1.56
Nitrogen	%	1.26	0.95	1.23	1.5
Total Sulphur	%	0.60	1.07	1.42	0.7
Carbonate (as CO2)	%	1.07	1.56	2.17	1.79
Oxygen (by difference)	%	8.39	7.23	5.91	8.2
Hydrogen/Carbon		0.0485	0.0529	0.0599	0.0315
Gross Calorific Value	MJ/kg	22.27	15.02	18.58	18.91
Ash Elementals					
Silicon reported as SiO_2	%	54.70	54.20	52.60	50.9
Aluminum reported as Al_2O_3	%	27.30	28.40	30.40	29.1
Iron reported as Fe_2O_3	%	3.40	4.90	5.51	2.5
Titanium reported as TiO_2	%	1.30	1.30	1.37	1.5
Phosphorus reported as P_2O_5	%	0.56	0.44	0.66	0.69
Calcium reported as CaO	%	4.40	4.40	4.63	6.2
Magnesium reported as MgO	%	1.70	1.50	1.56	1.8
Sodium reported as Na_2O	%	0.01	0.01	0.27	0
Potassium reported as K_2O	%	0.60	0.60	0.97	0.5
Sulphur reported as SO_3	%	2.70	4.40	2.02	3.3
Manganese reported as MnO	%	0.03	0.04	-	0.03
Abrasiveness Index	mg Fe	284	832	295	282
Hardgrove Grindability Index		56	58	48	51

4.2 DROP TUBE FURNACE RESULTS

The summary of ignition parameters that were obtained from the Drop Tube Furnace (DTF) for the validation coal samples are detailed in Table 4. The actual yield of the volatile material in the original coal as determined by the DTF has shown to be substantially greater than that determined by the ESKOM method 102 rev1 that is detailed in Appendix I. The major contributing factor is due to the difference in heating rates and the final temperature achieved; i.e. DTF 10 000°C/s versus Oven 100's°C/s (see Table 5). The operating temperatures of the oven and the DTF are 850°C and 1400°C respectively. It is suggested that the volatile yields derived by the DTF are more representative of the volatiles actually evolved during the combustion process in the flame of a furnace, where heating rates and final temperature achieved are similar to the DTF. The activation energy is a measure of the energy required to initiate the combustion reaction. The lower the activation energy value the easier the combustion process. The energy ratio calculation is as follows:

$$E_r = (CV_{vm} \times DTF_{vm})/((E/(12.01 \times 1000)) \times (100\text{-IM-ASH-}\ DTF_{vm})) \quad 9$$

TABLE 4: DROP TUBE FURNACE RESULTS

Ignition Parameters	Units	Small Wall-Fired	Large Wall-Fired A	Tangentially-Fired	Large Wall-Fired B
Volatiles by DTF, VM_{DTF}	%	31.3	29.5	29.7	25.89
CV of volatiles, CV_{VM}	MJ/kg	28.5	24.1	27.0	23.06
Heat in volatiles, HIV	%	28.4	44.1	40.3	29.50
Activation energy, E	kJ/mol	58.5	83.7	68.7	42.39
Energy ratio, E_r		2.7	1.4	2.0	2.57
Burnout Time*	sec	2.2	1.9	1.5	1.6

*Burnout Time is the time taken to achieve 98% combustion efficiency

Based on the higher volatile matter content as determined by the DTF results, it was anticipated that the fuel ratios for the coals as determined by the laboratory method would change. These results are illustrated in Table 5 where the two sets are graphically represented for comparison in Figure 4. Coal with good ignition properties will be located in the yellow quadrant (top left - Vitrinite rich coals) and coals with poorer ignition properties in the red quadrant (bottom right – Inertinite rich coals). In Figure 4, the values displayed on the graph are the volatile matter content as detailed in Table 5. The DTF fuel ratios for LWF A and TF coal samples are now shown to possess better ignition properties than the fuel ratios calculated from the basic chemical analysis. The LWF B coal sample still remains relatively low in the expected ignition combustion behaviour.

TABLE 5: FUEL RATIO RESULTS BETWEEN LABORATORY AND DTF

	Units	Small Wall-Fired		Large Wall-Fired A		Tangentially-Fired		Large Wall-Fired B	
		LAB	DTF	LAB	DTF	LAB	DTF	LAB	DTF
Volatile Matter Content	%	22.10	31.30	19.20	29.50	21.4	29.70	22.1	25.89
Fixed Carbon (by Diff)		48.70	39.50	35.00	24.7	40.1	31.80	41.1	37.31
Fuel Ratio		2.20	1.26	1.82	0.84	1.87	1.07	1.86	1.44

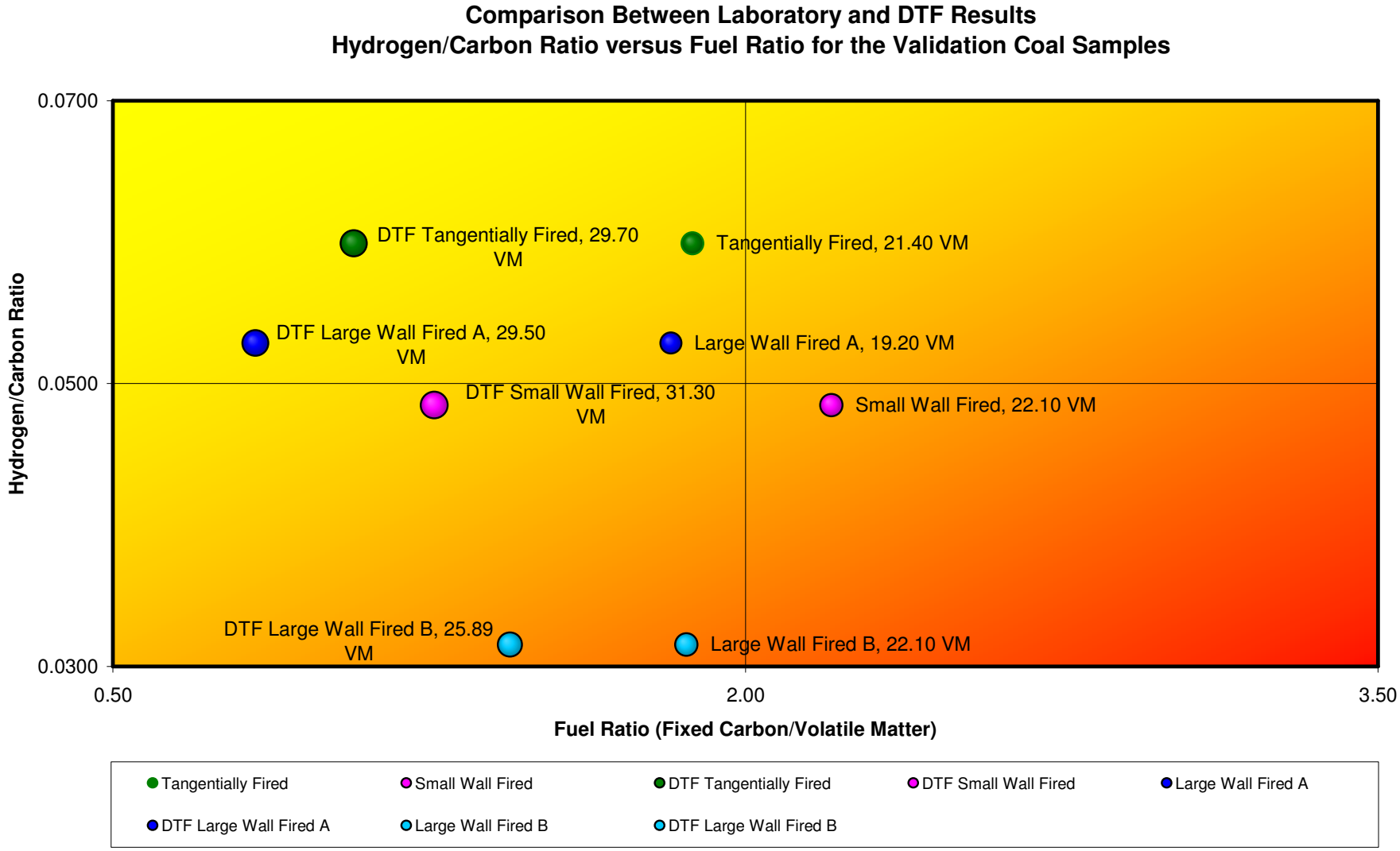


FIGURE 4: GRAPHICAL REPRESENTATION OF THE COMPARISON BETWEEN LABORATORY AND DTF RESULTS

4.3 SMALL WALL-FIRED BOILER (SWF) VALIDATION

The Small Wall-Fired (SWF) boiler is a 200 MW_e (Electrical), sub-critical unit with six vertical spindle mills. Five of these mills are required to generate the Maximum Continuous Rating (MCR) of 200 MW_e.

4.3.1 Raw Coal and Pulverized Fuel Sampling

Raw coal was sampled according to the ISO 1988:1975 Solid Fuel sampling. The pulverized fuel (pf) sampling was performed according to the ASME -1954 PTC 3.2 - Solid Fuels (Pulverized Fuel Sampling). PF samples were obtained from the five operating feeders A, C, D, E, and F at the SWF boiler. The representative raw coal sample was submitted for the following chemical analyses: Proximate, Ultimate, Calorific Value, Ash Elementals, Abrasiveness and Hardgrove Indexes (see Table 3)

TABLE 6: PULVERIZED FUEL FINENESSES FROM THE SMALL WALL-FIRED BOILER AND THE PSCTF

Pulverized Fuel Fineness From The Small Wall-Fired Boiler				
	% passing 300µm	**% passing 150µm**	**% passing 106µm**	**% passing 75µm**
Mill 9A	99.6	93.9	82.4	67.6
Mill 9B	99.8	95.3	85.0	70.6
Mill 9D	99.0	93.0	82.4	68.9
Mill 9E	99.8	92.0	79.0	62.8
Mill 9F	99.3	92.5	80.6	64.8
Average	**99.5**	**93.3**	**81.9**	**66.9**
Pulverized Fuel Finenesses From The PSCTF				
SWFV001	90.28	76.14	63.20	52.86
SWFV002	95.12	84.75	74.73	63.62
SWFV003	89.07	75.34	64.61	58.66
SWFV004	94.59	85.42	73.48	58.27
SWFV005	99.04	91.80	80.29	69.79
SWFV006	99.69	93.16	79.29	70.19
SWFV007	99.73	92.23	75.59	59.99
SWFV008	97.85	90.71	79.82	66.94
SWFV009	99.39	90.30	74.62	61.27
SWFV010	98.77	92.25	78.07	59.11
SWFV011	76.59	66.32	60.64	52.43
SWFV012	94.57	89.56	77.40	65.06
SWFV013	99.09	95.37	76.30	67.08
SWFV014	99.41	93.58	80.11	63.22
SWFV015	99.82	94.14	78.35	63.47

The pilot scale pf sample was captured during each test. Thereafter, it had been screened with the use of an Alpine A200 LS air jet particle size analyser. The air jet operates under suction and drew the pf test samples through similar test sieve apertures to that of the full-scale analysis. The determination of the percentage passing through each sieve was calculated by the final mass remaining on the sieve divided by the initial mass presented to the sieve. Table 6 details the pf fineness results from the full and pilot scale test mills. For the full analyses on pf sampling conducted at the SWF boiler and PSCTF refer to Appendix A. The pf sampling accuracy is within 10%.

4.3.2 Coarse and Fly Ashes

Coarse and fly ashes were sampled twice during the test period and in accordance with ISO 1988:1975 for Solid Fuel sampling. A stainless steel colander welded to a metal pipe was utilised to grab the coarse ash samples when the boiler was being ashed. A total coarse ash quantity of 300kg was collected and stored in plastic bags. The combustible results shown in Table 7 are a comparison of the fly and coarse ashes sampled from both the full and pilot furnaces. Both the pilot coarse and fly ash samples were accumulated over the duration of the operation of the facility. These samples reflected the results from the start-up to shutdown of the test facility whereas the samples obtained from the full-scale plant reflected the test period conditions only due to online ashing systems. Therefore, the full-scale results indicated the performance of the coal combustion condition for the test period and the PSCTF indicated the overall performance from start-up to shutdown. For the above reasons, a direct comparison of the combustible residue in ash samples between the pilot scale and the full-scale boiler was not achieved due to the lack of online ashing systems at the PSCTF.

TABLE 7: COMPARISON OF THE COMBUSTIBLE RESIDUE IN THE COARSE AND THE FLY ASH SAMPLES BETWEEN THE PSCTF AND THE SMALL WALL-FIRED BOILER

Description	Small Wall-Fired Boiler (Combustible Residue)	
	SWF	PSCTF
Coarse Ash	1.8%	15.8%
Fly Ash	2.1%	7.5%

4.3.3 Pilot Scale Validation of the Small Wall-Fired Boiler

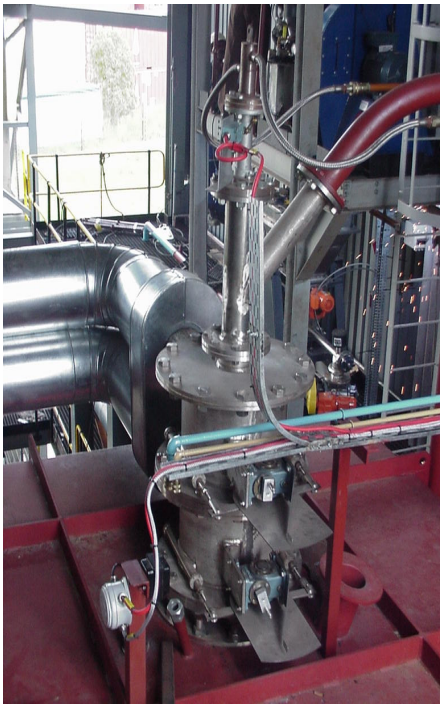
TABLE 8: RESULTS OBTAINED FROM THE SMALL WALL FIRED BOILER

.	SI Units	Level		
		20m / 0.74s (LH)	28m / 1.59s (LH)	34m / 2.2s (LH)
Combustible Residue	%	7.24	4.43	2.79
Combustion Efficiency	%	96.56	97.96	98.73
Oxygen (dry basis)	%	4.67	4.46	3.85
Carbon Monoxide (normalized to 6% O_2)	ppm	45	46	NM
Sulphur Dioxide (normalized to 6% O_2)	mg/Nm^3	1386*	1518*	NM
Oxides of Nitrogen (normalized to 6% O_2)	mg/Nm^3	1395**	1488**	974**
Temperature	℃		1452	984
Temperature 50 foot	℃	1358		
Temperature 60 foot	℃	1335		
		LH	RH	
Primary Air Flow	kg/s	32.63		
Primary Air Temperature	℃	80		
Secondary Air Flow	kg/s	180		
Secondary Air Flow Temperature	℃	254	266	
Secondary/Primary Air Ratio		2.25		
Backend Oxygen (wet basis)	%	3.10	2.74	
Backend Oxygen (dry basis)	%	3.29#	2.90#	
Furnace Pressure	Pa	-164		
Furnace Temperature Front	℃	1208	1135	
Furnace Temperature Side Front	℃	1215	1179	
Furnace Temperature Side Rear	℃	1239	1179	
Furnace Temperature Rear	℃	1230	1263	

*Density of SO_2 - 2.86kg/m^3, **Density of NO_x - 2.06kg/m^3, #Assumed 6% as the moisture content in flue gas

Table 8 details the results obtained during the full-scale validation tests on the Small Wall-Fired (SWF) boiler. For the detailed full-scale test logs, refer to Appendix B. Boiler flue dust samples were extracted from the boiler at the 28m (above the burner region) and the 34m (furnace exit) levels on the SWF. These samples were extracted at ½m intervals to a depth of 4m at each elevation. All the boiler flue dust samples from the PSCTF and SWF boiler underwent analyses to determine the combustible residue in the flue dust according to the ESKOM Method 126 rev1 (refer to Appendix I). Equations 2 and 3 in section 3.3.2 were utilized to convert the pf burnout results to the coal combustion efficiency results (see Table 8, 9 and 10). Boiler flue gas temperature measurements were recorded at each elevation with an optical pyrometer. The particle residence times for the 20m, 28m and 34m elevations were 0.74, 1.59 and 2.2 seconds respectively. These times were previously determined with sulphur injection residence time tests. The results from Table 8 were utilized to setup the PSCTF in an attempt to match the coal combustion efficiency of the SWF boiler.

The validation process for the SWF boiler focused on the optimization of PSCTF 1 $MW_{th,}$ low NO_x, variable swirl burner (see photograph alongside text). The SWF had the conventional circular burner; i.e. with primary and secondary air only. Therefore, the SWF validation tests were conducted with a variance in one or more of the inlet conditions (swirl settings, pf fineness, percentage secondary and/or tertiary air contribution). The 0 swirl setting (jet burner) on the PSCTF burner was eliminated from the evaluation due to the lack of mixing which produces significantly lower coal combustion performance. The 1 swirl (intermediate) and 2 swirl (high swirl) conditions were utilised during the SWF validation. The swirl blocks in both the secondary and tertiary air were set to the 1 swirl or intermediate position.



The comparison between full and pilot scales results was considered on the basis of the following factors:

- Solid samples were extracted at a third of the furnace width to a depth of 4m at ½m intervals on the full-scale furnace whereas solid samples were captured in the middle of the pilot scale furnace.

- The particle residence times for each extraction position at the pilot scale furnace was calculated whereas the particle residence time at the full-scale plant had been previously measured during 1996.
- The PSCTF is a single burner combustion system whereas the full-scale boilers are multi-burner combustion system. There is a significantly high surface to volume ratio at the PSCTF in comparison to the full-scale boilers. The air/fuel imbalances on the full-scale boilers could not be replicated at the PSCTF (Sotter et al,1986).

Tables 9 and 10 detail the PSCTF settings and results for each of the following series of test conditions utilized in the validation of the PSCTF:

- SWFV001: 100% Secondary air - Swirl 1
- SWFV002: 100% Secondary air - Swirl 1
- SWFV003: 100% Secondary air - Swirl 1
- SWFV004: 100% Tertiary air - Swirl 1
- SWFV005: 100% Tertiary air - Swirl 1
- SWFV006: 100% Secondary air - Swirl 1
- SWFV007: 100% Secondary air - Swirl 2
- SWFV008: 100% Tertiary air - Swirl 2
- SWFV009: 100% Secondary air - Swirl 2
- SWFV010: 100% Secondary air - Swirl 2
- SWFV011: 100% Secondary air - Swirl 2
- SWFV012: 100% Tertiary air - Swirl 1
- SWFV013: 24% Secondary air, 76% Tertiary Air - Swirl 1
- SWFV014: 50% Secondary air, 50% Tertiary Air - Swirl 1
- SWFV015: 77% Secondary air, 23% Tertiary Air - Swirl 1

Smart et al (1996) indicated that neither the constant-velocity nor the constant-residence - time scaled burner designs are able to reproduce adequate similarities in the flame structure and thermo-chemical fields. Therefore, this led to determining the optimum setting for the pilot burner by attempting to maintain the secondary/primary burner air ratio between 2.5 to 3.5. The actual burner air ratio measurements ranged between 2.78 and 4.57 (see Tables 9 and 10). Backend or exit oxygen concentration measurements ranged between 4.24 and 5.61% (dry basis). The coal combustion efficiency and flue gas temperature residence time positions were calculated by dividing the flue gas volume rate by the volume of furnace. The volume of the furnace was determined by calculating the volume between the inlet and extraction points. Figure 5 and 6 details the coal combustion efficiency results from the SWF and the PSCTF boiler and are represented as squares and other shapes respectively. The PSCTF coal combustion efficiency results are shown in different shapes for the various inlet configurations. A curve fit program was utilized to

generate the flue gas temperature curves (solid lines with the corresponding shapes). Colour coding was utilised to pair the coal combustion efficiency results with the flue gas temperature profiles. The pf burnout results were determined from 3 extraction points on the full-scale and pilot scale furnaces.

PSCTF coal tests were performed in an attempt to obtain the pf burnout that most closely matched the results obtained from the SWF boiler. Lindsay (1995) indicated that to simulate pf burnout of the full-scale plant the pilot scale furnace walls should be designed for temperatures >1000℃ to overcome the higher rates of heat loss. The wall temperatures for all the coal tests that are closest to the pilot burner were in excess of 1000℃. The validation tests were performed at both 1 and 2 swirl setting with either 100% secondary or variation in tertiary air contributions. The pilot scale validation coal tests for the 1 swirl setting (SWFV003 and from SWFV012 to SWFV015) and the 2 swirl setting (SWFV007 and SWFV008) are graphically represented in Figure 5 and Figure 6 respectively.

In Figure 5 the best and worst combustion efficiency results achieved in comparison to the SWF boiler for the 1 swirl setting were SWFV003 and SWF013 and are indicated in light blue and brown triangles respectively. The coal combustion efficiency results for the pilot test SWFV003 produced similar results to that of the SWF boiler. The SWFV003 was conducted with an excess air level being approximately 81% higher than the SWF boiler and 100% secondary air. Pilot scale test SWFV012 and SWFV015 produced similar results to that of the SWF boiler even though air distribution ratios were different; i.e. SWFV012 was fired with 100% tertiary air and SWFV015 was fired with 70/30 of secondary/tertiary air. The 2 swirl setting results have shown that the increased recirculation and/or mixing did not improve the combustion efficiency results in comparison to the 1 swirl setting. The PSCTF coal combustion efficiency results have shown that excess air levels are inversely proportional to the coal combustion efficiency. The change in air contribution through the secondary and tertiary annuli and associated swirl settings has shown variations in flame structure and the thermo-chemical fields (Figure 5 and 6).

A portable gas analyzer was utilized to measure the gaseous emissions at the pilot scale and full-scale furnaces. Equation 1 was utilized to normalize the gaseous emissions measured at both facilities to 6% oxygen concentration. Thereafter, the NO_x and the SO_2 volumetric concentrations (ppm) were converted to mass concentration (mg/Nm^3) with the use of the gas densities (see section 3.3.2). The pilot carbon monoxide (CO) measurements were comparable with the results obtained from the SWF boiler. The pilot oxides of nitrogen (NO_x) measurements were significantly lower than the SWF boiler.

TABLE 9: PILOT SCALE SETTINGS AND RESULTS FOR THE SMALL WALL-FIRED BOILER VALIDATION COAL TESTS – 1 SWIRL

Fuel	Units	SWF-V001	SWF-V002	SWF-V003	SWF-V004	SWF-V005	SWF-V006	SWF-V007	SWF-V008
Coal Flow	kg/hr	164	164	164	164	164	164	164	164
Output	MW_{th}	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Grind size - passing 75 microns	%	52.66	63.62	58.66	58.27	69.79	70.19	59.99	66.94
Blend Ratio									
Small Wall-Fired Validation Coal	%	100	100	100	100	100	100	100	100
Air									
Total Air Flow	kg/hr	1467	1468	1553	1554	1465	1466	1466	1465
Secondary Air/Primary Air Ratio		3.37	3.37	4.57	4.57	3.53	2.78	3.51	3.52
Swirl Setting – Secondary Air		1	1	1	1	1	1	2	2
Swirl Setting – Tertiary Air		1	1	1	1	1	1	2	2
Excess Air	%	33.35	30.39	36.66	31.56	27.65	29.83	33.68	31.48
Primary Air Flow	kg/hr	336	336	279	279	323	324	325	324
Primary Air Temperature	℃	93	93	93	93	93	93	93	93
Secondary Air Flow	kg/hr	1131	1132	1274	86	75	1142	1141	89
Secondary Air Temperature	℃	302	302	301	259	241	302	302	261
Tertiary Air Flow	kg/hr	0	0	0	1189	1066	0	0	1052
Tertiary Air Temperature	℃	170	170	173	301	302	234	204	302
Furnace									
Furnace Pressure	Pa	-341	-294	-171	-210	-286	-239	-260	-295
Flue Gas Temperature (0.274-0.304s)	℃	1193	1217	1193	1207	1237	1236	1234	1245
Flue Gas Temperature (0.789 0.874s)	℃	1278	1287	1244	1228	1242	1279	1251	1251
Flue Gas Temperature (1.235-1.368s)	℃	1218	1242	1214	1198	1205	1245	1291	1291
Flue Gas Temperature (3.362-3.725s)	℃	919	949	1006	1018	901	1048	944	939
Average Flue Gas Temperatures	℃	1152	1174	1164	1163	1146	1202	1180	1182
Furnace Wall Temperature 1	℃	1064	1065	1073	1077	1079	1084	1089	1089
Furnace Wall Temperature 2	℃	1108	1109	1124	1136	1146	1155	1166	1175
Furnace Wall Temperature 3	℃	826	835	847	853	873	898	910	914
Furnace Wall Temperature 4	℃	764	771	790	800	810	822	835	843
Furnace Wall Temperature 5	℃	779	790	805	819	835	850	863	874
Results-Normalized to 6% Oxygen									
Oxygen (wet basis)	%	4.45	4.26	5.00	4.38	4.01	4.41	5.09	4.69
Oxygen (dry basis)	%	5.23	4.87	5.61	5.01	4.53	4.80	5.27	5.00
Carbon Monoxide (dry basis)	ppm	45	33	42	44	34	33	32	28
Oxides of Nitrogen (dry basis)	mg/Nm^3	43**	106**	84**	89**	132**	166**	183**	186**
Combustion Efficiency/*CR*(1.818-2.015s)	%	95.10/10	95.85/8.6	97.88/4.6	96.53/7.3	96.01/8.3	95.69/8.9	96.58/7.2	96.68/7.0
Combustion Efficiency/*CR*(2.367-2.623s)	%	96.78/6.8	96.84/6.7	98.35/3.6	98.54/3.2	97.04/6.3	96.78/6.8	98.07/4.2	97.78/4.8
Combustion Efficiency/*CR*(3.362-3.725s)	%	98.07/4.2	98.26/3.8	98.82/2.6	99.01/2.2	98.82/2.6	98.73/2.8	99.01/2.2	98.31/3.7

CR – Combustible Residue, NM – Not Measured, **Density of NO_x - $2.06kg/m^3$

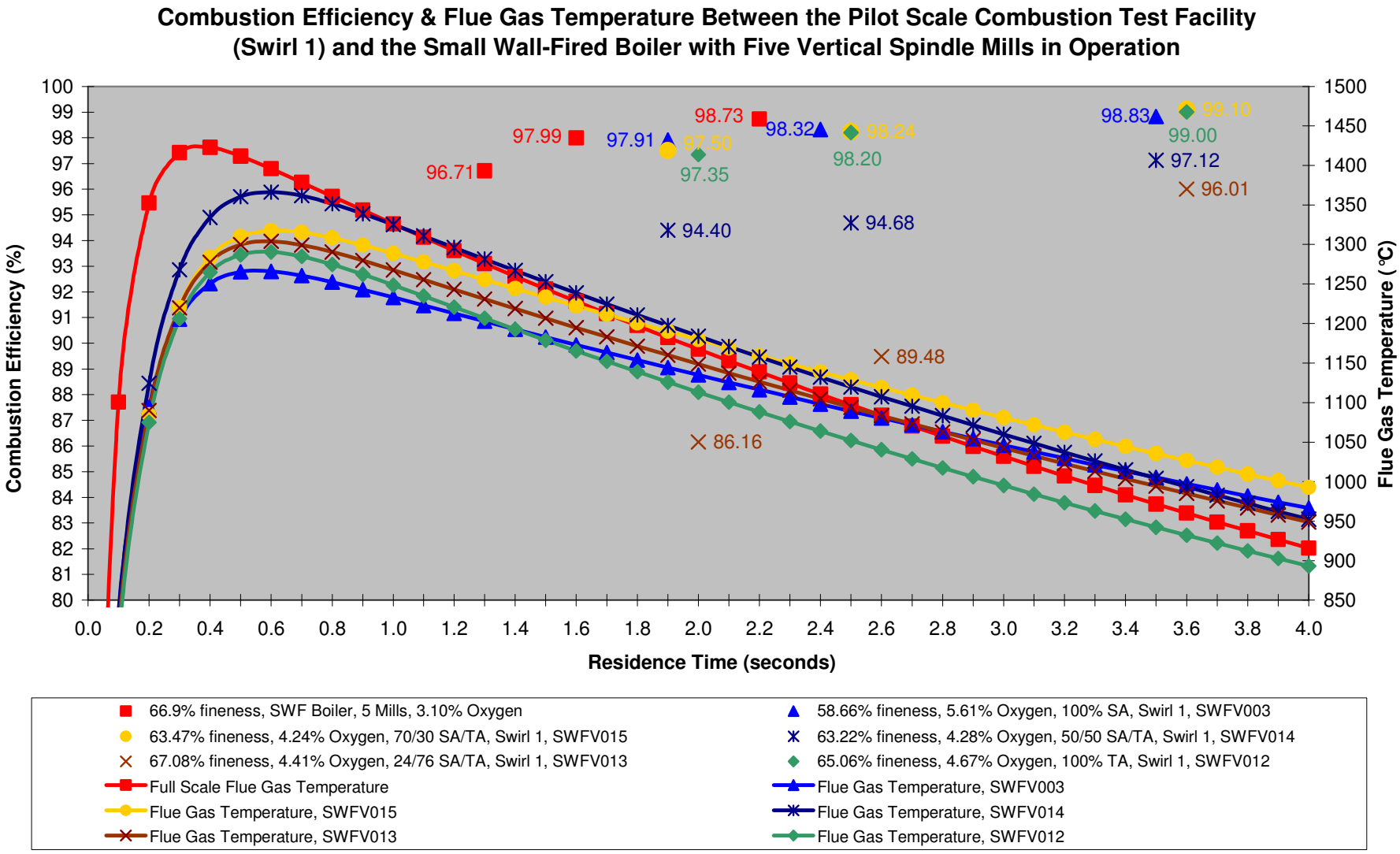


FIGURE 5: COMBUSTION PERFORMANCE BETWEEN THE PSCTF (1 SWIRL) AND THE SMALL WALL-FIRED BOILER

TABLE 10: PILOT SCALE SETTINGS AND RESULTS FOR THE SMALL WALL-FIRED BOILER VALIDATION COAL TESTS – 2 SWIRL

Fuel	Units	SWF-V009	SWF-V010	SWF-V011	SWF-V012	SWF-V013	SWF-V014	SWF-V015
Coal Flow	kg/hr	164	164	163	163	163	164	163
Output	MW_{th}	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Grind size - passing 75 microns	%	61.27	59.11	52.43	65.06	67.08	63.22	63.47
Blend Ratio								
Small Wall-Fired Validation Coal	%	100	100	100	100	100	100	100
Air								
Total Air Flow	kg/hr	1467	1475	1467	1464	1464	1467	1466
Secondary Air/Primary Air Ratio		3.74	4.34	3.20	3.18	3.20	3.19	3.19
Swirl Setting – Secondary Air		2	2	2	1	1	1	1
Swirl Setting – Tertiary Air		2	2	2	1	1	1	1
Excess Air	%	28.76	30.02	36.09	28.74	26.76	25.75	25.46
Primary Air Flow	kg/hr	309	276	350	350	349	350	350
Primary Air Temperature	℃	93	93	92	92	92	92	92
Secondary Air Flow	kg/hr	1157	1199	1118	54	269	557	915
Secondary Air Temperature	℃	302	302	302	271	279	293	299
Tertiary Air Flow	kg/hr	0	0	0	1060	846	559	202
Tertiary Air Temperature	℃	222	203	201	298	300	297	287
Furnace								
Furnace Pressure	Pa	-267	-266	-267	-300	-321	-303	-316
Flue Gas Temperature (0.288-0.298s)	℃	1237	1237	1184	1204	1219	1259	1215
Flue Gas Temperature (0.829-0.857s)	℃	1247	1248	1258	1231	1255	1306	1275
Flue Gas Temperature (1.297-1.342s)	℃	1297	1295	1286	1397	1262	1332	1289
Flue Gas Temperature (3.531-3.653s)	℃	960	970	967	920	973	990	1021
Average Flue Gas Temperatures	℃	1172	1187	1174	1188	1177	1222	1200
Furnace Wall Temperature 1	℃	1090	1088	1087	1084	1079	1076	1075
Furnace Wall Temperature 2	℃	1194	1200	1206	1209	1206	1203	1200
Furnace Wall Temperature 3	℃	934	941	956	962	971	981	985
Furnace Wall Temperature 4	℃	854	860	865	869	871	874	877
Furnace Wall Temperature 5	℃	881	886	893	900	905	910	914
Results-Normalized to 6% Oxygen								
Oxygen (wet basis)	%	4.13	4.32	5.08	4.32	4.00	3.22	3.65
Oxygen (dry basis)	%	4.67	4.83	5.54	4.67	4.41	4.28	4.24
Carbon Monoxide (dry basis)	ppm	27	24	28	27	30	35	34
Oxides of Nitrogen (dry basis)	mg/Nm^3	181**	195**	200**	165**	172**	181**	175**
Combustion Efficiency/*CR*(1.910-1.976s)	%	96.12/8.1	96.48/7.4	97.09/6.2	97.24/5.9	85.78/24.4	94.44/11.2	97.58/5.2
Combustion Efficiency/*CR*(2.486-2.572s)	%	98.16/4.0	98.26/3.8	97.97/4.4	98.26/3.8	89.26/19.6	94.66/10.8	98.26/3.8
Combustion Efficiency/*CR*(3.531-3.653s)	%	98.92/2.4	98.68/2.9	98.82/2.6	99.01/2.2	96.12/8.1	97.14/6.1	99.10/2.0

CR – Combustible Residue, NM – Not Measured, **Density of NO_x - $2.06kg/m^3$

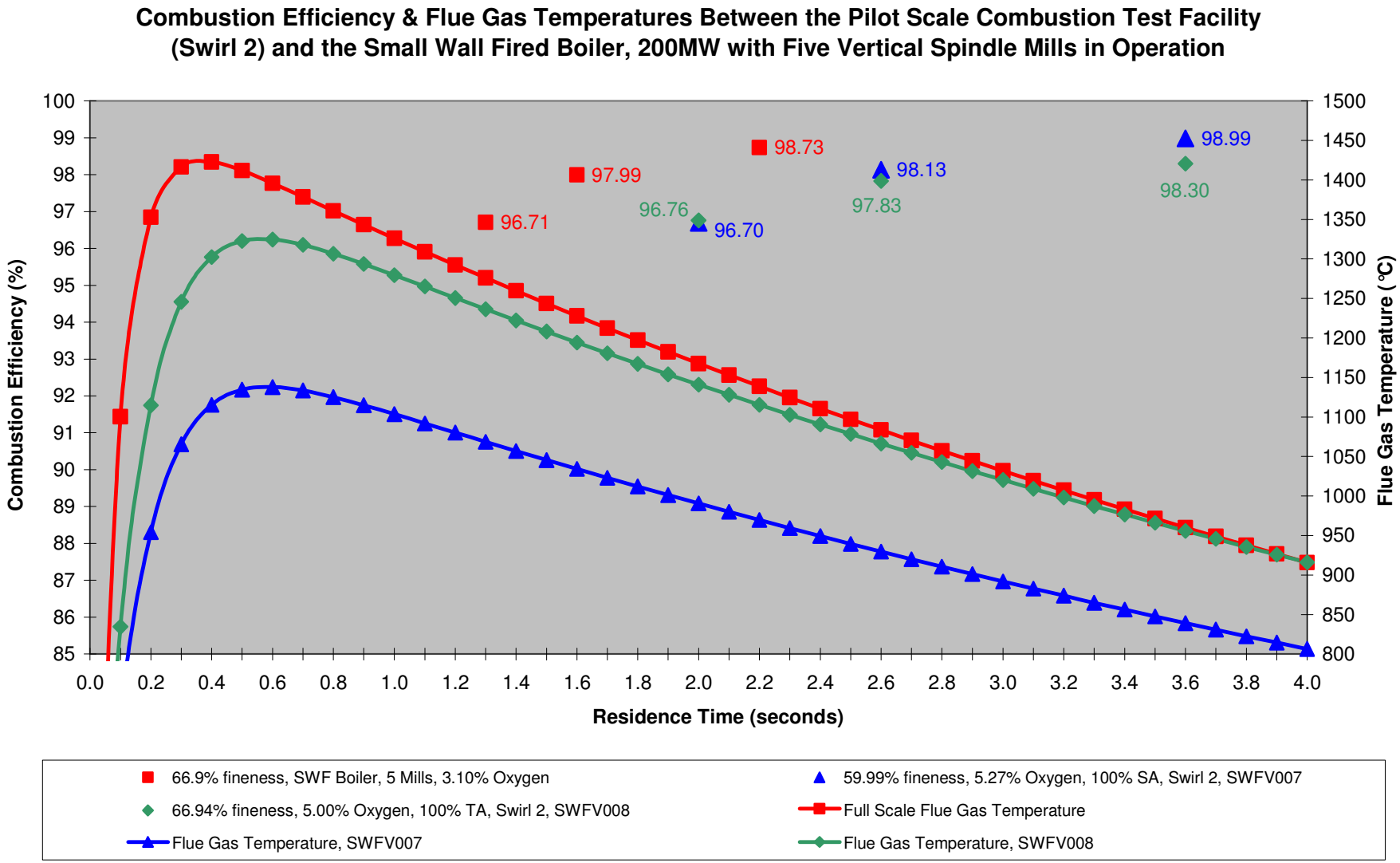


FIGURE 6: COMBUSTION PERFORMANCE BETWEEN THE PSCTF (2 SWIRL) AND THE SMALL WALL-FIRED BOILER

4.4 LARGE WALL-FIRED BOILER A (LWF A) VALIDATION

The Large Wall-Fired (LWF) boiler A is a 600 MW_e (Electrical), sub-critical unit with six tube/ball mills. Five of these mills are required to generate the Maximum Continuous Rating (MCR) of 600 MW_e

4.4.1 Raw Coal and Pulverized Fuel Sampling

Raw coal samples were captured from the feeders in service and in accordance with ISO 1988:1975 for Solid Fuel sampling. A representative raw coal sample underwent the basic chemical analyses and these results are detailed in Table 3.

TABLE 11: PULVERIZED FUEL FINENESSES FROM THE LARGE WALL-FIRED BOILER A AND THE PSCTF

Pulverized Fuel Finenesses From The Large Wall-Fired Boiler				
	% passing 300µm	**% passing 150µm**	**% passing 106µm**	**% passing 75µm**
Mill 4A	99.5	98.0	94.9	88.8
Mill 4B	99.4	95.8	91.0	82.3
Mill 4C	99.2	96.1	91.2	83.0
Mill 4D	97.8	91.4	85.8	77.0
Mill 4F	99.4	95.4	90.2	81.0
Average	**99.1**	**95.3**	**90.6**	**82.4**
Pulverized Fuel Finenesses From The PSCTF				
LWFV001A	99.93	98.29	93.77	84.78
LWFV002A	99.96	98.61	93.10	83.55
LWFV003A	99.96	98.25	93.98	84.80
LWFV004A	99.95	98.57	96.94	92.40
LWFV005A	99.98	98.22	92.65	83.72
LWFV006A	99.99	98.77	96.39	89.29
LWFV007A	99.98	98.55	94.81	84.57
LWFV008A	100.00	98.35	92.37	81.08
LWFV009A	99.93	97.51	93.84	88.39

Table 11 details the results obtained during the full-scale validation tests at the LWF boiler A (refer to section 3.1.4 for method and accuracy). For the full analyses on pf sampling conducted at the PSCTF and the LWF refer to Appendix C. These results were utilized to setup the PSCTF in an attempt to simulate the pf burnout achieved at the LWF boiler A.

4.4.2 Coarse and Fly Ashes

TABLE 12: COMPARISON OF THE COMBUSTIBLE RESIDUE IN THE COARSE AND THE FLY ASH SAMPLES BETWEEN THE PSCTF AND THE LARGE WALL-FIRED BOILER A

Description	**Large Wall-Fired Boiler (Combustible Residue)**	
	LWF A	**PSCTF**
Coarse Ash	2.7%	0.01%
Fly Ash	1.3%	3.8%

Coarse and fly ashes were continuously sampled for the duration of the test period from all 16 conveyor belts in accordance with the ISO 1988 1975 standard. As previously mentioned in section 4.3.2, there is no direct comparison between the combustible residue

in fly and coarse ash samples for both furnaces as can be seen in Table 12. This is due to ashes being exposed to different combustion environments and time periods.

4.4.3 Pilot Scale Validation of the Large Wall-Fired Boiler A

Boiler flue dust samples were extracted from the 41m (burner belt region) and 66m (furnace exit) levels on LWF boiler A. All the boiler flue dust samples from the PSCTF and LWF boiler A underwent analyses to determine the combustible residue in the flue dust according to the ESKOM Method 126 rev1 (refer to Appendix I). Equations 2 and 3 in section 3.3.2 were utilized to calculate the coal combustion efficiency results (see Table 13 and 14). For detailed tests logs performed at the full-scale plant, refer to Appendix D. Table 13 and 14 detail the settings and results obtained from the full and pilot furnaces respectively. The full-scale settings and results were utilized in the setup of the PSCTF in an attempt to match the pf burnout obtained at the LWF boiler A.

TABLE 13: RESULTS OBTAINED FROM THE LARGE WALL-FIRED BOILER A

	SI Units	Level	
		41m (Burner belt)1.23s	66m (Furnace Exit)2.95s
Combustible Residue	%	0.79	0.47
Combustion Efficiency	%	99.24	99.55
Oxygen (dry basis)	%	9.44	1.49
Carbon Monoxide (Normalized to 6% O_2)	ppm	1155	857
Oxides of Nitrogen (Normalized to 6% O_2)	mg/Nm^3	964**	661**
Temperature	℃	1341	1054
		LH	**RH**
Primary Air Flow	kg/s	156	
Primary Air Temperature	℃	84	84
Secondary Air Flow	kg/s	460	
Secondary Air Flow Temperature	℃	269	276
Secondary/Primary Air Ratio		2.95	
Backend Oxygen (wet basis)	%	0.18	1.12
Backend Oxygen (dry basis)	%	0.19#	1.17#
Furnace Pressure	Pa	-436	-291
Flame 1	℃	1083	1107
Flame 2	℃	1192	1121
Flame 3	℃	1189	1180
Flame 4	℃	1157	1129

**Density of NO_x - 2.06kg/m^3, #Assumed 6% as the moisture content in flue gas

From the experience gained with the first validation test conducted for the SWF boiler, the focus had shifted from the burner to the excess air level due to its impact on the pf burnout of the coal. Therefore, the LWF boiler A validation coal tests were conducted with 100% secondary air and a variance in excess air percentage with the 1 swirl setting or the intermediate position. The following series of coal test conditions were performed to validate pilot scale coal combustion performances:

- LWFV001A: 84.78% passing 75µm, 23.10% Excess Air
- LWFV002A: 83.55% passing 75µm, 22.92% Excess Air
- LWFV003A: 84.80% passing 75µm, 18.30% Excess Air

- LWFV004A: 92.40% passing 75µm, 20.59% Excess Air
- LWFV005A: 83.72% passing 75µm, 19.36% Excess Air
- LWFV006A: 89.29% passing 75µm, 9.69% Excess Air
- LWFV007A: 84.57% passing 75µm, 7.52% Excess Air
- LWFV008A: 81.80% passing 75µm, 8.35% Excess Air
- LWFV009A: 88.39% passing 75µm, 26.07% Excess Air

Equations 4 and 5 to 8 detailed in section 3.3.2 was utilised to calculate the stoichiometric air requirements and variations in excess air requirements. The actual burner air ratio (SA/PA) measurements ranged from 2.63 to 3.65 (see Table 14). Backend or exit oxygen concentrations measurements ranged between 1.46 and 4.32% (dry basis).

As previously mentioned, the particle residence times were calculated by dividing the volume flow rate by the define volume of the furnace. Figure 7 details the coal combustion efficiency results from the LWF boiler A and the PSCTF are represented as squares and other shapes respectively. The PSCTF coal combustion efficiency results are shown in different colours and shapes for the various excess air level settings. A curve fit program was utilized to generate the flue gas temperature curves (solid lines with corresponding shapes). Shapes and colour codes were used to match flue gas temperatures to the corresponding set of coal combustion efficiency results, which are shown in Figures 7. PF burnout results were determined at 2 and 3 extraction points on the full-scale and pilot scale furnaces respectively. Therefore, the coal combustion efficiency results less than 1.23 seconds from the PSCTF are not comparable due to the lack of measurements from the LWF boiler A.

PSCTF coal tests were performed in an attempt to obtain the pf burnout that simulated the results obtained from the LWF boiler A. Figure 7 graphically represents the following pilot scale validation coal tests LWFV002A, LWFV005A, LWFV007A and LWFV009A. In Figure 7 the best and worst coal combustion efficiency results were achieved with test LWFV009A and LWF007A relative to the LWF A. Test LWFV009A was combusted at an exit oxygen concentration which was approximately 263% higher than that of the LWF boiler A and produced combustion efficiency results that most closely matched the LWF boiler A. The flue gas temperature profiles trends have shown that with better combustion, the coal ignites and burns out much faster as is indicated by the temperature profile in Figure 7. A decrease in excess air level resulted in delayed ignition and was depicted by the flue gas temperature profiles and coal combustion efficiency results.

Test LWFV007A with an exit oxygen concentration of approximately 23% higher than that of the LWF boiler A produced combustible residue results at 2.95 seconds residence time position of 3.1% and 0.47% respectively. Therefore, the PSCTF combustible residue results were approximately 6.6 times higher in comparison to that of the LWF boiler A under conditions of similitude. The PSCTF results have shown that combustible residue is inversely proportional to the excess air levels. The higher exit oxygen/excess air and furnace wall temperatures at the PSCTF produced similar aerodynamics of mixing air, flue gas and particles and these factors aided in the simulation of the pf burnout.

The gaseous emissions measured at the LWF boiler A and the PSCTF were conducted with a portable gas analyzer and an online gas analyzer respectively. Equation 1 was utilised to normalize the measured gas species to the 6% oxygen concentration. Thereafter, the NO_x and SO_2 emissions were converted from a volumetric concentration (ppm) to a mass concentration which is reported as mg/Nm3. Carbon Monoxide (CO) values were similar to that of the full-scale furnace when the PSCTF was under conditions of similitude. These gaseous emission results are detailed in Tables 13 and 14.

TABLE 14: PILOT SCALE RESULTS FOR THE LARGE WALL-FIRED BOILER A VALIDATION COAL

Fuel	Units	LWF-V001A	LWF-V002A	LWF-V003A	LWF-V004A	LWF-V005A	LWF-V006A	LWF-V007A	LWF-V008A	LWF-V009A
Coal Flow	kg/hr	244	242	242	244	241	242	240	244	242
Output	MW_{th}	1.02	1.01	1.01	1.02	1.01	1.01	1.00	1.02	1.01
Grind size - passing 75 microns	%	84.78	83.55	84.80	92.40	83.72	89.29	84.57	81.80	88.39
Blend Ratio										
LWF - Feeder	%	100	100	100	100	100	100	100	100	100
Air										
Total Air Flow	kg/hr	1582	1561	1438	1431	1431	1322	1311	1317	1567
Secondary Air/Primary Air Ratio		3.65	3.09	3.47	3.14	2.79	3.31	3.03	2.63	3.31
Swirl Setting – Secondary Air		1	1	1	1	1	1	1	1	1
Swirl Setting – Tertiary Air		1	1	1	1	1	1	1	1	1
Excess Air	%	23.10	22.92	18.30	20.59	19.36	9.69	7.52	8.35	26.07
Primary Air Flow	kg/hr	340	381	322	346	377	306	325	363	364
Primary Air Temperature	℃	87	87	87	87	87	87	87	87	87
Secondary Air Flow	kg/hr	1242	1180	1116	1086	1054	1016	985	954	1203
Secondary Air Temperature	℃	273	273	273	272	271	271	271	270	273
Tertiary Air Flow	kg/hr	0	0	0	0	0	0	0	0	0
Tertiary Air Temperature	℃	177	170	166	160	162	158	155	152	155
Furnace										
Furnace Pressure	Pa	NM	NM	-108	-170	-176	NM	NM	-25	45
Flue Gas Temperature (0.273-0.330s)	℃	1148	1119	1103	1088	1095	1085	1084	1078	1077
Flue Gas Temperature (0.785-0.948s)	℃	1344	1326	1344	1332	1335	1340	1339	1327	1338
Flue Gas Temperature (1.229-1.483s)	℃	1230	1239	1261	1270	1268	1264	1273	1269	1264
Flue Gas Temperature (3.346-4.038s)	℃	1034	1053	1051	1075	1073	1053	1067	1075	1072
Average Flue Gas Temperatures	℃	1189	1184	1190	1191	1193	1186	1190	1187	1188
Furnace Wall Temperature 1	℃	1151	1149	1142	1130	1134	1115	1115	1114	1115
Furnace Wall Temperature 2	℃	1247	1239	1250	1249	1249	1235	1234	1236	1239
Furnace Wall Temperature 3	℃	1046	1055	1061	1070	1066	1073	1074	1077	1081
Furnace Wall Temperature 4	℃	NM	NM	NM	NM	NM	NM	NM	NM	946
Furnace Wall Temperature 5	℃	866	876	888	903	897	915	917	921	924
Results – Normalized to 6% Oxygen										
Oxygen (wet basis)	%	3.36	3.36	1.89	2.29	2.17	1.49	0.99	1.29	3.48
Oxygen (dry basis)	%	3.92	3.90	3.23	3.57	3.39	1.85	1.46	1.61	4.32
Carbon Monoxide (dry basis)	ppm	32	24	64	58	79	951	964	513	15
Sulphur Dioxide (dry basis)	mg/Nm^3	1994*	1958*	1927*	1859*	1771*	613*	282*	152*	12*
Oxides of Nitrogen (dry basis)	mg/Nm^3	1773**	1769**	1416**	1542**	1558**	1143**	1046**	1253**	1828**
Combustion Efficiency/*CR*(1.809-2.184s)	%	99.04/1.0	98.65/1.4	97.26/2.8	98.45/1.6	98.35/1.7	96.14/3.9	95.93/4.1	97.06/3.0	99.04/1.0
Combustion Efficiency/*CR*(2.356-2.843s)	%	99.23/0.8	98.94/1.1	97.36/2.7	98.75/1.3	98.45/1.6	97.06/3.0	96.96/3.1	97.16/2.9	99.52/0.5
Combustion Efficiency/*CR*(3.346-4.038s)	%	99.43/0.6	99.43/0.6	98.16/1.9	99.99/0.001	99.14/0.9	97.36/2.7	97.46/2.6	97.86/2.2	99.52/0.5

CR – Combustible Residue, NM – Not Measured, *Density of SO_2 - 2.86kg/m^3, ** Density of NO_x - 2.06kg/m^3

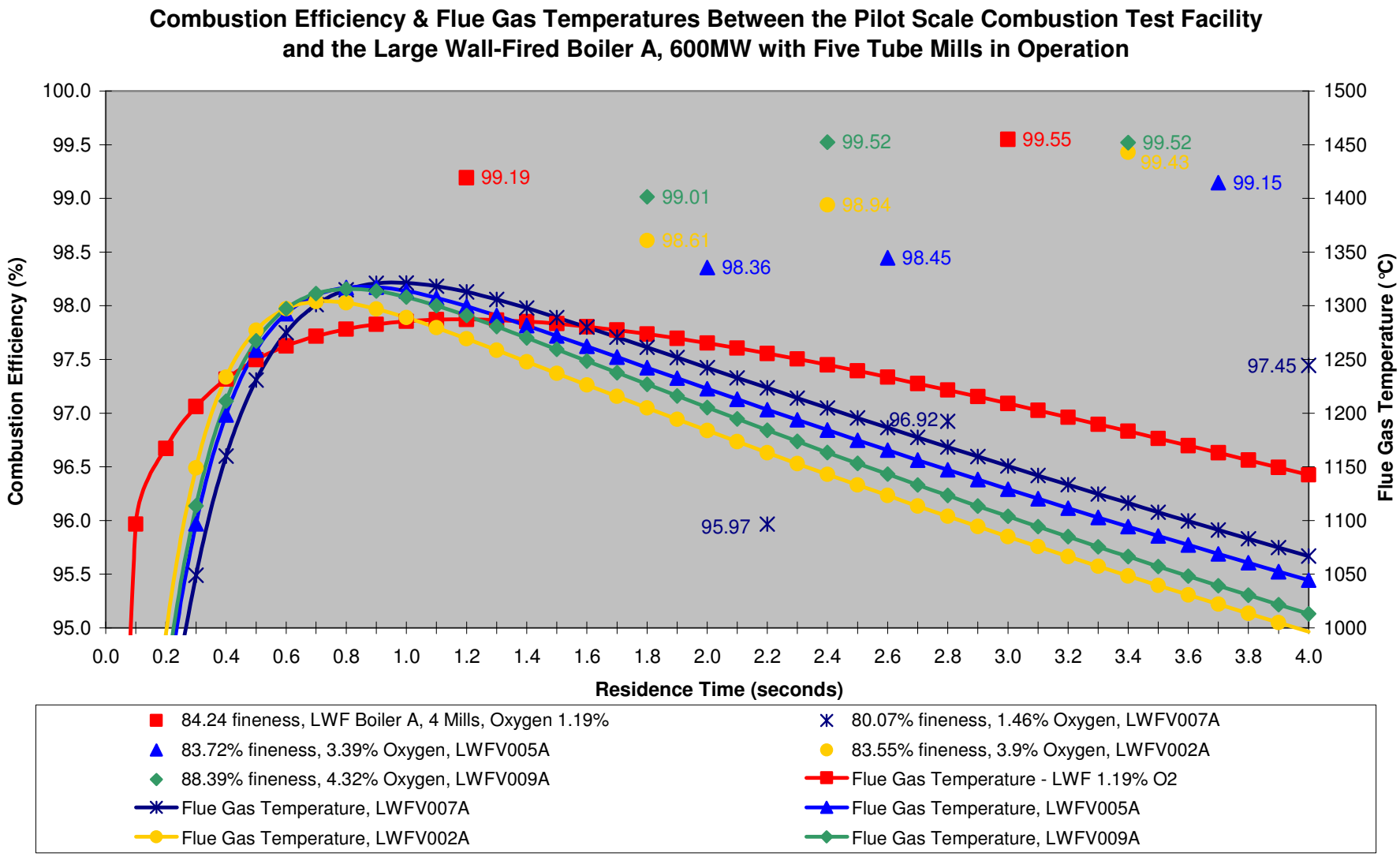


FIGURE 7: COMBUSTION PERFORMANCE BETWEEN THE PSCTF AND THE LARGE WALL-FIRED BOILER A

4.5 TANGENTIALLY-FIRED BOILER (TF) VALIDATION

The Tangentially-Fired (TF) boiler is a 700 MW_e (Electrical), sub-critical unit with five tube/ball mills. Four of these mills are required to generate the Maximum Continuous Rating (MCR) of 700 MW_e

4.5.1 Raw Coal and Pulverized Fuel Sampling

Two sets of raw coal samples were obtained directly from the operating feeders of TF boiler for the two different excess oxygen levels during the full-scale validation tests. These composite samples were then prepared and evaluated at the PSCTF. The raw coal sample was pulverized at the test mill to produce a similar size grading to that obtained from the full-sale plant during the test. The pf sampling results for both TF and the PSCTF are detailed in Table 15 (refer to section 3.1.4 for method and accuracy). PF sampling was not performed on Mill E at the TF boiler due to the lack of access sampling point. The pf fineness results showed that the test mill produced a slightly finer product in comparison to the industrial mills. For the full analyses on pf sampling for the PSCTF and the TF boiler refer to Appendix E.

TABLE 15: PULVERIZED FUEL FINENESSES FROM THE TANGENTIALLY-FIRED BOILER AND THE PSCTF

Pulverized Fuel Finenesses From The Tangentially Fired Boiler @ 2.44% Oxygen (Dry basis)				
	% passing 300µm	**% passing 150µm**	**% passing 106µm**	**% passing 75µm**
Mill B	99.0	92.7	85.8	75.7
Mill C	98.8	92.7	86.0	76.4
Mill D	99.4	96.1	91.7	84.5
Average	**99.1**	**93.8**	**87.8**	**78.8**
Pulverized Fuel Finenesses From The Tangentially Fired Boiler @ 3.42% Oxygen (dry basis)				
Mill B	99.0	93.1	86.8	77.4
Mill C	98.8	93.5	87.5	78.3
Mill D	99.3	95.0	90.0	81.7
Average	**99.0**	**93.9**	**88.1**	**79.1**
Pulverized Fuel Finenesses From The PSCTF				
TFV001	99.99	99.31	96.50	84.71
TFV002	99.97	99.22	95.60	82.73
TFV003	99.98	99.31	95.25	82.80
TFV004	99.97	99.26	95.26	83.39
TFV005	99.96	99.17	94.04	80.58
TFV006	99.96	99.23	95.45	81.43
TFV007	99.97	99.36	96.13	83.34
TFV008	99.99	99.45	95.96	82.21
TFV009	99.98	99.31	95.84	84.17
TFV010	99.99	99.36	96.22	83.99
TFV011	99.93	96.57	87.05	72.43
TFV012	99.87	97.70	90.65	73.88
TFV013	99.97	97.67	92.60	75.46
TFV014	99.87	97.03	91.02	75.96
TFV015	99.94	96.68	91.73	79.06
TFV016	99.91	98.59	93.73	81.08
TFV017	99.97	98.30	92.30	75.02
TFV018	99.97	97.80	91.60	75.74

4.5.2 Fly and Coarse Ash Samples

Coarse ash was sampled from the submerged scraper conveyor and samples were taken intermittently with spades from both ends and the middle of the conveyor. A total coarse ash quantity of 400kg was collected and stored in plastic bags. 3 to 5 kgs of fly ash samples were taken from the conveyor box. The sample was first placed into a 100 litre metal drum to cool down. Once ambient conditions were reached, the sample was emptied into a plastic bag.

4.5.3 Pilot Scale Validation of the Tangentially-Fired Boiler

TABLE 16: RESULTS OBTAINED FROM THE TANGENTIALLY-FIRED BOILER

Description	SI Units	Level		
		39m	54m (Burner Belt)	66m (Furnace Exit)
Exit Oxygen - 2.3% (wet basis), 2.44%# (dry basis)				
Residence Time from Middle Burner Row		0.5m / 0.06s	22m / 2.63s	34m / 4.09s
Combustible Residue	%	12.26	1.34	1.20
Combustion Efficiency	%	89.21	99.11	99.61
Oxygen	%	NM	NM	NM
Carbon Monoxide-Normalized 6% O_2	mg/Nm^3	NM	NM	NM
Oxides of Nitrogen Normalized 6% O_2	mg/Nm^3	NM	NM	NM
Temperature	℃	1025	1332	1073
Primary Air Flow Upper / lower	kg/s	184		
Mill Outlet Temperature	℃	88		
Secondary Air Flow	kg/s	201		200
Secondary Air Temperature	℃	285		276
Secondary/Primary Air Ratio		2.21		
Secondary A/H Gas Inlet O_2 (wet basis)	%	2.23		2.38
Secondary A/H Gas Inlet O_2 (dry basis)	%	2.36#		2.52#
Furnace Pressure	Pa	-177		
Exit Oxygen – 3.23% (wet basis), 3.42%# (dry basis)				
Residence Time from Middle Burner Row		0.5m / 0.05s	22m / 2.27s	34m / 3.54s
Combustible Residue	%	12.49	1.0	1.0
Combustion Efficiency	%	88.94	99.34	99.34
Oxygen	%	NM	NM	5.94
Carbon Monoxide-Normalized 6% O_2	ppm	NM	NM	10
Sulphur Dioxide Normalized 6% O_2	mg/Nm^3	NM	NM	1546
Oxides of Nitrogen Normalized 6% O_2	mg/Nm^3	NM	NM	914**
Temperature	℃	1215	1302	1130
Primary Air Flow Upper / lower	kg/s	183		
Mill Outlet Temperature	℃	88		
Secondary Air Flow	kg/s	204		207
Secondary Air Temperature	℃	281		269
Secondary/Primary Air Ratio		2.24		
Secondary A/H Gas Inlet O_2 (wet basis)	%	3.05		3.41
Secondary A/H Gas Inlet O_2 (dry basis)	%	3.23#		3.61#
Furnace Pressure	Pa	-180		

NM – Not Measured, *Density of SO_2 - 2.86kg/m^3, **Density of NO_x - 2.06kg/m^3, #Assumed 6% as the moisture content in flue gas

Flue dust samples were extracted from the boiler at the 39m (through burner B2), 54m (burner belt region), and the 66m (furnace exit) levels at TF boiler. These samples were extracted at ½m intervals to a depth of 4.5m at each elevation. All the boiler flue dust

samples from the PSCTF and TF boiler underwent analyses to determine the combustible residue in the flue dust according to the ESKOM Method 126 rev1 (refer to Appendix I). An optical pyrometer or a K-type thermocouple was utilized to record the temperature measurements of flue gas at each elevation. For the detailed full-scale test logs refer to Appendix F. The volume flow rate through the volume of the TF furnace was utilized to calculated particle residence times. Two excess air levels settings were tested at the TF boiler to determine the change in combustion performance and these full-scale boiler results were utilized to setup the PSCTF.

The two conditions measured at the TF boiler are shown in red squares and yellow circles. The TF results with the higher excess air level indicated faster ignition and better combustion efficiencies due to the higher oxygen content which improved the diffusional reaction and thereby the chemical reaction (see Figure 8)

Two series of pilot scale tests were performed with the first series of tests being conducted under conditions of similitude (see Table 17) and the second series of tests being conducted with the primary and secondary air temperatures at 90℃ and 300℃ (see Table 18) respectively. Two pilot scale tests were performed for each excess air level to determine the repeatability for the coal combustion efficiency results. The stoichiometric and excess air levels were calculated according to the equations 4 and 5 to 8 detailed in section 3.3.2. The actual burner air ratio (SA/PA) measurements ranged from 2.77 to 3.01 (see Tables 17 and 18). Backend or exit oxygen concentrations measurements ranged between 3.52 and 7.57% on a dry basis.

Coal combustion efficiency results were determined at 3 extraction points on both furnaces. A curve fit program was utilized to generate the flue gas temperature curves (solid lines with corresponding). Shapes and colour codes were utilized to match the flue gas temperatures to the corresponding set of combustion efficiency results which are shown in Figure 8. Pilot scale tests were performed at a low, medium, and high oxygen concentration to simulate the pf burnout obtained in the TF boiler.

Figure 8 graphically represented the following pilot scale tests TFV010, TFV011, TFV014 and TFV016. The best and worst coal combustion efficiency results were achieved with test TFV014 and TFV010 in comparison to the TF boiler. These test are indicated by light and dark blue shapes respectively. Pilot scale tests TFV010 and TFV011 were combusted at exit oxygen concentrations, which had been 5% and 18% higher than that of the TF boiler. These tests produced comparable pf burnout results relative to the TF boiler. Tests TFV014 and TFV016 achieved a better pf burnout in comparison to the full-scale plant. The

flue gas temperature profiles were inversely proportional to the coal combustion efficiency results.

The gaseous emissions measured at the TF boiler and the PSCTF were conducted with a portable gas analyzer and an online gas analyzer respectively. Equation 1 was utilised to normalize the measured gas species to 6% oxygen concentration. The sulphur dioxide (SO_2) concentration for test TVF009 was comparable to the full scale test evaluated at 3.42% oxygen. The pilot flame temperatures were directly proportional to the formation of the oxide of nitrogen (NO_x) concentration.

Slag formation occurs when the flame temperature is higher than that of the ash melting temperature of the specific coal source and/or blend being combusted. Slagging is a complex process, which involves pf fineness, inlet conditions, excess air levels, coal quality, mineralogy, combustion system configuration, and other combustion related settings. A slagging probe was inserted at approximately 0.3 seconds from the pilot scale burner to determine the rate of slag formation (see Tables 17 and18). The rate of slag formation increased with a decrease in excess oxygen levels. This is due to the heating of a lower volume of flue gas that resulted in higher flame temperatures which exceeded the ash fusion temperatures of the boiler flue dust.

TABLE 17: PILOT SCALE RESULTS FOR THE TANGENTIALLY-FIRED VALIDATION COAL UNDER CONDITIONS OF SIMILITUDE

Fuel	Units	TFV001	TFV002	TFV003	TFV004	TFV005	TFV006	TFV007	TFV008	TFV009	TFV010
Coal Flow	kg/hr	197	196	197	196	196	198	197	197	196	197
Output	MW_{th}	1.02	1.01	1.02	1.01	1.01	1.02	1.02	1.02	1.01	1.02
Grind size - passing 75 microns	%	84.71	82.73	82.80	83.39	80.58	81.43	83.34	82.21	84.17	83.99
Blend Ratio											
Tangentially Fired Validation - Feeder	%	100	100	100	100	100	100	100	100	100	100
Air											
Total Air Flow	kg/hr	1719	1718	1553	1551	1458	1458	1369	1370	1285	1291
Secondary Air/Primary Air Ratio		3.01	3.01	2.95	2.96	2.84	2.85	2.85	2.85	2.85	2.78
Swirl Setting – Secondary Air		1	1	1	1	1	1	1	1	1	1
Excess Air	%	56.60	54.02	37.73	39.20	33.39	34.18	27.55	23.97	20.28	20.81
Primary Air Flow	kg/hr	428	428	393	392	380	378	356	356	333	341
Primary Air Temperature	℃	91	91	91	91	91	91	91	91	91	91
Secondary Air Flow	kg/hr	1291	1290	1160	1160	1079	1080	1013	1014	951	950
Secondary Air Temperature	℃	274	275	275	275	274	274	274	274	273	273
Furnace											
Furnace Pressure	Pa	-327	-318	-180	-205	-174	-140	-125	-165	-195	-203
Flue Gas Temperature (0.250-0.328s)	℃	1067	1065	1065	1064	1072	1078	1091	1099	1106	1107
Flue Gas Temperature (0.719-0.942s)	℃	1307	1304	1325	1326	1351	1354	1368	1367	1372	1371
Flue Gas Temperature (1.125-1.474s)	℃	1267	1268	1292	1281	1302	1301	1305	1304	1329	1330
Flue Gas Temperature (3.2 seconds)	℃	1054	1059	1077	1060	1072	1075	1103	1101	1113	1123
Average Flue Gas Temperatures	℃	1174	1173	1189	1182	1199	1201	1216	1217	1229	1232
Furnace Wall Temperature 1	℃	1131	1122	1115	1109	1105	1105	1106	1122	1131	1133
Furnace Wall Temperature 2	℃	1082	1067	1075	1068	1068	1072	1079	1089	1075	1069
Furnace Wall Temperature 3	℃	1088	1089	1092	1091	1091	1090	1089	1092	1093	1094
Furnace Wall Temperature 4	℃	867	873	884	889	894	897	901	909	916	920
Furnace Wall Temperature 5	℃	788	797	815	824	838	845	852	854	863	868
Results – Normalized to 6% O_2											
Oxygen (wet basis) - O_2	%	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Oxygen (dry basis) - O_2	%	7.18	7.20	5.14	5.79	4.71	5.12	3.80	3.54	2.79	3.18
Carbon Monoxide - CO	ppm	87	87	77	81	76	78	70	67	64	97
Carbon Dioxide - CO_2	%	13.51	13.61	13.33	13.61	13.27	13.61	13.01	13.09	12.78	18.84
Sulphur Dioxide - SO_2	mg/Nm^3	1581*	1626*	1591*	1607*	1570*	1607*	1586*	1553*	1471*	2152*
Oxides of Nitrogen - NO_x	mg/Nm^3	1890**	1580**	1624**	1896**	1765**	1779**	1332**	1507**	1388**	2083**
Combustion Efficiency/*CR*(1.656 to 2.170s)	%	99.55/0.6	98.01/2.6	98.79/1.6	99.55/0.6	99.40/0.8	99.40/0.8	97.69/3.0	98.63/1.8	98.79/1.6	99.09/1.2
Combustion Efficiency/*CR*(2.156 to 2.825s)	%	99.63/0.5	99.55/0.6	99.40/0.8	99.78/0.3	99.47/0.7	99.47/0.7	98.32/2.2	99.17/1.1	98.87/1.5	99.17/1.1
Combustion Efficiency/*CR*(3.063 to 4.013s)	%	99.70/0.4	99.63/0.5	99.70/0.4	99.85/0.2	99.63/0.5	99.55/0.6	99.09/1.2	99.40/0.8	99.25/1.0	99.40/0.8
Rate of Slag Formation	g/hr	Fell Off		54		33		39		129	

CR – Combustible Residue, NM – Not Measured, *Density of SO_2 - 2.86kg/m^3, ** Density of NO_x - 2.06kg/m^3

TABLE 18: PILOT SCALE RESULTS FOR THE TANGENTIALLY-FIRED VALIDATION COAL UNDER STANDARD CONDITIONS

Fuel	Units	TFV011	TFV012	TFV013	TFV014	TFV015	TFV016	TFV017	TFV018
Coal Flow	kg/hr	196	197	197	196	196	195	197	197
Output	MW_{th}	1.01	1.02	1.02	1.01	1.01	1.01	1.02	1.02
Grind size - passing 75 microns	%	72.43	73.88	75.46	75.96	79.06	81.08	75.02	75.74
Blend Ratio									
Tangentially Fired Validation - Feeder	%	100	100	100	100	100	100	100	100
Air									
Total Air Flow	kg/hr	1362	1361	1720	1719	1567	1567	1428	1428
Secondary Air/Primary Air Ratio		2.87	2.87	2.94	2.95	2.77	2.77	2.95	2.95
Swirl Setting – Secondary Air		1	1	1	1	1	1	1	1
Excess Air	%	23.87	25.55	55.85	56.79	44.64	36.51	26.97	32.88
Primary Air Flow	kg/hr	352	352	437	435	415	416	352	352
Primary Air Temperature	℃	93	93	92	92	92	93	94	94
Secondary Air Flow	kg/hr	1010	1009	1283	1284	1152	1152	1036	1036
Secondary Air Temperature	℃	298	298	298	298	298	299	299	299
Furnace									
Furnace Pressure	Pa	-200	-209	-241	-217	-198	-167	-185	-156
Flue Gas Temperature (0.3 seconds)	℃	1110	1110	1076	1063	1056	1056	997	1025
Flue Gas Temperature (0.8 seconds)	℃	1368	1366	1319	1304	1305	1310	1339	1358
Flue Gas Temperature (1.3 seconds)	℃	1342	1342	1283	1276	1289	1294	1253	1273
Flue Gas Temperature (3.2 seconds)	℃	1131	1133	1107	1107	1111	1118	1094	1110
Average Flue Gas Temperatures	℃	1237	1237	1196	1187	1190	1194	1171	1191
Furnace Wall Temperature 1	℃	1137	1138	1143	1139	1127	1123	1016	1022
Furnace Wall Temperature 2	℃	1070	1068	1078	1067	1058	1062	987	1005
Furnace Wall Temperature 3	℃	1097	1099	1105	1106	1103	1103	1014	1019
Furnace Wall Temperature 4	℃	928	931	943	947	950	951	875	879
Furnace Wall Temperature 5	℃	878	883	898	904	913	916	863	837
Results – Normalized to 6% O_2									
Oxygen (wet basis) - O_2	%	NM	NM	NM	NM	6.00	5.48	4.13	4.36
Oxygen (dry basis) - O_2	%	3.35	3.68	7.45	7.46	6.60	5.99	4.92	5.45
Carbon Monoxide - CO	ppm	68	70	90	90	84	81	42	51
Carbon Dioxide - CO_2	%	12.90	13.02	13.47	13.56	14.29	14.22	14.33	14.44
Sulphur Dioxide - SO_2	mg/Nm^3	1445*	1597*	1634*	1725*	1620*	1487*	866*	1090*
Oxides of Nitrogen - NO_x	mg/Nm^3	1421**	1468**	1838**	1819**	1895**	1875**	2195**	2125**
Combustion Efficiency/CR (1.4 to 1.9 s)	%	99.25/1.0	99.32/0.9	99.55/0.6	99.55/0.6	99.17/1.1	99.47/0.7	97.69/3.0	97.62/3.1
Combustion Efficiency/CR (2.1 to 2.5 s)	%	99.32/0.9	99.40/0.8	99.70/0.4	99.70/0.4	99.55/0.6	99.70/0.4	98.79/1.6	98.79/1.6
Combustion Efficiency/CR (2.9 to 3.6 s)	%	99.40/0.8	99.70/0.4	99.78/0.3	99.85/0.2	99.85/0.2	99.85/0.2	99.32/0.9	99.40/0.8
Rate of Slag Formation	g/hr	137		Fell off		NM		NM	

CR – Combustible Residue, NM – Not Measured, *Density of SO_2 - 2.86kg/m^3, ** Density of NO_x - 2.06kg/m^3

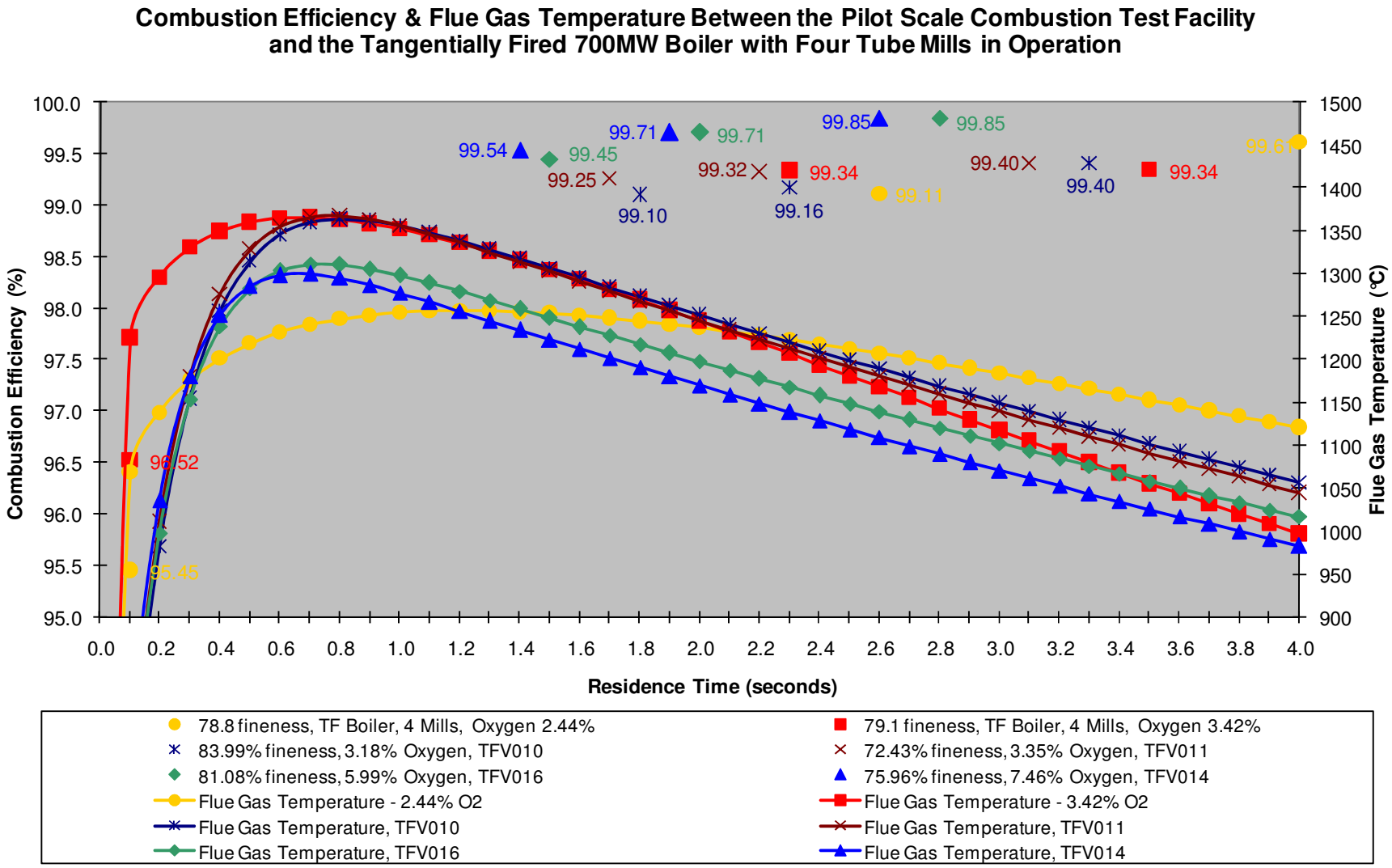


FIGURE 8: COMBUSTION PERFORMANCE BETWEEN THE PSCTF AND THE TANGENTIALLY-FIRED BOILER

4.6 LARGE WALL-FIRED BOILER B (LWF B) VALIDATION

The Large Wall-Fired (LWF) boiler B is a 600 MW_e (Electrical), sub-critical unit with six vertical spindle mills. Five of these mills are required to generate the Maximum Continuous Rating (MCR) of 600 MW_e

4.6.1 Raw Coal and Pulverized Fuel Sampling

Raw coal, coarse ash, fly ash and pf sampling was obtained in accordance to the standards previously mentioned in section 3.1.

TABLE 19: PULVERIZED FUEL FINENESSES FROM THE LARGE WALL-FIRED BOILER B AND THE PSCTF

Pulverized Fuel Finenesses From The Large Wall-Fired Boiler B – Six Mills				
	% passing 300µm	**% passing 150µm**	**% passing 106µm**	**% passing 75µm**
Mill 4A	99.83	95.30	86.15	70.58
Mill 4B	99.92	95.12	85.92	73.12
Mill 4C	99.92	94.72	87.12	75.12
Mill 4D	99.70	96.30	88.70	76.50
Mill 4E	99.94	96.74	90.14	78.54
Mill 4F	99.85	95.40	87.35	75.50
Average	**99.86**	**95.60**	**87.56**	**74.89**
Pulverized Fuel Finenesses From The Large Wall-Fired Boiler B – Five Mills				
	% passing 300µm	**% passing 150µm**	**% passing 106µm**	**% passing 75µm**
Mill 4A	99.83	94.68	86.68	75.28
Mill 4C	99.64	94.24	86.04	74.64
Mill 4D	99.20	94.20	87.20	74.60
Mill 4E	99.64	95.04	86.44	74.84
Mill 4F	99.90	95.13	86.78	74.48
Average	**99.64**	**94.66**	**86.63**	**74.77**
Pulverized Fuel Finenesses From The PSCTF				
LWFV001B	99.91	93.08	85.76	77.36
LWFV002B	99.95	93.02	84.32	76.68
LWFV003B	99.90	92.87	84.16	77.14
LWFV004B	99.96	91.59	85.05	80.20
LWFV005B	99.95	92.49	84.05	74.83
LWFV006B	99.95	93.91	87.08	79.23
Average	**99.94**	**92.82**	**85.07**	**77.57**

Table 19 details the pf results from the LWF boiler B and PSCTF. The PSCTF pf sampling average results were similar to that obtained from the LWF B. For the full analyses on pf sampling for the PSCTF and the LWF boiler B refer to Appendix G.

4.6.2 Pilot Scale Validation of the Large Wall-Fired Boiler B

Two different mill configurations were tested at the LWF boiler B to determine the change in coal combustion performance. Table 20 details the results obtained from the three elevations tested at the LWF boiler B. Boiler flue dust samples were extracted from the 23m (burner), 38.5m (burner belt region), and 49m (furnace exit) levels on LWF boiler B. All the boiler flue dust samples from the PSCTF and LWF boiler B underwent analyses to determine the combustible residue in accordance to the ESKOM Method 126 rev1 (refer to

Appendix I). For detailed full-scale test logs refer to Appendix H. These results form the basis for the setup of the pilot scale tests. The six mill configuration indicated better combustion performance in comparison to the five mill configuration (see Figure 9).

TABLE 20: RESULTS OBTAINED FROM THE LARGE WALL-FIRED BOILER B

	SI Units	23m (Burner)		38.5m (Burner belt)		49m (Furnace Exit)	
No of Mills in service		6	5	6	5	6	5
Particle Residence Time	s	0.25	0.30	1.34	1.55	2.62	2.94
Combustible Residue	%	64.2	67.32	1.58	1.82	1.01	0.88
Combustion Efficiency	%	1.42	1.73	98.95	99.27	99.33	99.42
Oxygen (dry basis)	%	19.44	19.66	NM	NM	4.68	3.5
Carbon Monoxide Normalized 6% O_2	ppm	4590	4776	NM	NM	2	9
Sulphur Dioxide Normalized 6% O_2	mg/Nm^3	5189*	1512*	NM	NM	2336*	1471*
Oxides of Nitrogen Normalized 6% O_2	mg/Nm^3	667**	477**	NM	NM	NM	1217**
Temperature	℃	433	307	1449	NM	757	794
Primary Air Flow	kg/s	164.5	160.3	164.5	160.3	164.5	160.3
Primary Air Temperature	℃	88.2	91.2	88.2	91.2	88.2	91.2
Secondary Air Flow	kg/s	523.9	525.2	523.9	525.2	523.9	525.2
Secondary/Primary Air Ratio		3.18	3.28	3.18	3.28	3.18	3.28
Backend Oxygen (wet basis)	%	4.91	4.85	4.91	4.85	4.91	4.85
Backend Oxygen (dry basis)	%	5.20#	5.14#	5.20#	5.14#	5.20#	5.14#

NM Not Measured, *Density of SO_2 2.86kg/m^3,**Density of NO_x 2.06kg/m^3,#Assumed 6% as the moisture content in flue gas

The experience gained from the LWF boiler A validation has led to the focus on the evaluation of excess air levels at the PSCTF. Therefore, the following series of coal test conditions were performed to validate pilot scale combustion performances:

- LWFV001B: 77.36% passing 75µm, 18.40% Excess Air
- LWFV002B: 76.68% passing 75µm, 19.24% Excess Air
- LWFV003B: 77.14% passing 75µm, 36.28% Excess Air
- LWFV004B: 80.20% passing 75µm, 35.35% Excess Air
- LWFV005B: 74.83% passing 75µm, 26.58% Excess Air
- LWFV006B: 79.23% passing 75µm, 26.25% Excess Air

The stoichiometric air calculation was used to determine the excess air requirements (see equations 4 and 5 to 8 in section 3.3.2). The actual burner air ratio (SA/PA) measurements ranged from 2.39 to 2.91 (see Table 21). Backend or exit oxygen concentrations measurements ranged between 3.25 and 5.56% (dry basis). A curve fit program was utilized to generate the flue gas temperature curves (solid lines with corresponding shapes). Shapes and colour codes were utilized to match the flue gas temperatures to the corresponding set of combustion efficiency results, which are shown in Figure 9. Flue dust samples were extracted at 3 points on both the full-scale and the pilot scale facilities.

Figure 9 graphically represented the following pilot scale tests LWFV002B, LWFV003B and LWFV005B. The best and worst coal combustion efficiency results in comparison to the LWF boiler B were LWFV003B and LWFV002B and are indicated by dark blue asterisks

and light blue triangles respectively. Pilot scale test LWFV003B was combusted at exit oxygen concentration, which had been 8% higher than that of the LWF boiler B at the five-mill configuration. The pf burnout results from test were comparable to that of the LWF boiler B. Tests LWFV002B and LWFV005B achieved a poorer pf burnout in comparison to the full-scale plant. The PSCTF results have shown that combustible residue is inversely proportional to the excess air levels. The combustible residue result for LWF003B at furnace exit (2.94s) is similar when compared to the full-scale configuration of 5 and 6 mills operation respectively.

The gaseous emissions measured at the LWF boiler B and the PSCTF were conducted with a portable gas analyzer and an online gas analyzer respectively. All the gas species were normalized to 6% oxygen concentration for comparative purposes. A comparison of the gas species between the two furnaces was not achievable due to a lack of gaseous measurements at furnace exit of the LWF boiler B.

TABLE 21: PILOT SCALE RESULTS FOR THE LARGE WALL-FIRED BOILER B VALIDATION COAL

Fuel	Units	LWF-V001B	LWF-V002B	LWF-V003B	LWF-V004B	LWF-V005B	LWF-V006B
Coal Flow	kg/hr	192	193	193	192	192	192
Output	MW_{th}	1.01	1.01	1.01	1.01	1.01	1.01
Grind size - passing 75 microns	%	77.36	76.68	77.14	80.20	74.83	79.23
Blend Ratio							
LWF - Feeder	%	100	100	100	100	100	100
Air							
Total Air Flow	kg/hr	1421	1435	1709	1712	1558	1552
Secondary Air/Primary Air Ratio		2.91	2.84	2.81	2.77	2.39	2.40
Swirl Setting – Secondary Air		1	1	1	1	1	1
Swirl Setting – Tertiary Air		1	1	1	1	1	1
Excess Air	%	18.40	19.24	36.28	35.35	26.58	26.25
Primary Air Flow	kg/hr	325	333	410	415	414	412
Primary Air Temperature	℃	94	93	93	92	93	93
Secondary Air Flow	kg/hr	946	947	1150	1150	991	991
Secondary Air Temperature	℃	284	287	288	287	288	289
Tertiary Air Flow	kg/hr	0	0	0	0	0	1552
Tertiary Air Temperature	℃	174	173	172	1712	173	2.40
Furnace							
Furnace Pressure	Pa	-258	-257	-244	-227	-258	-272
Flue Gas Temperature (0.241-0.291s)	℃	1297	1304	1283	1281	1271	1277
Flue Gas Temperature (0.694-0.836s)	℃	1435	1441	1414	1411	1425	1435
Flue Gas Temperature (1.086-1.308s)	℃	1289	1301	1291	1293	1309	1313
Flue Gas Temperature (2.956-3.560s)	℃	1004	1019	1030	1039	1063	1064
Average Flue Gas Temperatures	℃	1256	1266	1254	1256	1267	1272
Furnace Wall Temperature 1	℃	1139	1137	1136	1137	1138	1138
Furnace Wall Temperature 2	℃	1093	1099	1114	1127	1143	1152
Furnace Wall Temperature 3	℃	1076	1075	1076	1078	1086	1088
Furnace Wall Temperature 4	℃	775	773	768	769	776	783
Furnace Wall Temperature 5	℃	869	869	870	871	874	875
Results – Normalized to 6% Oxygen							
Oxygen (wet basis)	%	NM	NM	NM	NM	NM	NM
Oxygen (dry basis)	%	3.25	3.37	5.56	5.46	4.39	4.35
Carbon Monoxide (dry basis)	ppm	23	27	39	33	25	22
Carbon Dioxide (dry basis)	%	13.15	13.31	13.75	13.66	13.51	13.48
Sulphur Dioxide (dry basis)	mg/Nm^3	1198*	1191*	1179*	1151*	1138*	1119*
Oxides of Nitrogen (dry basis)	mg/Nm^3	2367**	2496**	3638**	3727**	3300**	3245**
Combustion Efficiency/*CR*(0.121-0.145s)	%	13.11/57.2	7.97/58.6	37.28/49.1	36.78/49.3	78.44/24.9	78.44/24.9
Combustion Efficiency/*CR*(1.599-1.925s)	%	95.70/6.2	95.78/6.1	98.61/2.1	98.54/2.2	96.58/5	96.51/5.1
Combustion Efficiency/*CR*(2.956-3.560s)	%	96.87/4.6	96.94/4.5	99.41/0.9	99.48/0.8	98.81/1.8	98.88/1.7

CR – Combustible Residue, NM – Not Measured, *Density of SO_2 - 2.86kg/m^3, ** Density of NO_x - 2.06kg/m^3

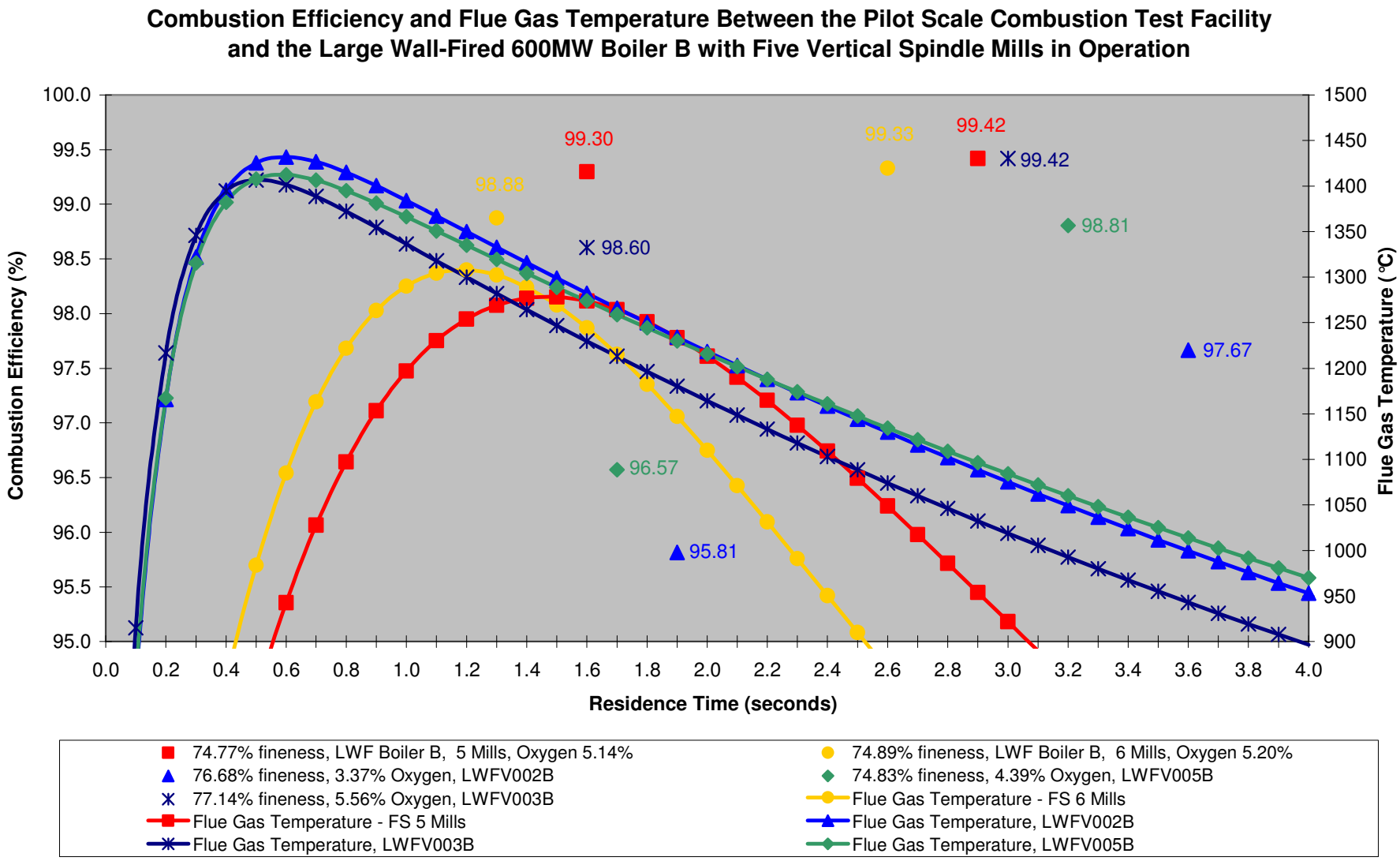


FIGURE 9: COMBUSTION PERFORMANCE BETWEEN THE PSCTF AND THE LARGE WALL-FIRED BOILER

5 DISCUSSIONS

This chapter presents the evaluation of the results, advantages, disadvantages and application of each test equipment that relates to the results of the original objectives.

Coal contracts are based on proximate analysis, gross calorific value, Abrasiveness Index and Hardgrove Index. The chemical analyses for the SWF coal sample reported the highest calorific value with the corresponding lowest ash and the LWF boiler A coal sample reported the lowest calorific value with the corresponding highest ash.

The Drop Tube Furnace (DTF) test provides ignition parameters and char burnout profiles at specified combustion temperatures and variable residence times. The DTF provides a screening procedure for coals, but does not allow for the evaluation of coal in the dynamic combustion environment. The DTF ignition parameters and char burnout times for the four pf samples were evaluated on a qualitatively basis. Therefore, the results from the DTF are indicative of the predicted performance. All four coal samples analysed at the DTF reported a higher volatile matter content in comparison to the chemical analyses. The major contributing factor is due to the difference in heating rates and the final temperature achieved; i.e. DTF 10 000℃/s versus Oven 100's℃/s. The operating temperatures of the oven and the DTF are 850℃ and 1400℃ respectively. The DTF is deficient in determining the impacts of coal combustion for slagging, fouling, gaseous emissions, ignition stability, erosion, corrosion, pf fineness, excess air strategies and others due to the lack of a diffusional reaction between the pf and air.

The best indication of pf combustion behaviour in a particular boiler would be obtained from a full scale test burn in the plant itself, but this is impractical, costly, and risky to the plant. For the above reasons, pilot scale coal combustion testing has been increasingly used to evaluate coal combustion behaviour at a relatively low cost on limited sample sizes. The pilot scale test facility also enables a wide range of combustion conditions and hardware problems to be studied in a short time to identify the causes of problems and find solutions.

The major objectives of this research focused on determining the capability of the ESKOM PSCTF to simulate the pf burnout and gaseous emissions of full-scale boilers. Makino et al (1996) study had shown that the furnace size inversely proportional to the pf burnout of the coal. Lindsay (1995) study had shown that the design criteria of the pilot scale furnace wall temperatures is required to be above 1000℃ to simulate the pf burnout of the full-scale furnaces. The PSCTF furnace wall temperature 1 and 2 for all the coal combustion evaluations were in excess of 1000℃; i.e. wall temperature 1 is closest to the burner. All the coal combustion evaluations had been performed in duplicate to determine the

reproducibility of the results. The coal combustion efficiency calculations and flue gas temperature measurements for all the evaluations were within 10% accuracy.

Smart et al (1996) indicated that scaled burner designs are not able to reproduce adequate similarities in the flame structure and thermo-chemical fields. Therefore, the validation in the current study of Small Wall-Fired (SWF) boiler coal combustion evaluations focused on optimizing of the PSCTF burner. The pilot scale temperature profiles and coal combustion efficiency results have shown that the flame structure and thermo chemical fields varies with changes to the swirl setting, excess air levels and air contribution for the secondary and tertiary air. The coal combustion efficiency results that most closely match the SWF boiler were with the PSCTF burner set at the 1 swirl setting. The 100% secondary air contribution through the pilot burner is the most appropriate setting due to the conventional circular burners (only primary and secondary air) being installed at the SWF boiler. The pilot scale secondary/primary air ratio was maintained between 2.78 to 4.57 in an attempt to simulate the global aerodynamics of the full-scale boiler. Holcombe et al (1994) study showed that the pilot and full-scale NO_x results were correlated on the basis of the severity of mixing and temperature conditions. The level of severity of conditions had loosely been termed a “mixing number”. This “mixing number” incorporated the various boiler configurations; namely boiler size, burner type and burner arrangement. Makino et al (1996) indicated that the NO_x results increased with a decrease in furnace size. The NO_x results from the pilot furnace were significantly lower than that of the SWF boiler. This is assumed to be that the SWF boiler configuration with wall-fired circulated burners promoted higher flame temperature which resulted in a higher production of thermal NO_x. The pilot furnace carbon monoxide (CO) results were similar to that of the SWF boiler.

The major focus for the LWF boiler A validation was to determine the influence of excess air levels at the pilot furnace on pf burnout and gaseous emissions. The pilot scale combustible residue results were approximately 6.6 times higher than that of the full-scale boiler at similar particle residence time positions. The pilot scale CO results were inversely proportional to the exit oxygen concentrations and were comparable under conditions of similitude. The pilot scale pf burnout simulated the LWF boiler A with an exit oxygen concentration being at 263% and with the burner at 1 swirl or intermediate setting, and the burner air ratio of 3.31 for the SA/PA. Therefore, the PSCTF can quantitatively evaluate the pf burnout of the LWF boiler A at this specific setting. The pilot scale evaluations have shown that the excess air levels have the major influence on the pf burnout in comparison to the other inlet settings. The pilot scale NO_x results were significantly higher than that of the LWF boiler A. The major contributing factor for the significantly higher NO_x results is

due to higher flame temperatures observed at the pilot furnace. These higher flame temperatures favours the production thermal NO_x.

The validation of the Tangentially Fired (TF) boiler adopted a similar approach to the validation of the Large Wall-fired boiler A. Two excess air levels and/or oxygen settings were performed at the TF boiler to observe the change in coal combustion performance. The best and worst coal combustion efficiency results at the TF boiler were achieved at the 3.42% and the 2.44% exit oxygen concentrations respectively. The TF boiler has jet burners at each corner of the boiler at different elevations. These burners introduce jets of pulverized coal and air into a vortex at the centre of the furnace. This phenomenon is different to the conventional circular burner that is arranged on the boiler walls. In the circular burner the mixing of pulverized coal and air occurs at the burner whereas in the TF boilers the mixing occurs in the furnace. The pilot scale was able to simulate the full-scale results on the CO and SO_2 emissions and pf burnout under conditions of similitude. The pilot NO_x results were higher than that of the TF boiler.

The LWF boiler B validation was conducted with the influence of excess air levels at the pilot furnace on pf burnout and gaseous emissions. A 5 and 6 mill configuration test were performed at the LWF boiler B to observe the change in coal combustion performance. Better pf burnout and low gaseous emissions was achieved with the 5 mill configuration. The pilot scale is able to simulate the pf burnout of the LWF boiler B at elevated excess air levels. Pilot CO and SO_2 emission results are comparable to the LWF boiler B under conditions of similitude.

Based on the research, test work and investigations conducted during the assessment of this work, it was established that the pilot furnace was able to simulate the pf burnout for three full-scale wall-fired and tangentially fired boilers at elevated excess air levels and under conditions of similitude respectively. The pilot CO and SO_2 emission results were simulated under conditions similitude for all four boilers. The pilot NO_x emission results were significantly higher for all the validations with the exception of the SWF boiler. The setup conditions of PSCTF to quantitative predict the pf combustion performance will be dependent on the boiler configuration and the mixing of the pf and air.

6 CONCLUSIONS

The results emanating from this research have shown that:

- When evaluating the combustion performance of a coal, the PSCTF can provide a direct correlation from pilot scale to full scale boiler operations including the production of attendant gaseous emissions (with one exception) and pf burnout. This is subject to certain conditions.
- The quantitative determination of the pulverised fuel burnout is dependent on the boiler configuration (boiler size, burner type and burner arrangement) of the full-scale boiler, which will indicate the setup conditions for the PSCTF. The quantitative pf burnout will assist power stations in sourcing and/or supplying the correct coal to the relevant boiler as well as optimising the pf combustion of that boiler
- The PSCTF needs to be operated under conditions of similitude in order to quantitatively predict carbon monoxide (CO) and sulphur dioxide (SO_2) emissions. This will assist power stations to evaluate their current and future gaseous emissions and provide strategies to meet the emission regulations.
- The pilot furnace produces higher flame temperatures which resulted in thermal oxides of nitrogen (NO_x) and inevitably significantly higher NO_x emissions. Therefore, the NO_x emission needs to be further investigated.

7 RECOMMENDATION

Based on the results of the tests and considering the fact that 85% of ESKOM boilers are wall-fired which operates within 1.5% to 5% exit oxygen concentrations, it is recommended that:

- The PSCTF should be used for all future coal evaluations
- All future coals should be tested at 6% exit oxygen concentration due to the design limitation of the draught group at the PSCTF or alternatively install a larger capacity combustion air blower to cater for the increased air requirements
- Validation of more boilers is required to increase the degree of confidence in the PSCTF results and understanding the impact of the full-scale boiler configurations
- The validation tests should incorporate other pf combustion aspects; e.g. slagging fouling, flame stability, corrosion and erosion
- A quantitative methodology for NO_x emission should be developed.

8 REFERENCES

8.1 Harding NS, Krcil CL, Lewis GH (1984), "Proving combustion feasibility in a model coal furnace - The Conoco/Consol 1.5 MM BTU/hr combustion research facility", Third Engineering Foundation Conference on slagging and fouling due to impurities in combustion gases

8.2 Holcombe D and Trenaman KJ (1994), "Correlation of NO_x measurements in Pilot Scale and Full-scale Plant", Workshop on Impact of Coal Quality on Power Plant Performance, ACTC, Brisbane

8.3 Juniper LA (1995), "Design of Pilot scale rigs to simulate combustion processes", Energy International

8.4 Johnson TR, Sotter JG (1988), "Application of Pilot-Scale Coal Testing to Full-scale Boilers", EPRI Research Project 1266-42, California

8.5 Makino H, Kimoto M (1996), "Scale-up Effect for Emission Characteristics of NO_x and Unburned Carbon in Fly Ash on Pulverized Coal Combustion", Joint Power Generation Conference, Volume 1, Page 95-100

8.6 Padayachy D (1996), "Feasibility study for a Pilot Scale Combustion Test Facility", ESKOM, Report TRR/P96/011

8.7 Smart JP, Woycenco DM, Morgan DJ, van de Kamp WL (1996), "Studies on scale-up of swirl-stabilized pulverized-coal burners in the thermal input range 2.5-12MW", Journal of the institute of energy, pp 131-143

8.8 Sotter JG, Folsom BA, Richter W (1986), "Application of Pilot-Scale coal evaluation to Full-scale Boilers", Paper 86-JPGC FACT-1, ASME/IEEE Joint Power Conference, Portland, Oregon

9 APPENDIX A: PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY AND THE SMALL WALL-FIRED BOILER

PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY – SWF BOILER

Test No	300µm			150µm			106µm			75µm		
	Before	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**
SWFV001	9.9948	0.9712	**90.28%**	9.9948	1.4136	**76.14%**	9.9948	1.2935	**63.20%**	9.9948	1.0328	**52.86%**
SWFV002	7.0435	0.3434	**95.12%**	7.0435	0.7306	**84.75%**	7.0435	0.7058	**74.73%**	7.0435	0.7828	**63.62%**
SWFV003	10.0687	1.1004	**89.07%**	10.0687	1.3822	**75.34%**	10.0687	1.081	**64.61%**	10.0687	0.5984	**58.66%**
SWFV004	5.9399	0.3211	**94.59%**	5.9399	0.545	**85.42%**	5.9399	0.709	**73.48%**	5.9399	0.9039	**58.27%**
SWFV005	11.5558	0.1109	**99.04%**	11.5558	0.8366	**91.80%**	11.5558	1.3301	**80.29%**	11.5558	1.213	**69.79%**
SWFV006	10.5241	0.0328	**99.69%**	10.5241	0.6868	**93.16%**	10.5241	1.4599	**79.29%**	10.5241	0.9573	**70.19%**
SWFV007	13.2084	0.0358	**99.73%**	13.2084	0.9909	**92.23%**	13.2084	2.1979	**75.59%**	13.2084	2.06	**59.99%**
SWFV008	11.3761	0.2447	**97.85%**	11.3761	0.8121	**90.71%**	11.3761	1.2386	**79.82%**	11.3761	1.4652	**66.94%**
SWFV009	21.974	0.1336	**99.39%**	21.974	1.9972	**90.30%**	21.974	3.4452	**74.62%**	21.974	2.9337	**61.27%**
SWFV010	11.3597	0.1399	**98.77%**	11.3597	0.74	**92.25%**	11.3597	1.611	**78.07%**	11.3597	2.1544	**59.11%**
SWFV011	12.8274	3.0023	**76.59%**	12.8274	1.3175	**66.32%**	12.8274	0.7295	**60.64%**	12.8274	1.0529	**52.43%**
SWFV012	16.7558	0.9097	**94.57%**	16.7558	0.8395	**89.56%**	16.7558	2.0382	**77.40%**	16.7558	2.0663	**65.06%**
SWFV013	10.4519	0.0946	**99.09%**	10.4519	0.3896	**95.37%**	10.4519	1.9929	**76.30%**	10.4519	0.9636	**67.08%**
SWFV014	12.457	0.074	**99.41%**	12.457	0.7259	**93.58%**	12.457	1.6782	**80.11%**	12.457	2.1038	**63.22%**
SWFV015	13.7596	0.0249	**99.82%**	13.7596	0.7814	**94.14%**	13.7596	2.173	**78.35%**	13.7596	2.0469	**63.47%**

PF SAMPLING RESULTS

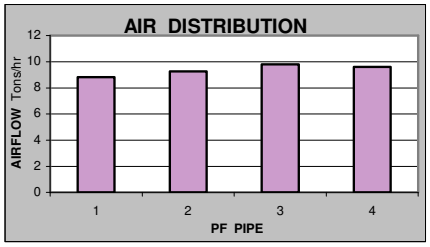
SWFB

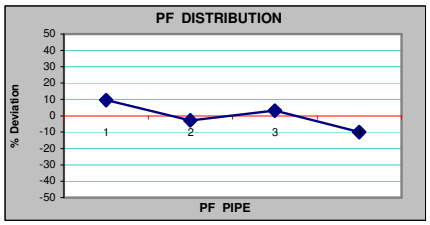
MILL	9A
DATE	2008/04/15
Mill Running Hours	

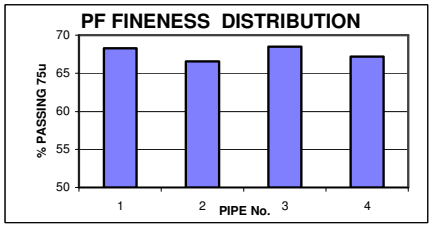
PA FLOW 8.5 kg/s COALFLOW 4.5 kg/s

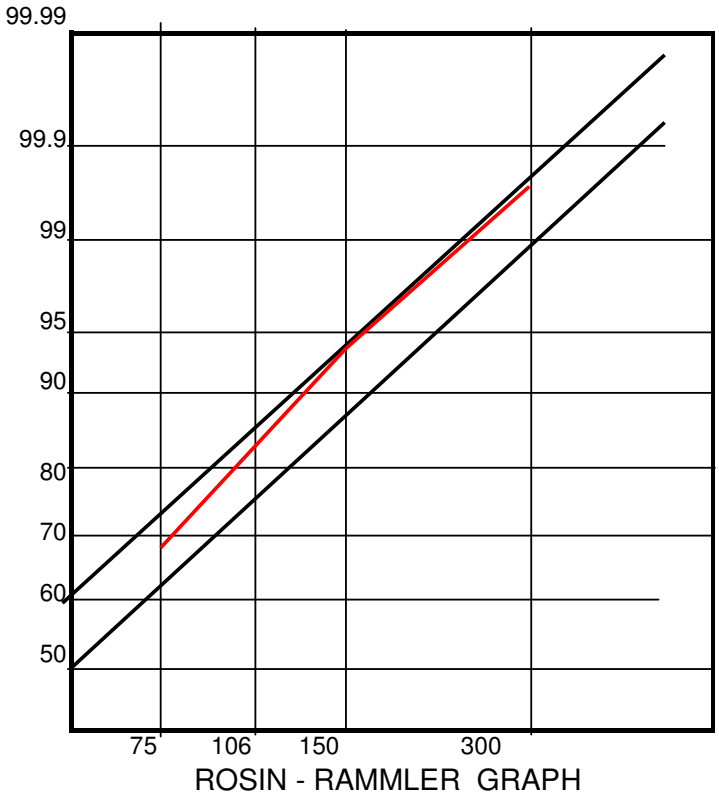
PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	4.6	9.6	8.8	-5.8	27	99.2	94.2	82.4	68.3
2	4.0	-2.8	9.3	-1.2	28	99.2	91.9	80.6	66.6
3	4.3	3.1	9.8	4.4	29	100.0	95.5	83.8	68.5
4	3.7	-10.0	9.6	2.6	29	99.8	94.2	82.6	67.2
TOTAL	16.6	TOTAL	37.5			AVERAGES			
						% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
						99.6	**93.9**	**82.4**	**67.6**

% PF Moisture	7.3
% Recovery rate	105.4









ROSIN - RAMMLER GRAPH

PF SAMPLING RESULTS

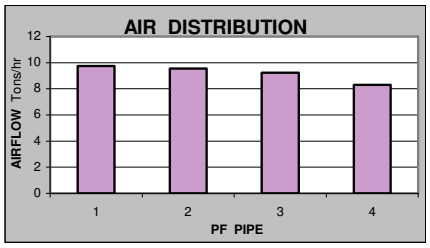
SWFB

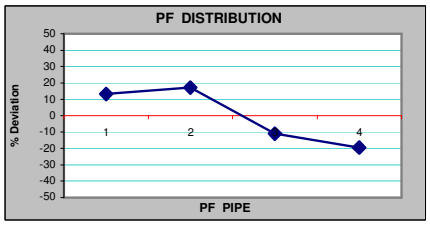
MILL	9B
DATE	2008/04/15
Mill Running Hours	

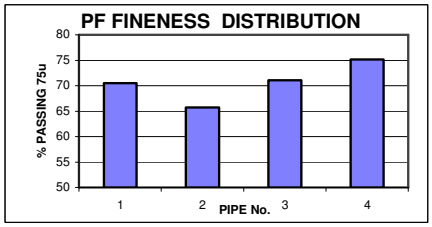
PA FLOW 8.5 kg/s COALFLOW 4.5 kg/s

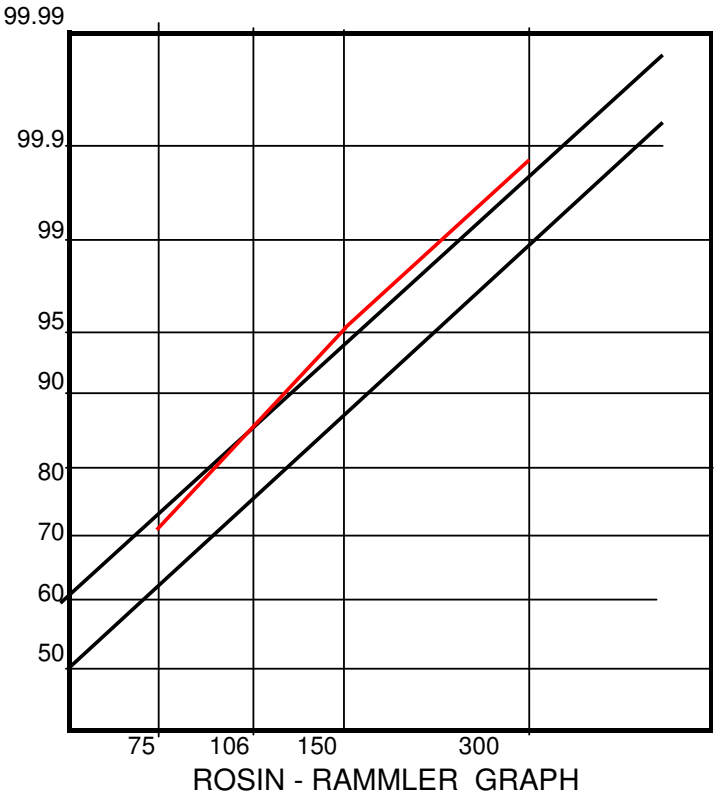
PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	5.3	13.3	9.8	5.9	29	99.8	95.1	85.4	70.5
2	5.5	17.2	9.6	3.8	29	100.0	94.7	81.9	65.7
3	4.2	-11.0	9.2	0.2	28	99.4	94.9	84.9	71.1
4	3.8	-19.4	8.3	-9.9	25	100.0	96.4	87.9	75.2
TOTAL	18.9	TOTAL	36.8			AVERAGES			
						% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
						99.8	**95.3**	**85.0**	**70.6**

% PF Moisture	5.3
% Recovery rate	107.0









PF SAMPLING RESULTS

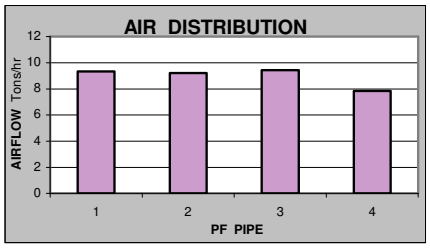
SWFB

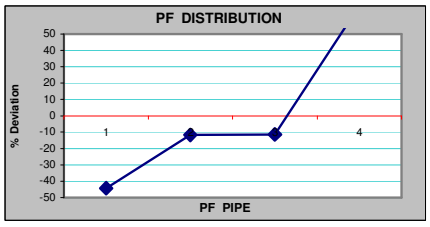
MILL	9D
DATE	2008/04/15
Mill Running Hours	

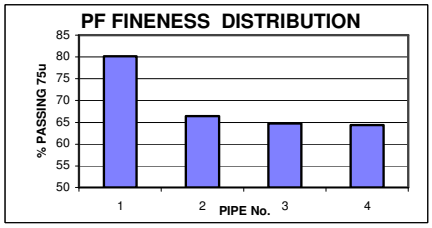
PA FLOW 8.6 kg/s COALFLOW 4.5 kg/s

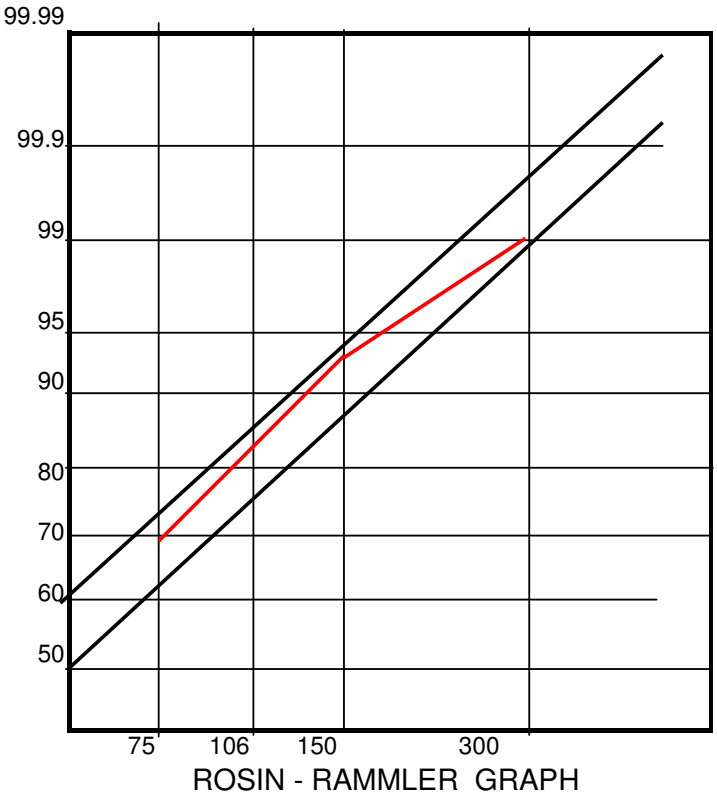
PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	2.1	-44.2	9.4	4.4	29	99.4	96.4	89.0	80.2
2	3.4	-11.8	9.2	2.8	28	98.5	92.1	80.7	66.4
3	3.4	-11.3	9.4	5.3	28	98.7	90.2	78.1	64.7
4	6.4	67.3	7.8	-12.5	24	99.2	93.2	81.7	64.4
TOTAL	15.3	TOTAL	35.9			AVERAGES			
						% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
						99.0	**93.0**	**82.4**	**68.9**

% PF Moisture	3.6
% Recovery rate	98.1









PF SAMPLING RESULTS

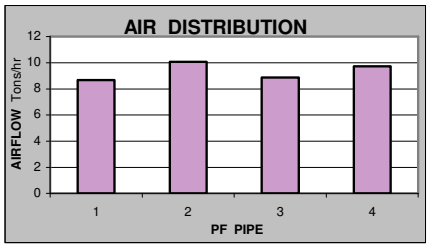
SWFB

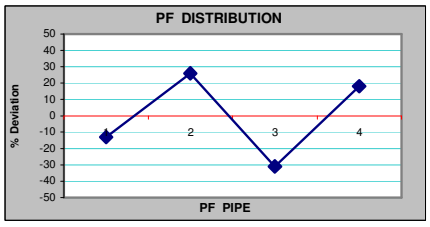
MILL	9E
DATE	2008/04/15
Mill Running Hours	

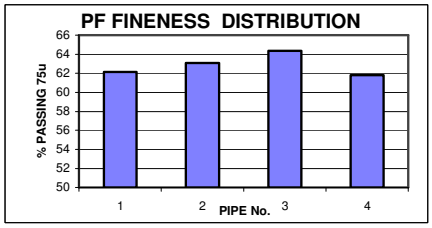
PA FLOW 8.5 kg/s COALFLOW 5.7 kg/s

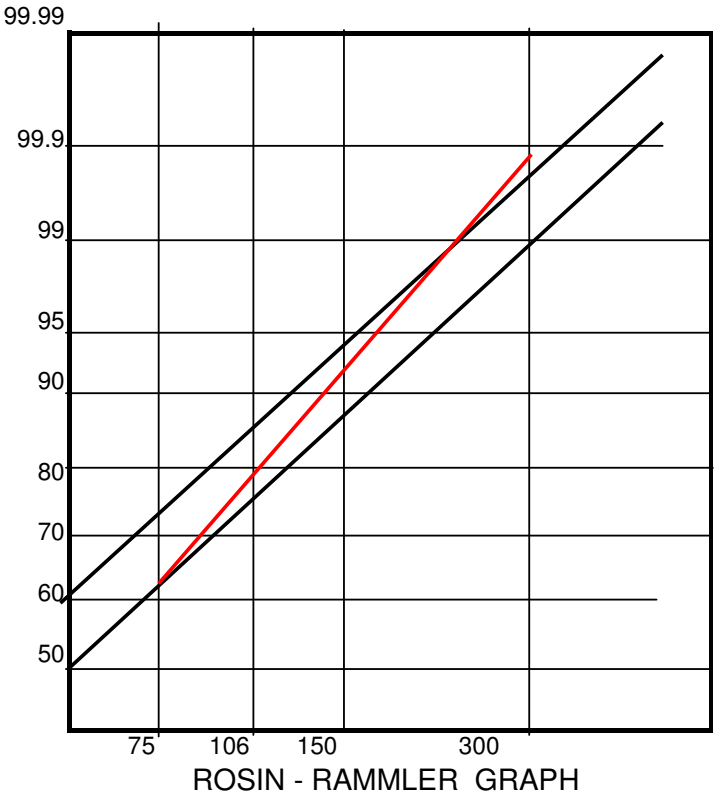
PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	4.6	-13.0	8.7	-7.1	26	99.6	91.3	78.0	62.1
2	6.6	26.0	10.1	7.8	31	99.8	92.1	78.9	63.1
3	3.6	-31.0	8.9	-4.8	27	99.6	92.1	79.8	64.4
4	6.2	18.0	9.7	4.2	30	100.0	92.5	79.3	61.8
TOTAL	21.0	TOTAL	37.3			AVERAGES			
						% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
						99.8	**92.0**	**79.0**	**62.8**

% PF Moisture	3.5
% Recovery rate	104.6









PF SAMPLING RESULTS

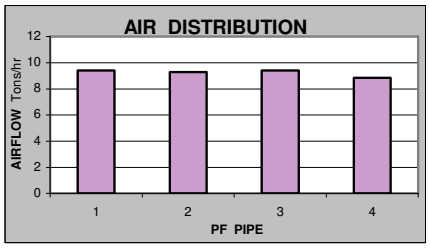
SWFB

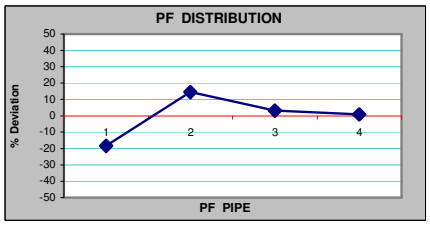
MILL	9F
DATE	2008/04/15
Mill Running Hours	

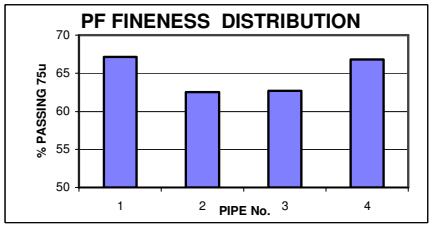
PA FLOW 8.5 kg/s COALFLOW 5.8 kg/s

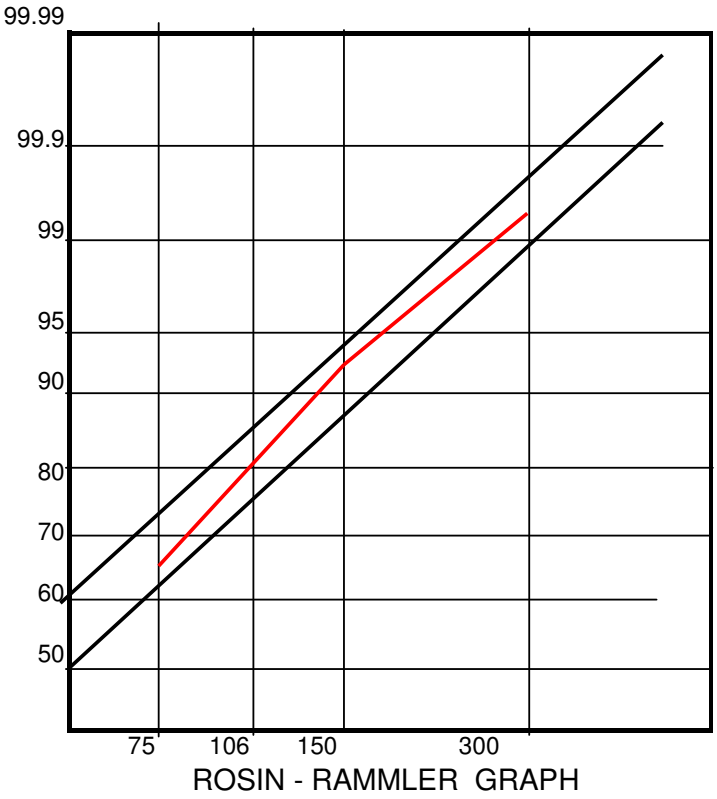
PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	4.2	-18.4	9.4	1.9	28	99.2	92.8	81.7	67.2
2	5.9	14.4	9.3	0.3	28	99.2	91.5	79.4	62.5
3	5.3	3.1	9.4	2.0	28	99.2	91.9	78.7	62.7
4	5.2	0.9	8.9	-4.2	27	99.6	93.8	82.4	66.8
TOTAL	20.7	TOTAL	37.0			AVERAGES			
						% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
						99.3	**92.5**	**80.6**	**64.8**

% PF Moisture	1.6
% Recovery rate	104.6









10 APPENDIX B: SMALL WALL-FIRED BOILER TEST LOGS

SMALL WALL-FIRED BOILER TEST LOGS

Time	Temp (°C)	Time	Level (foot)	Depth (m)	Combustible Residue (%)	Combustion Efficiency	Oxygen (%)	CO (%)	NO (ppm)	SO2 (ppm)	RTD from Middle burner row (s)
Average	**1359**		**50**								**0.21s**
Average	**1335**		**60**								**0.53s**
		14:17	83	0.5	10.60	94.77	4.40	33	695	585	
		14:22	83	1.0	7.60	96.38	4.90	37	742	451	
		14:27	83	1.0	7.90	96.22					
		14:30	83	1.5	5.30	97.53	4.75	59	745	545	**1.27s**
		14:35	83	1.5	5.60	97.39					
		14:40	83	2.0	6.70	96.84	4.60	60	766	535	
		14:49	83	2.0	7.00	96.68	4.70	60	769	545	
Average					**7.24**	**96.56**	**4.67**	**50**	**743**	**532**	
Average (normalized to 6% Oxygen)							**6.00**	**45**	**677**	**485**	
13:30	1447	12:35	93	1.0	4.90	97.73	3.60	62	886	659	
	1466		93	1.0	4.80	97.78					
	1431	12:48	93	1.5	5.20	97.58	4.45	40	866	634	
13:35	1456	12:52	93	1.5	4.20	98.07					
	1466	12:58	93	2.0	4.40	97.97	4.90	49	814	455	
13:40	1443	13:10	93	2.0	4.20	98.07					**1.59s**
		13:17	93	2.5	5.00	97.68	4.90		606		
		13:19	93	2.5	3.60	98.35					
		13:23	93	2.5	3.60	98.35					
Average	**1452**	**Average**			**4.43**	**97.96**	**4.46**	**50**	**793**	**583**	
Average (normalized to 6% Oxygen)							**6.00**	**46**	**722**	**531**	
	882		112	1.0	2.7	98.78					
	980	14:36	112	1.5	2.1	99.05	2.89		564		
	1026	14:50	112	2.0	5.4	97.48	4.16		498		
	1008	15:08	112	2.5	2.5	98.87	4.68				
		15:08	112	2.5	2.6	98.82					
	1079	15:12	112	3.0	2.4	98.92					
	926	15:12	112	3.0	2.6	98.82	3.68		454		**2.2s**
		15:26	112	3.5	2.80	98.73	3.48		505.00		
		15:26	112	3.5	2.8	98.73	3		570		
		15:35	112	4	2	99	4.77		525		
		15:43	112	4	2.40	98.92					
Average	**984**	**Average**			**2.79**	**98.73**	**3.85**		**519**		
Average (normalized to 6% Oxygen)							**6.00**		**473**		

11 APPENDIX C: PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY AND THE LARGE WALL-FIRED BOILER A

PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY LWF BOILER A

Test No	300µm			150µm			106µm			75µm		
	Before	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**
LWFV001A	16.0298	0.0118	**99.93%**	16.0298	0.2629	**98.29%**	16.0298	0.7238	**93.77%**	16.0298	1.4406	**84.78%**
LWFV002A	17.0311	0.0074	**99.96%**	17.0311	0.2301	**98.61%**	17.0311	0.9381	**93.10%**	17.0311	1.6257	**83.55%**
LWFV003A	16.8415	0.0074	**99.96%**	16.8415	0.2878	**98.25%**	16.8415	0.7193	**93.98%**	16.8415	1.5458	**84.80%**
LWFV004A	16.0215	0.0085	**99.95%**	16.0215	0.2214	**98.57%**	16.0215	0.26	**96.94%**	16.0215	0.7283	**92.40%**
LWFV005A	16.4547	0.0041	**99.98%**	16.4547	0.2888	**98.22%**	16.4547	0.9172	**92.65%**	16.4547	1.468	**83.72%**
LWFV006A	16.6035	0.0022	**99.99%**	16.6035	0.2022	**98.77%**	16.6035	0.3944	**96.39%**	16.6035	1.1794	**89.29%**
LWFV007A	16.0907	0.0029	**99.98%**	16.0907	0.2305	**98.55%**	16.0907	0.6015	**94.81%**	16.0907	1.6475	**84.57%**
LWFV008A	16.6336	0.0006	**100.00%**	16.6336	0.2732	**98.35%**	16.6336	0.9954	**92.37%**	16.6336	1.8774	**81.08%**
LWFV009A	12.0004	0.0085	**99.93%**	12.0004	0.2898	**97.51%**	12.0004	0.4407	**93.84%**	12.0004	0.6547	**88.39%**

PF SAMPLING RESULTS

LARGE WALL-FIRED BOILER A

MILL	4A
DATE	2008/07/08

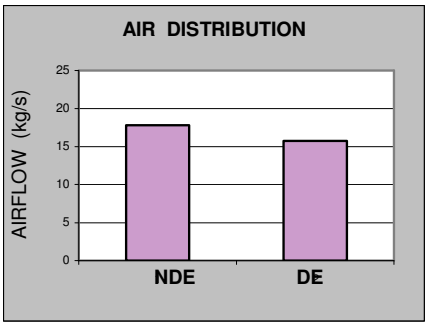
Mill load of 1477 Kw

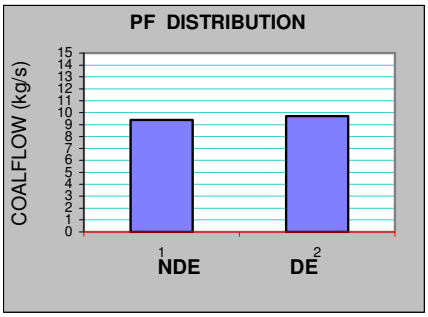
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
NDE	9.4	-1.6	17.8	6.1	39	99.4	97.8	94.4	87.6
DE	9.7	1.6	15.8	-6.1	35	99.6	98.2	95.4	90.0

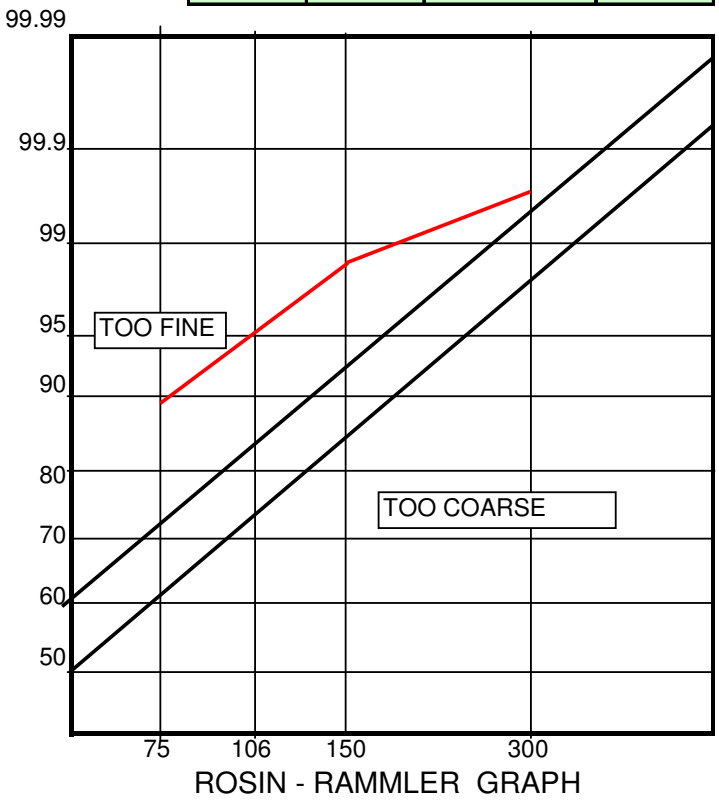
TOTAL		TOTAL	
19.1	kg/s	33.6	kg/s
68.7	tons/hr	120.9	tons/hr

% PF Moisture	1.7

AVERAGES % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.5	**98.0**	**94.9**	**88.8**







PF SAMPLING RESULTS

LARGE WALL-FIRED BOILER A

MILL	4B
DATE	2008/07/08

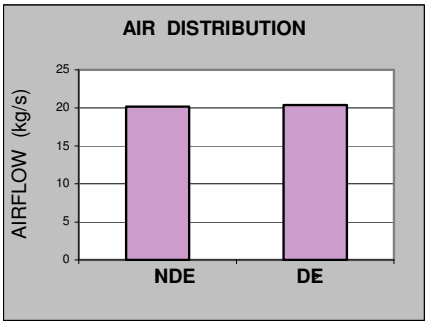
Mill load of 1481 Kw

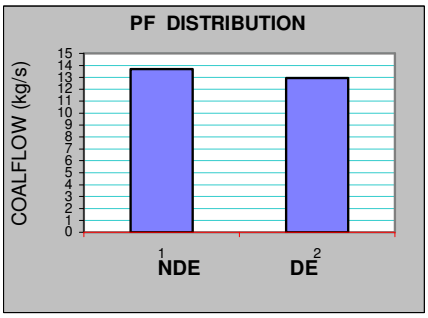
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
NDE	13.7	2.7	20.2	-0.5	40	100.0	98.0	94.2	86.6
DE	13.0	-2.7	20.4	0.5	40	98.8	93.6	87.8	78.0

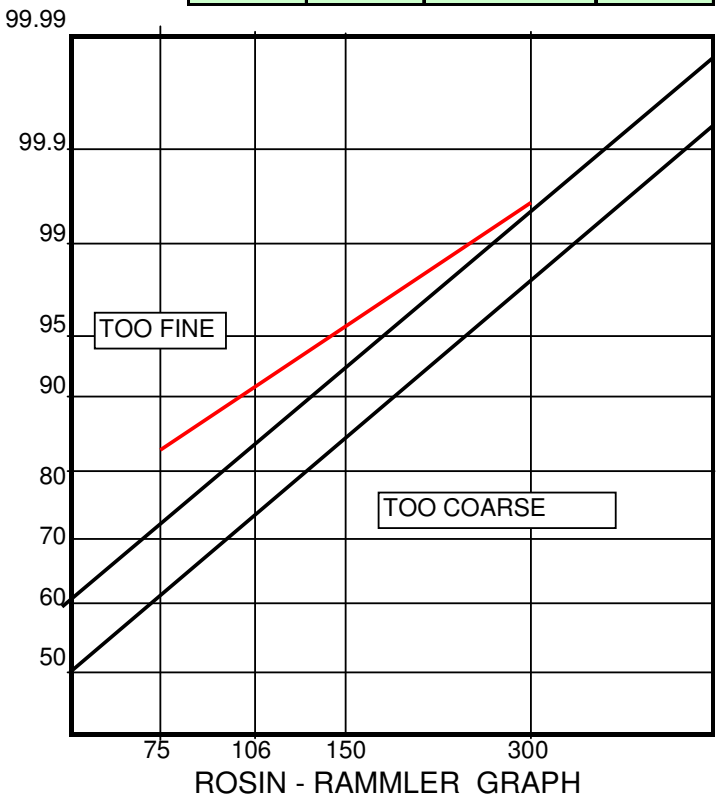
TOTAL		TOTAL	
26.6	kg/s	40.6	kg/s
95.9	tons/hr	146.0	tons/hr

% PF Moisture	1.8

AVERAGES % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.4	**95.8**	**91.0**	**82.3**







PF SAMPLING RESULTS

LARGE WALL-FIRED BOILER A

MILL	4C
DATE	2008/07/08

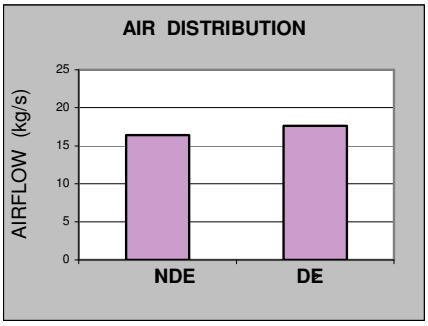
Mill load of 1478 Kw

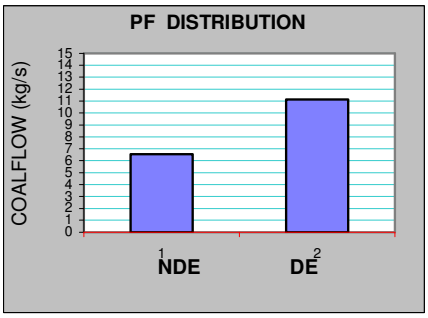
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
NDE	6.5	-26.0	16.4	-3.7	32	99.4	97.0	92.0	83.0
DE	11.1	26.0	17.6	3.7	34	99.0	95.2	90.4	83.0

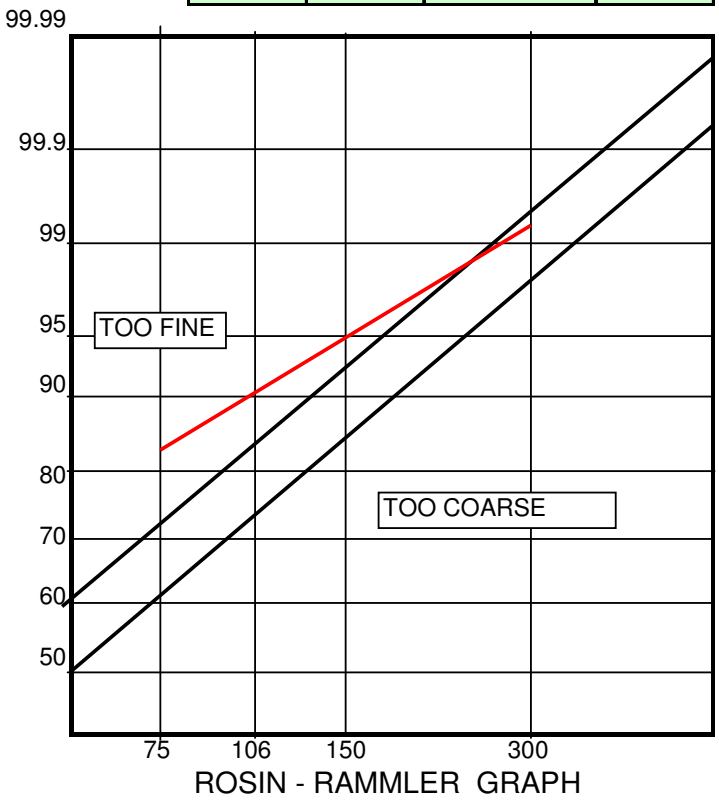
TOTAL		TOTAL	
17.7	kg/s	34.0	kg/s
63.7	tons/hr	122.5	tons/hr

% PF Moisture	1.5

AVERAGES			
% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.2	**96.1**	**91.2**	**83.0**







PF SAMPLING RESULTS

LARGE WALL-FIRED BOILER A

MILL	4D
DATE	2008/07/08

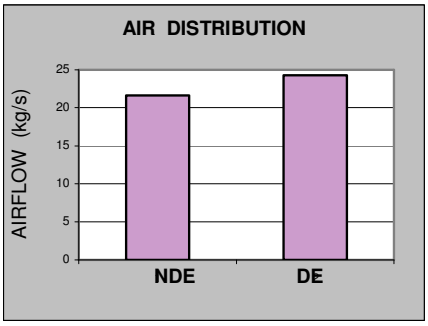
Mill load of 1479 Kw

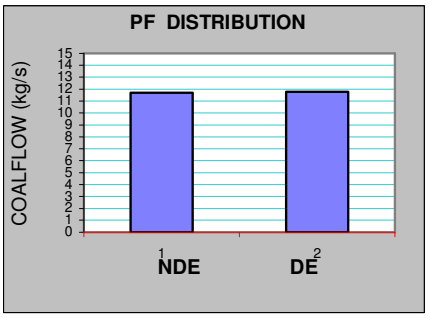
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	% Deviation	Pipe Velocity m/s	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
NDE	11.7	-0.3	21.6	-5.7	41	97.6	91.0	85.2	76.4
DE	11.8	0.3	24.3	5.7	46	98.0	91.8	86.4	77.6

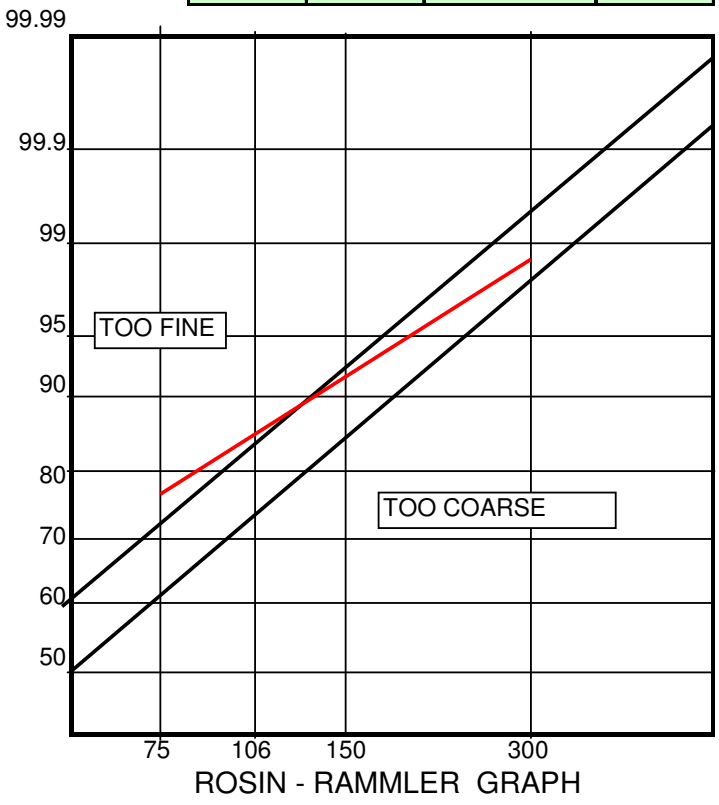
TOTAL		TOTAL	
23.5	kg/s	45.9	kg/s
84.6	tons/hr	165.3	tons/hr

% PF Moisture	1.4

AVERAGES % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
97.8	**91.4**	**85.8**	**77.0**







12 APPENDIX D: LARGE WALL-FIRED BOILER A TEST LOGS

LARGE WALL-FIRED BOILER A TEST LOGS

Time	Temp (°C)	Time	Level (m)	Depth (m)	Combustible Residue (%)	Combustion Efficiency (%)	Oxygen (%)	CO (ppm)	NO (ppm)	SO_2 (ppm)	RTD from Middle burner row (s)
09:04	1307	09:04	41	0.5	0.80	99.23	9.58	276	372		2.857
	1315		41	1.0	1.00	99.04	9.50	476	379		2.857
	1324		41	1.5	0.63	99.39	9.47	582	381		2.857
	1331		41	2.0	0.65	99.38	9.48	712	384		2.857
	1338		41	2.5	0.75	99.28	9.51	836	384		2.857
	1348		41	3.0	0.70	99.33	9.56	1078	385		2.857
	1355		41	3.5	0.80	99.23	9.64	1368	382		2.857
	1365		41	4.0	0.95	99.09	9.41	1407	381		2.857
13:38	1382	13:38	41	4.5	0.85	99.18	8.78	1714	373		2.857
Average	**1341**	**Average**			**0.79**	**99.24**	**9.44**	**939**	**380**		**2.857**
Average (Normalized to 6% Oxygen)							**6**	**1155**	**468**		
13:55	1041		66	0.50	0.80	99.23	2.23	110	588		3.127
	1028		66	1.00	0.60	99.43	1.60	150	602		3.127
	1047		66	1.50	0.70	99.33	1.16	226	610		3.127
	1051		66	2.00	0.40	99.62	0.96	880	613		3.127
	1057		66	2.50	0.40	99.62	0.90	1545	579		3.127
	1068		66	3.00	0.40	99.62	0.93	2391	546		3.127
	1069		66	3.50	0.30	99.71	0.92	3295	541		3.127
	1070		66	4.00	0.30	99.71	3.22	2887	222		3.127
17:45			66	4.50	0.30	99.71					3.127
	1054	**Average**			**0.47**	**99.55**	**1.49**	**1436**	**537**		**3.127**
Average (Normalized to 6% Oxygen)							**6**	**857**	**321**		

13 APPENDIX E: PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY AND THE TANGENTIALLY-FIRED BOILER

PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY – TF BOILER

Test No	300µm			150µm			106µm			75µm		
	Before	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**
TFV001	11.5119	0.0015	**99.99%**	11.5119	0.0783	**99.31%**	11.5119	0.3232	**96.50%**	11.5119	1.3577	**84.71%**
TFV002	10.4906	0.0028	**99.97%**	10.4906	0.0789	**99.22%**	10.4906	0.3801	**95.60%**	10.4906	1.3497	**82.73%**
TFV003	10.5197	0.0016	**99.98%**	10.5197	0.0707	**99.31%**	10.5197	0.4269	**95.25%**	10.5197	1.3102	**82.80%**
TFV004	11.3102	0.0039	**99.97%**	11.3102	0.0802	**99.26%**	11.3102	0.4522	**95.26%**	11.3102	1.3418	**83.39%**
TFV005	12.2207	0.0051	**99.96%**	12.2207	0.0967	**99.17%**	12.2207	0.6271	**94.04%**	12.2207	1.6447	**80.58%**
TFV006	10.4327	0.0044	**99.96%**	10.4327	0.0756	**99.23%**	10.4327	0.3943	**95.45%**	10.4327	1.463	**81.43%**
TFV007	10.818	0.003	**99.97%**	10.818	0.0664	**99.36%**	10.818	0.3496	**96.13%**	10.818	1.3829	**83.34%**
TFV008	9.9268	0.0011	**99.99%**	9.9268	0.0538	**99.45%**	9.9268	0.3464	**95.96%**	9.9268	1.365	**82.21%**
TFV009	11.0257	0.0021	**99.98%**	11.0257	0.0743	**99.31%**	11.0257	0.3825	**95.84%**	11.0257	1.2866	**84.17%**
TFV010	9.6225	0.0012	**99.99%**	9.6225	0.0607	**99.36%**	9.6225	0.3017	**96.22%**	9.6225	1.1769	**83.99%**
TFV011	10.8796	0.008	**99.93%**	10.8796	0.3657	**96.57%**	10.8796	1.0348	**87.05%**	10.8796	1.5911	**72.43%**
TFV012	12.3174	0.0162	**99.87%**	12.3174	0.2668	**97.70%**	12.3174	0.8684	**90.65%**	12.3174	2.0658	**73.88%**
TFV013	11.8555	0.0032	**99.97%**	11.8555	0.2728	**97.67%**	11.8555	0.6014	**92.60%**	11.8555	2.0318	**75.46%**
TFV014	11.2317	0.015	**99.87%**	11.2317	0.3185	**97.03%**	11.2317	0.6753	**91.02%**	11.2317	1.6917	**75.96%**
TFV015	9.7405	0.0057	**99.94%**	9.7405	0.3172	**96.68%**	9.7405	0.4823	**91.73%**	9.7405	1.2344	**79.06%**
TFV016	10.0454	0.009	**99.91%**	10.0454	0.1327	**98.59%**	10.0454	0.4882	**93.73%**	10.0454	1.2708	**81.08%**
TFV017	11.8555	0.0032	**99.97%**	11.8555	0.2728	**97.67%**	11.8555	0.6014	**92.60%**	11.8555	2.084	**75.02%**
TFV018	11.8555	0.0032	**99.97%**	11.8555	0.325	**97.23%**	11.8555	0.6534	**91.72%**	11.8555	1.895	**75.74%**

Sampling Systems (South Africa)

PF SAMPLING RESULTS

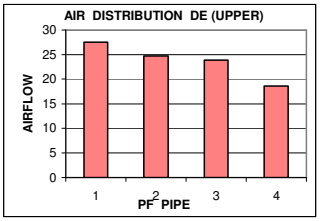
TFB | MILL | 2B

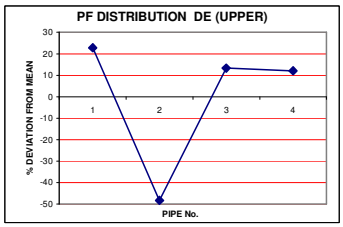
DATE | Sept'08 | TEST | 1

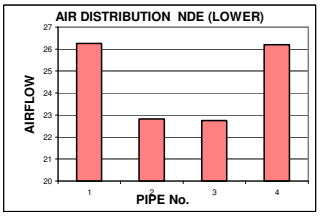
TEST 1

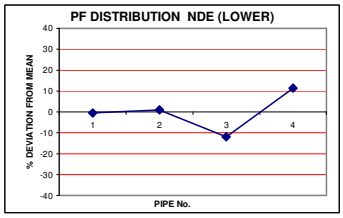
PIPE No.	COALFLOW Tons / hr	% DEVIATION				VELOCITY m/s	AIRFLOW Ton / hr	% DEVIATION	PF Moisture %	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
D1U	14.6	23				29.5	27.5	16	1.2	99.2	93.4	85.6	72.0
D2U	6.2	-48				26.1	24.7	4	1.8	100.0	93.6	86.6	76.2
D3U	13.5	13				25.5	23.9	1	1.5	99.6	96.2	90.6	82.2
D4U	13.3	12				19.8	18.6	-21	1.7	100.0	95.2	90.0	81.0
D1L	11.4	0				28.1	26.3	7	1.8	99.2	94.4	89.0	81.8
D2L	11.6	1				24.2	22.8	-7	1.7	98.8	90.4	81.4	69.0
D3L	10.1	-12				24.3	22.7	-7	1.8	97.8	89.6	82.4	72.0
D4L	12.8	11				28.1	26.2	7	1.3	97.2	88.4	81.0	71.0

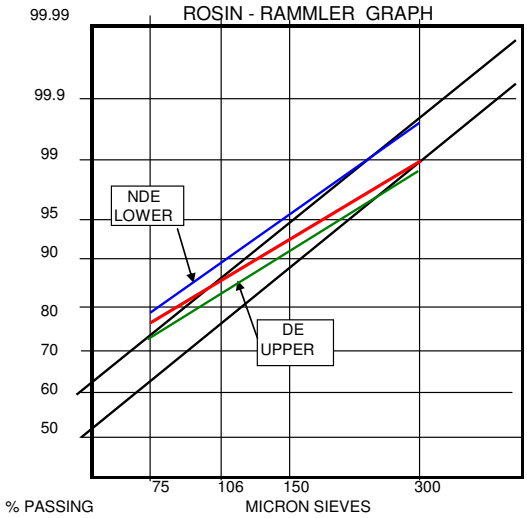
								WEIGHTED AVERAGES			
DE	47.6	tons/hr		kg/s	DE	94.7					
NDE	45.9				NDE	98.0	DE	99.7	94.6	88.2	77.9
TOTAL	93.5	tons/hr		kg/s			NDE	98.3	90.7	83.5	73.5
Mill Load	91	tons/hr			TOTAL	192.8	1.6	99.0	92.7	85.8	75.7
Recovery	103	%									











Sampling Systems (South Africa)

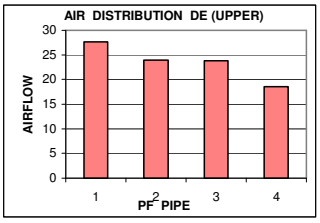
PF SAMPLING RESULTS

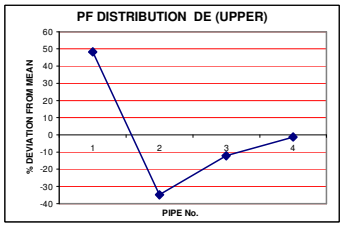
TFB | MILL 2B | DATE Sept'08 | TEST 2

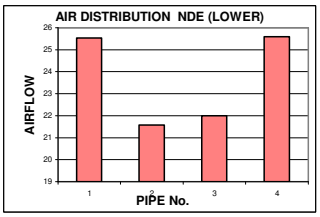
TEST 1

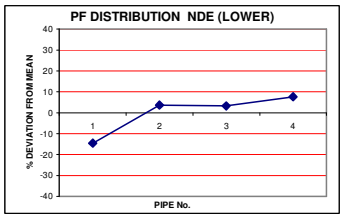
PIPE No.	COALFLOW Tons / hr	% DEVIATION				VELOCITY m/s	AIRFLOW Ton / hr	% DEVIATION	PF Moisture %	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
D1U	17.2	48				29.4	27.6	18	2.8	99.8	94.2	86.0	73.8
D2U	7.5	-35				25.4	23.9	2	0.5	98.6	90.2	82.0	70.4
D3U	10.2	-12				25.5	23.8	2	2.5	99.2	95.4	91.0	83.4
D4U	11.4	-1				19.9	18.5	-21	2.2	99.2	95.2	90.6	83.2
D1L	9.6	-15				27.4	25.5	8	2.0	99.0	94.8	90.0	83.6
D2L	11.6	4				23.1	21.6	-9	2.7	99.0	92.6	85.0	72.8
D3L	11.6	3				23.4	22.0	-7	2.0	98.4	91.8	85.0	75.6
D4L	12.0	8				27.4	25.6	8	3.7	98.4	90.8	84.8	76.2

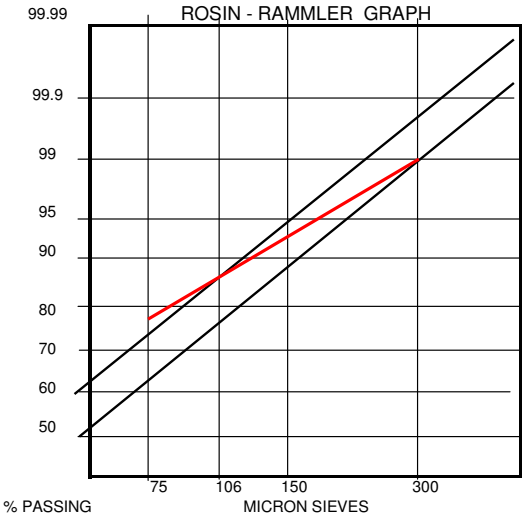
							WEIGHTED AVERAGES			
DE	46.3	tons/hr		kg/s	DE	93.9				
NDE	44.8				NDE	94.7	DE	99.2	93.8	87.4	77.7
TOTAL	**91.1**	tons/hr		kg/s			NDE	98.7	92.5	86.2	77.1
Mill Load	91	tons/hr			TOTAL	**188.6**	**2.5**	**99.0**	**93.1**	**86.8**	**77.4**
Recovery	100	%									











Sampling Systems (South Africa)

PF SAMPLING RESULTS

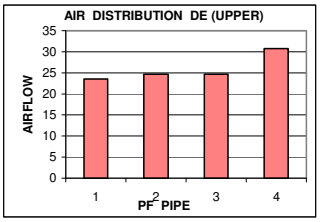
TFB | MILL | 2C

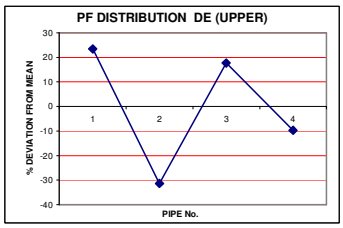
DATE | Sept'08 | TEST | 1

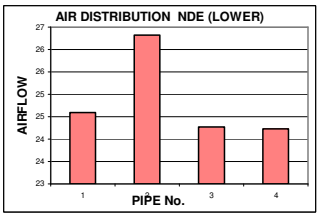
TEST 1

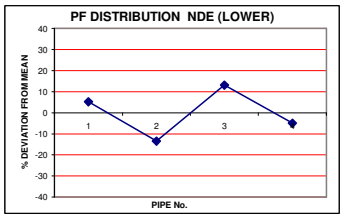
PIPE No.	COALFLOW Tons / hr	% DEVIATION				VELOCITY m/s	AIRFLOW Ton / hr	% DEVIATION	PF Moisture %	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
D1U	17.4	23				25.1	23.5	-9	2.2	99.0	90.8	82.4	69.4
D2U	9.7	-31				26.2	24.6	-5	3.2	98.4	91.6	85.0	74.8
D3U	16.6	18				26.2	24.7	-5	2.8	99.4	96.0	92.0	85.4
D4U	12.7	-10				33.0	30.7	19	2.2	98.0	89.6	81.4	71.6
D1L	9.9	5				26.2	24.6	-1	2.0	98.0	91.6	84.8	76.4
D2L	8.2	-13				28.0	26.3	6	1.7	99.0	93.8	88.2	79.8
D3L	10.7	13				25.8	24.3	-2	2.5	99.2	95.2	89.8	81.6
D4L	9.0	-5				25.9	24.2	-3	1.8	99.4	92.2	84.2	72.0

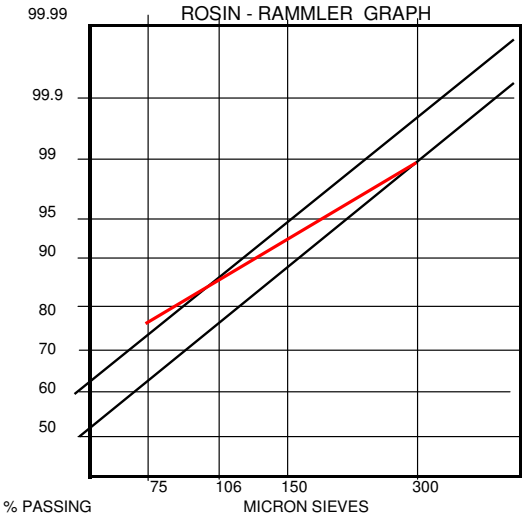
								WEIGHTED AVERAGES			
DE	56.4	tons/hr		kg/s	DE	103.5					
NDE	37.8				NDE	99.4		DE	98.7	92.0	85.2	75.3
TOTAL	**94.2**	tons/hr		kg/s				NDE	98.9	93.2	86.8	77.5
Mill Load	92	tons/hr			TOTAL	**202.9**		**2.2**	**98.8**	**92.6**	**86.0**	**76.4**
Recovery	102	%										











Sampling Systems (South Africa)

PF SAMPLING RESULTS

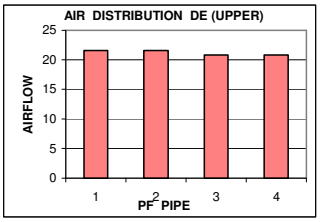
TFB | MILL | 2C

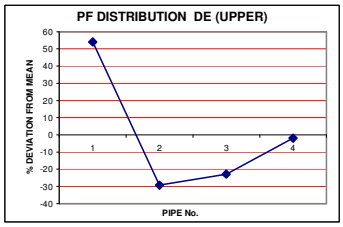
DATE | Sept'08 | TEST | 2

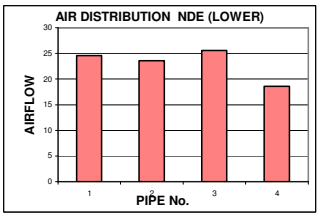
TEST 1

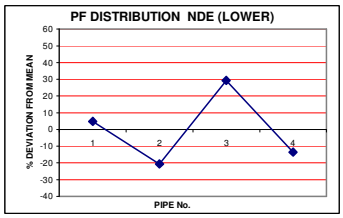
PIPE No.	COALFLOW Tons / hr	% DEVIATION				VELOCITY m/s	AIRFLOW Ton / hr	% DEVIATION	PF Moisture %	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
D1U	17.0	54				23.0	21.6	2	2.7	98.4	90.8	82.8	70.8
D2U	7.8	-29				23.0	21.6	2	3.2	98.4	93.6	87.6	79.0
D3U	8.5	-23				22.2	20.8	-2	2.8	99.6	98.4	96.4	93.4
D4U	10.9	-2				22.2	20.8	-2	2.2	99.0	94.8	89.8	80.8
D1L	11.8	5				26.3	24.6	6	2.0	98.2	92.2	86.0	77.6
D2L	9.0	-21				25.0	23.6	2	1.7	99.0	92.8	86.2	74.4
D3L	14.6	29				27.4	25.6	11	2.5	98.8	93.4	86.8	77.2
D4L	9.8	-13				19.8	18.6	-19	1.8	98.8	91.6	84.2	73.0

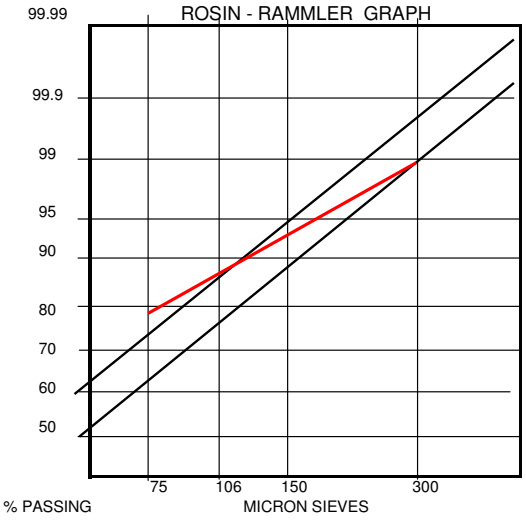
								WEIGHTED AVERAGES			
DE	44.2	tons/hr		kg/s	DE	84.8			98.9	94.4	89.2	81.0
NDE	45.1				NDE	92.3		DE				
TOTAL	89.4	tons/hr		kg/s				NDE	98.7	92.5	85.8	75.6
Mill Load	91	tons/hr			TOTAL	177.1		2.2	98.8	93.5	87.5	78.3
Recovery	98	%										











Sampling Systems (South Africa)

PF SAMPLING RESULTS

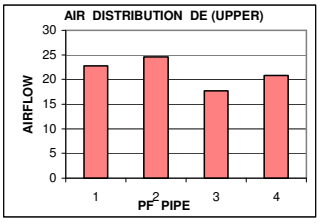
TFB | MILL | 2D

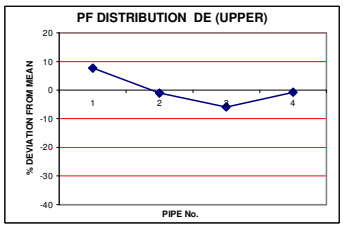
DATE | Sept'08 | TEST | 1

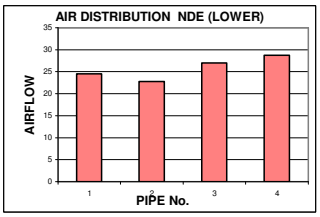
TEST 1

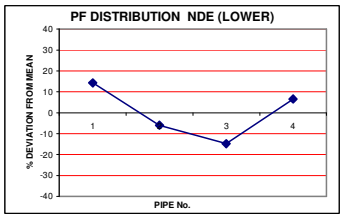
PIPE No.	COALFLOW Tons / hr	% DEVIATION				VELOCITY m/s	AIRFLOW Ton / hr	% DEVIATION	PF Moisture %	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
D1U	13.6	8				24.3	22.8	6	3.3	98.6	92.8	87.0	78.4
D2U	12.5	-1				26.2	24.6	15	2.2	99.8	97.4	93.8	87.0
D3U	11.9	-6				18.8	17.7	-18	1.7	98.8	94.8	89.6	81.6
D4U	12.6	-1				22.1	20.8	-3	2.0	99.0	94.2	88.6	79.6
D1L	10.0	14				26.3	24.5	-5	2.5	100.0	97.6	93.8	87.6
D2L	8.2	-6				24.3	22.8	-12	1.0	99.4	95.8	90.2	81.8
D3L	7.4	-15				28.7	27.0	5	1.8	99.6	97.4	94.4	89.8
D4L	9.3	7				30.8	28.7	12	2.3	99.8	98.6	96.2	90.0

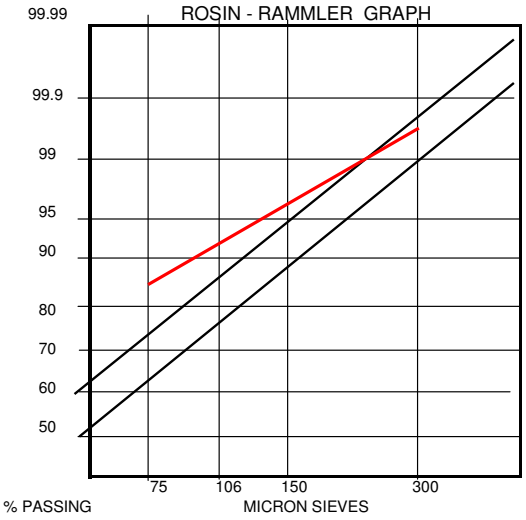
								WEIGHTED AVERAGES			
DE	50.6	tons/hr		kg/s	DE	85.9					
NDE	34.9				NDE	103.0		DE	99.1	94.8	89.8	81.7
TOTAL	**85.6**	tons/hr		kg/s				NDE	99.7	97.4	93.7	87.3
Mill Load	90	tons/hr			TOTAL	**189.0**		**1.9**	**99.4**	**96.1**	**91.7**	**84.5**
Recovery	95	%										











Sampling Systems (South Africa)

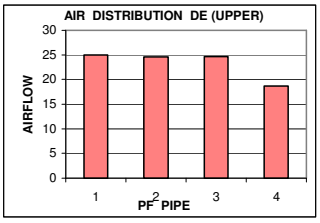
PF SAMPLING RESULTS

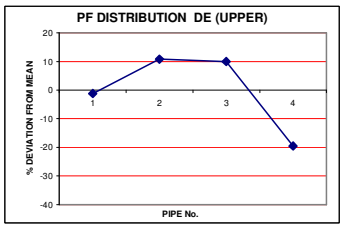
TFB | MILL 2D | DATE Sept'08 | TEST 2

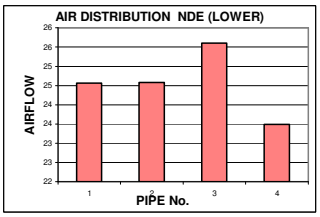
TEST 1

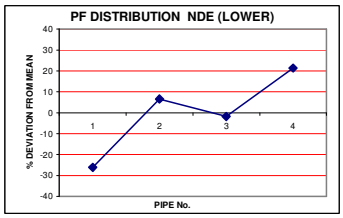
PIPE No.	COALFLOW Tons / hr	% DEVIATION				VELOCITY m/s	AIRFLOW Ton / hr	% DEVIATION	PF Moisture %	PF GRADING % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
D1U	11.6	-1				26.6	24.9	7	2.2	99.4	95.2	90.6	83.4
D2U	13.0	11				26.2	24.6	6	2.2	99.4	96.0	91.6	83.4
D3U	12.9	10				26.2	24.6	6	1.7	98.2	94.2	89.0	80.2
D4U	9.5	-20				19.8	18.6	-20	2.0	100.0	95.2	90.2	82.2
D1L	8.3	-26				26.3	24.6	0	2.5	99.6	97.4	94.0	88.8
D2L	12.0	7				26.2	24.6	0	1.0	99.2	91.4	83.8	71.4
D3L	11.0	-2				27.4	25.6	4	1.8	100.0	96.2	91.4	83.0
D4L	13.7	21				25.1	23.5	-4	2.3	98.8	94.4	89.2	80.8

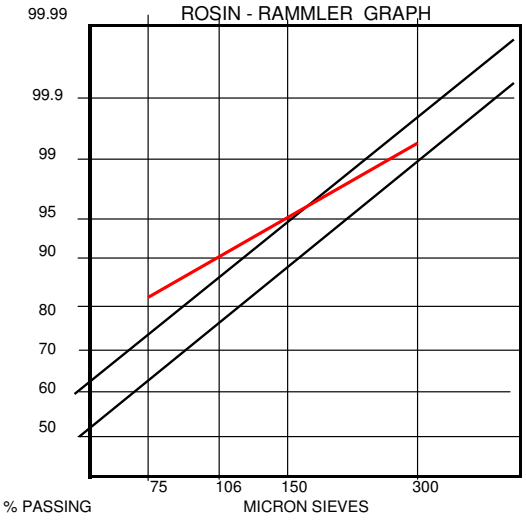
							WEIGHTED AVERAGES			
DE	47.1	tons/hr		kg/s	DE	92.8				
NDE	45.0				NDE	98.2	DE	99.3	95.2	90.4	82.3
TOTAL	**92.1**	tons/hr		kg/s			NDE	99.4	94.9	89.6	81.0
Mill Load	91	tons/hr			TOTAL	**191.1**	**1.9**	**99.3**	**95.0**	**90.0**	**81.7**
Recovery	101	%									











14 APPENDIX F: TANGENTIALLY-FIRED BOILER TEST LOGS

TANGENTIALLY FIRED BOILER TEST LOGS AT EXIT OXYGEN OF 2.44%

Time	Temp (℃)	Time	Level (m)	Depth (m)	Combustible Residue (%)	Combustion Efficiency (%)	Oxygen (%)	CO (ppm)	NO (ppm)	SO_2 (ppm)	RTD from Middle burner row (s)
11:00	636	11:00	39	4.0	8.10	93.43					
	646		39	4.0	20.80	80.43					
	804		39	4.5	9.20	92.45					
	920		39	4.5	21.20	79.95					
	1048		39	5.0	7.20	94.22					**0.060**
	1076		39	5.0	14.40	87.46					
	1119		39	5.5	5.40	95.75					
16:00	1183	16:00	39	5.5	11.80	90.03					
Average	**1025**	**Average**			**12.26**	**89.21**					
11:00	1261	11:00	54	0.5	1.50	98.87					
	1412		54	1	1.20	99.09					
	1229		54	1.5	1.60	98.79					
	1403		54	2	1.60	98.79					
	1289		54	2.5	1.20	99.09					**2.300**
	1401		54	3	1.00	99.25					
	1310		54	3.5	1.30	99.02					
16:00	1350	16:00	54			100.00					
Average	**1332**	**Average**			**1.34**	**99.11**					
11:00	1118		66	1.00		100.00					
	1069		66	1.50		100.00					
	1069		66	2.00		100.00					
	1044		66	2.50		100.00					
	1077		66	3.00	1.40	98.94					**4.300**
	1077		66	3.50	1.30	99.02					
	1061		66	4.00	0.90	99.32					
			66	4.50		100.00					
	1073	**Average**			**1.20**	**99.61**					

TANGENTIALLY FIRED BOILER TEST LOGS AT EXIT OXYGEN OF 3.42%

Time	Temp (℃)	Time	Level (m)	Depth (m)	Combustible Residue (%)	Combustion Efficiency (%)	Oxygen (%)	CO (ppm)	NO (ppm)	SO_2 (ppm)	RTD from Middle burner row (s)
09:00	970	09:00	39	4.0	11.40	90.41					
	1056		39	4.0	22.40	78.49					
	1141		39	4.5	9.20	92.45					
	1180		39	4.5	21.20	79.95					
	1208		39	5.0	7.00	94.39					**0.05s**
	1236		39	5.0	14.80	87.05					
	1223		39	5.5	4.60	96.41					
16:00	1302	16:00	39	5.5	9.30	92.36					
Average	**1215**	**Average**			**12.49**	**88.94**					
09:00	1137	09:00	54	0.5	1.60	98.79					
	1315		54	1	1.30	99.02					
	1392		54	1.5	1.00	99.25					
	1375		54	2	0.80	99.40					
	1271		54	2.5	0.80	99.40					**2.15s**
	1360		54	3	0.70	99.47					
	1262		54	3.5	0.80	99.40					
16:00		16:00	54			100.00					
Average	**1302**	**Average**			**1.00**	**99.34**					
09:00	1104	09:00	66	0.50			7.30	12	363	150	
	1105		66	1.00			5.25	10	446	549	
	1117		66	1.50			6.70	13	416	538	
	1166		66	2.00			6.55	15	455	489	
	1173		66	2.50			7.45	16	465	212	
	1144		66	3.00			4.10	18	399	314	**3.75s**
	1141		66	3.50			4.60	22	436	520	
	1134		66	4.00			5.75	19	440	496	
16:00	1090	16:00	66	4.50			5.80	17	406	470	
	1130	**Average**			**1.00**	**99.34**	**5.94**	**15**	**425**	**415**	
Average (Normalized to 6% Oxygen)							**6**	**10**	**444**	**547**	

15 APPENDIX G: PF SAMPLING RESULTS FOR THE PSCTF THE LWF BOILER B

PULVERIZED FUEL SAMPLING RESULTS FOR THE PILOT SCALE COMBUSTION TEST FACILITY – LWF BOILER B

Test No	300µm			150µm			106µm			75µm		
	Before	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**	**Before**	**After**	**Sieve**
LWFV001B	16.1134	0.0146	**99.91%**	16.1134	1.1012	**93.08%**	16.1134	1.178	**85.76%**	16.1134	1.3543	**77.36%**
LWFV002B	11.3467	0.0055	**99.95%**	11.3467	0.7866	**93.02%**	11.3467	0.9867	**84.32%**	11.3467	0.8673	**76.68%**
LWFV003B	11.5587	0.0112	**99.90%**	11.5587	0.8134	**92.87%**	11.5587	1.0067	**84.16%**	11.5587	0.8110	**77.14%**
LWFV004B	12.0356	0.0048	**99.96%**	12.0356	1.0076	**91.59%**	12.0356	0.7866	**85.05%**	12.0356	0.5840	**80.20%**
LWFV005B	13.1132	0.0061	**99.95%**	13.1132	0.9788	**92.49%**	13.1132	1.1066	**84.05%**	13.1132	1.2091	**74.83%**
LWFV006B	14.5677	0.0073	**99.95%**	14.5677	0.8799	**93.91%**	14.5677	0.9956	**87.08%**	14.5677	1.1429	**79.23%**

PF SAMPLING RESULTS

MILL **4A**

LARGE WALL FIRED BOILER B

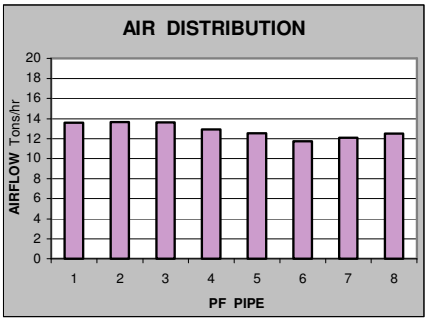
DATE **2008/12/02**

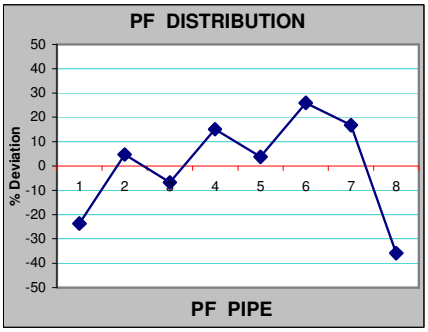
PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF PARTICLE SIZE ANALYSIS % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	5.0	-23.6	13.6	5.7	24	99.6	95.8	88.4	76.4
2	6.8	4.7	13.7	6.5	24	100.0	95.6	88.2	77.2
3	6.1	-6.8	13.6	6.3	24	99.6	94.0	82.6	65.8
4	7.5	15.1	12.9	0.8	23	100.0	95.0	84.4	63.6
5	6.8	3.7	12.6	-2.2	22	100.0	97.2	88.8	72.8
6	8.2	26.0	11.7	-8.7	21	99.8	93.0	79.8	58.8
7	7.6	16.8	12.1	-5.8	21	100.0	96.2	88.8	76.6
8	4.2	-35.9	12.5	-2.5	22	99.6	95.6	88.2	73.4
						AVERAGES			
						% Passing 300 u	% Passing 150 u	% Passing 75 u	% Passing 75 u
						99.83	**95.30**	**86.15**	**70.58**

1 to 4	25.4
5 to 8	26.8
TOTAL	52.2

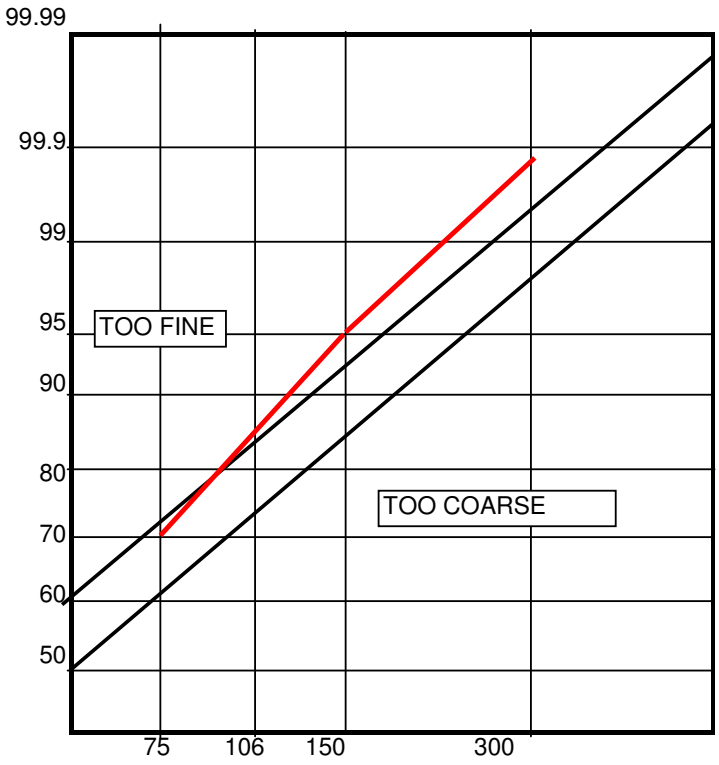
TOTAL 102.7

% PF Moisture	3.1
% Recovery rate	100.5





ROSIN - RAMMLER GRAPH



PF SAMPLING RESULTS

MILL **4A**

LARGE WALL FIRED BOILER B

DATE **2008/12/03**

PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF PARTICLE SIZE ANALYSIS % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	6.4	23.7	16.3	-0.4	30	100.0	95.6	88.4	76.0
2	3.1	-40.8	15.7	-4.2	29	99.6	97.2	92.8	86.0
3	3.9	-24.0	15.7	-4.1	29	99.6	97.4	92.2	83.4
4	6.1	17.2	16.1	-2.2	29	100.0	95.2	85.8	72.4
5	4.8	-7.5	17.3	5.1	31	100.0	97.4	90.4	79.0
6	6.5	25.6	15.5	-5.7	28	99.8	92.6	81.6	67.6
7	5.6	7.9	16.7	1.5	30	99.6	91.4	81.0	68.2
8	5.1	-2.1	18.1	10.0	33	100.0	90.6	81.2	69.6

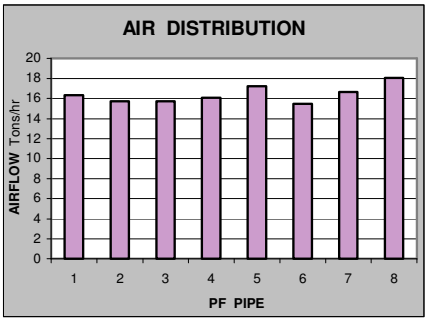
1 to 4	19.5
5 to 8	21.9
TOTAL	41.4

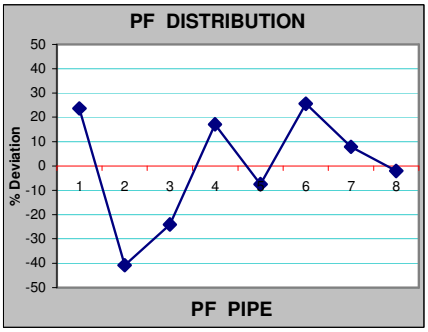
TOTAL 131.3

AVERAGES

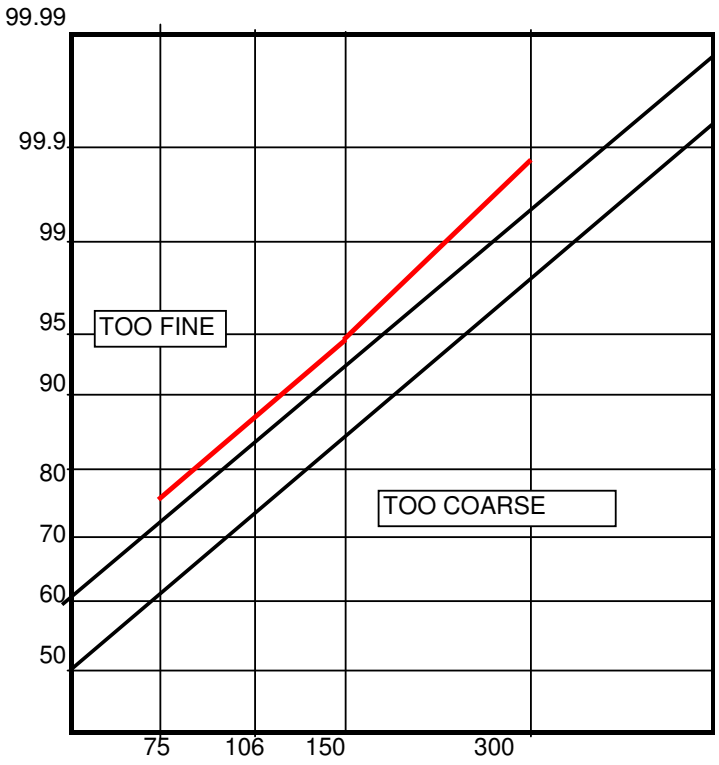
% Passing 300 u	% Passing 150 u	% Passing 75 u	% Passing 75 u
99.83	**94.68**	**86.68**	**75.28**

% PF Moisture	3.1
% Recovery rate	97.1





ROSIN - RAMMLER GRAPH



PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4B
TEST	1
DATE	08-12-02

CONDITIONS :

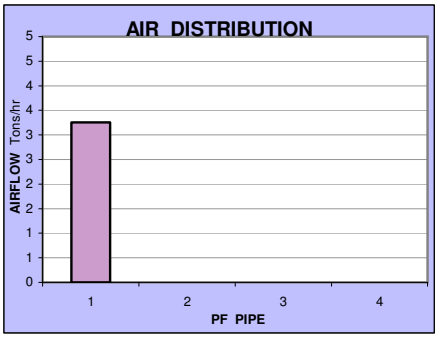
BOILER ON STEADY LOAD FOR VALIDATION TESTS

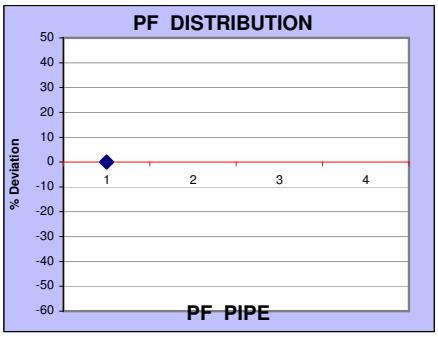
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	14.6	0.0	3.3	91	35	99.9	95.1	85.9	73.1

TOTAL	14.6	TOTAL	3.3
tons/hr	52.7	tons/hr	11.7

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.92	**95.12**	**85.92**	**73.12**

% PF Moisture	2.3
% Recovery rate	101.5







PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4C
TEST	1
DATE	2008/12/02

CONDITIONS :

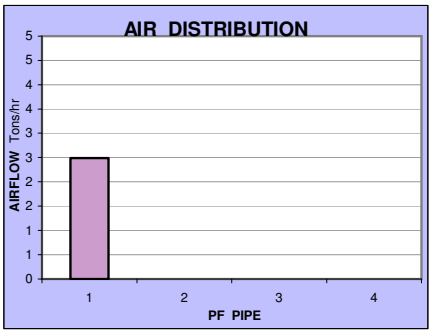
BOILER ON STEADY LOAD FOR VALIDATION TESTS

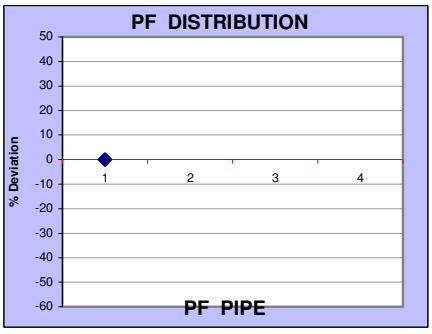
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	13.0	0.0	2.5	91	27	99.9	94.7	87.1	75.1

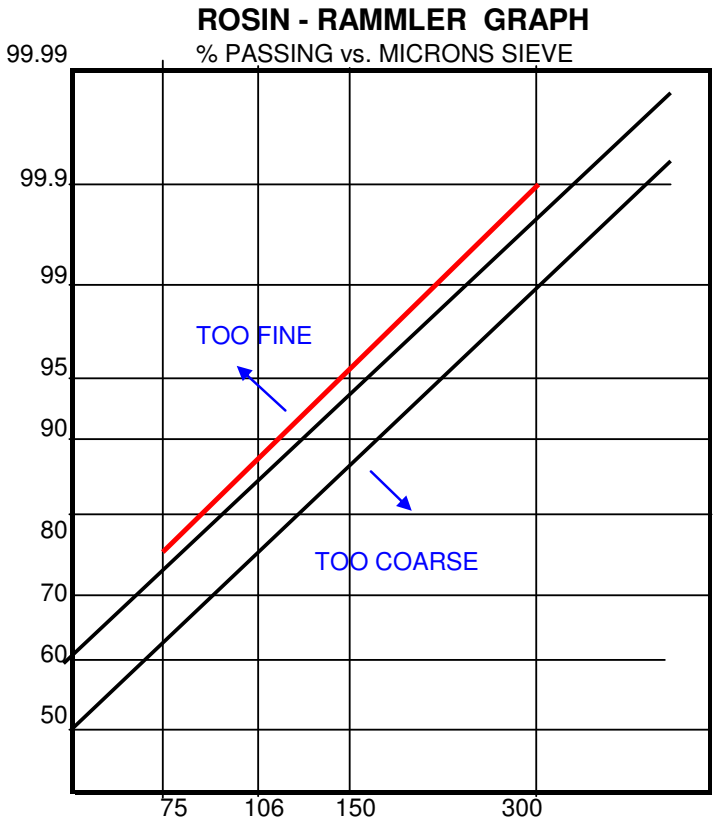
TOTAL	13.0	TOTAL	2.5
tons/hr	46.7	tons/hr	9.0

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.92	**94.72**	**87.12**	**75.12**

% PF Moisture	4.8
% Recovery rate	87.6







PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4C
TEST	2
DATE	2008/12/03

CONDITIONS :

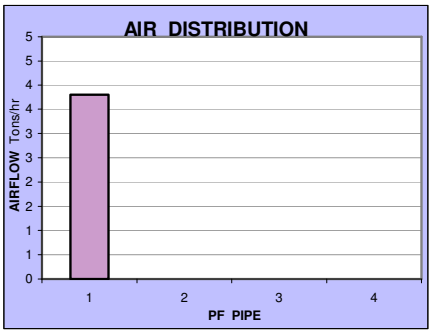
BOILER ON STEADY LOAD FOR VALIDATION TESTS

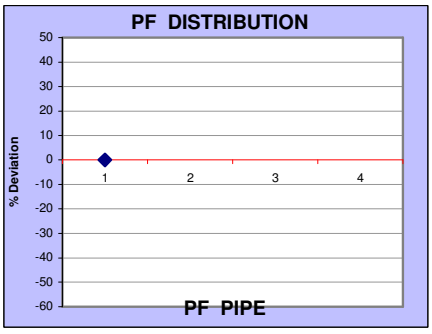
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	15.3	0.0	3.8	94	41	99.6	94.2	86.0	74.6

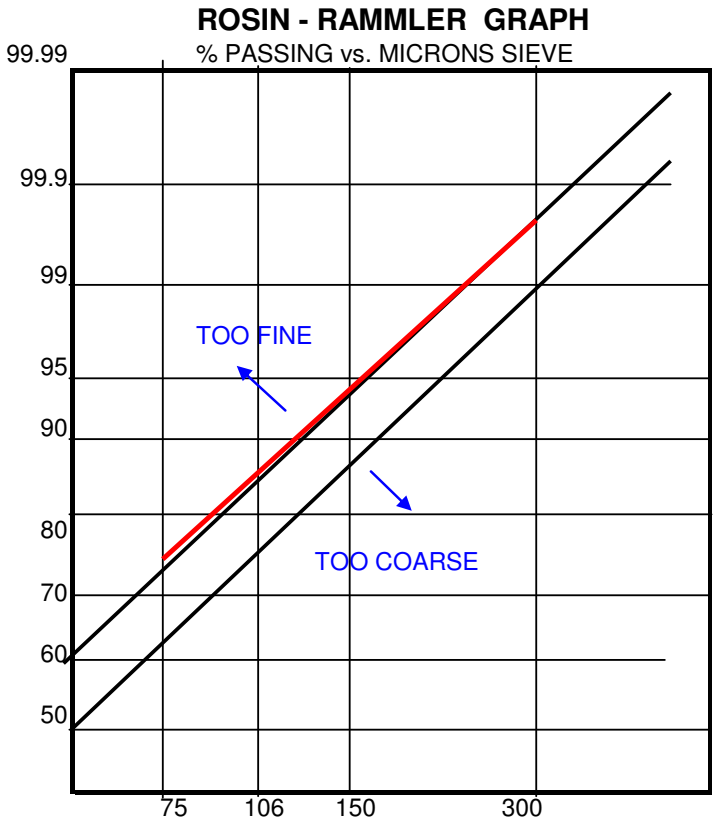
TOTAL	15.3	TOTAL	3.8
tons/hr	55.1	tons/hr	13.7

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.64	**94.24**	**86.04**	**74.64**

% PF Moisture	4.8
% Recovery rate	103.4







PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4D
TEST	1
DATE	2008/12/02

CONDITIONS :

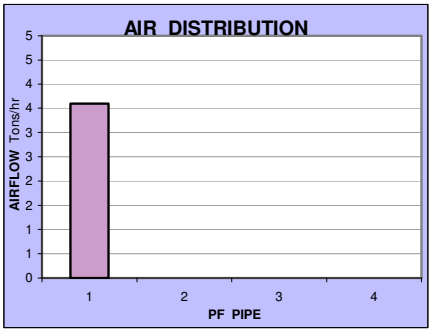
BOILER ON STEADY LOAD FOR VALIDATION TESTS

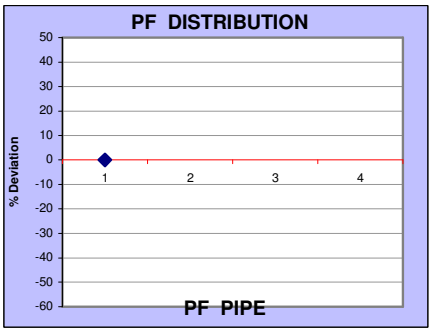
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	14.2	0.0	3.6	88	39	99.7	96.3	88.7	76.5

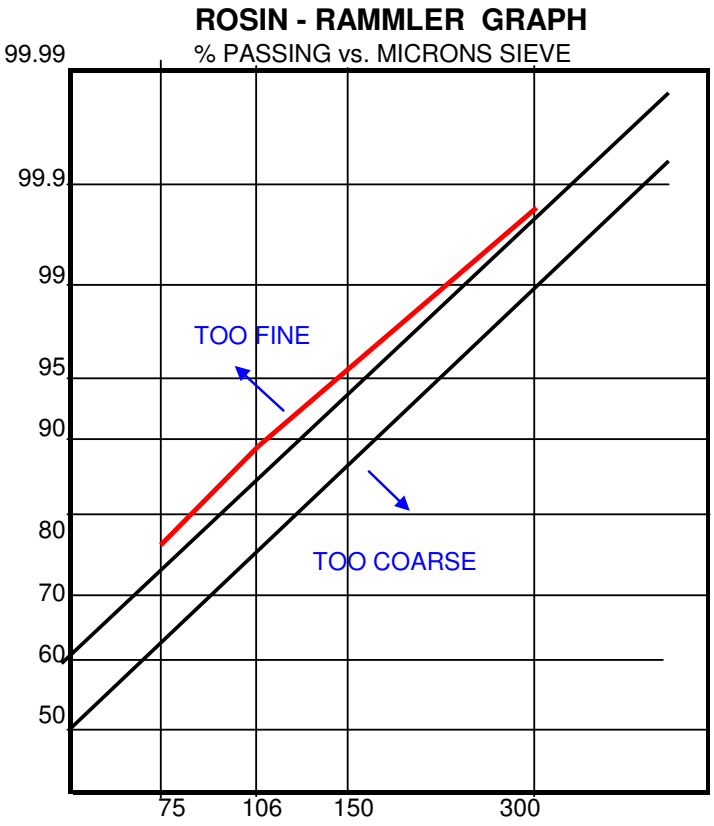
TOTAL	14.2	TOTAL	3.6
tons/hr	51.1	tons/hr	13.0

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.70	**96.30**	**88.70**	**76.50**

% PF Moisture	3.0
% Recovery rate	96.1







PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4D
TEST	2
DATE	2008/12/03

CONDITIONS :

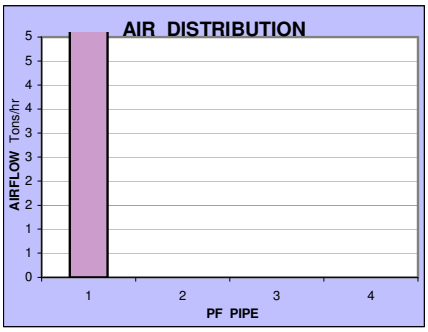
BOILER ON STEADY LOAD FOR VALIDATION TESTS

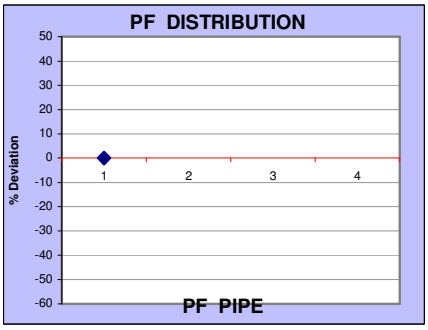
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	19.3	0.0	49.7	96	42	99.2	94.2	87.2	74.6

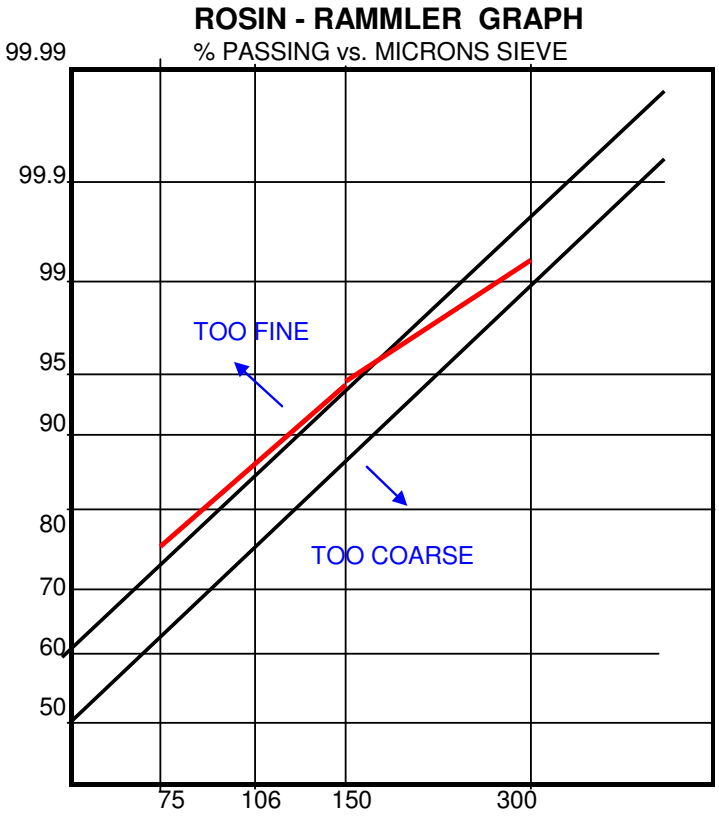
TOTAL	19.3	TOTAL	49.7
tons/hr	69.4	tons/hr	178.8

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.20	**94.20**	**87.20**	**74.60**

% PF Moisture	4.2
% Recovery rate	111.0







PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4E
TEST	1
DATE	2008/12/02

CONDITIONS :

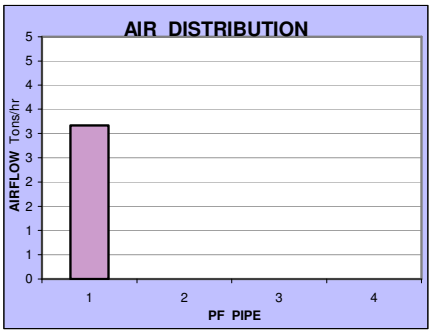
BOILER ON STEADY LOAD FOR VALIDATION TESTS

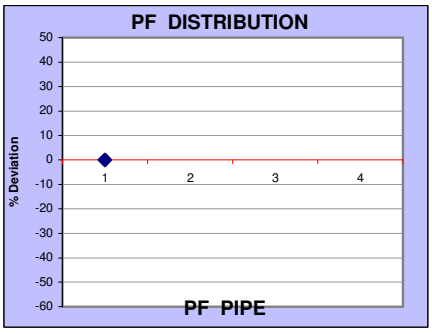
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	12.2	0.0	3.2	88	34	99.9	96.7	90.1	78.5

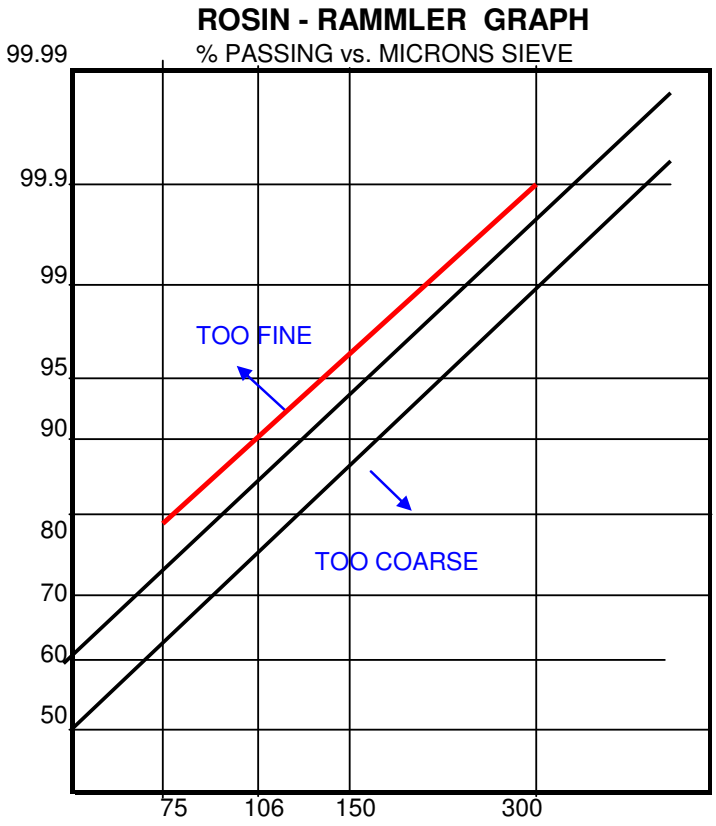
TOTAL	12.2	TOTAL	3.2
tons/hr	43.9	tons/hr	11.4

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.94	**96.74**	**90.14**	**78.54**

% PF Moisture	2.3
% Recovery rate	91.3







PF SAMPLING TEST RESULTS

LARGE WALL FIRED BOILER B

MILL	4E
TEST	2
DATE	2008/12/03

CONDITIONS :

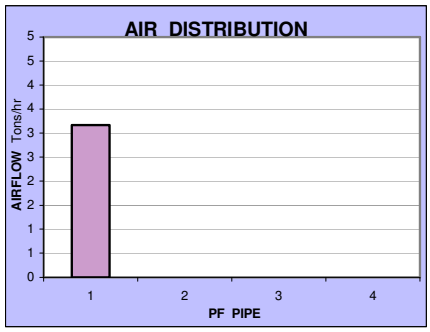
BOILER ON STEADY LOAD FOR VALIDATION TESTS

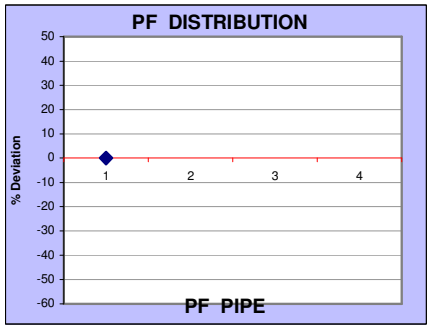
PF PIPE MEASUREMENTS						PF GRADING RESULTS			
PIPE No.	Coalflow kg/s	% Deviation	Airflow kg/s	Temp ºC	Velocity m/s	% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	15.3	0.0	3.2	88	34	99.6	95.0	86.4	74.8

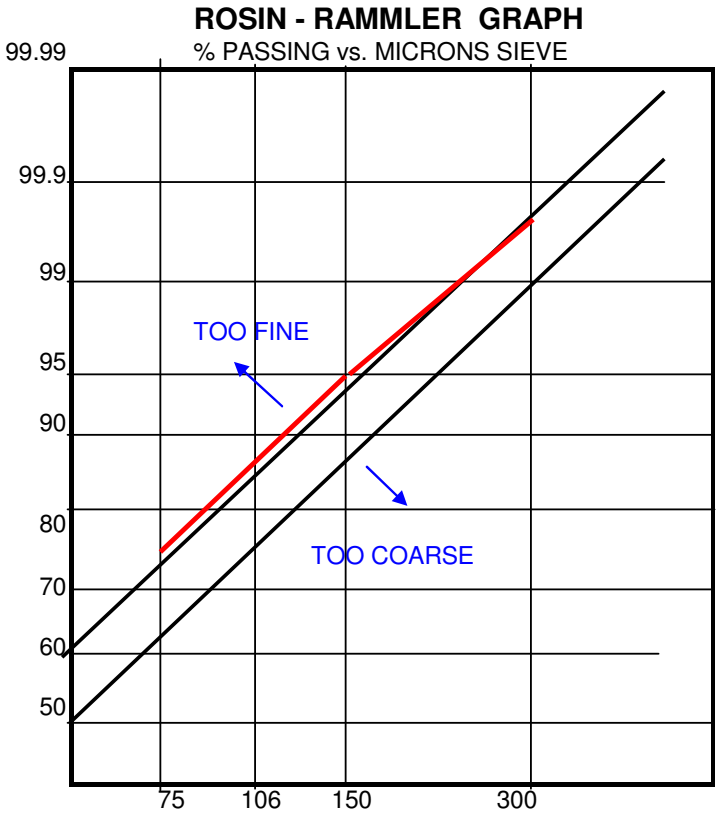
TOTAL	15.3	TOTAL	3.2
tons/hr	55.2	tons/hr	11.4

% Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
99.64	**95.04**	**86.44**	**74.84**

% PF Moisture	3.8
% Recovery rate	113.0







PF SAMPLING RESULTS

MILL **4F**

LARGE WALL FIRED BOILER B

DATE **2008/12/02**

PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF PARTICLE SIZE ANALYSIS % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	8.7	33.8	12.3	-20.1	22	99.6	88.4	72.4	54.4
2	6.8	3.9	13.1	-15.1	24	99.8	94.2	85.8	73.0
3	6.4	-1.1	14.7	-5.1	27	100.0	96.0	87.0	75.0
4	6.4	-1.1	15.5	0.2	28	99.8	95.6	88.8	78.8
5	6.8	5.1	18.1	17.0	33	100.0	96.4	88.6	75.6
6	9.1	39.1	16.0	3.8	29	100.0	97.0	90.0	77.6
7	4.5	-31.6	16.7	7.8	30	100.0	97.0	90.2	78.6
8	3.4	-48.0	17.2	11.6	31	99.6	98.6	96.0	90.6

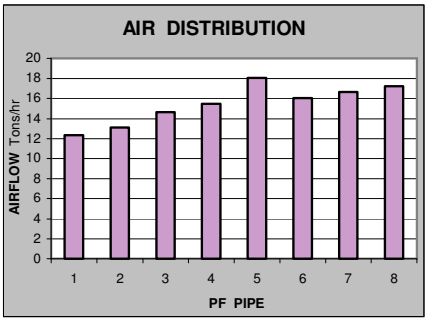
AVERAGES

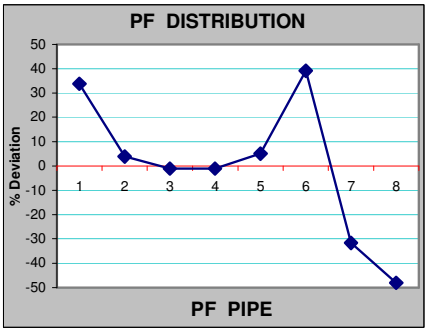
% Passing 300 u	% Passing 150 u	% Passing 75 u	% Passing 75 u
99.85	**95.40**	**87.35**	**75.45**

1 to 4	28.4
5 to 8	23.8
TOTAL	52.1

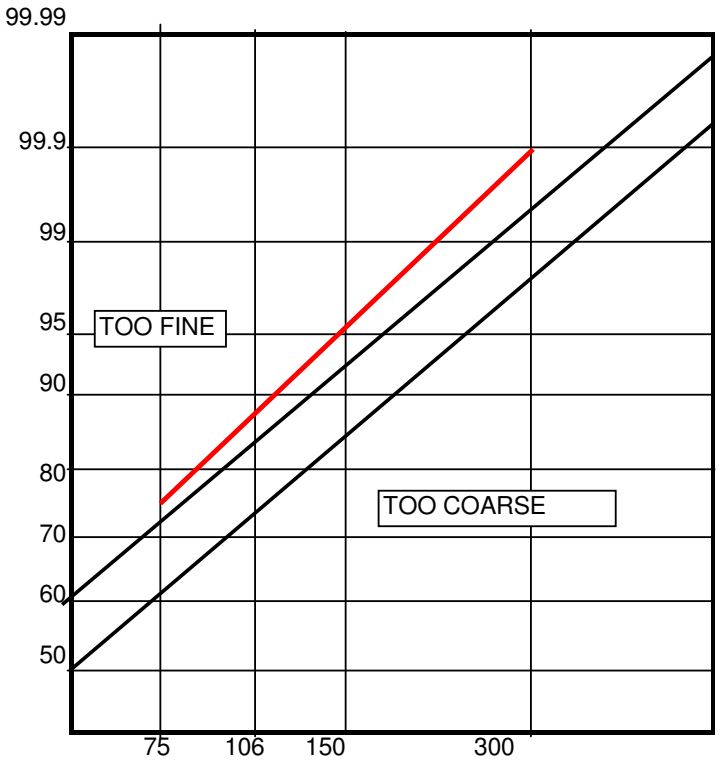
TOTAL 123.6

% PF Moisture	3.5
% Recovery rate	100.0





ROSIN - RAMMLER GRAPH



PF SAMPLING RESULTS

MILL **4F**

LARGE WALL FIRED BOILER B

DATE **2008/12/03**

PIPE No.	Coalflow Tons/hr	% Deviation	Airflow Tons/hr	% Deviation	Pipe Velocity m/s	PF PARTICLE SIZE ANALYSIS % Passing 300 u	% Passing 150 u	% Passing 106 u	% Passing 75 u
1	6.2	-33.4	18.1	-4.6	33	99.6	91.4	80.8	67.8
2	6.6	-29.5	20.1	6.0	36	100.0	96.2	89.0	78.0
3	5.2	-44.0	17.0	-10.2	31	99.8	93.8	84.8	72.8
4	5.4	-42.8	18.4	-3.0	33	100.0	95.8	87.8	75.8
5	10.2	8.6	20.6	8.7	37	100.0	95.8	87.8	74.6
6	8.8	-5.8	20.7	9.2	37	100.0	95.6	86.8	74.0
7	5.4	-42.7	17.6	-6.9	31	99.8	96.8	90.4	80.0
8	8.4	-10.4	19.1	0.8	34	100.0	95.6	86.8	72.8

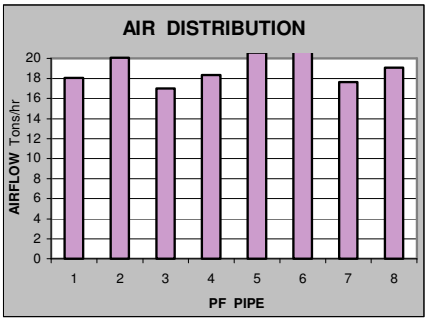
AVERAGES

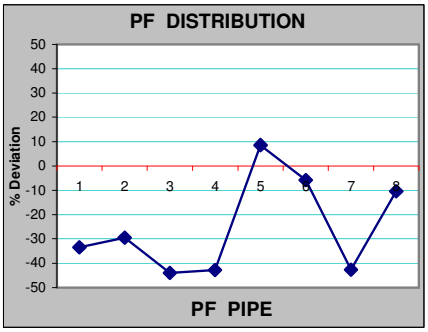
% Passing 300 u	% Passing 150 u	% Passing 75 u	% Passing 75 u
99.90	**95.13**	**86.78**	**74.48**

1 to 4	23.4
5 to 8	32.8
TOTAL	56.2

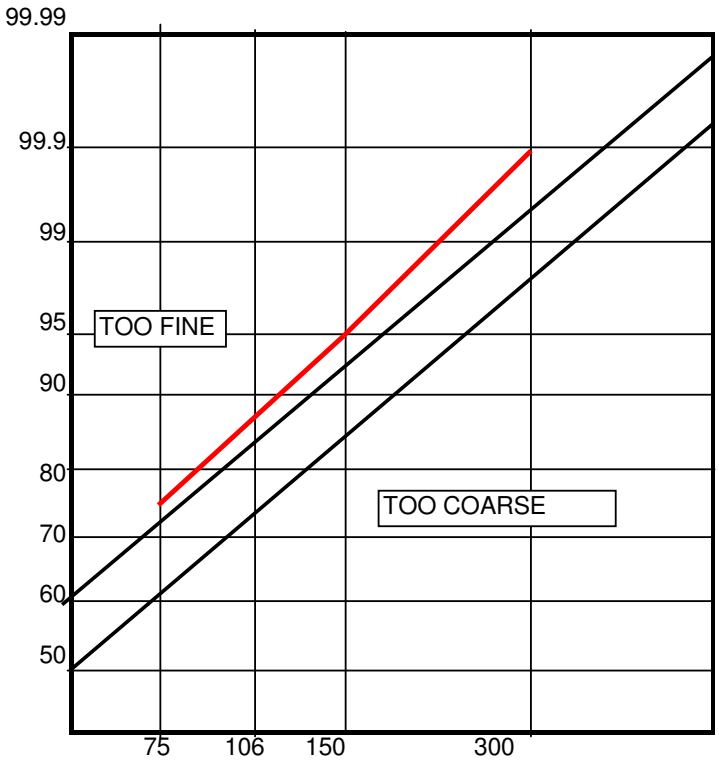
TOTAL 151.5

% PF Moisture	3.0
% Recovery rate	108.4





ROSIN - RAMMLER GRAPH



16 APPENDIX H: LARGE WALL-FIRED BOILER B TEST LOGS

LARGE WALL-FIRED BOILER B TEST LOGS WITH 6 MILLS

Time	Temp (°C)	Time	Level (m)	Depth (m)	Combustible Residue (%)	Combustion Efficiency (%)	Oxygen (%)	CO (%)	NO (ppm)	SO_2 (ppm)	CO_2 (%)	RTD from Middle burner row (s)
14:17	82		23.018	0.00	66.90	0.00	21.10	127	14	141		
	152		23.018	0.25								
	186		23.018	0.50	64.20	0.00	20.95	496	46	268		
	428		23.018	0.75								**0.25s**
	738		23.018	1.00	66.60	0.00	19.20	4807	209	1458		
	1011		23.018	1.25								
			23.018	1.50	59.10	5.70	16.50	4225	414	1950		
Average	**433**	**Average**			**64.20**	**1.42**	**19.44**	**2414**	**170**	**954**		
							6	**4590**	**324**	**1814**		
16:36	1458		38.5	0.50	1.40	99.07						
	1490		38.5	1.00	1.20	99.21						
	1393		38.5	1.50	1.50	99.01						
	1459		38.5	2.00	2.20	98.53						
	1447		38.5	2.50	1.50	99.01						
			38.5	3.00	1.20	99.21						**1.55s**
			38.5	3.50	1.80	98.80						
			38.5	4.00	2.00	98.67						
			38.5	4.50	1.40	99.07						
Average	**1449**	**Average**			**1.58**	**98.95**						
16:00	750	11:29	49	0.50	1.7	98.87	5.09	1		665		
	764	12:00	49	1.00	1.3	99.14	4.95	3		909		
		12:18	49	1.50	1	99.34	4.69	1		878		
		12:34	49	2.00	1	99.34	4.63	1		885		
		12:45	49	2.50	0.8	99.47	4.80	1		914		**2.62s**
		13:05	49	3.00	0.7	99.54	4.52	2		962		
		13:25	49	3.50	0.7	99.54	4.41	3		984		
		13:40	49	4.00	0.9	99.41	4.33	6		976		
Average	**757**				**1.01**	**99.33**	**4.68**	**2**		**896**	**15.17**	
							6	**2**		**817**	**13.82**	

LARGE WALL-FIRED BOILER B TEST LOGS WITH 5 MILLS

Time	Temp (℃)	Time	Level (m)	Depth (m)	Combustible Residue (%)	Combustion Efficiency (%)	Oxygen (%)	CO (%)	NO (ppm)	SO_2 (ppm)	CO_2 (%)	RTD from Middle burner row (s)
12:06	85	12:07	23.018	0.00	68.20	0.00	20.50	65	6	11		
12:18	169	12:24	23.018	0.25			20.40	180	15	22		
12:42	194	13:00	23.018	0.50	68.60	0.00	20.20	343	43	56		
13:06	278	13:09	23.018	0.75	66.80	0.00	19.80	1697	74	210		**0.300**
13:16	342	13:19	23.018	1.00	68.50	0.00	19.40	3506	124	408		
13:38	477	13:40	23.018	1.25	67.10	0.00	19.05	5409	201	683		
13:52	605	13:54	23.018	1.50	64.70	0.00	18.30	6240	383	1290		
Average	**307**	**Average**			**67.32**	**1.73**	**19.66**	**2491**	**121**	**383**		
							6	**4776**	**231**	**734**		
14:31			38.5	0.50	1.90	98.74						**1.550**
			38.5	1.00	1.20	99.21						
			38.5	1.50	1.10	99.27						
			38.5	2.00	1.40	99.07						
			38.5	2.50	0.90	99.41						
				3.00	0.90	99.41						
				3.50	0.90	99.41						
				4.00	0.60	99.61						
				4.50	0.80							
			Average		**1.08**	**99.29**						
12:10	739		49	0.50	1.4	99.07	4.15	4			14.90	**2.940**
12:20	762		49	1.00	1.2	99.21	3.85	4			15.00	
12:33	773		49	1.50	1	99.34	3.85	4			15.00	
12:42	818		49	2.00	0.8	99.47	3.40	10			15.00	
12:51	796		49	2.50	0.8	99.47	3.35	6			15.40	
13:00	820		49	3.00	0.8	99.47	3.25	8			15.30	
13:10	810		49	3.50	0.4	99.74	3.40	9			15.75	
13:17	838		49	4.00	0.6	99.61	2.75	38			15.65 / 15.95	
Average	**794**		**Average**		**1.01**	**99.33**	**3.50**	**10**	**710**	**858**	**15.37**	
							6	**9**	**591**	**714**	**12.79**	

17 APPENDIX I: ESKOM'S COAL ANALYSES METHODS

THE DETERMINATION OF ASH CONTENT OF COAL

GRAVIMETRIC METHOD

BASIS OF METHOD

Coal is heated in air, at a specified rate, up to a temperature of 815 +/-10°C and is maintained at this temperature until constant mass is attained. The ash content is then calculated from the mass of the residue after incineration.

SAMPLE PREPARATION

Coal is ground to <212µm and is prepared according to SABS 0135 Part II – 1977.

TIME REQUIRED FOR ANALYSIS

For one sample in duplicate. Response time = 315 minutes. Operator time = 12 minutes

TOLERANCES

Tolerance within laboratory	<10%	0,2% absolute,	>10%	2% of mean result
Tolerance between laboratory	0,3% absolute,		3% of mean result	

SPECIAL APPARATUS

Muffle furnace A muffle furnace capable of maintaining an adequate zone at a uniform temperature of 500 +/-10°C in 30 minutes from ambient conditions and being able raise to 815 +/-10°C in a further 60 to 90 minutes and maintain this latter temperature to the end of the run-up period. The ventilation will be such as to give at least five atmosphere changes per minute at 815°C.

Balance An analytical balance having a sensitivity of 0,1mg.

Interface The CP 503 universal laboratory interface: a microprocessor based data collection and storage device with computational facilities.

Dish A silica dish, 10mm to 15mm deep, of such a size that will ensure that the coal layer does not exceed 0,5g/cm^2

Dessicator A suitable dessicator containing fresh (or freshly generated) self indicating silica gel.

ANALYTICAL PROCEDURE

Identification Enter GID into GP 503 universal laboratory interface.

NOTE: GID is an identification code, maximum of 7 digits. The submission number of the sample can be entered as GID. Enter SID into CP 503. SID is an unique identification code specific to a particular sample within the group specified by the GID. The sample number can be entered as SID. Press FIELD and enter 7.

Weigh Tare the balance. Place the empty dish on pan and press AUTO. Press STORE when mass reading is displayed in the DATA field. Weigh out 1 +/- 0,1g of coal sample into the dish. Press AUTO. Press STORE when mass reading is displayed in the DATA field.

NOTE: For duplicate analyses use the same GID and SID but add an A to the SID of the duplicate analysis.

Insert dish Insert the dish in to the muffle furnace at room temperature.

NOTE: For multiple determinations, all dishes are inserted together.

Temperature Raise the temperature of the muffle furnace to 500 +/-10°C in 30 minutes and to 815 +/-10°C for a further 60 to 90 minutes and maintain this temperature for at least 3 hours.

Remove dish Remove the dish from the furnace and allow to cool, first on a thick metal plate for 5 minutes and finally in a dessicator.

Weigh When the dish is at ambient temperature, enter the GID. Enter the SID of the first sample in batch. Press FIELD and enter 9. Tare the balance. Place dish on pan and press AUTO. Press STORE when mass reading is displayed in the DATA field.

Calculation Press PRINT to get a printout of the calculation ash content to the coal on an air-dried basis.

NOTE: If inherent moisture and volatile matter are also determined on the same sample, the PRINT command can be given after all three tests have been completed.

Report: Report the result (preferably the mean of duplicate determinations) to the nearest 0,1% and state the basis (i.e. “ash content on air-dried basis”).

REFERENCE

South African bureau of Standards: Standard Method SABS Method 926.

THE DETERMINATION OF THE VOLATILE MATTER CONTENT OF COAL

GRAVIMETRIC METHOD

BASIS OF METHOD

Coal is heated for 7 minutes at 900 +/-10°C out of contact with air. The volatile matter content is then calculated from the loss in mass of the sample less the loss in mass due to the inherent moisture content.

SAMPLE PREPARATION

Coal is ground to <212μm and prepared according to SABS 0135 Part II – 1977.

TIME REQUIRED FOR ANALYSIS

For one sample in duplicate. Response time = 90 minutes. Operator time = 15 minutes

TOLERANCES

Tolerance within laboratory	<10%	0,3% absolute,	>10%	3% of mean result
Tolerance between laboratory	0,5% absolute,		4% of mean result	

SPECIAL APPARATUS

Muffle furnace An electrically heated muffle furnace capable of maintaining an adequate heat zone which is able to be maintained at a uniform temperature of 900 +/-10°C. A muffle furnace with internal dimensions approximately 250mm long by 100mm wide by 65mm high is suitable. It may be closed at one end or fitted at the back with a flue, not larger than 25mm in diameter by 150mm tall. The heat capacity of the furnace shall be such that, with an initial temperature of 900°C, a minimum temperature of 885°C is regained within 3 minutes of the insertion of a cold stand and its crucibles. A position of the crucible stand shall be chosen within the zone of uniform temperature and this same position shall be used in all determinations.

Crucible and lid A cylindrical crucible with a capsule type lid, both of translucent silica. The dimensions shall be approximately as follows:

Crucible	Overall height	38mm
	External diameter	25mm
	Internal diameter	22mm
Lid	Overall diameter	27mm
	Diameter of well	21mm (External)
	Depth of well	4mm (External)

As the fit of the lid on the crucible is critical to the determination, a lid shall be selected to match the crucible so that the horizontal clearance between them is not greater than 0,5mm.

Stand A suitable stand in which to place the crucibles in the muffle furnace and such that the appropriate rate of heating can be achieved.

Stop Watch A suitable stop watch to measure 7 minutes accurately.

Balance An analytical balance having a sensitivity of 0,1mg.

Interface The CP 503 Universal laboratory interface: a microprocessor based data collection and storage device with computational facilities.

Dessicator A suitable dessicator containing fresh (or freshly generated) self-indicating silica gel.

ANALYTICAL PROCEDURE

Prep. of crucible Heat the crucibles and lids, in the stand, for 7 minutes in the muffle furnace. Remove the stand from the furnace and allow to cool on a thick metal plate for 5 minutes and then finally in a desiccator.

ID of sample As soon as the crucibles and lids are at ambient temperature, enter GID into CP 503 Universal laboratory interface.

NOTE: GID is an identification code, maximum 7 digits. The submission number of the sample can be entered as GID. Enter SID into CP 503. SID is a unique identification code specific to a particular sample within the group specified by the GID. The sample number can be entered as SID. Press FIELD and enter 4.

Weighing Tare the balance. Place the empty crucible and lid on the pan and press AUTO. Press STORE when mass reading is displayed in DATA field. Introduce 1 – 1,0g of the coal sample into the crucible. Press AUTO. Press STORE when mass reading is displayed in DATA field.

NOTE: For duplicate analysis use the same GID and SID but add an A to the SID of the duplicate analysis.

Tap crucibles Tap the crucible on a clean hard surface until the test sample forms a layer of uniform thickness on the bottom of the crucible. Place the covered crucible containing the sample in the stand.

NOTE: Fill any vacant places in the stand with empty crucibles. Insert the stand rapidly into the furnace and start the top watch when the stand touches the furnace floor. Position the stand in the furnace within the zone of uniform

temperature. Close the furnace door. Open the furnace door 3 seconds before the end of the 7 minute period. At the end of the 7 minute period lift the stand from the muffle floor and withdraw it rapidly. Cool the stand with crucibles and lids for 5 minutes on a thick metal plate and finally in a desiccator.

Weigh When the crucibles and lids are at ambient temperature enter the GID. Enter the SID of the first sample in the batch. Press FIELD and enter 6. Tare the balance. Put crucible with lid on the pan and press AUTO. Press STORE when mass reading is displayed in DATA field.

Calculation Press PRINT to get a printout of the calculated volatile matter content of the coal on an air-dried basis.

NOTE: The CP 503 would not print the volatile matter content unless an inherent moisture test has been conducted on the same sample. If the ash content has also been determined on the same sample the PRINT command can be given after all three tests have been completed, allowing for the fixed carbon content to be calculated and printed.

Report Report the result (preferably the mean of duplicate determinations) to the nearest 0,1% and state the basis (i.e. volatile matter content on air-dried basis).

REFERENCE

South African Bureau of Standards: Standard method SABS Method 927.

THE DETERMINATION OF THE INHERENT MOISTURE CONTENT OF COAL

GRAVIMETRIC METHOD (AIR-OVEN)

BASIS OF METHOD

Coal is heated in an air-oven at a temperature of 105 - 110°C for 1½ hours and the moisture content is calculated from the loss in mass.

SAMPLE PREPARATION

Coal ground smaller than 212µm, prepared according to SABS 0135 Part II – 1977.

TIME REQUIRED FOR ANALYSIS

For one sample in duplicate. Response time 130 minutes. Operator time 15 minutes

TOLERANCES

Tolerances within laboratory Less than 5% 0,1%, More than 5% 0,2%

NOTE: Limits for tolerances between labs have not yet been established because results obtained in different laboratories depend on the humidity conditions, which may vary from laboratory to laboratory.

SPECIAL APPARATUS

Oven An air-oven that can maintain a temperature of 105 - 110°C, such that the atmosphere is changed at a rate of at least five times/hour.

Weighing vessel A shallow cylindrical vessel of at least 30mm diameter and having a well-fitting cover. The vessel and cover shall be of glass and mating surfaces that are ground**.**

Balance An analytical balance having a sensitivity of 0,1mg.

Interface The CP 503 Universal laboratory interface: a microprocessor based data collection and storage device with computational facilities.

Dessicator A suitable desiccator containing fresh (or freshly generated) self indicating silica gel.

ANAYTICAL PROCEDURE

Identification enter GID into CP 503 Universal laboratory interface.

NOTE: GID is an identification code, maximum 7 digits. The submission number of the sample can be entered as GID. Enter SID into CP 503. SID is a unique identification code specific to a particular sample within the group specified by the GID. The sample number can be entered as SID.

Weighing Tare the balance. Place the clean, dry and empty weighing vessel and cover on the pan and press AUTO. Press STORE when mass reading is displayed in DATA field. Remove cover. Uniformly spread 1 – 1,1g of coal sample in the weighing vessel. Replace the cover. Press AUTO. Press STORE when the mass reading is displayed in the DATA field.

INSERT WEIGHING

Vessel in oven Ensure the temperature of the oven is at 105 - 110°C. Place the cover in the dessicator. Place the uncovered weighing vessel in the oven for 1½ hours after 1½ hours remove the weighing vessel from the oven. Replace the cover and allow the vessel to cool on a thick metal plate for 10 minutes. Transfer to the desiccator and allow to cool for a further period of 10 minutes.

Weigh Enter the GID. Enter the SID of the first sample in the batch. Press FIELD and enter 3. Tare the balance. Place the weighing vessel and cover on the pan and press AUTO. Press STORE when mass reading is displayed in DATA field.

Calculation Press PRINT to get a printout of the calculated inherent moisture content of the coal sample on an air-dried basis.

NOTE: If the volatile matter and ash content are also determined on the same sample, the PRINT command can be given after the weighing of all three tests has been completed.

Report Report the result (preferably the mean of duplicate determinations) to the nearest 0,1% and state the basis (i.e.. inherent moisture content on air-dried basis)

REFERENCE

South African Bureau of Standards: Standard method SABS Method 925.

THE DETERMINATION OF THE TOTAL SULPHUR CONTENT OF COAL

LECO SC-32 METHOD

BASIS OF METHOD

Coal is combusted in an oxygen atmosphere where the sulphur in the coal oxidises to SO_2. Moisture and dust are removed and the SO_2 gas is then measured by a solid state infrared detector. The microprocessor formulates the analysis results, which are displayed and printed on the control console, by combining the outputs of the infrared detector and system ambient sensors with pre-programmed calibration, linearisation and weight compensation factors.

SAMPLE PREPARATION

Coal is ground to <212µm prepared according to SABS 0135 Part II - 1977

TIME REQUIRED FOR ANALYSIS

For one sample in duplicate 10 minutes.

TOLERANCES

Within laboratory tolerances	0,05%
Between laboratory tolerances	0,10%

SPECIAL APPARATUS

LECO SC32 system	The LECO SC32 sulphur analyser
Combustion boat	Combustion boat (LECO part no. 528 – 203)
Reagent tube	Two glass reagent tubes (LECO part no. 767-541) that must be packed with any anhydrone as shown in the instruction manual.

SPECIAL REAGENTS

Oxygen	Medical grade oxygen.
Anhydrone	Anhydrone (Magnesium perchlorate) to pack in reagent tubes to remove moisture and dust.
Standard	A coal standard(s) with certified value(s) for total sulphur content to calibrate the instrument.

ANALYTICAL PROCEDURE

SYSTEM CHECKOUT

Switch on printer	Set the printer POWER ON/OFF switch to the ON position
Switch on system	Set the system power ON/OFF switch to the ON position.

Enter time and date Enter the time (according to a 24 hour clock) and the date, by pushing the number keys. Push the ENTER key to start the clock.

Power supplies Push the MONITOR key on the control console keyboard.

NOTE: The printer will provide a list showing the current status of various system parameters. Power supply voltages that are out of the allowed range will be printed in red with an alarm message. If this occurs, immediately switch off the power and refer to the LECO instruction manual for further action.

O_2 pressure and flows Open the valve on the oxygen supply cylinder and set pressure to 210kPa (30psi). Push the GAS key on the control console and observe the OXYGEN PRESSURE gauge on the front of the measurement unit. The OXYGEN PRESSURE gauge must indicate greater than 8psi (56kPa). Observe the PURGE rotameter and ensure that the flow is 4,0 litres/minute.

NOTE: The purge rotameter is located inside the left side panel. Observe the LANCE rotameter and ensure that the flow is 1,0 litre/minute.

Check constants Push the SYSTEM UPDATE key and then press the YES key to print the system constants. Compare these values with those listed on the test report which came with the instrument. If any constant parameters do not agree, reset them accordingly.

SYSTEM OPERATION

Warm up The system electronics must be allowed to warm up for a minimum of two hours after electrical power is applied and the operating temperature must be at 1350ºC before attempting analysis.

Analytical performance The good analytical performance of the instrument, the following is necessary: Three to five “conditioning” analyses should be run at the start of the day, any time the instrument has been idle for a length of time, or when fresh anhydrone has been installed. A system blank may be necessary if low sulphur analyses are to be performed. The system should be calibrated. The balance should be calibrated.

CALIBRATION

ID Code Push the ID code key for identification purposes. Select the correct ID number by pushing the appropriate number of keys to enter digits from left to right. When the ID code is displayed correctly, push the ENTER key to store it.

Weigh Place combustion boat on the balance.

NOTE: The balance will tare automatically. Add 0,25g of a suitable certified coal standard to the combustion boat. The message centre will display the

sample mass, fluctuating at first. When the weight is stable, press the ENTER key. Remove the combustion boat containing the sample from the balance and spread the sample evenly by gently shaking the combustion boat in a back and forth motion.

Analyse Push the ANALYSE key. Wait until the message centre displays LOAD FURNACE and then slide the combustion boat into the furnace until it touches the stop inside the combustion tube.

NOTE: The analysis cycle will begin automatically as soon as sulphur is detected. When the analyses is complete the SULPHUR display will indicate the result and the printer will print the value. Remove the combustion boat from the furnace. Repeat analysing the calibration standard until 5 results are obtained.

Calibrate Select the calibration channel (A,B,C, or D) to be used by pressing the SELECT key and the appropriate number key. Press the SYSTEM UPDATE key and the "1" key. In response to the query CALIBRATE SYSTEM press the YES key. The message centre will display CALIBRATE BY STD YES/NO. Press the YES key. Enter the value of the standard. Analysis results will be displayed one by one in the message centre for selection for the calibration calculation. Press the YES key to include the print a result or the NO key to exclude it. Press the ENTER key to go to the next step when all desired results have been responded to.

NOTE: The printer will print the new calibration and the last ten answers in the answer stack recalculated to the new calibration value. The system will then revert to operate mode idle loop.

SAMPLE ANALYSIS

Analyse sample Repeat the procedure as described under CALIBRATION for ID code, weigh and analyse.

Report Report the result (preferably by means of duplicate determinations) to the nearest 0,01% and state the basis (i.e.. total sulphur on an air-dried basis).

STANDARD CHECK

Standard check Push the STANDARD CHECK key. Enter the sulphur value of a suitable certified reference standard. Analyse the sample as described above. When the analyses is complete, the printer provides a printout of the sulphur result from the analysis and of the sulphur standard value entered.

Compare the analysis result to the standard value to verify that the result is within specification.

MAINTENANCE

Collection tube The collection tube portion of the combustion/collection tube assembly requires cleaning approximately every 400 to 500 analyses. Follow the procedure as described in the LECO instruction manual.

Delivery tube assembly The delivery tube assembly periodically requires cleaning. The required cleaning interval varies depending upon the amount of residue released by various types of samples. Follow the procedure as described in the LECO instruction manual.

Anhydrone tubes The two anhydrone tubes, especially the tube nearest the furnace area, require cleaning and repacking with fresh anhydrone after approximately 75 analyses of coal samples. Regardless of the number of samples analysed, the tube nearest to the furnace must be changed when the upper third of the anhydrone in the tube is visibly wet and caked.

REFERENCE

LECO instruction manual for SC-32 sulphur analyser.

THE DETERMINATION OF CALORIFIC VALUE OF COAL

IKA INSTRUMENT METHOD

BASIS OF METHOD

A known mass of the sample of coal is burned in oxygen in a bomb calorimeter under standardised conditions. A high speed micro-processor performs the temperature measurement of the bomb and calculates the calorific value from the individual measurements taken

SAMPLE PREPARATION

Coal ground smaller than 212µm prepared according to SABS 0135: Part II – 1977.

TIME REQUIRED FOR ANALYSIS

For one sample in duplicate 30 minutes using the isoperibolic method.

TOLERANCES

Within lab tolerances	Between lab tolerances
0,120MJ/kg	0,30 MJ/kg

SPECIAL APPARATUS

IKA C2000 calorimeter The IKA single channel microprocessor and parheranials calorimeter

IKA Bomb vessel The Bomb with built in electronics.

INTEGRATED COOLING

System The continuous circulating of water at ambient. With built in-chiller.

Integrated filling station The oxygen filling station and self release function.

Crucible Nickel/Stainless steel crucible to fit in bomb crucible holder.

Ignition wire Pre-cut Nichrome 0,1mm diameter fixed firing wire.

Ignition Cotton Specified and pre-packed

Balance An analytical balance having a sensitivity of 0,1mg.

SPECIAL REAGENTS

Benzoic acid Certified thermo-chemical standard benzoic acid or suitable Equivalent (NIST Standard)

Oxygen Oxygen free from combustible matter and at such Pressure as to fill the bomb to 3000 kPa. (99.5%)

ANALYTICAL PROCEDURE

PREPARING BOMB VESSEL FOR A DETERMINATION

Start conditions Ensure that the bomb is depressurised. Open the bomb and clean the inside of the body with paper. Remove the crucible. Remove the old firing residue. Clean the ignition wire and attach the ignition cotton to this wire.

NOTE: Clean crucibles after each firing with a wire brush.

Ignition wire This wire is permanent and is used to attach the cotton to. This is cleaned after each firing.

Weigh sample Tare analytical balance with the crucible on the pan. Fill crucible with approximately 1.0000g record accurately the mass. Within 0.250g of a gram of sample. Weigh sample and record the mass on pc as well as the sample I.D. and the analyst name. Select the appropriate bomb code.

Load sample Insert the crucible into crucible holder, ensuring that the firing cotton touches the surface of the sample.

NOTE: The ignition cotton should not touch the sides of the crucible.

Close bomb Insert crucible assembly carefully into body of the bomb. Screw the ring down until it touches the top. Tighten the ring with a slight additional strength. Do not over tighten.

Auto Filling The bomb pressurises itself once placed in the bomb holding unit.

DETERMINATION OF CALORFIC VALUE

Bomb Loading Load bomb into measuring cell assembly. The I.D. has already been entered into the pc. Once the bomb inserted the pc commands that you start, click on start button. Analyses starts and all relevant activity performed by the bomb is digitally indicated. By selecting the measurement screen all the relevant information is displayed.

Final result The completion of the test is noticed by the display on the selected screen.

Quality The samples after performed one after the other. A Quality Check sample is analysed before and after calibration. The provision is that should a QC and the duplicates be within tolerances than the process of analyses can continue.

Tolerances: Duplicates: ≤ 0.120 MJ/Kg

Q C Sample: **≤** than the required limits on the QC charts being used at that applicable time.

Remove bomb Open the lid, remove the bomb.

Depressurise Depressurise bomb with the defill cap. The bomb is now ready for the next determination.

CALIBRATION - PREPARING BOMB VESSEL FOR CALIBRATION

Prepare the bomb exactly the same way as described in PREPARING BOMB VESSEL FOR A DETERMINATION, except for the following steps:

Benzoic acid Weigh out benzoic acid instead of coal as follows: Weigh 1benzoic tablets of ±1.0000g and record weight accurately. Insert crucible into crucible holder. Put one tablet in crucible. Make a twisted loop of the firing cotton and ensure it touches the top of tablet.

Calibration Select the calibration mode. Then analyse three benzoic acid standards. The values have been pre-entered as the stated certified value. After the completion of such analyses then select the Select the appropriate device icon. Bomb selection icon is also chosen. Select calibration on the next screen, choose calibration sequence. The previous calibration values and the present calibration values are displayed. Delete the old calibration standard values. Select the new calibration values. Accept them and the calibration is complete.

Acceptance Analyse the QC standard being used at that time. If the QC standard is acceptable then continue with analyses.

NOTE: When using more than one bomb each one must be calibrated separately. Each bomb will have its dedicated channel, which is don by choosing the applicable number

REFERENCE

IKA Operating manual.

Quality manual referenced.

Procedure manual referenced.

ISO 1928: 1995

APPENDIX

THE CALCULATION OF GROSS CALORIFIC VALUE

The calculation of gross calorific value involves the determination of the total sulfur content - Eskom method 139

Calculation: Gross calorific value = Instrument calorific value - (0.02 + (0.0946 x total sulfur content)

Reference: SABS method 929

THE DETERMINATION OF THE HARDGROVE GRINDABILITY INDEX OF COAL

HARDGROVE MACHINE METHOD

BASIS OF METHOD

This method is used to determine the relative grindability or ease of pulverisation of coal. A prepared sample receives a definite amount of grinding energy in a miniature pulveriser, and the change in size is determined by sieving.

TIME REQUIRED FOR ANALYSIS

For one sample 60 minutes

TOLERANCES

Within laboratory tolerance : 2 index points

Between laboratory tolerance : 3 index points

SPECIAL APPARATUS

Test sieves A set of circular sieves is required in the following sizes, together with cover and receiver. 16mm, 1,18mm, 600 micron, 75 micron

Sieving machine A mechanical sieving machine which can accept an assembly of vertical nested circular test sieves together with cover and receiver.

Grindability A grindability machine consisting of stationary grinding bowl, of iron and steel , with horizontal track which holds eight steel balls, each 25,4 +/- 0,13mm in diameter. The balls are driven by an upper grinding ring which is rotated at 20 +/-1 rpm by means of the upper spindle and which, in turn, is driven by an electric motor through reduction gears. Weights are added to the driving spindle so that the total vertical force on the balls due to the weights, shaft, top grinding ring and gear is equal to 29 ± 0,2kg. The machine is equipped with a counter and automatic device for stopping the machine after 60 ± 0,25 revolutions.

Balance Balance with sensitivity of at least 10mg.

Crusher A laboratory mill capable of reducing the size of the coal particles to less than 1,18mm with the production of a minimum of minus 600 micron sieve size material.

ANALYTICAL PROCEDURE

Sample divider A suitable riffle divider or turning tube divider.

Divide Divide the quantity of the air-dried coal to about 1kg using the riffle or turning tube divider.

Crush Stage crush the 1kg sample to yield the maximum amount of material passing the 1,18mm sieve, but being retained on the 600 micron sieve.

Sieve Sieve the entire amount of coal in lots of approximately 200 grams each for 2 minutes in the mechanical sieving machine. Use a set of nested sieves consisting of 1,18mm sieve on top of a 600 micron sieve.

Crush Crush the material retained on the 1,18mm sieve with the crusher adjusted so that only the largest particles are crushed.

Sieve Sieve the crushed material for 2 minutes and return the oversize to the crusher, again set the crusher so that only the largest particles are crushed. Continue crushing and sieving until all the material passes the 1,18mm sieve.

Weigh Discard that part of the portion passing through the 600 micron sieve and weigh, to the nearest gram, the coal passing the 1,18mm sieve and retained on the 600 micron sieve. If the yield in this size range is less than 500 gram, the sample should be discarded and another sample of approximately 1kg shall be taken from the gross sample and the sample preparation repeated.

NOTE: If after careful crushing of softer coals (those with a Hardgrove grindability index greater than 80), less than 50% is retained on the 600 micron sieve, proceed with the test and qualify the result.

Mix Mix thoroughly the size fraction passing the 1,18mm sieve and retained on the 600 micron sieve.

Divide Divide this sample using a riffle (or tube divider) to obtain approximately 120g.

Dedust As the final step in preparation of the test sample, dedust the 120g sample by sieving on a 600 micron sieve for 5 minutes using the mechanical sieving machine.

Clean machine Clean the grindability machine thoroughly and space the balls evenly around the grinding bowl.

Set stopping device Set the automatic stopping device so that it will stop after 60 ± 0,25 revolutions of the upper grinding ring.

Weigh sample Weigh out 50 ±0,01 gram of the dedusted sample and distribute it evenly in the grinding bowl, brushing any material falling on the elevated section of the lower grinding element into the lower grinding elements towards the balls.

Fasten Bowl Fasten the bowl in position and make sure that the load is fully applied to the driving spindle.

Start instrument Start the instrument.

Remove bowl When the rotation has stopped, switch OFF the instrument and dismantle the bowl assembly. Lift out the upper grinding ring and carefully brush adhering coal dust onto a 16mm sieve nested on a 75 micron sieve and a closely fitting receiving pan.

Remove coal Empty the grinding balls and ground coal onto the 16mm sieve and carefully brush coal adhering to the bowl, balls and the 16mm sieve into the 75 micron sieve.

Sieve coal Replace the 16mm sieve with a close fitting cover and shake the 75 micron sieve cover, and pan assembly for 10 minutes in the mechanical sieving machine.

Brush Coal Dust Carefully brush coal dust from the underside of the sieve into the receiving pan, using a soft brush that will not damage the 75 micron sieve. Repeat the shaking and underside-of-sieve cleaning for two more periods, each of 5 minutes duration.

Weigh Weigh separately to the nearest 0,01 gram, the coal retained on the 75 micron sieve and the coal passing the 75 micron sieve.

NOTE: If the sum of these masses differ by more than 0,75 gram from the initial mass of 50 ± 0,01 gram, reject the test and repeat.

Calculate Calculate the mass of coal passing the 75 micron sieve by subtracting the mass retained on the 75 micron sieve from the test sample mass. Let this mass be W.

Calibration graph Use W to record the grindability index from the calibration graph.

Report results Perform duplicate determinations on test portions taken from the 1,18mm to 600 micron fraction. Report the mean of the two determinations, rounded to the nearest whole number, as the Hardgrove grindability index.

CALIBRATION

Standard Coal A set of four standard reference coal samples shall be used for the preparation of the calibration graph. Prepare and test each sample in duplicate as described in the ANALYTICAL PROCEDURE above.

Calibration graph Plot, on linear scale co-ordinates, the mean calculated mass (W) passing the 75 micron sieve against the certified grindability index for each sample.

NOTE: Calibration graphs shall be checked whenever equipment is renewed or repaired, or if the instrument is suspected of being defective.

REFERENCE

British standard methods for analysis and testing of coal. BS 1016: Part 20: 1981 Determination of Hardgrove grindability index of coal. ASTM Method no. D 409-71: Part 26.

THE DETERMINATION OF THE CARBON, HYDROGEN AND NITROGEN CONTENT OF COAL

LECO CHN-600 METHOD

BASIS OF METHOD

Pelletised coal is combusted at 950℃ in an oxygen rich atmosphere. Gaseous products formed are inter alia the oxides of carbon (COx), hydrogen (H_2O) and nitrogen (NO_x). The remaining gases are collected in a ballast volume after removing the oxides of sulphur with an inline calcium oxide reagent train. The gases are allowed to mix thoroughly. An aliquot of 10ml is taken by helium through a hot copper reagent train. This ensures the removal of oxygen from and the reduction of NO_x to elemental nitrogen in the gas stream. The nitrogen concentration is now measured by a thermal conductivity cell. Further reagent trains of sodium hydroxide and magnesium perchlorate remove the CO_2 and H_2O gases respectively. Simultaneous to the nitrogen being measured, the carbon as CO_2 and hydrogen as H_2O, from the main ballast tank in the gas stream, is measured by the infrared cells. The outputs from the cells are linearised and multiplied by a calibration factor. The factor corrects for barometric pressure, ballast volume pressure and chemical interference. The percentage concentration levels of carbon, hydrogen and nitrogen are then calculated with the necessary blank and weight adjustments.

SAMPLE PREPARATION

Coal ground smaller than 212μm in accordance with the SABS 0135 Part 2 1977 procedure.

Pelletising Coal A mass of 140mg of the pulverized coal is placed into a dye set and pressed into a pellet. The pressure is maintained at 100 bar for 30 seconds.

TIME REQUIRED FOR ANALYSIS

For one sample in duplicate 10 minutes

NOTE: This is only instrument analysis time and does not include the sample preparation, instrument stabilisation and calibration time.

TOLERANCES

Within laboratory tolerances	0,20%
Between laboratory tolerances	0,30%

SPECIAL APPARATUS

The LECO CHN-600 Carbon, Hydrogen and Nitrogen determination assembly. The LECO CHN-600 Console Control assembly. The LECO LB-20 Balance assembly

PRESS The ENERPAC hydraulic hand press.

SPECIAL REAGENTS

Oxygen Ultra-pure quality with an assay of 99.995%.

Helium Instrument grade quality suitable for instruments, being oil free.

Air Suitable for instruments, being oil free.

Coal Standard The coal standard should match the carbon, hydrogen and nitrogen range of the coal being analysed.

Copper Copper shavings of high purity grade. Part no. 501-621.

Anhydrone Magnesium perchlorate. Part no. 501-171

Ascarite Sodium hydroxide. Part no. 183-001

Furnace reagent Calcium oxide. Part no. 501-609

ANALYTICAL PROCEDURE

SYSTEM SETUP

Furnace temp. The instrument is kept energised and the furnace temperature is maintained at 600 degrees when not in an analysing status. Prior to analysis the instruments furnace temperature is increased to 950°C. The instrument is allowed to stabilise for at least 2 hours.

Analytical gases Open all three gases to the instrument and remove the two screw caps at the back of the left hand side of the instrument. Initiate gas flow through the instrument by pressing the GAS key. The instrument is purged for 60 seconds, during which a count down sequence is indicated.

Blank determination The blank determination values are required prior to the determination. Press the BLANK key. The blank value of carbon is requested on the main display. Enter 00.00 with the numerical keys. Press the ENTER key. The blank value of hydrogen is requested. Repeat as for carbon. The blank value for nitrogen is requested. Enter the nominal value of 00.16 and press the ENTER key. The request of REPEAT BLANK YES/NO is displayed. Press the YES key. The number of blanks to be determined is requested. Ten blanks are entered using the appropriate numerical keys. Press ENTER. The blank determinations are automatically started and continued until the tenth determination. The blank values for carbon, hydrogen and nitrogen should be checked to ascertain if the values are not outside the values that were entered prior to blank determination.

CALIBRATION

Weigh sample Tare the balance using the TARE key on the control console. The message centre will display “TARE”. Place a pelletised standard coal sample on the external LB 20 balance pan and wait until weight indication on the main display is stable. The ENTER key is pressed and the pellet mass has now been recorded. The samples can be weighted in succession and the

masses recorded respectively. The calibration determination is done in triplicate

.

Analysis of sample The weighed pellet is now carefully transferred using a tweezers to the sample holder seated above the sample port. More than one sample can be analysed. Press the ANALYSE key and the analysis sequence is automatically started.

Calibrate instrument The values obtained from the analysis of the standard coal samples are used to calibrate the instrument. The calibration is initiated by pressing the STANDARD CHECK key. The message centre will display "CALIBRATE BY BURNS YES/NO"" Press the YES key. All the standard values previous obtained from the analyses are printed out. The display message indicates CALCULATING. After the print out, the displayed message CALIBRATE CARBON YES/NO is shown. Pressing the YES key indicate the CARBON STD % 066.10 MOD BY KBD. Enter the standard samples certified values in percentage using the numerical keys. Ensure the correct location of the decimal point before accepting the value by pressing ENTER.

Accepting values After the previous standard value is entered the message centre displays the result of the last sample analysed in the format of INCLUDED 135700004 65.01 YES/NO. The value is either accepted by pressing YES or disregarded by pressing NO. This will cause the results stack to scroll forward to the next value. Each value is treated in exactly the same way until all standard values has been used. The stack might display values of previous analyses and these must be disregarded. The calibration of hydrogen and nitrogen is done as for carbon. After entering the values the last ENTER command causes the printer to print the correct calibration values and values of previous analyses. Analyse the standard pellet to ensure the correct standardisation of the instrument.

ANALYSIS

Sample preparation Two pellets are made of the coal sample to be analysed. Store the two pellets in an air tight container, ready for when the analysis can be made. Coal samples should be prepared prior to calibration due to costly gas consumption and to ensure the analysis starts once the calibration has been completed.

Identification code When more than one sample must be analysed the sample identification can be entered as the samples are loaded into the automatic sample loader. The samples ID must be entered prior to the samples mass. Press the ID CODE key. The message centre displays a digital display of 00000000000 MOD by KBD.

Enter the ID from left to right and once the ID is in the ENTER key is pressed.

Sample Analysis The sample is analysed in the same manner as for the calibration procedure. The standard sample should be re-analysed after every 10 to 15 samples.

Report Repeat the result (preferably the mean of duplicate determinations) to the nearest 0,01% and state the basis (i.e. carbon on air-dried basis).

Maintenance The maintenance of the instrument is comprehensive and can not be detailed within the scope of this method. Reference should be made to the instruction manual for the CHN-600 system 785-500. Pages 45 to 52.

REFERENCE

Instruction Manual CHN-600, 785-500 SYSTEM

THE DETERMINATION OF MAJOR AND MINOR ELEMENTS IN COAL ASH

PHILIPS PW 1404 X-RAY FLUORESCENCE SPECTROMETER (XRF) METHOD

BASIS OF METHOD

The surface of a glass ash bead is radiated with primary x-rays. Secondary x-rays are produced by the elements present in the ash sample. The secondary x-rays are detected by the spectrometer, submitted to a computer where the data reduction is done, upon which the analysis results are either displayed on the terminal screen, printed or transmitted directly into the LIMS system.

TIME REQUIRED FOR ANALYSIS

For one sample: 30 minutes

SPECIAL APPARATUS

XRF	Philips PW 1404 x-ray fluorescence spectrometer
Computer	Digital micro PDP 11/23 computer
Terminal	Tektronix 4205 video terminal
Printer	Digital 210 letter printer
Sampler holder	Sample holders with the facility of interchangeable masks.
Masks	Copper masks with 35mm holes.
Balance	Top pan balance (2 decimal places)
Fluxer	Katanax K_2 Automatic fluxer
Platinum crucible	Platinum/gold crucible
Platinum mould	Platinum/gold mould

SPECIAL REAGENTS

Acetone	Chemically pure acetone
Lithium metaborate	Lithium metaborate (AR grade)
Lanthanum oxide	Lanthanum oxide (AR grade)
Bromine solution	Weigh out 10g lithium carbonate into glass beaker. Add 40g of hydrobromic acid into the beaker. Stir until dissolved. Dilute with demin water to obtain a 1:1 ratio.

SAMPLE PREPARATION

Milling of ash	The sample of ash is milled in the SPECTRO MILL for ten minutes at a preset speed of 70 for the pot and 40 for the paddle.
Drying of ash	The ash sample is dried at 100°C for approximately one hour.

Sources of Ash Note that two types of ashes may be submitted for ash elemental analyses. The one is were a combustible matter is performed prior to fluxing. Such ashes are all power station generated ashes. Ash on which combustible matter content is not determined is laboratory produced ash, which originates from raw coal or directly from coal samples for which ash elemental analyses are requested.

Combustible matter Combustible matter is only performed on sample which is received as an ash. Coal ash is not combusted for combustible matter. A mass of 2 grams of ash sample is weighed accurately into a suitable crucible. The ash sample is then placed into a furnace at ambient temperature. The sample is then combusted for 3.5 hours at 850°C. The sample is allowed to cool in a dessicator after which it is weighed to record the combustible matter content. The sample is now mixed thoroughly and suitably stored so that no moisture can be taken up by the sample.

Weigh Weigh 1.5 grams of ash sample, 1.35 gram of Lanthanum oxide and 7.8 gram Lithium metaborate into a Pyrex glass beaker. Mix well using a glass rod. Store and ensure no atmospheric contamination.

Note: It is extremely important that no flux ever touch the elements. Element life would dramatically be reduced. No flux must be spilled on the crucible or mold holders.

Load Transfer the prepared sample to the crucible. Add three drops of Bromine solution using a plastic pipette, to the top of the sample.

Safety Wear suitable eye protection and once the instrument is operational and use gloves, laboratory tongs to manipulate the crucible, mold and glass disk, in order to avoid risks of burns and eye damage.

Operation Turn the instrument on by flipping the rocker switch at the back of the instrument. The main screen appears and plutinumware holders are automatically pulled out of the furnace. Furnace heating is automatically turned on, to reach the present holding temperature. Place molds and crucibles in their holders **(Very Important !)** make sure that they are rigidly in place by gently pulling on each crucible , as if to remove them. Touch ok to start the fusion and the door will automatically open and closes.

Remove The instrument opens the door and the crucibles are tilted forward to empty their contents into the molds. Fans located underneath cool the molds. When the molds are completely cooled, gently pick up the perfectly homogeneous glass beads. The beads can now be identified by marking a plastic bag into which the bead is placed, ready for analyses for XRF.

ANALYTICAL PROCEDURE

SYSTEM CHECKOUT

Temperature Ensure that the temperature of the XRF spectrometer is at 29.8°C by pressing either the UP or DOWN button at the right hand side of the front panel.

NOTE: If the temperature is not correct ensure that the cooling system is functioning properly.

Vacuum Ensure that the vacuum of the XRF spectrometer is under 20 Pascal by pressing either the UP or DOWN button at the right hand side of the front panel.

NOTE: If the vacuum is higher than 20 Pascal, inform the responsible person of XRF.

SAMPLE ANALYSIS

Mask Select the 35mm copper mask and fit into sample holder.

Clean the sample Clean the sample by wiping it with a soft paper tissue that has been moistened with a small amount of acetone.

Load sample Put the sample into the sample holder. Ensure that the hole in the mask is completely covered by the sample.

NOTE: If the sample does not fit tightly in the sample holder, secure it with a piece of masking tape.

Load into XFR Load the sample holder into the XRF. Enter the command MUS into the computer and press RETURN.

NOTE: If the computer is in the MENU mode, select “MEASURE UNKNOWN SAMPLE” or type MUS. For the purpose of this method it will be assumed that the computer is in the asterisk (*) mode, where only three letter commands are typed in. If the computer is in the MENU mode, it can be set to the asterisk mode by typing .SME.

Programme The computer will prompt for PROGRAM. Enter ASH. Press RETURN.

Task ID The computer will prompt for ID. Enter the task ID, stipped from the 3 and the leading zeros. Press Return.

NOTE: The task ID is obtained from the work sheet produced by LIMS during the login process.

Save results The computer will prompt with a request SAVE RESULTS. Enter Y or N. Press RETURN.

File name If the response above were Y the computer will prompt for FILENAME. Enter the name of a file where the results must be stored. Usually the name of the ANALYTICAL PROGRAMME is used. Press RETURN.

Transmission The computer will prompt with TRANSMISSION STATIONS. Enter 2. Press RETURN

NOTE: If the results are not transmitted directly into LIMS the following commands can be entered. O (will only display results on terminal). 1 (will display results on terminal as well as print it out on the printer)

Initial weight The computer will prompt for initial weight. Enter "1"

Final weight The computer will prompt for FINAL WEIGHT. Enter "X". Where X = (100 – combustible matter) / 100

NOTE If the sample was obtained by ashing a coal sample, "1" is entered for both the INITIAL WEIGHT and FINAL WEIGHT.

Loss on ignition The computer will prompt for LOI (%). Enter the combustible matter content.

NOTE: If the sample was obtained by ashing the coal, "O" is entered.

Next sample After entering the last command above, the spectrometer will move the sample into the analysis chamber, and more to the second sample loading position. The computer will prompt for the ANALYTICAL PROGRAMME for the second sample. Repeat the procedure as described above. If no more samples need to be analysed, enter / followed by RETURN.

NOTE: A maximum of four samples can be analysed in one run.

Sample analysis A spectrometer will automatically run through the analysis programme. At the end of the cycle the results will be computed and presented according to the response to the TRANSMISSION STATIONS prompt.

QUALITY CONTROL

Quality Standard At the completion of the analysis, inspect the results and select a quality standard with approximately the same concentration of elements as the sample.

Measure standard Repeat the procedure as described under SAMPLE ANALYSIS, except that the command MQS is given. The computer will prompt for QUALITY STANDARD LIST. Enter the name of the quality standard followed by RETURN. The standard will then be analysed.

Limits The computer will indicate whether any upper or lower limit has been exceeded for any element. If any element is outside the limit, repeat the analysis of the quality standard. If it is still outside the limit, recalibrate the

XRF spectrometer, and repeat the analysis of the sample(s) and the quality standard.

RECALIBRATION OF THE XRF SPECTROMETER

Recalibration programme Enter the command MRS. The computer will prompt for RECALIBRATION PROGRAMME. Enter the name of the ANALYTICAL PROGRAMME to be recalibrated and press ENTER.

Recalibration standards The computer will respond with STANDARDS ACTIVE FOR THE RECALIBRATION PROGRAMME and a list of standards to be used for recalibration. The computer will prompt each time for a specific standard to be loaded into the spectrometer. Load the standard into the spectrometer. Enter YES and press RETURN.

NOTE: Up to four samples can be loaded.

Calibration constants At the end of the recalibration cycle the computer will display the old and new calibration constants for each element. The computer will prompt for a YES or NO whether the constants are acceptable or not. After the acceptance stage has been completed the spectrometer is ready for normal use.

REFERENCE

Philips operation manual: Software for XRF X44

THE DETERMINATION OF ABRASIVENESS INDEX OF COAL

BASIS OF METHOD

The test consists of rotating four removable wearing blades in a charge of coal with a specified mass for a fixed number of revolutions. The loss in weight sustained by the blades is expressed in mg and is the abrasiveness of the coal. The test is a empirical test performed in a standardised instrument and used for comparison and monitoring purposes to assess the possible stone contaminant increase in coal.

TIME REQUIRED PER TEST

For a single test : 8 minutes. (Sample preparation time excluded)

SPECIAL APPARATUS

Abrasiveness test unit A standardised unit manufactured in accordance with the specifications as by TRI drawings.

Balance Heavy duty balance capable of weighing a mass of not less than 14kg with a precision of 10 grams or better.

Jaw crusher Coal pulveriser capable of being set to at least 10mm.

Oven Electrically operated oven with a controllable temperature facility to maintain a temperature of 105°C and adequate capacity to ensure satisfactory drying of a sample with a mass of 14kg.

Riffler To comply with the requirements as stipulated in SABS 0135.

Sieves The wire mesh test sieves must comply as with the requirements specified in SABS 0135: Part 2 – 1977.

Wear blades Wear blades as supplied by Desmek in an accordance with the agreement.

Analytical balance The balance must be capable of weighing a mass of up to 200 grams with a precision of up to 1 mg.

ANALYTICAL PROCEDURE

PREPARATION OF WEAR BLADES:

New blades The new set of blades must be conditioned prior to a test being performed. This is achieved by doing a trial run on the instrument together with the new blades using a coal similar to the prepared coal meant for the analysis. This coal could have a mass of between 2kg and 4kg so that a cumulative wear of at least 100 mgFe is accomplished on the set of blades. These results are disregarded.

Storing and Cleaning The blades are cleaned prior to use with alcohol or methylated spirits and stored in a dessicator.

Wear The blades are discarded if the total cumulative wear is 2 grams or when the individual blade masses differs by more than 20% between the maximum and minimum.

Grub screws The grub screws are used to fix the blades to the rotor and are replaced on a monthly basis or sooner should the number of analyses increase. The grub screws are also replaced if more than three sets of blades are used during a month.

PREPARATION OF THE TEST COAL SAMPLE

Coal The size of sample received will depend on the method employed to initiate the sample preparation. The total sample will be air dried prior to crushing. If the sample is >60 kg then the sample must be mixed well and coning and quartering be done for not less than 6 segments. Three sample segments are taken and combined and this sub-sample is then riffled to obtain a working sample of not less than 25kg after air drying. Samples less than 25kg but more than 8kg are treated as sub-samples. Samples less than 8kg are also treated as sub-samples but the duplicate determination of the Abrasiveness Index of these samples can not be done and should be reported as such.

Screening Set up a next of sieves of 9mm, 6mm, 4.8mm. Screen the coal sample through the sieves and retain fractions larger than 9mm, 6mm and 4.8mm separately as well as the fraction < 6mm.

Crusing of coal The jaw crusher is set to 10mm. The sample fraction >9mm is now crushed using the jaw crusher to pass the sieve of 9mm. This sample fraction is now sieved through the 6mm sieve and the fraction < 6mm is combined with the initial >4.8mm fraction. The jaw crusher is now set to 5mm and the sample fraction >6mm is passed through the jaw crusher and sieved through the 4.8mm sieve. Hand crush the fraction remaining above 4.8mm and ensure complete passing through the 4.8mm sieve. Combine with the initial sample of 4.8mm and mix well. The stage crushing of coal is vital to ensure the minimum creation of fines. Eventually combine all retained fractions <4.8mm and at no stage must any coal be disregarded.

Riffeling The samples of 8kg to 25kg are now riffled to obtain two analysis samples of 4,0 ± 0,01kg. The rest of the sample will be retained.

Dry Dry the samples in the oven at 105°C for not shorter than three hours but preferably for 6 hours. Keep the samples in the oven until the samples will be used for the determination of the Abrasiveness Index of the coal.

DETERMINATION METHODOLOGY

Mill Pot Measure the internal diameter of the mill pot, using a inside micrometer. Record the average value of a least two measurements performed on the pot opposite to each other.

Blades The blades are numbered individually from 1 to 4. Weigh the set of blades individually and record the masses to the fourth the decimal place. Note that only preconditioned blades are used.

Fix The blades are fixed in position onto the blade holder using the grub screws. Assemble the pot onto the base plate.

Sample Place the hot dried coal sample into the mill pot. Level the top layer of the coal.

Reset The instrument is reset by pressing the R function key while holding down the P key.

Initiation of test Start the motor by pressing down the two (green) push buttons simultaneously. Allow the test to proceed until the pre-programmed test time (8 minutes) has been completed.

Mass of blades The lid is removed from the pot and the coal from the mill pot. Remove the blades and clean with alcohol or methylated spirits. Weigh the blades individually and record the numbers and corresponding masses.

NOTE: The pot of the instrument might be hot and must be handled with gloves.

REPORTING OF RESULTS

Calculation Use the formula below to calculate the Abrasiveness Index of the coal.

A.I. = (m1 – m2)

Where m1= initial mass of the blade

Where m2= mass of the blade after the test

The above mass differences of all four individual blades will be noted and the total sum of these blades will be reported as the index of abrasion in mgFe.

Acceptance Criteria The Abrasiveness Index between two samples should not be more than 15%. If the difference exceeds this limit then a third test should be performed on the same retained sample and the average of the two closest values be used.

REFERENCE

Internal Eskom standard no national standard exists.

THE DETERMINATION OF THE COMBUSTIBLE MATTER CONTENT OF ASH

GRAVIMETRIC METHOD

BASIS OF METHOD

Ash is heated in air, at a specified rate of 800°C and maintained at this temperature, until constant mass is obtained. The combustible matter is calculated from the loss in weight.

SAMPLE PREPARATION

Dry the ash at 105°C for 90 minutes. Grind the sample to less than 75 micron particle size.

TIME REQUIRED FOR ANALYSIS

For one sample: Response time = 315 minutes, Operator time = 12 minutes

TOLERANCES

Within laboratory tolerance : 0,2 % absolute

Between laboratory tolerance : 0,3% absolute

SPECIAL APPARATUS

Muffle furnace A muffle furnace capable of giving an adequate zone at a uniform temperature of 500°C in 30 minutes from cold, of being raised to 800°C in a further 60 – 90 minutes and of maintaining this latter temperature at the end of the run up period. The ventilation will be such as to give at least five atmosphere changes per minute at 800°C.

Balance An analytical balance having a sensitivity of 0,1mg.

Dish A silica dish, 10mm to 15mm deep of such a size that will ensure that the ash layer does not exceed 0,5g/cm².

Dessicator A suitable dessicator containing fresh (or freshly generated) self-indicating silica gel.

ANALYTICAL PROCEDURE

Weigh dish Weigh the dish. Let this mass be M1

Weigh dish and ash Add approximately one gram of the ash to the dish. Weigh the dish plus ash. Let this mass be M2.

Insert dish Insert the dish into the furnace at room temperature.

Temperature Raise the temperature of the muffle furnace to 500℃ in 30 minutes and to 800°C in a further 60 to 90 minutes and maintain at this temperature for at least 3 hours.

Remove dish Remove the dish from the furnace and allow to cool, first on a thick metal plate for 5 minutes and finally in a dessicator.

Weigh Weigh the dish when it is at ambient temperature. Let this mass be M3.

Calculate Calculate the combustible matter as follows:

$$\text{Combustible matter (\%)} \quad \frac{(M2 - M3)}{(M2 - M1} *$$

* Multiply above answer by 100

NOTE: The above method can also be used for the determination of LOSS ON IGNITION in deposits.

THE CALCULATION OF THE FIXED CARBON CONTENT OF COAL

BASIS OF METHOD

The fixed carbon is calculated by subtracting the sum of the inherent moisture, ash and volatile matter from 100.

ANALYTICAL PROCEDURE

Calculate

The calculation of the fixed carbon content of coal involves the determination of:

Inherent moisture – ESKOM method 103

Ash – ESKOM method 101

Volatile matter – ESKOM method 102

Fixed carbon (%) = 100 - (inherent moisture + ash + volatile matter).

REFERENCE

South African Bureau of Standards: Standard Method SABS 928

THE CALCULATION OF THE OXYGEN CONTENT OF COAL

BASIS OF METHOD

The oxygen is calculated by subtracting the sum of the inherent moisture, ash, carbon, hydrogen, nitrogen, total sulphur and carbonate from 100.

ANALYTICAL PROCEDURE

Calculate

The calculation of the oxygen content of coal involves the determination of:

Inherent moisture – ESKOM method 103

Ash – ESKOM method 101

Carbon – ESKOM method 118

Hydrogen – ESKOM method 118

Nitrogen – EKOM method 118

Total sulphur – ESKOM method 104

Carbonate – ESKOM method 100

Oxygen (%) = 100 - (inherent moisture + ash + carbon + hydrogen + nitrogen + total sulphur + carbonate).