Performance optimisation of vertical spindle coal pulverisers

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ABSTRACT

Coal pulverisers' performance optimisation is an important process in power generation plants. Pulveriser operation is costly; reliability and availability is key to power generation and cost reduction is achieved by the optimal performance of associated plants. The objective of this dissertation was to investigate the effect of coal feedstock property variation on the vertical spindle coal pulverising mill's performance to facilitate optimal plant performance. Plant design and mill's acceptance test data was analysed to understand the design and subsequent changes over the years of the mill's operation. The mill outputs, pulverised coal fineness and distribution tests were carried out and evaluated from the data measured during plants tests.

A mathematical spreadsheet was used to observe mill performance when operating parameters are varied. A mill's heat balance evaluation was done using an Excel spreadsheet to evaluate the mill drying capacity constraint. Coal analysis was done on hard grove grind ability, abrasive indices and calorific value of coal. The effect of low calorific value coal was observed on mill's response to match the boiler energy requirements.

Evaluation of the current operating pulveriser data enabled the determination of the areas that need improvement to achieve mill-optimal performance. Coal feed to the mill is important, this was observed to be a limiting constraint on mill capacity when the coal required exceed nominal load requirement.

KEYWORDS:

Air fuel ratio; pulverised fuel distribution; classifier; elutriation; heat balance; isokinetic sampling; load line; mill throat; pulverisers; optimisation; pulverised fuel; recirculation; settling velocity; models and control.

OPSOMMING

Steenkool pulverisers se prestasie optimalisering is 'n belangrike proses in kragopwekking plante. Pulveriser werking is duur; betroubaarheid en beskikbaarheid is die sleutel tot kragopwekking en kostevermindering word bereik deur 'n optimale prestasie van gepaardgaande plante. Die doel van hierdie verhandeling was om die effek van steenkool roumateriaal eiendom variasie op die vertikale spil steenkool pulverising mill prestasie om optimale plant prestasie te fasiliteer te ondersoek. Aanlegontwerp en Mill’s aanvaarding

SLEUTELTERME:

Air fuel ratio; pulverised fuel distribution; classifier; elutriation; heat balance; isokinetic sampling; load line; mill throat; pulverisers; optimisation; pulverised fuel; recirculation; settling velocity; models and control.

DECLARATION

I declare that this is my own work and that the work used here from others is referenced in the thesis reference in-text and in the reference chapter.

……………………………………………

S.R. Chateya

Date

…………….……………………………..

DEDICATION

The thesis is dedicated to my wife Sylvia Dorcas and my two children, Kudzai Hazel and Munashe Blessing Chateya.

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NOMENCLATURE

A	Area in m^2
M_c	Coal flow kg/s
M_a	Air flow kg/s
ρ	Density kg/m^3
g	Constant of acceleration 9.81 m/s
ΔP	Differential pressure
M	Mass flow kg/s
V	Volumetric flow rate
v	Velocity m/s
Cp	Specific heat capacity kJ/kg.K
h_f	Enthalpy of saturated liquid kJ/kg
h_{fg}	Enthalpy of change phase (latent heat)
T_w	Temperature at wall conditions
T	Temperature at free stream conditions
W	Power (kW)
HGI	Hard grove grind ability index
Wi	Bond work index
μ	Absolute viscosity
VSM	Vertical spindle mill
M_{pitot}	Pitot-mass flow as determined from a pitot traverse kg/s
Delta P	Differential pressure across measuring device
H_g	Enthalpy of saturated vapour kJ/kg
Im	Inherent moisture %
N_{sp}	Number of sampling points
P	Pressure (Pa)
P_b	Barometric pressure (Pa)
P_s	Static pressure (Pa)
h_v	Dynamic pressure (Pa) velocity head pressure
sm	Surface moisture %
T	Temperature (K)
T	Temperature (^{o}C)
Tm	Total moisture
I	Number of mills in service
Q_{ca}	Tempering air to the mill kg/s

Q_{ha}	Hot air to the mill Kg/s
Q_{sa}	Sealing air to the mill Kg/s
R_a	Ideal gas constant for air, 287.04 J/kg.K
T_{sa}	Temperature of sealing air (K)
I	Mill drive current (A)
T_o	Temperature of coal/air at mill outlet (K)
V_{pf}	Pulverised coal air velocity m/s

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1 Introduction

1.1 Introduction

According to Singh (2011:1), 86% of South Africa's electricity is generated from coal fuelled power stations. A significant number of these power stations were designed to burn coal from a dedicated coal mine. This minimised mill throughput and efficiency problems due to variation of coal parameters.

Over the years the expansion of the coal market and the changes in price of coal resulted that power stations use coal from different mines. The blending of coal from different suppliers has resulted in noticeable coal quality variations from the design. The deviations from the designed coal quality adversely impact power plant performance.

According to Etzinger (2013:1-10), Eskom initiated expansion of its generating fleet by building new generation power stations Medupi and Kusile and returning to service the mothballed power stations, namely, Grootvlei, Komati and Camden. The collieries that were dedicated to supply these mothballed power stations remain closed. Thus new coal supplies were sourced, resulting in significant challenges such as load losses and meeting desired mill throughput.

An investigation into the effect of coal feedstock property variation on the vertical spindle coal pulverising mill performance has the potential to improve the performance of the power stations.

1.2 Problem statement

Due to variation in the coal feedstock properties the coal pulverising mills at the Power Utility are not operating optimally. This may have an effect on the fineness distribution of pulverised fuel, pulverised fuel burner distribution, mill bias, mill throughput, mill outlet temperature, power consumption, reliability and pulverised fuel settling velocity. It is currently not clear to what extent this variation in feedstock properties influences a mill's performance and product.

1.3 Research aim

The aim of this research project is to investigate the effect of coal feedstock property variation on the vertical spindle coal pulverising mill's performance to facilitate optimal plant performance. This implies that research undertaken was a means to:

a. evaluate the current state of technology with regards to comminution of current coal feed stock and compare with the equivalent initial design data;
b. assess the current plant performance of the mills under investigation;
c. develop a mathematical tool that may be used to optimise plant performance;
d. evaluate plant performance with the aim to optimise; and
e. conclude and make recommendations with regards to optimal plant operation.

1.4 Scope of research

To address the aims as presented above the scope is outlined as follows:

a. conduct a detailed literature review that establishes the current state of technology as relevant to coal pulverisation technology, with specific emphasis on the vertical spindle mills at Power Utility;
b. conduct plant tests at Power Utility X Unit 4 Mills A-E to evaluate plant performance as related to fineness distribution of pulverised fuel, pulverised fuel burner distribution, mill bias, mill throughput, mill outlet temperature, power consumption, reliability and pulverised duel settling velocity;
c. conduct laboratory experimentation to determine coal fineness, calorific value, hardgrove grindability index, abrasiveness index, ash and moisture content;
d. develop a mathematical model in Excel that simulates mill performance as a function of variable coal feedstock properties and basic plant operation parameters;
e. optimise plant performance based on the mathematical model and tests through evaluation of coal parameters and mill throughput; and
a. conclude and make recommendations on the current operational efficiency of the coal pulveriser mills at Power Utility X Unit 4 Mill A-F and how they may be optimised.

1.5 Research background

Coal fuelled power stations use pulverised fuel in order to achieve optimum combustion and ease of control. Coal is pulverised to obtain a noticeable increase in specific area per unit mass, thus promoting efficient combustion when mixed with air. Increase in coal specific areas due to pulverisation widens the choice of coal type that can be used in the power stations, such as lignite, bituminous coal, anthracite, coke and even peat (Association & Field, 1967:175-231).

The performance of vertical spindle coal mills is considerably affected by variation in feedstock quality, such as coal particle size, moisture content, calorific value, ash content, hardgrove grindability index and Abrasive Index. The mill has four main functions, namely: grinding, drying, transporting and classification of the pulverised coal.

The performance of the mill significantly impacts the burner efficiency and thus the energy output of the burners. The pulverised coal fineness significantly impacts the performance of the burners. Mill product with coarse particles results in noticeable incomplete combustion in the burner.

The primary air supplied from the air pre-heater to the mill dries and transports the pulverised coal to the burners. The design mill inlet and outlet temperature is 245^{o}C and 85^{o}C respectively. The distribution of pulverised fuel to the burners is configured in such a way that an equal mass of pulverised coal is split into equal masses to exit into the burners.

The temperature difference between the mill's primary air temperature and the pulverised fuel air temperature at mill outlet indicate the mill drying capacity. The mill receives the raw coal of a particular size and of a specific moisture content. At Power Utility X , total moisture content of the coal is around 10%.

Power Utility X has six units, Unit One to Unit Six, rated at 220 MW capacity. Each unit is powered with five vertical spindle coal mills to achieve the design full load.

To maintain fluctuations in energy demand, the unit operator manually sets the mill load to respond up or down. Three mills are set to increase coal feed when an increase in load is required. The two mills are also set to decrease coal flow when load reduction is required on the unit. This process is called 'biasing'. Mill combination is another parameter that influences the energy output from the furnace.

Mill capacity is the throughput the mill is able to deliver at the required unit load. Power Utility mills have a designed throughput of 25 480 kg/hr of coal, which translates to 7.07 kg/s. The total coal delivered to the unit for the five mills is 30 kg/s rated on design coal calorific value.

Mill power consumption affects the amount of auxiliary power for the power station unit. Power Utility X units are rated at 220 MW each. The power station unit auxiliary power consumption is designed at seven percent of the total generation. Thus, mill power consumption is a critical parameter in the overall performance of the power station. Mill power usage above design value has a negative impact on energy sent out by the unit. The other effect is that the auxiliary power consumption affects the plant heat rate and efficiency.

When velocity drops as the air-pulverised fuel mixture travels along the pipes, coarse particles tend to segregate around bends and form layers on parts of pipes with reduced velocity. The velocity at which the segregation starts is called the ‘settling velocity’. Operating mills at velocities lower than settling velocity causes pulverised fuel settling in pipes. This might result in coal ignition in the pipes due to the continuous passing of hot air on stationary fuel.

Determination of pulverised fuel air mixture velocity is critical in minimising the chance of flash-back and blow-off of flames on the burners. Flashback occurs when combustion velocity is faster than fuel flow velocity; blow-off occurs when fuel flow velocity is faster than combustion or burning velocity at the burner. This results in the injected coal not igniting.

The objective of maintaining mills is to maintain the capability of the mills while controlling costs. Maintenance of the mills seeks to keep the equipment in working order while reliability is the probability that the equipment will function properly for a specified time.

To improve the reliability of the mill, the maintenance strategy requires a focus upon individual components such as the mill balls and the grinding rings. Implementing and improving preventive maintenance significantly increases the availability of the mills.

The process of achieving pulverised fuel has noticeable costs, thus optimisation of the process can significantly contribute to minimising operating costs.

1.6 Outline of dissertation

The dissertation consists of eight chapters, and each chapter focuses on a specific area of investigation in the vertical spindle milling plant performance optimisation. This section gives a brief summary of the chapters in the dissertation.

Chapter 1: This chapter introduces the dissertation, the objectives of the investigation, and the limitations of the study. The chapter also covers the research proposal to motivate the need for this research and clearly defines the scope of the research project. This chapter also serves as a guide during the research process to ensure that the objective of the study is achieved. The chapter presents an introduction to the investigation, the background and the problem statement for the research project.

Chapter 2: This chapter presents the literature review and available technology for similar work that has been done in vertical spindle coal pulveriser performance optimisation.

Chapter 3: This chapter gives details of the engineering design of vertical spindle coal pulverisers and is the characterisation of vertical spindle pulverisers.

Chapter 4: This chapter deals with the methodology adopted in this research to carry out mill performance optimisation tests, both at the power station and at the University facilities. The results obtained from the tests should be applicable to any vertical spindle coal mills and achieve performance optimisation.

Chapter 5: The chapter deals with the analysis of the mill and boiler design and acceptance data to identify design changes over the mill operation.

Chapter 6: This chapter details the plant tests carried out to investigate the mill performance.

Chapter 7: This chapter details mill power consumption and heat balance Excel spreadsheets.

Chapter 8: This chapter provides the conclusions and recommendations drawn from the results of the research. The recommendations and future work that can be done in the coal mills performance optimisation to improve combustion efficiency.

1.7 Conclusion

Against the background given in this chapter, the purpose of this dissertation is defined as the investigation of the effect of coal feedstock property variation on the vertical spindle coal pulverising mill performance to facilitate performance optimisation of vertical spindle coal pulverisers.

This chapter presented the introduction, the problem statement, aim of the research, scope of the research, research background and dissertation outline. The next chapter focuses on the literature review that establishes the current state of technology as relevant to coal pulverisation.

2 Literature survey and existing technology

2.1 Introduction

The aim of this study is to perform an investigation on the effect of coal feedstock property variation on the vertical spindle coal pulverising mill performance to facilitate optimal plant performance. This chapter focuses on a detailed literature review that establishes the current state of technology as relevant to coal pulverisation technology with specific emphasis on the vertical spindle mill's at Power Utility X Unit 4.

The chapter presents an overview on the theories of comminution in Section 2.2 and hardgrove grindability in Section 2.3. This is followed by the Abrasive Index in Section 2.4 and Rosin and Rammler Theory in Section 2.5. A discussion of mill internal streams (Section 2.6) and mill operating parameters (Section 2.7), as well as mill models and controls (Section 2.8) trails. The chapter ends with a conclusion in Section 2.9.

2.2 Theories of comminution

Comminution of solids in to fine powder in the industry involves a process of grinding, classification and further size reduction until the required size is achieved. The process of grinding is expensive if proper monitoring and plant optimisation are not implemented (Rubiera *et al.*,1999). In some industries the grinding process becomes prohibitively costly, to the point where the final product is not price-competitive. This section will emphasise theories of comminution relevant to vertical spindle coal mills.

When the high cost persists, business continuation may be hampered, hence the need to reduce operational costs. The way to reduce costs is by understanding the cost of grinding and analysing the areas that need optimising in order to reduce costs. The comminution process involves the provision of material to be ground, as well as the state of the grinding components. The optimisation is meant to extend the life of the grinding components and improve the pulverised coal throughputs (Walqui *et al.*, 2003; Kawatra & Eisele, 2005).

The coal pulverisation process is significantly costly as the grinding mills wear/replacements costs escalate. Companies dealing in powder products have tried to reduce the grinding costs of these processes. The mill manufacturers have been involved in wear research of mill grinding components with the aim of reducing and understanding the grinding processes to ultimately extend grinding components' life.

Rittinger, Bond and Kick came up with theoretical and empirical energy size reduction equations and these became known as the three laws of comminution (Rittinger, 1867; Bond, 1952; Kick, 1855). Further work by Walker (1937) and Hukki (1962) resulted in the combination of the three laws to give an energy relationship during comminution. The three empirical grinding energy relationships are defined in the energy requirements. The laws of comminution are summarised as:

- Rittinger's law, which assumes that the energy consumed is proportional to the newly-generated surface area; it is considered to be the first law of comminution;
- Kick's law, which relates the energy to the sizes of the feed particles and the product particles, the second law of comminution;
- Bond's law, which assumes that the total work useful in breakage is inversely proportional to the square root of the diameter of the product particles, implying theoretically that the work input varies as the length of the new cracks are made in breakage, the third law of comminution; and
- Holmes's law, which modifies Bond's law by substituting the square root with an exponent that depends on the material.

2.2.1 Rittinger’s law

Rittinger’s law states that during grinding the work done is proportional to the new surface created during the grinding process (Rittinger, 1879). The size of the solids entering the mill is continuously reduced to achieve the required size. Significant amounts of energy are used to achieve the desired particle size. According to Rittinger (1867) the work done is proportional to the energy used.

Rittinger’s law is mathematically expressed as follows:

$$\boldsymbol{E} = \boldsymbol{C}\left(\frac{\boldsymbol{1}}{\boldsymbol{D_p}} - \frac{\boldsymbol{1}}{\boldsymbol{D_f}}\right) \qquad 2.1$$

where E = energy required, C = a constant, D_p = 80% passing size product and D_f = passing size of feed.

2.2.2 Kick's law

Kick’s law states that during grinding the work done is proportional to reduction in volume (Kick, 1885). Equation 2.2 mathematically expresses Kick’s law.

$$\boldsymbol{E = C.log\left(\frac{D_f}{D_p}\right)} \tag{2.2}$$

where E = energy required, C = a constant, D_p = 80% passing size product and D_f = 80% passing size of feed.

This implies that the grinding rate is independent of particle size because it is based on a constant as well as a reduction ratio. Equal amounts of energy would be required to achieve size reductions regardless of particle size.

2.2.3 Bond's law

On analysing the laws that govern grinding, another important law was proposed by Bond (1952). The law is known as Bond's Third Theory. Bond postulated that work done during grinding is proportional to the new crack-tip length produced. Equation 2.3 shows Bond's law.

$$\boldsymbol{E = C\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right)} \tag{2.3}$$

where E = energy required, C = a constant, P_{80} = 80% passing size product and F_{80} = 80% passing size feed.

Bond's law was considered to be in-between Kick's and Rittinger's and this is shown in Equation 2.4.

$$\boldsymbol{W = \frac{10\,W_i}{\sqrt{P_{80}}} - \frac{10W_i}{\sqrt{F_{80}}}} \tag{2.4}$$

where W = work output (kWh/t), W_i = work index, P_{80} = 80% passing size product and F_{80} = 80% passing size of feed.

2.2.4 The energy equation

Rittinger, Kick and Bond's laws can be combined into the general form of a comminution energy equation, shown in Equation 2.5 (Hukki, 1961; Jankovic *et al.*, 2010:1-10).

$$\boldsymbol{dE = -\frac{C\ \ dx}{x^n}} \tag{2.5}$$

where E = net specific energy, x = characteristic dimension of the product, n = the exponent and C = constant related to material.

Equation 2.5 shows that the required energy for a differential decrease in size is proportional to the size change (dx) and inversely proportional to the power n.

When Equation 2.5 is integrated and exponent n given values of 2, 1 and 1.5, the three laws of comminution equations are obtained.

The comminution laws are usable to the evaluation of energy consumption in the grinding processes, as solid materials are being reduced to fine grinding. In power stations coal needs to be pulverised to a fine powder for ease of combustion in the burners.

The mill power draw is important and parameters that contribute to high mill power-draw have to be monitored in order to reduce a high power-draw, which can power-draw increase the auxiliary power consumption on a running plant. The high auxiliary power consumption has a negative impact on the increase of the heat rate on the running unit, as this power consumption is included in the calculation of the heat rate.

High heat rate means that high energy is required for power generation, creating a reduction in efficiency as input increases more than design energy requirements. Due to the high impact of energy usage during solids grinding and size reduction, it is very important that the grinding process and mechanisms be understood and optimum running achieved in order to run economically.

Reliability and Power-plant Performance engineers use these laws to formulate programmes that are used to monitor the efficiency and reliability of grinding plants. The knowledge of the coal's physical properties that affect comminution should be understood and their effect evaluated.

The physical coal properties that are considered in coal comminution are the Hardgrove Grindability Index, Abrasiveness Index and the coal strength (Speight, 2015:155-165; Sligar, 1996:569-581; Sligar, 1998)

2.3 Hardgrove Grindability Index

Coal pulveriser output is rated through the use of the Hardgrove Grindability Index (HGI). Mill outputs are rated according to how hard or soft the coal is and the parameter used is the HGI. HGI is the coal property that describes how soft or hard the coal is to grind. The measure is on a scale of 0-100. The mill manufacturers give an HGI of 50-60 for a particular mill and if the coal changes to an HGI above 50, the coal is getting softer and, vice versa, a lower HGI means the coal is getting harder to grind (Sligar, 1998:1-8)

The HGI developed by Hardgrove is intended to measure empirically the relative difficulty of grinding coal to the particle size necessary for relatively complete combustion. This was used in the then newly-developed pulverised coal boiler furnace. Its use has been extended to grinding coal for the iron-making, cement and chemical industries utilising coal (Tichanek, 2008:27-32; ACARP, 1998:1-8).

More recently it has acquired another role as one of the properties of specification when purchasing coal from different potential suppliers. The specification usually lists a range of values for every property within which the plant is known to function efficiently. These values may arise from the original design or from practical experience with a specific plant.

2.3.1 HGI test procedure

According to ACARP (1998:1-8), HGI test is done using a small pulverising machine which resembles a Babcock E-type vertical spindle coal mill. The test coal is air-dried and of a specific size, and the HGI test resembles the operation of a ball and track type of industrial coal pulveriser manufactured by Babcock. The test is accomplished by taking batch samples with specified sizes.

A 50g sample of coal, which has been prepared in a specific manner with a limited particle size range (1.18 x 0.6 mm), is placed in a stationary grinding bowl. The grinding bowl has eight steel balls which run in a circular path. A loaded ring is placed on top of the set of balls with a gravity load of 284 N. The machine is run for 50 revolutions.

The grounded coal is graded according to the sizes passing through a 75 Microns Sieve. The coal less than 75 microns recorded is converted to an HGI value using a calibration graph.

The HGI test standards differs from one country to another. These differences are well understood by boiler and coal pulveriser designers but have led to noticeable confusion when used commercially for coal trading. The method of preparing samples before the test poses significant variances in standards.

The characteristics of the HGI are (ACARP, 1998:1-8, Hower, 1990):

- an empirical test not linked with a known physical property of coal;
- exhibits a non-linear change in difficulty to grind; and
- it is not additive.

Coal with low values of HGI is significantly difficult to grind, while high HGI values are easier to grind. Thus, a mill designed to crush coal with an HGI of 60 when used with lower HGI values is harder coal, while an HGI value of above 60 means softer coal (ACARP, 1998:1-8, Hower, 1990).

2.4 Abrasive Index

The coal-grinding process results in wear of grinding components due to the grounded material's hardness. The loss in weight of material from initial mass to the final mass is a measure of the abrasiveness of the material being handled.

The life of pulverised coal handling equipment depends on the errosiveness of the coal being used (Speight, 2005:155-165). The wear rate of grinding components depends on the hardness of the material in use and the amount of air being handled by the mill (Gill, 1984:343-361).

The Yancey Gear Price Index is used for the abrasiveness index determination. The tests are done on a batch system but applying this to real plant results may be different, due to the conditions encountered during operations.

The mill has a hydraulic pressure system that presses on the grinding ring. The grinding maintains a specified clearance between the rings and the balls. This gap prevents any metal to metal contact of the balls and rings. The wear rate of grinding elements is due to the abrasiveness character of coal during the coal pulverisation process.

Equation 2.6 shows the relationship between wear rate and the mill grinding pressure (Sligar, 1995). Equation 2.6 has a correlation coefficient of 82% (Sligar, 1995; Scott, 1995:42-44). Equation 2.6 was modified to Equation 2.7 to give improved results.

$$\boldsymbol{Wear\ rate = 1.24 \times grinding\ pressure + 0.77} \tag{2.6}$$

$$\boldsymbol{Wear\ rate = 0.17 \times Abrasion\ index(grinding\ pressure + 1.8) \times 97\%} \tag{2.7}$$

2.5 Rosin and Rammler theory

According to Association and Field (1967:245-249), the milling of coal produces a powder containing particles in a wide range of sizes. Theoretical analysis of combustion must take account of the particle size distribution of the fuel, and the application of the theoretical results demands a knowledge of the fineness of fuels in industrial use. In power plants' various technologies of milling plants are employed and the fineness may depend on the type of mill in use. The mill performance is monitored by analysing the fineness of coal produced by the grinding mill (Association & Field, 1967:245-249).

The grinding process aims to achieve a specified fineness to enable usage of the product. Further work has been done to improve upon the formulation of the relationship between comminution and the energy used to grind the particles to the required size.

After the grinding of the solids into powder, the product is assessed in terms of the suitability of the fineness. In power stations, the mills are monitored by isokinetic-taking representative samples from the exit of the mill. The samples are mechanically sieved and graded to give data that represent particle size distribution (Association & Field, 1967:245).

The frequently used method of analysing the particle size is by plotting the sieving results on the Rosin-Rammler graph. Figure 2.1 shows the standard Rosin-Rammler graph. The distribution of particle sizes follows an exponential law shown in Equation 2.8 (Association & Field, 1967:245; Rosin and Rammler, 1933:29-36).

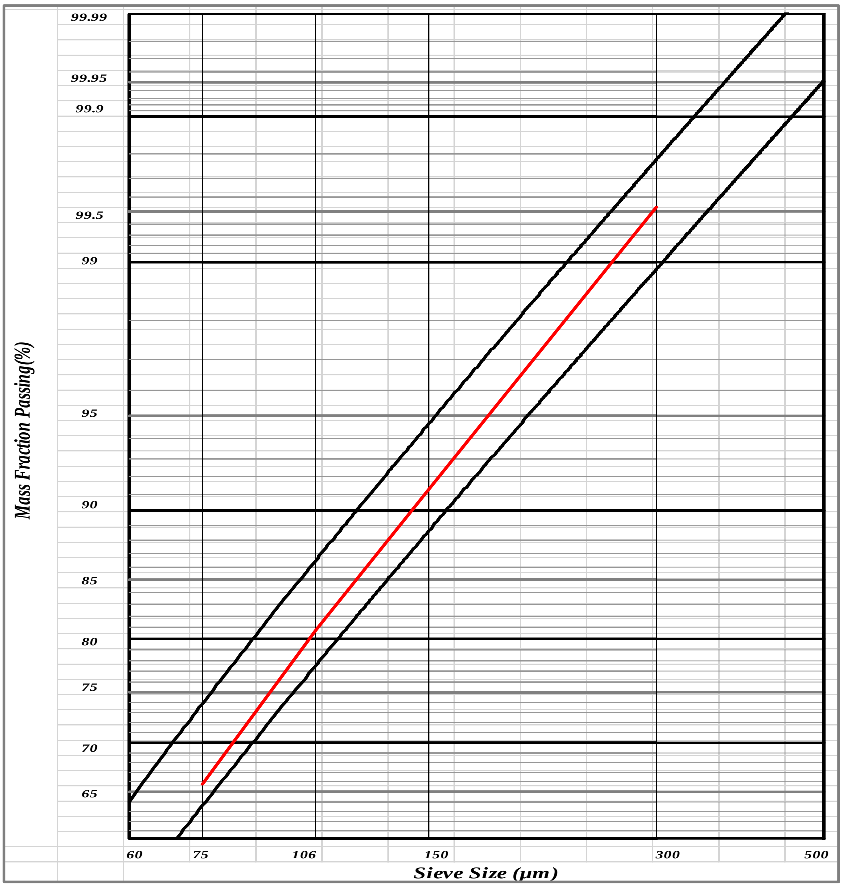

Figure 2.1: Rosin-Rammler graph

$$R_d = 100e^{-bd^n} \tag{2.8}$$

Taking the natural logarithm of the Equation 2.8, which results in a log-log graph plot that will give a straight line of the powder particle distribution. This is shown in Equation 2.9.

$$log\left(log\frac{100}{R_d}\right) = n.logd + logc \tag{2.9}$$

The graphic representation of the particle distribution is important for decision-making with regards to mill performance. The isokinetic sampling of pulverised coal is done in order to determine true representation. The graph is affected by plant operations that affect the coarseness and fineness of the pulverised powder going to the burners for combustion to take place.

2.6 Mill internal streams

There are three coal streams to the mill during operation namely, elutriator rejects, classifier rejects and fresh feed as illustrated in Figure 2.2. The mill in operation carries out four functions simultaneously namely, grinding, drying, classification and transportation of product to the burners.

The heavier particles drop to the grinding zone for further size reduction and the lighter particles go through for further classification. The first classification is the elutriation and the particles recirculated back to grinding zone are termed ‘elutriator rejects’ and at the classifier are termed ‘classifier rejects’. The streams of coal going to the mill are new feed, elutriator and classifier rejects. The combination of the three streams gives a vertical spindle coal pulveriser the re-circulation load (Kojovic *et al.*, 2015:602-611).

According to Shi *et al.* (2015:57-69), mill internal streams are measurable. The total coal on the grinding table is the sum of elutriator rejects, classifier rejects and the fresh coal feed. The pulverised coal that leaves the table is equal to the feed coal (Shi *et al.*, 2015:57-69).

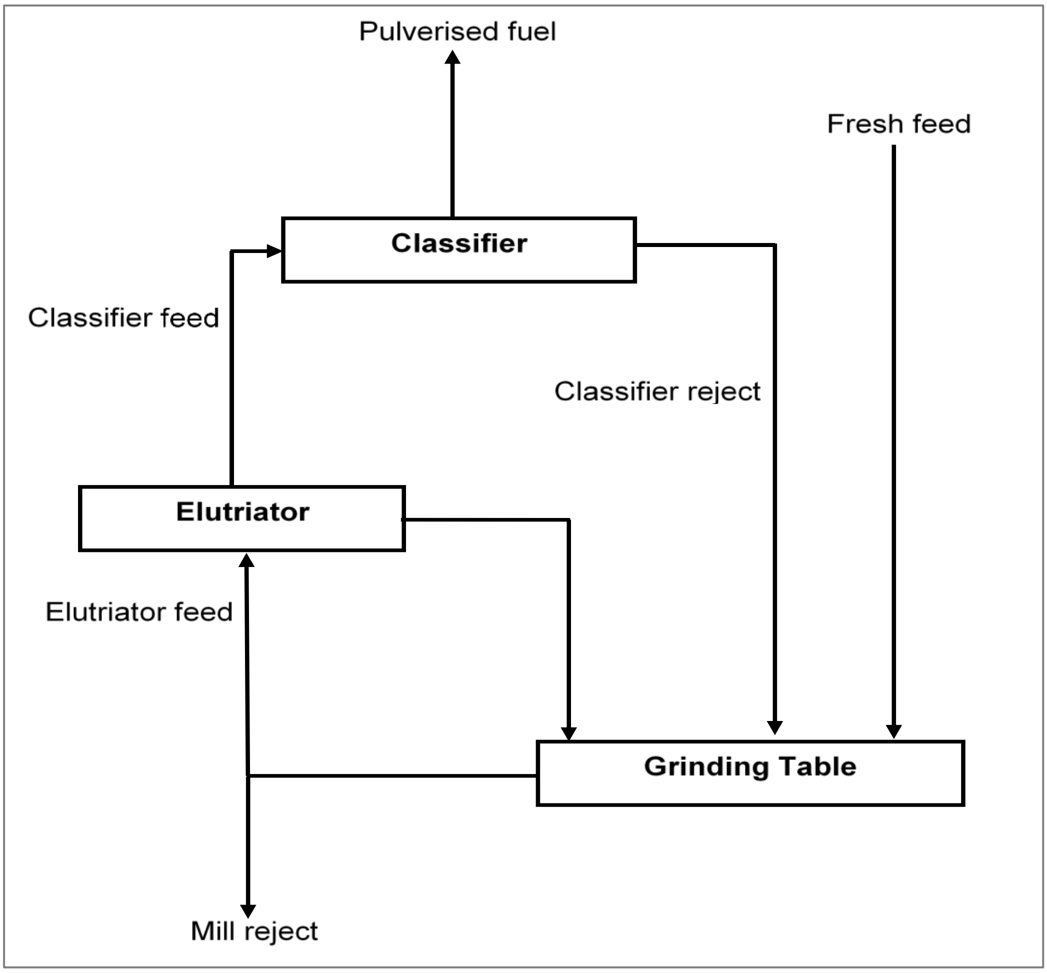

Figure 2.2: Internal streams (Shi, 2011:59; Kojovic *et al.*, 2015:602-611).

2.7 Mill operating window

According to Gill (1984: 339-353), mill operating parameters are considered for the mill to achieve acceptable fineness and load. The parameters when considered will give a graphical representation of the mill operating window. The mill operating window is plotted using the mill operating parameters, such as: drying limit, erosion limit, milling capacity limit, tampering limit, flame stability limit and pulverised coal transport (Gill, 1984:339-353). Figure 2.3 shows the mill operating window.

The operating window provides the limits in which a mill best operates outside of when constraints are experienced (Gill, 1984:339-353).

Arauzo and Cortes (1995), further explored the diagnosis of milling systems' performance based on the operating window and mill power consumption correlation. Procedures for analysing milling performance were formulated and these were to be the modified operating window and semi-empirical correlations for predicting mill power consumption.

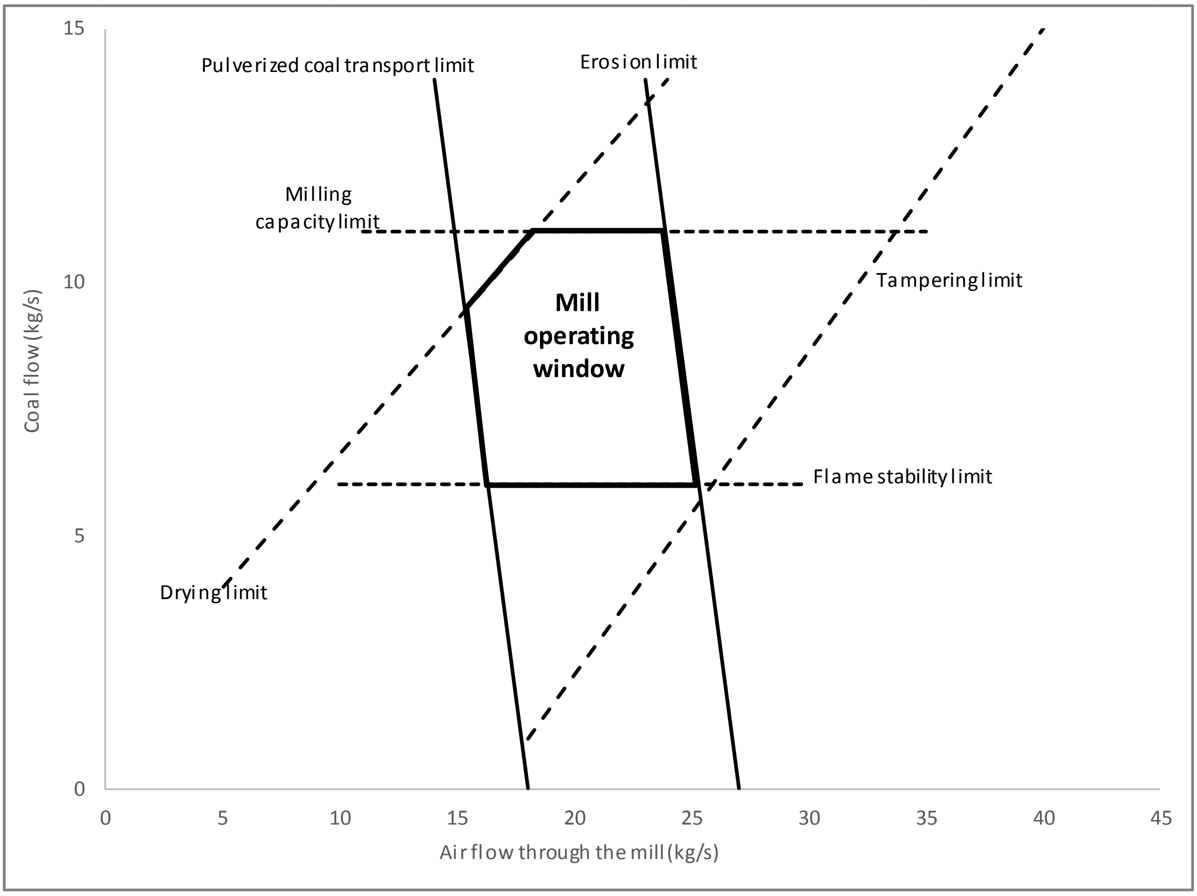

Figure 2.3: Mill operating window (Gill, 1984:339-353)

Fan power, the primary air fans, are designed to deliver the air-entraining pulverised fuel to the burners. When these fans start to operate at full capacity with low loads this is considered a constraint because the fan will not manage to pick up any more pulverised fuel. There must be spare capacity for the fan to enable it to pick up the required load.

In terms of flame stability during operation, there is a limit of coal flow that still supports the flame on the burners. Below a specified limit flame stabilisation is carried by use of oil burners. The operators are aware of these conditions when oil support is required for flame stability. The above, when considered, will give an operating range for the mill in which the mill operates efficiently.

2.8 Mill operating parameters

2.8.1 Coal moisture

According to Bhambare *et al.* (2010:566-571), the mills are designed to operate efficiently at a specified moisture content. Ten percentage moisture content is acceptable for the mills' drying capacity constraints. High coal moisture content causes prolonged pulverised fuel-residence time in the mill before being transported to the burners. Thus, moisture content significantly affects the mill drying capacity (Gill, 1984; Bhambare *et al.*, 2010:566-571).

Odgaard *et al.* (2007:4734-4739), carried out tests on estimation of moisture content in coal mills. Methods for estimating the moisture content of the coal were proposed, based on a simple dynamic energy model of a coal mill which pulverises and dries the coal before transporting it to the burners for combustion. An optimal unknown input observer was used to estimate the moisture content, based on an energy balance model. The tests performed on a range of measurement data proved that the designed estimator can be used to estimate moisture content (Odgaard *et al.*, 2007:4734-4739).

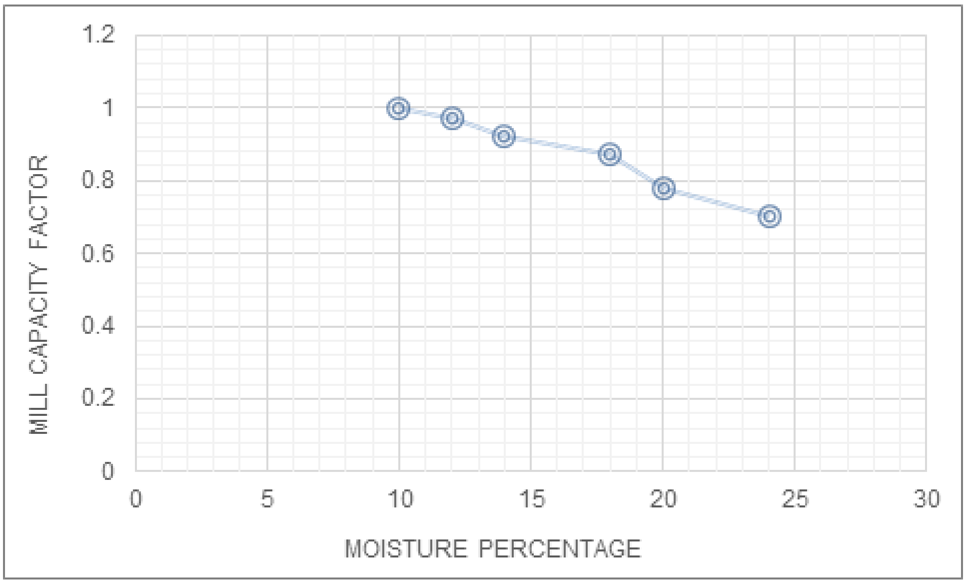

Figure 2.4: Moisture percentage vs mill capacity factor (ACARP 2008:3-4)

2.8.2 Mill inlet temperature

Mill inlet temperature is the temperature of the air to the mill from the air preheater. Noticeable power stations have mill inlet temperatures above 200ºC with an example of Power Utility X mills operating with a mill inlet temperature of 245ºC. The temperature is reduced to a range of 80ºC to 90ºC during the coal-drying process.

According to Niemczyk (2010:32-36), the coal and air flow thermodynamic and hydrodynamic effects must be considered when modelling vertical spindle coal mills. The mill is supplied with hot air from the air preheater to heat and dry the coal during conveyance to the burners. The temperature of the primary air is noteworthy in the evaluation of the drying capacity of the mill (Niemczyk, 2010:32-36).

During operation there is pressure drop across the mill as coal enters the mill and is ground during the plant operation. A fraction of coal is transferred to the elutriator via hot air during grinding and a fraction remains on the grinding table for further pulverisation. This balance has to be maintained for continuous operation of the plant.

2.8.3 Mill differential pressure

The amount of recirculation load in the mill at any time is indicated by the pressure drop across the mill. This pressure drop is called the mill differential pressure. The change in the mill differential pressure has a relation to how much coal is circulating in the mill during the grinding process. The circulating coal during the load is termed ‘re-circulating load’ and the relationship is evaluated using differential pressure.

The primary air is directed through the mill to dry the coal and convey the dry pulverised fuel to the burners. The amount of coal in the mill causes resistance to the flow of coal, setting up the differential pressure across the mill.

The differential pressure is used to control the amount of coal circulating at any particular time. The mill-differential pressure versus the primary air-differential pressure gives a graph that is used as a load line. The load line is the relationship between the coal flow and the air flow. In normal operations of the mill the load line represents the air and fuel ratios. The air/fuel ratios are used to evaluate air flows to the mill and to the boilers when coal flow is known.

2.8.4 Primary air differential pressure

The primary air measurement is done by a measuring device called a Venturi also known as ‘orifice’. The differential pressure across the primary air measuring instrument indicates the amount of air flowing across the instrument to the coal mills. The primary air differential pressure is the measure of air flow to the mill.

A graphic relationship is used to indicate the air flow to the mill versus the opening of air vanes on the primary air fan. The vane openings are calibrated using the pitot tube traverse data to evaluate the amount of air passing at a vane opening. A graph of vane opening percentage versus air flow is plotted and is used as a performance monitoring tool.

2.9 Heat balance

The mill heat balance is evaluated using Equation 2.10 to Equation 2.21. These equations are derived from Fan and Rees's proposed equations. (Fan & Rees, 1994:235). Equation 2.10 to Equation 2.14 shows the mill energy input.

$$\boldsymbol{Q_{eci} = (1 - W_{tm})C_{pc}M_{cf}(T_{ct} - T_a)} \qquad 2.10$$

where Q_{eci} = energy of coal in, C_{pc} = specific heat coal, M_{cf} = coal flow rate, T_{ct} = coal temperature, T_a = ambient temperature and W_{tm}= total percentage moisture of coal.

$$\boldsymbol{Q_{emi} = W_{tm} \times M_{cf} \times H_{fi}} \qquad 2.11$$

where Q_{emi} = energy of moisture in, M_{cf} = mass of raw coal and H_{fi} = enthalpy of saturated liquid at mill inlet.

$$\boldsymbol{Q_{epai} = M_{pa} \times C_{pa}(T_{pat} - T_a)} \qquad 2.12$$

where Q_{epai} = energy of primary air in, M_{pa} = primary air flow rate, T_{pat} = temperature of primary air, C_{pa} = specific heat capacity of air.

$$\boldsymbol{Q_{esai} = M_{sa} \times C_{pa}(T_{at} - T_a)} \qquad 2.13$$

where Q_{esai} = energy of seal air energy, M_{sa} = seal air flow rate, T_{at} = temperature of seal air, C_{pa} = specific heat capacity of air.

$$\boldsymbol{Q_{in} = Q_{eci} + Q_{emi} + Q_{epai} + Q_{esai}} \qquad 2.14$$

where Q_{in} = mill total energy input.

Equation 2.15 to Equation 2.19 shows the mill energy output.

$$\boldsymbol{Q_{eco} = (1 - W_{tm})C_{pc}M_{cf}T_{ft}} \qquad 2.15$$

where Q_{eco} = energy of coal out and T_{pft} = mill outlet temperature.

$$\boldsymbol{Q_{emi1} = W_{im} \times M_{cf} \times H_g} \qquad 2.16$$

where Q_{emi1} = energy of inherent moisture, W_{im} = percentage inherent moisture of coal and H_g = enthalpy of saturated vapour.

$$Q_{emi2} = W_{im} \times M_{cf} \times H_f \tag{2.17}$$

where Q_{emi1} = energy of inherent moisture and H_f = enthalpy of saturated liquid.

$$Q_{esm} = W_{sm} \times M_{cf} \times H_g \tag{2.18}$$

where Q_{esm} = energy of surface moisture and W_{sm} = percentage surface moisture of coal.

$$Q_{epao} = M_{pa} \times C_{pa} \times T_{ft} \tag{2.19}$$

where Q_{epao} = energy of primary air out.

$$Q_{esao} = M_{sa} \times C_{pa} \times T_{ft} \tag{2.20}$$

where Q_{esao} = energy of seal air.

$$Q_{out} = Q_{eco} + Q_{emi1} + Q_{emi2} + Q_{esm} + Q_{epao} + Q_{esao} \tag{2.21}$$

where Q_{out} = mill total energy output.

2.10 Mill power consumption

Shi *et al.*, (2015:595-601), carried out coal mill performance evaluations using models to assess the performance of coal mills. Mill power consumption significantly affects a unit's overall performance.

The Grootvlei Power Station is designed to run the Babcock 8.5 E-type mills at control set points of 22 amperes and 25 amperes upper and lower limits, respectively. Equation 2.22 shows the equation used to calculate the mill power consumption.

$$P = \sqrt{3}.V.I.cos\emptyset \tag{2.22}$$

where P = power, V = voltage, I = current and cosØ= power factor.

The maximum and minimum power consumption is evaluated by substituting maximum and minimum current correspondingly. The mill maximum and minimum design power consumption is 179 kW and 204 kW, respectively.

According to Kojovic *et al.* (2015:602-611), evaluation of mill power-draw is done using the parameters at various design loads for the mill and this compared with that measured during mill running.

The mill force on each ball is exerted by incorporating a hydraulic system that presses on the roller system in the case of roller mills. The Babcock E-type has top and bottom rings with the grinding balls in between the rings. The bottom ring rotates with the table and the top ring is stationary. The pressure on each ball is exerted on the top ring by the hydraulic system as the mill runs, resulting in the effective grinding of coal in the mill.

Roller mill's power consumption can alternatively be evaluated by using Equation 2.23 (Shi *et al.*, 2015:595-601).

$$\boldsymbol{Power\ drawn} = \boldsymbol{I}.\mu.\boldsymbol{k}.\boldsymbol{D_R}.\boldsymbol{D_m}.\boldsymbol{\pi}.\frac{\boldsymbol{n}}{\mathbf{60}} \qquad 2.23$$

where I = number of rollers, μ = frictional coefficient, k = specific roller pressure, D_R = roller radius, D_m = grinding table track diameter and N = speed of grinding table.

According to Shi *et al.*, (2015:595-601), the Babcock E-type mill's power consumption can be evaluated using Equation 2.24.

$$\boldsymbol{P_m} = (\boldsymbol{F} \times \boldsymbol{\mu} \times \boldsymbol{R} \times \boldsymbol{n})(\frac{\mathbf{2}\boldsymbol{\pi} \times \boldsymbol{rpm}}{\mathbf{60}}) \qquad 2.24$$

where P_m = mill power consumption in kW, F = force on each ball, μ = frictional coefficient, n = number of balls and rpm = speed of rotation of table.

According to Shi *et al.*, (2015:69-113) the frictional coefficient is evaluated using Equation 2.25.

$$\mu = \boldsymbol{C_1}\left(\mathbf{1} - \mathbf{exp}^{\left(-\left(\frac{\boldsymbol{GTF}}{\boldsymbol{c_2}} \times \boldsymbol{Fine}^{\boldsymbol{C_3}}\right)\right)}\right) \qquad 2.25$$

where μ = predicted friction coefficient of 10 balls in the coal bed, GTF = grinding table feed t/hr, Fine =% passing 75μm in the GTF, C_1, C_2, C_3 = parameters fitted to survey data and these were 0.1337, 848.6 and 0.4509, respectively and GTF/C_2 = mill race filling ratio.

2.11 Conclusion

The purpose of this chapter was to conduct a detailed literature review that establishes the current state of technology relevant to coal pulverisation technology, with specific emphasis on the vertical spindle mills at Grootvlei Power Station.

The next chapter focuses on presenting a detailed review of the operation of the vertical spindle mill (Babcock E-type mills).

3 Characterisation of vertical spindle coal pulverisers

3.1 Introduction

This chapter gives an overview of the design features of vertical spindle coal pulverisers and the functionality of the associated mill components. The Babcock 8.5 E-type mill is a compact mill that occupies a relatively ergonomic space compared to Tube Ball mills. The mill carries all four functions during the grinding of coal to pulverised state, namely:

- grinding of raw coal to fine powder;
- drying the pulverised coal to the required moisture content;
- classification of the pulverised particles to specified fineness; and
- transportation of the pulverised fuel in primary air suspension to the burners.

3.2 Types of vertical spindle coal pulverisers

There are various types of vertical spindle coal pulveriser applications in powder industries, such as pharmaceutical and power plants. The vertical spindle coal mills are Babcock E-type, Loesche Roller mills and the MPS Bowl mills. Mills are compact and occupy relatively small spaces compared to ball and tube mills... The mills are identified according to their rotational speeds. :

- Low speed mills are balls and tube type mills. These are large steel cylinders containing hardened steel balls of various sizes. Coal is pulverised by the tumbling of the balls in the cylinder during rotation.
- The medium speed coal pulverisers are vertical spindle coal pulverisers that grind the coal between rollers or balls and a bowl or race.
- High speed mills have high speed rotor which impacts on and breaks the coal.

The vertical spindle coal pulverisers are:

- Ring Roller mills
- Bowl mills
- Babcock E-type mills
- Loesche Roller mills
- MPS mills

The different vertical spindle coal pulveriser's configurations are shown below

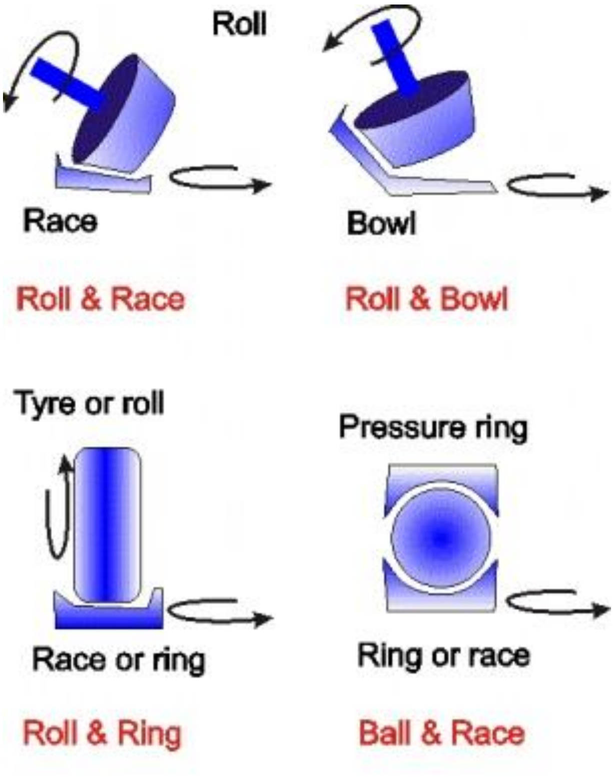

Figure 3.0: Different vertical spindle pulveriser's configurations (CoalTech: 2007:1-2)

The principle of operations is the same, the mills are hot air swept. The hot air is called the primary air and is used for drying the pulverised coal before exiting to the burners for combustion. The grinding components are monitored under a pulveriser maintenance strategies... In practice the stations monitor the grinding components in terms of running hours the components take grinding coal before replacement.

3.3 Mill arrangement

Figure 3.1 shows the global mill arrangement.

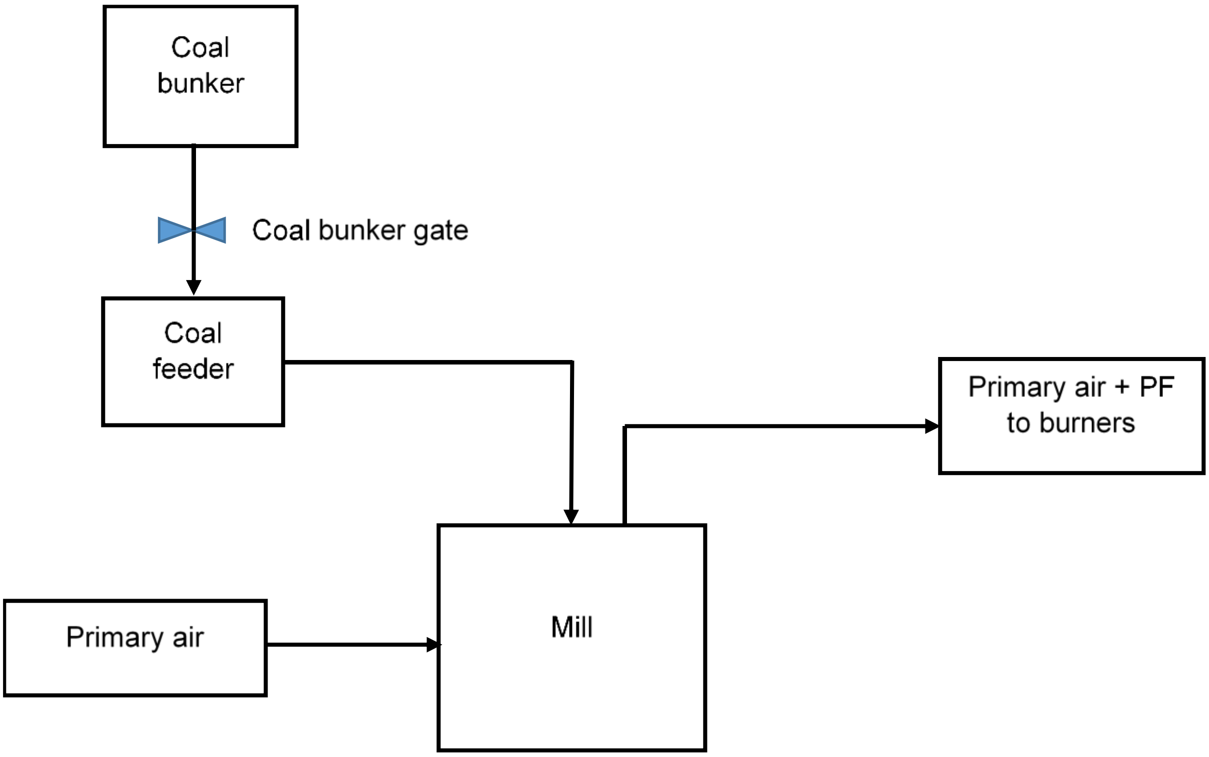

Figure 3.1: Mill arrangement schematic illustration of mill coal and air flow of unit 4 at Power Utility X.

3.3.1 Mill coal feeder

Coal from the mill feeders is directed to the centre of the grinding elements by a pipe that runs in the centre of the mill. This pipe is called a ‘raw coal chute’. It is designed so that raw coal not yet pulverised be directed to the centre during pulverising, the movement of the mill’s centrifugal force forces the ground coal to go to the mill peripheral zone where it will be carried to the burners by the primary air coming to the mill through the throat or air nozzles.

The stations are using rotary table coal feeders, volumetric and gravimetric coal feeders for feeding coal to the mills. Figure 3.2.shows a table coal feeder still in use in some Eskom power stations. The feeder receives coal from the bunkers and due to the variable speed gearbox the feeder is able to respond to the load demand on the unit. The increase in coal demand is indicated by an increase in feeder speed. The reduction in coal flow is indicated by low feeder speed. The feeder has a plough mechanism that regulates the amount of coal exiting to the mill. The feeder is called a table feeder. Modern power plants have upgraded the feeders to gravimetric feeders for their accuracy.

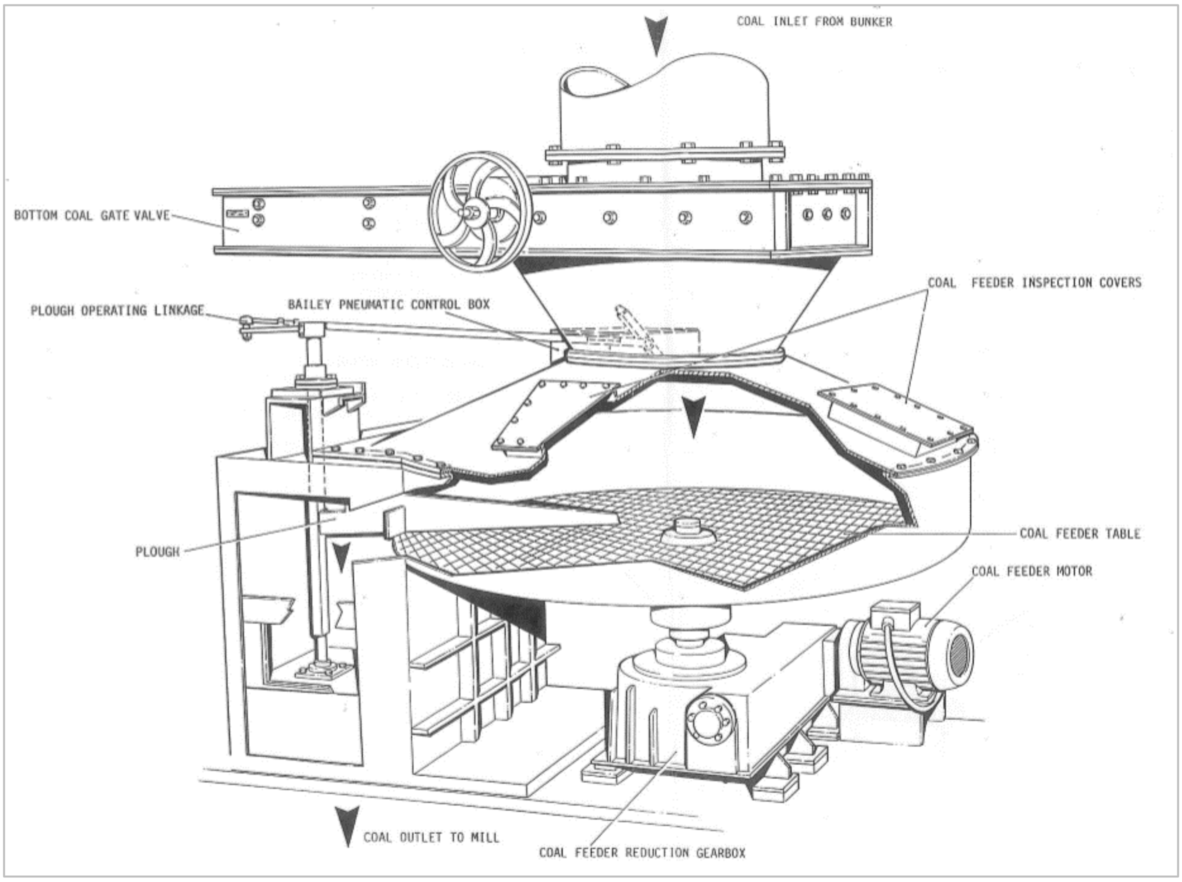

Figure 3.2: Table coal feeder (Power Utility X Operating Manual volume 4)

3.3.2 Seal air system

The mill is equipped with a seal air system as a means of protecting the gearbox from the ingress of pulverised fuel and associated dirt. The seal air is clean and cold air is supplied to the mill at a higher pressure than the primary air in the mill. This air prevents pulverised fuel from entering the gearbox by maintaining a higher pressure than the primary air pressure. Figure 3.3 shows seal air system arrangement.

3.3.3 Mill overview

Figure 3.4 shows the mill components that are involved in the coal comminution process. Each component has a specific task to carry in conjunction with the other components.

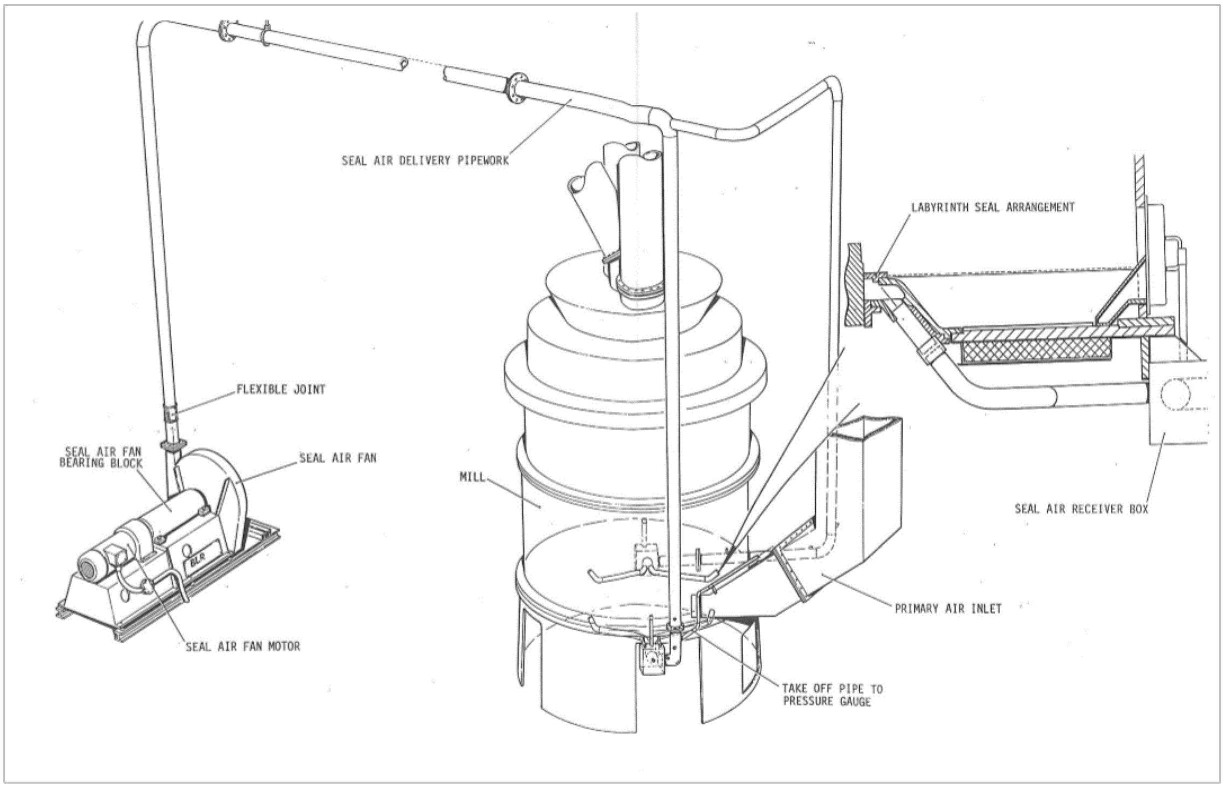

Figure 3.3: Schematic illustrating seal air flow of mills at unit 4 of Power Utility X)

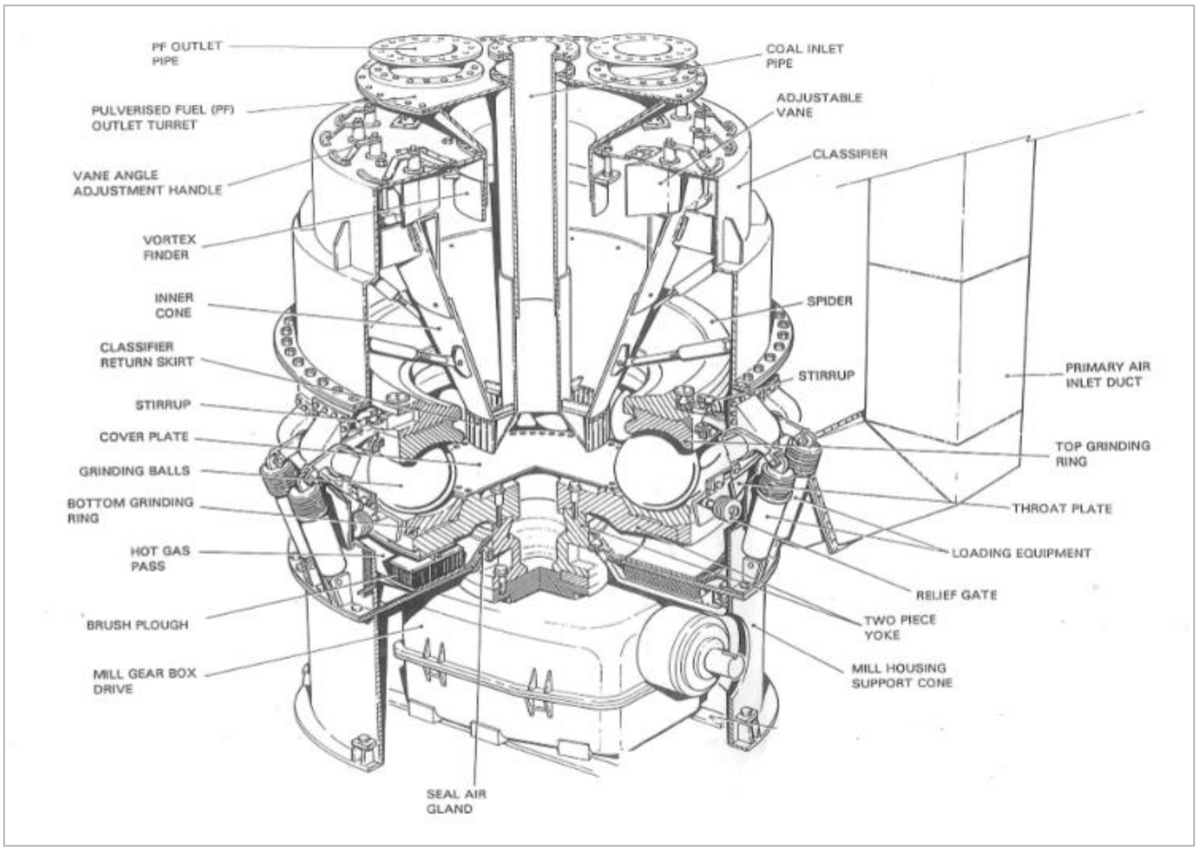

Figure 3.4: Mill cross-section overview (Babcock 8.5 E-type Mill)

Figure 3.5 shows the regions that are involved in the grinding of the coal, the throat, the mill balls, the elutriator zone and then classifier zones for grinding and classification of the coal to required fineness. The ground coal's first classifications achieved in the elutriation zone, where particles separate.

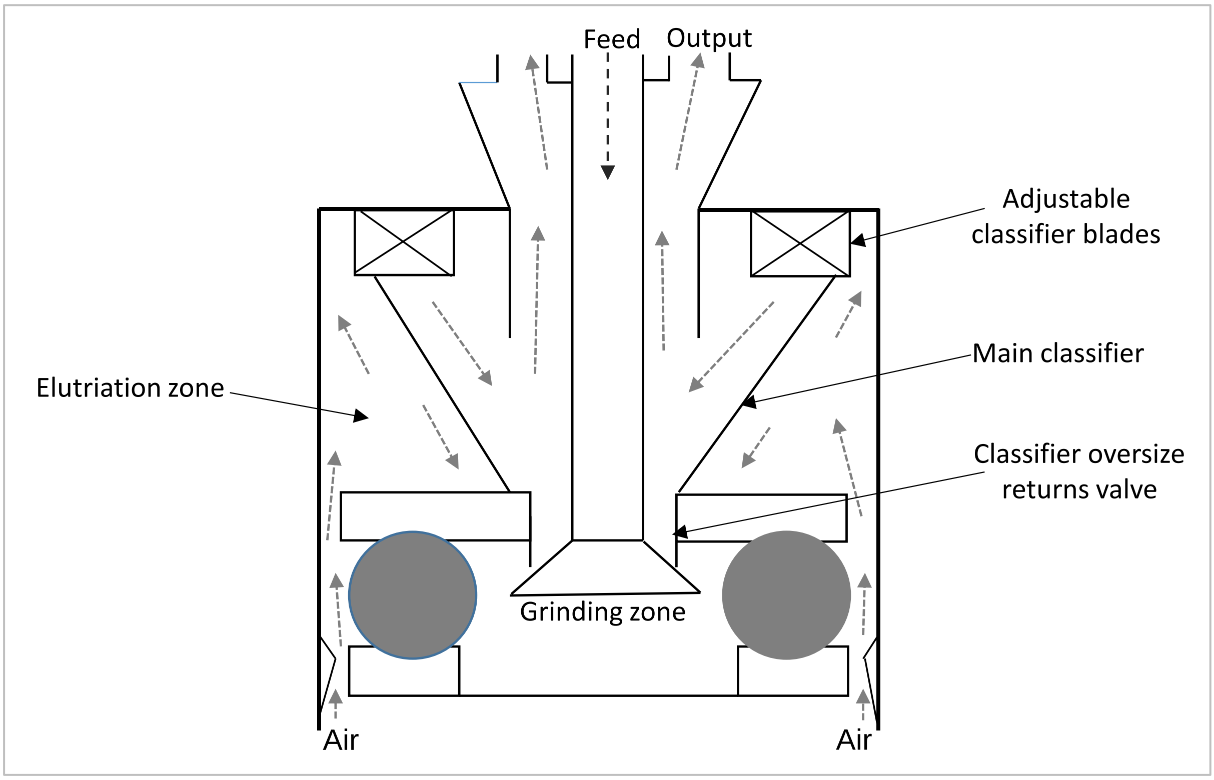

Figure 3.5: Mill internal overview

3.3.4 Mill throat area

The vertical spindle coal mills have a system that provides hot air for the purposes of drying the coal and transporting the final product to the burners for combustion. The air introduction to the mill is through nozzle areas called the 'throat'. The throat area consists of a louvre ring, carrying the nozzles around the periphery of the grinding table or the grinding rings. The design of the throat should be to allow critical velocity during mill operations to pneumatically pick up ground coal, pulverised fuel to the burners without experiencing flow at below minimum flow velocity. The throat area makes a large contribution to the performance of the mill.

The throat areas have seen changes from stationary to rotating throats on most of the mills. The aim for a rotating throat is reduction of the mill's primary air differential pressure, power reduction and reduced wear rate on the mill. The rotating throat is still in the optimising stage and there are experiments being done to optimise the use of rotating throats and evaluation of benefits in terms of mill operating costs. The throat velocities were measured by pulverised fuel sampling and determining the velocities in the pipes and calculating fuel quantities in each pipe.

3.3.5 Primary air system

The primary air system provides the drying hot air to the coal being pulverised on the mill-grinding elements. This air is supplied from the air pre-heating system of the boiler. As the combustion air is supplied to the boiler, it is pre-heated in the air heaters and then split into two streams. The stream of the air termed ‘primary air’ goes to the milling plant as part of air that helps with the drying of the coal and, on its way to the burners, carries in suspension pulverised fuel to the burners. The velocity of flow is provided by the throat area around the mill. The other part, the secondary air, is directed to the furnace and helps in the combustion of pulverised fuel exiting at the burners. The velocity traverses the primary air duct and provides information to calculate velocity and air-flow mass flow rates (Gill,1984:234-239, (Vijiapurapu *et al.*, 2006:854-866; Shi & He, 2013) **.**

3.3.6 Grinding elements

The grinding elements of the vertical spindle coal mills depend on the type of mill. The Babcock E-type mill has grinding balls in between two rings forming a ball-bearing like structure for coal grinding. The upper ring is stationary while the bottom ring is moving as it is coupled to the gearbox input shaft. The loading pressure is exerted on the upper ring during grinding. The grinding elements are of high-wear resistance material and the wear rate is comparable to the hours the mill would have operated. The roller and table/roller and bowl have rollers that have metal tyres to grind the coal. The tyres are also made of high-wear resistant material and replacements are due to measurements and wear monitoring programs. The rollers are also incorporated with the hydraulic pressure-exerting system that makes sure pressure is applied to the grinding rollers for effective grinding and fineness.

The mills are fitted with a hydraulic loading pressure system that applies pressure on the grinding top ring. Figure 3.6 shows the mill hydraulic configuration. The applied force is produced by the oil pressure on the piston ring bottom face (grinding pressure). The reduction is by the oil pressure acting on the piston bottom (counter pressure) of the loading cylinder.

The counter pressure also reduces the noise made by the mill and the pressure is adjustable depending on the coal properties and fineness required. The grinding force is achieved by adjustment of the pressure in accordance with the feeder speed whilst the control valves adjust the pressure.

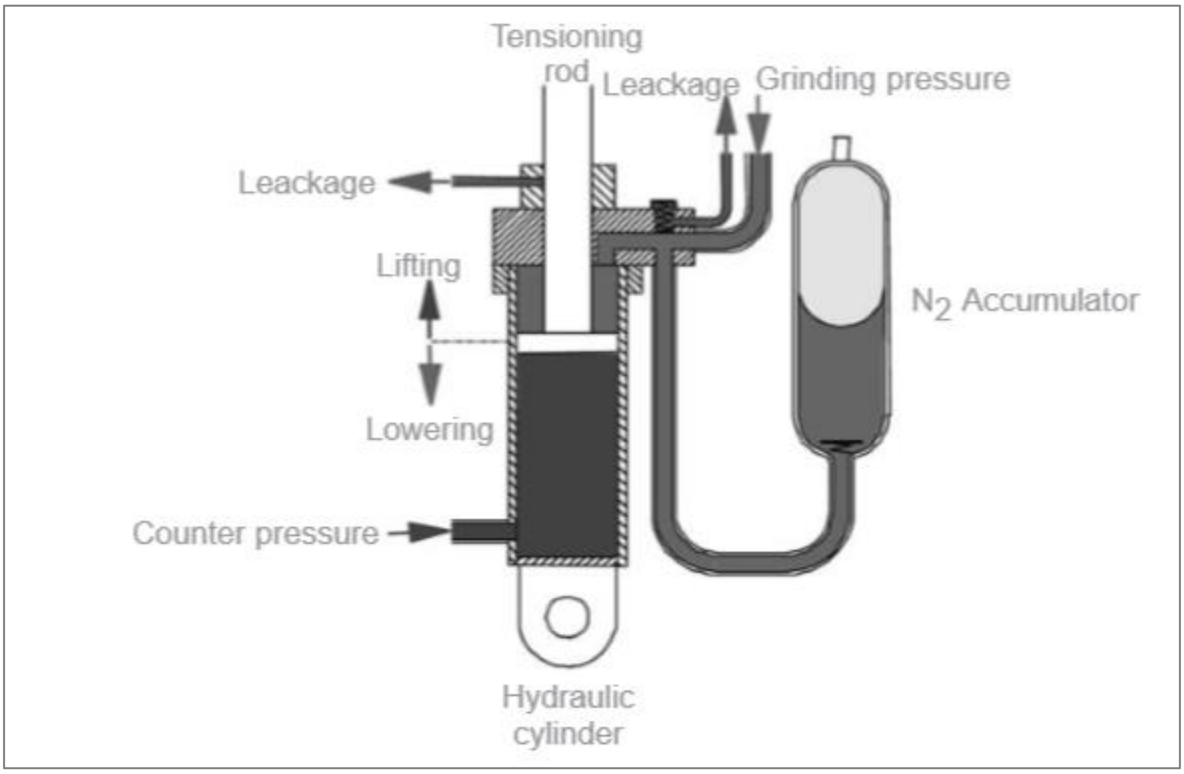

Figure 3.6: Hydraulic cylinder configuration (Lin and Penterson, 2004:6)

3.3.7 Mill pyrites rejecting system

The primary air through the nozzle system transports the fine pulverised fuel to the burners for combustion to take place. The heavier particles are returned to the grinding zone for further reductions in size. The materials that cannot be lifted by the primary air fall into the throat area and are directed to the reject boxes.

3.4 Mill configuration

The design of the boiler is for the mills to supply the required heat by supplying the amount of coal required. The boiler running under design coal is manageable within the coal envelope. Most power stations are running with coal that was taken account of in the design. It was explained in Chapter 1 in the problem statement, that coal has found better paying customers. The stations have to use the available coal and this is blended to make a mixture similar to the design coal. The configuration of mills is that they supply specific burners to give the heat required.

According to Arauzo and Cortés (1995:397-397) mill configuration is represented through the Average Burner Height (ABH) which is evaluated as follows:

$$\boldsymbol{ABH = \frac{\sum rpm_i H_i}{\sum rpm_i}} \tag{3.1}$$

where: i = mill's in service, $rpm_i =$ the angular velocity of the volumetric feeder of each mill coal flow of mill I and H_i = the burner plane height associated with each mill.

The power station has the mills categorised as top, middle and bottom mills. Table 3.1 shows the mill configuration. The bottom mills and the middle mills are in service during boiler operation. One top mill is selected to maintain the steam temperatures. The mills are run with the heat requirement for the load. The load on a unit requires five mills in service out of the six mills available on a unit. Each level of the boiler heat design is allocated burners that are associated with that level and supplied coal by the mills associated with the levels.

Table 3.1: Mills configuration of Power Utility X unit 4

Top mills	C	F
Middle mills	B	D
Bottom mills	A	E
Average burner height (m)	**Mills in service**	**Burners supplied by mills**
14.85	A	A1,A2,A3,A4
14.85	B	B1,B2,B3,B4
14.85	C	C1,C2,C3,C4
17.44	D	D1,D2,D3,D4
12.19	E	E1,E2,E3,E4
17.44	F	F1,F2,F3,F4

The top, middle and bottom positions are average burner heights associated with the mills.

3.5 Conclusion

The purpose of this chapter was to give an overview of the design features of vertical spindle coal pulverisers and the functionality of the associated mill components.The Babcock 8.5 E-type mill configuration on Unit Four was presented in this chapter. The next chapter presents the methodology of testing the mill and performance evaluation.

4 Simulation of the vertical spindle coal pulverisers effectiveness

4.1 Introduction

The aim of this research project is to investigate the effect of coal feedstock property variation on the vertical spindle coal pulverising mill performance to facilitate optimal plant performance. This chapter focuses on the methods of the test to be carried out in evaluating the performance and optimisation of vertical spindle coal pulverisers.

4.2 Research methodology overview

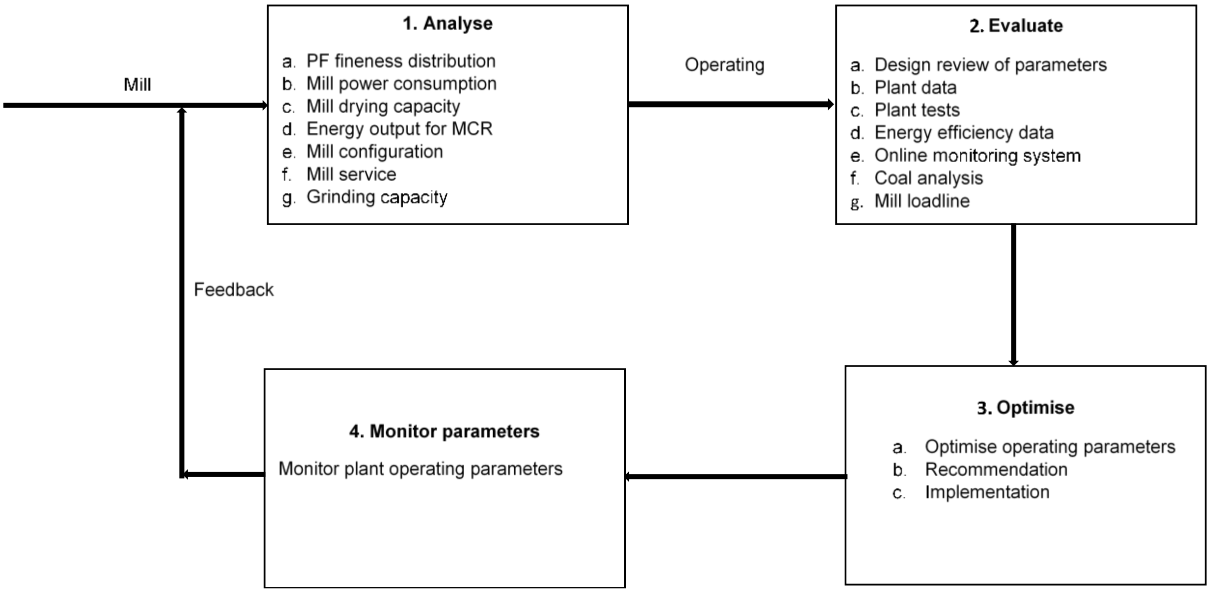

Figure 4.1: Research methodology overview

4.3 Plant design data analysis

In order to understand the performance of the mills at present, the design data is analysed to check any changes that have been implemented since acceptance time. The data analysis is performed on the following:

- design data of the mills, the mills are 8.5 Babcock E-type mills and vertical spindle;
- acceptance test data from the acceptance tests that were carried out by Babcock when the mills were handed over to Eskom after installation. The acceptance test of mills give detail on mill performance, pulverised fuel fineness and pulverised fuel distribution achieved during the test;
- acceptance test proves the design and these values are used when assessing the mill performance;

- the boiler design data is analysed to assess the energy requirement that the mills supply to the boiler to generate steam;
- rating of the mills in tonnes/hr; and
- coal analysis and properties that were considered in rating the mills.

4.4 Plant tests

4.4.1 PF sampling

The mill performance is evaluated by use of the acceptance test data as the baseline and by using the current operating data. The mill test is carried out to collect data that is analysed to discover potential areas of improvement .Present data gives the operation of the mill. Plant tests that assess the performance of the mill are:

- pulverised fuel sampling in the pipes leading to the burners;
- pulverised fuel pipes are traversed during sampling to measure velocity pressure, static pressure and temperature of pulverised air mixture;
- all the associated activities in conducting pulverised fuel sampling is to use the test data to determine;
- coal flow through the mill;
- air flow through the mill;
- particle carrying velocities;
- pulverised fuel mass flow and distribution;
- mill performance evaluation; and
- pulverised fuel fineness.

4.4.2 Mill load simulations

Simulation of mill loads using air flows is done to check the mill output. A comparison between control room mill load readings, simulated mill load and sampled mill load is carried out.

4.4.3 Hardgrove Grindability index

Using the method developed by Hardgrove the Hardgrove Grindability Index is determined. The HGI serves as a means for estimating how various coals behave in commercial pulverisers. The mill rated output is based on the Hardgrove grindability index. Grootvlei Power Station is supplied with coal from more than 12 mines. The mines blend the coal to meet the ash content and the calorific values of the coal. The HGI is evaluated to determine the current mill output with the new coal supply. Refer to table 6.3 for the HGI results.

4.4.4 Abrasive Index

The coal hardness causes wear as the mill operates. Wear affects the life of mill components and pulverised fuel pipes. The understanding of the wear induced by the coal is evaluated by an index called the ‘Abrasive Index’. This index is defined as the material’s ability to remove material from the grinding surface. A sample of coal is used to determine the Abrasive Index. Four metal blades of known weight are fixed on the Abrasive Index testing machine and run through the coal for specified times and revolutions. The loss in mass of the four blades is used to determine the Abrasive Index. The Abrasive Index is evaluated to determine the wear rate on mill grinding components from the new coal the station is using. Refer to table 6.1 for the abrasive Index results.

4.4.5 Excel spreadsheet for mill performance evaluation

An Excel spreadsheet is formulated using Equations 2.22 to 2.25. The spreadsheet input parameters are: coal flow, primary air flow, primary air temperature, mill grinding pressure and mill dimensions.

The mill outputs of the spreadsheet are: mill frictional factor, mill power consumption, cut of velocity of pulverised fuel and cut of diameter of pulverised fuel. The spreadsheet is used to evaluate the effect of varying operating parameters on the mill during operation.

4.4.6 Heat balance

A heat balance spreadsheet is used to evaluate the heat into the mill used for drying the coal. Heat out of the mill is determined by calculating the heat out. The energy available is evaluated to determine the drying constraint of the mill. The heat balance spreadsheet is based on Equations 2.10 to 2.21.

4.4.7 Conclusion

This chapter focused on the methods of the test to be carried out in evaluating the performance and optimisation of vertical spindle coal pulverisers. An overview on plant tests which include PF sampling, mill load simulation, Hardgrove Grindability Index, Abrasive Index and an Excel spreadsheet for mill performance evaluation and heat balance was presented.

5 Mill design and acceptance test data

5.1 Introduction

This chapter focuses on the mill and boiler design and acceptance data for Unit 4's 8.5 E-type vertical spindle mills. The objective in this section is to evaluate design and measured data compare with present mill operating parameters.

5.2 Mill and boiler design data

5.2.1 Mill design data

The mill design data was obtained from design and operational manuals and acceptance test results carried out on Unit 4 in the 1987 Acceptance Test. Table 5.1 shows the mill specified data obtained from the Babcock design manuals.

Table 5.1: Mill specified data

Mill parameter	Description	Quantities
Mill type		8.5 E
Number of mills per boiler		6
Number of balls		10
Ball diameter		730 mm
Mill output at Hardgrove Index 60		24 890 kg/hr
Mill motor speed		970 rpm
Mill table speed		40 rpm
Mill operating temperature	Minimum	50^{o}C
	Maximum	95^{o}C
Air/coal ratio	Minimum	2.1Kg air to 1.0 kg coal
	maximum loading	1.4 Kg air to 1.0kg coal
Classifier blade setting		35^{o}C
Mill operating current	Minimum	22-23 A
	Maximum	25
Mill power consumption		177.80 Kw
		185.88 kW
		202.05 kW
PA fan suction	Maximum output	0.6 kPa
PA fan discharge	Maximum output	9.82 kPa

Mill exhaust	Maximum output	3.32 kPa
Seal air pressure	Maximum output	12.9 kPa
Mill loading system pressure gas	Gas	2.97 mPa
	Oil	3.6 mPa
Loading pressure per ball		4.082 kg
Pulveriser height		5.33 m
Pulveriser Diameter		3.18m
Classifier Diameter		2.9 m

5.2.2 Boiler design data

Table 5.2 shows the boiler specified data obtained from the boiler operating manual.

Table 5.2: Boiler specified data

Designation	**Specified**
Evaporation (calculated)	214.2 kg/s
Fuel (Design Coal Analysis)	
Moisture	9%
Ash	22.5%
Volatile matter	21.6%
Fixed carbon	45.9%
Moisture – total	9.0%
Moisture – inherent	22.5%
Ash	24.72%
Carbon	45.90%
Hydrogen	2.75%
Nitrogen	1.35%
Sulphur	0.71%
Oxygen	9.47%
Calorific value-gross	20.83 MJ/kg

Hardgrove grindability index	60
Ash fusion	°C

5.3 Mill and boiler acceptance test data

According to Storm (1999) mills should be able to give the desired output without failing to produce the fineness. This is done within the coal envelope with high and low calorific values being considered.

5.3.1 Mill acceptance data

Table 5.3 shows the mill acceptance data obtained from acceptance test report.

Table 5.3: Mill particle size distribution

Designation	**Units**	**Specified**	**Particle size Distribution in mill pipes (1-4)**			
Mill pipes			1	2	3	4
Mill A						
Passing 52 mesh sieve	%		100	100	100	100
Passing 100 mesh sieve	%	90	97	97	99	98
Passing 200 mesh sieve	%	70	74	72	78	68
Passing 300 mesh sieve	%		34	32	36	29
Weight of sample collected	Grams		388	425	420	503
Mill B						
Passing 52 mesh sieve	%		100	100	100	100
Passing 100 mesh sieve	%	90	95	100	100	100
Passing 200 mesh sieve	%	70	64	76	73	65
Passing 300 mesh sieve	%		25	35	49	46
Weight of sample collected	Grams		682	447	656	533
Mill C						

Passing 52 mesh sieve	%		100	100	100	100
Passing 100 mesh sieve	%	90	99	97	98	100
Passing 200 mesh sieve	%	70	65	66	62	67
Passing 300 mesh sieve	%		39	35	19	32
Weight of sample collected	Grams		459	588	488	603

5.3.2 Boiler Specified Data acceptance data

Table 5.4 shows the boiler acceptance data obtained from acceptance test report.in

Table 5.4: Boiler guaranteed operation data

Description	**Units**	**Specified Data**	**Measured Data**
Evaporation (calculated)	kg/s	214.2	207.9
Steam pressure	Bar	110.3	111.2
Steam temperature	^{o}C	543.3	543.6
Feed-water temperature	^{o}C	218.3	221.2
Air heater gas outlet temperature	^{o}C	137.8	131.7
Air intake temperature	^{o}C	14.75	14.82
Heat account (on gross CV)	MJ/kg		30.00
Dry gas loss	%	4.68	4.62
Moisture loss	%	4.68	4.48
Combustible refuse loss	%	1.25	0.70
Radiation loss	%	0.19	0.19
Unaccounted losses	%	0.50	0.50
Total heat loss	%	11.30	10.49
Boiler efficiency (by difference)	%	88.70	89.51

5.4 Discussion

Table 5.3 shows the mill acceptance data obtained from the acceptance test data manual. The mill grindability index was analysed for the acceptance tests and these are summarised in the Table 5.3.

The 75 µm sieve is critical in the mill acceptance pulverised coal fineness data analysis. The fineness for Mill A, Mill D and Mill E were above the design of 70% coal fineness. Mill B was on par and the lowest fineness was on Mill C that registered 65% through the 75µm sieve.

The pulverised fuel distribution measured during the acceptance test show that the unit mass was equally distributed to the burners. The Mill F was not available during the acceptance tests, and the performance is considered to be of the same standard as achieved by the five mills.

The design was based on the coal from a dedicated coal mine which was closed when Power Utility X was mothballed. During the acceptance test the coal analysis was at 62 Hardgrove Grindability Index. The coal was soft as indicated by the HGI value in table 5.2.

Mill A's design pulverised coal fineness is 70% through the 75µm sieve. During the acceptance test the pulverised coal fineness measured on all four 4A mill pipes as:

- pipe 1 fineness of pulverised fuel was 74% through the 75 µm sieve;
- pipe 2 fineness of pulverised fuel was 72% through the 75µm sieve;
- pipe 3 fineness of pulverised fuel was 78% through the 75µm sieve;
- pipe 4 fineness of pulverised fuel was 68% through the 75µm sieve; and
- average pulverised fuel fineness of the four pipes was 74% through the 75µm sieve.

The coal moisture was 9.1%, this is the mill drying capacity constraint. The boilers have been retrofitted with low NO_x burners replacing the axial flow burners that were originally installed on all units, including Unit 4 at the Power Utility X. The classifier vanes' setting was angled at a 35-degree opening during the acceptance test of the mill. Currently the mill classifier blades' setting is at a 40-degree angle opening.

The acceptance test data show that the mills achieved the design output and fineness above 70% through the 75µm sieve. The pulverised fuel was equally distributed in the pipes to the burners. The coal had an HGI of 62, which was above the 60 design. This means the coal pulverised was softer than the design coal. Mill output was achieved using the softer coal.

Unit 4 at Power Utility X is retrofitted with low NO_x burners replacing the Babcock axial flow burners. The impact of the low NO_x burners on the performance of the mill be considered. The mill classifier blades’ setting is 40-degrees, giving a 5-degree opening of the classifier vanes from the 35-degree design and acceptance test setting.

5.5 Conclusion

The mill and boiler design and acceptance test data were analysed in this chapter.

6 Plant tests

6.1 Introduction

The aim of this chapter is to present the Plant Test performed to evaluate the mill performance. The tests covered in this chapter include Abrasive Index, Hardgrove Grindability Index, PF sampling and the power consumption tests. The tests were conducted at an Eskom Power Utility X Unit 4 Mills A-F.

6.2 Abrasive Index

The Abrasive Index is measured by using an abrasion testing machine. Four metal blades made from carbon steel with a hardness of 160/-15 Vickers and dimensions of 38 x 38 x 11 mm (+- 0.1mm). The index is defined as an index that shows the abrasion properties of coal on the equipment used to grind the coal before the coal is used as fuel in the boilers. Coal users like to have abrasion index less than 200, greater than 200 users prefer to pay less for this type of coal.

The test of the abrasion index is measured using the equipment called Abrasion Test Apparatus. The station carries out this test at the station laboratory. The equipment has four blades knives which are made from carbon steel with a hardness of 160/-15 Vickers and the dimensions of 38x38x11 mm (+-0.1 mm).

The test will be spinning the blades in coal sample being tested with a speed of 1470/- 30 rounds /min, 1200/-20 rounds /min. The sample size used is 10 kg with a top size greater than 16mm.

The samples are milled to obtain particle size 6.7mm and test is carried out on samples of the milling results with a weight 0f 2/-0.1 kg for each test. The loss in weight of the blades is used to calculate the abrasion Index (BS, 1016: Part 19).

6.2.1 Abrasive Index test procedure

The testing machine blade weights are measured before they are spun, stirring coal samples are tested with a speed of 1470 rpm for 30 minutes. After the 30 minutes the blade weights are measured. The index unit is milligrams of metal blades that erode per kilogram of coal sample used.

The blades' mass loss is calculated by subtracting the mass of the blades after (B_i) the test from the mass of the blades before (A_{1i}), where subscript I is the blade number.

The Abrasive Index is calculated by multiplying the summation of blade mass loss by 1000.

6.2.2 Abrasive Index test results

Table 6.1: Abrasive Index test results

Power Utility			
Date of test	02/09/2013		
Coal Abrasiveness Index	Test 1		
	Mass before (A_1)	Mass after (B_1)	Mass Loss (A_1-B_1)
Mass of blade 1	23.4	23.2	0.2
Mass of blade 2	23.4	23.3	0.1
Mass of blade 3	23.4	23.3	0.1
Mass of blade 4	23.2	23.1	0.1
Total Mass Weight	A1=93.4	B1=92.9	0.5
Abrasiveness=(A_1-B_1)*1000	500	mgFe	
	Test 2		
	Mass before(A_2)	Mass after(B_2)	Mass Loss (A_2-B_2)
Mass of blade 1	23.40	23.34	0.06
Mass of blade 2	23.23	23.17	0.06
Mass of blade 3	23.39	23.32	0.07
Mass of blade 4	23.35	23.29	0.06
Total Mass Weight	A_2=93.37	B_2=93.12	0.25
Abrasiveness =(A_2-B_2)*1000	250.0	mgFe	
Average (500 +250.)/2	375	mgFe	

6.2.3 Abrasive Index test results discussion

The Abrasive Index test results in Table 6.1 show an average Abrasive Index of 375 mgFe. The desired coal Abrasive Index is less or equal to 200 mgFe. Coal above 200 mgFe is considered abrasive and this results in a significant wear rate, grinding components and other auxiliary parts. Thus, the coal being used at Power Utility is considered abrasive (Sligar, 1996:569-581).

6.3 Hardgrove Grindability Index

The method used to determine the Hardgrove Grindability Index (HGI) is the Hardgrove Machine Method. The machine is calibrated for accuracy. On purchase of the machine, standard reference materials are supplied with the machine. The relationship of the machine is determined by these samples.

The equation used for calculating HGI is a linear equation of the form:

$$\boldsymbol{y = a + bm} \tag{6.1}$$

where y = HGI, a = Y axis intercept, b = slope of the regression line and m = calculated oversized particles on 75µm sieve.

Table 6.2 shows the data used to determine the Hardgrove machine constants (a and b). Equation 6.2 shows the relationship used to calculate the Hardgrove Index in the plant tests performed.

$$\boldsymbol{HGI = 10.66 + 6.75 \times m} \tag{6.2}$$

Table 6.2: Constants determination for HGI machine from standard reference samples

Sample	**Y(HGI)**	**X(m)**	**X^2**	**Y^2**	**XY**
1	40	4.35	18.922	1600	174
2	58	7.14	50.98	3364	414.12
3	83	10.44	108.99	6889	866.52
4	100	13.38	179.02	10000	1338
Total	**281**	**35.31**	**357.912**	**21853**	**2792.64**
$\sum x$	35.31				
$\sum y$	281.00				

$\sum xy$	**2792.64**				
$\sum x^2$	357.912				
$\sum y^2$	21853				

The constants a and b in equation 6.1 are determined as in equation 6.3 and equation 6.4 respectively.

$$\boldsymbol{a} = \frac{(\sum y)(\sum x^2)-(\sum x)(\sum xy)}{n(\sum x^2)-(\sum x)2} = \mathbf{10.66} \qquad 6.3$$

$$\boldsymbol{b} = \frac{\mathrm{n}(\sum yx)-(\sum x)(\sum y)}{n(\sum x^2)-((\sum x)\text{^}2} = \mathbf{6.75} \qquad 6.4$$

Equation 6.5 shows the overall HGI index.

$$\boldsymbol{HGI} = \frac{(\sum y)(\sum x^2)-(\sum x)(\sum xy)}{n(\sum x^2)-(\sum x)\text{^}2} + (\frac{\mathrm{n}(\sum yx)-(\sum x)(\sum y)}{n(\sum x^2)-((\sum x)\text{^}2}\boldsymbol{m} \qquad 6.5$$

6.3.1 Hardgrove Index test procedure

The HGI was determined in the station laboratory by taking a sample of coal within a grain size of 4.75 mm that was ground and screened for a sample of size 0.6 to 1.18mm. The 50 gram ± 0.01g accuracy was taken from the 0.6 to 1.18mm and placed in a Hardgrove Index testing machine on the grinding track. Figure 6.1 shows the cross section of a Hardgrove testing machine. The machine was covered after the balls had been inserted in the track. The machine's upper grinding part was loaded and the machine was run for 60 revolutions and stopped. The ground sample was graded by using the 75µm sieve and shaking the sample for ten minutes. The HGI is calculated from the equation (the values of the HGI are indicated as Y in table below).

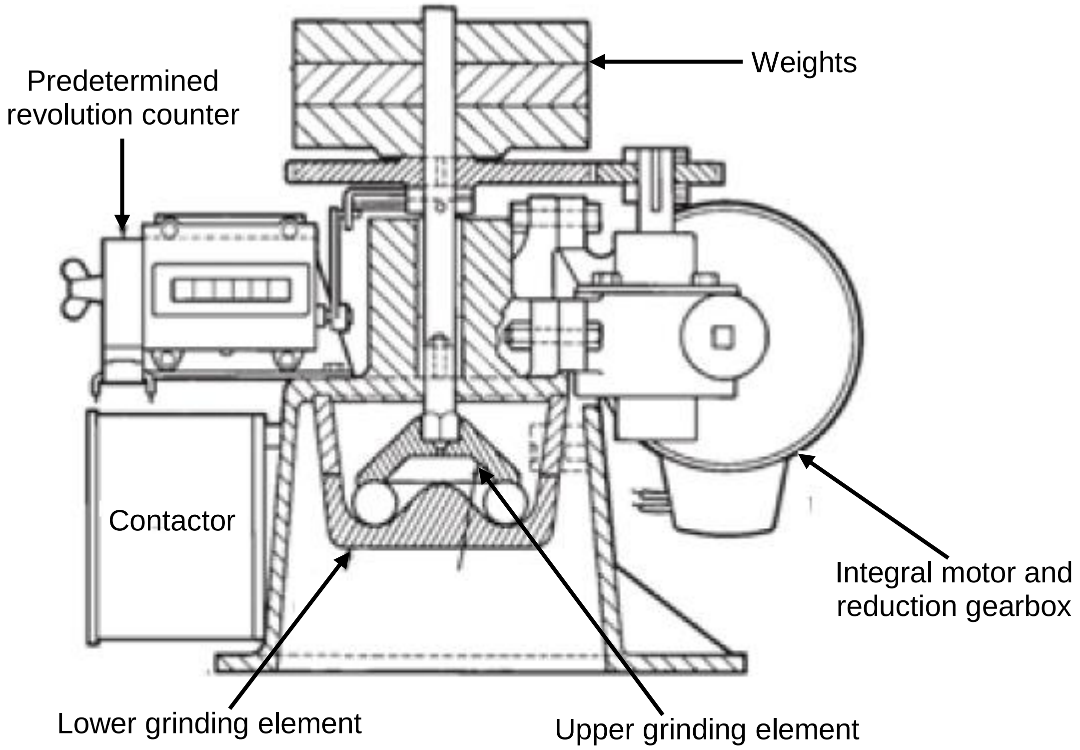

Figure 6.1: Hardgrove testing machine cross section (ACARP 2008).

6.3.2 Hardgrove Grindability Index test results

Table 6.3 and Figure 6.2 show the Coal Hardgrove Index test results at Power Utility X, Unit 4 Mill A.

Table 6.3: HGI test results for Power Utility X coal

Test No.	**Y**	**a**	**b**	**X (-75)**	
	Hardgrove Index HGI				Calorific Value(CV)
1	57.37	10.66	6.75	6.92	20.69
2	62.30	10.66	6.75	7.65	20.48
3	59.40	10.66	6.75	7.22	20.32
4	64.26	10.66	6.75	7.94	20.19
5	57.44	10.66	6.75	6.93	20.13
6	58.25	10.66	6.75	7.65	20.56
7	66.21	10.66	6.75	8.23	19.55
8	62.64	10.66	6.75	7.79	19.54
9	68.10	10.66	6.75	8.51	20.67
10	52.51	10.66	6.75	6.20	20.46
11	56.22	10.66	6.75	6.78	21.2

12	64.26	10.66	6.75	7.94	20.16
13	62.30	10.66	6.75	7.94	21.48
14	58.38	10.66	6.75	7.65	18.59
15	67.16	10.66	6.75	7.07	20.9
16	56.22	10.66	6.75	8.37	20.93
17	53.52	10.66	6.75	6.35	21.33
18	45.69	10.66	6.75	5.19	20.84
19	56.29	10.66	6.75	6.78	20.06
20	53.52	10.66	6.75	6.35	19.47
21	59.40	10.66	6.75	7.22	20.9
22	65.20	10.66	6.75	8.08	20.27
23	73.84	10.66	6.75	7.36	21.3
24	70.06	10.66	6.75	8.80	20.67
25	56.43	10.66	6.75	6.78	20.71
26	62.30	10.66	6.75	7.65	21.29
27	62.30	10.66	6.75	7.65	20.92
28	46.71	10.66	6.75	5.34	20.82
29	48.66	10.66	6.75	5.63	21.33
30	60.34	10.66	6.75	7.36	21.14
Total	1787.25				616.9
Average	**59.58**				**20.56**

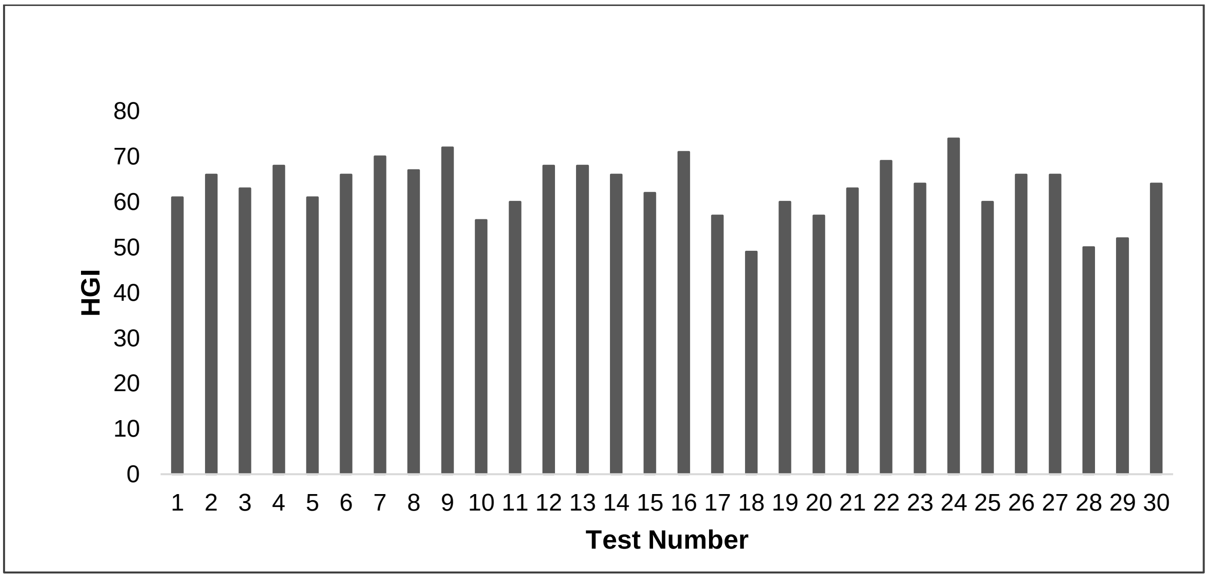

Figure 6.2: Histogram of HGI test results

6.3.3 Hardgrove Index test results discussion

The coal determined HGI show that the value was averaging 59.58 compared to the acceptance test value of 62. The coal supply to the station is still within the HGI design and tested in the acceptance test.

From the values determined of the HGI the mill capacity has decreased given the HGI of 59.58. This apparent capacity decrease will be measured during pulverised fuel sampling of the mill. Figure 6.3 shows impact of HGI on mill capacity .

The coal is hard , as indicated by the HGI determined. The CV of the coal on average is 20.56 MJ/kg, which is the design coal CV. The problem shown by the CV trend is that CV values on daily coal supply vary significantly.

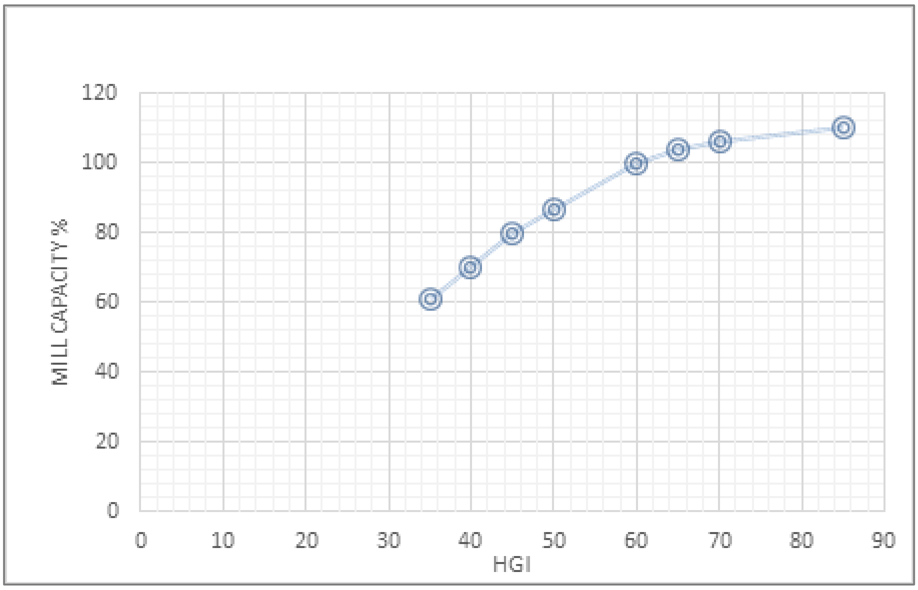

Figure 6.3: Mill capacity vs HGI (ACARP 2008:3-4)

6.4 PF sampling

Pulverised fuel sampling and all the associated activities are ideally conducted to determine and collect the following information (Steyn & Holtshauzen, 1999:5):

- coal flow through the mill;
- air flow through the mill and associated bypass system;
- particle-carrying velocities;

- pulverised fuel mass flow and distribution; and
- mill performance evaluation.

The test involves recording all the operating parameters, sampling pulverised coal, grading the sampled coal and analysing the fineness quality as per the mill design.

6.4.1 PF sampling results

Table 6.4 shows mill data measured during PF sampling for Unit 4 mills.

Table 6.4: Mills test data

Unit	**4**	**Mill**	**A**	
Pipe	Velocity pressure	Static pressure	Temperature	Atmospheric pressure
	kPa	kPa	◦C	KPa
1	0.42	1.8	94	84
2	0.42	1.8	88	84
3	0.48	1.8	89	84
4	0.38	1.3	89	84
Unit	**4**	**Mill**	**B**	
Pipe	Velocity pressure	Static pressure	Temperature	Atmospheric pressure
	kPa	kPa	◦C	KPa
1	0.58	0.6	79	84
2	0.42	0.6	80	84
3	0.32	0.5	79	84
4	0.32	0.6	80	84
Unit	**4**	**Mill**	**C**	
Pipe	**Velocity pressure**	**Static pressure**	**Temperature**	**Atmospheric pressure**
	kPa	**kPa**	**◦C**	**KPa**
1	0.64	1.5	84	84
2	0.68	1.8	87	84
3	0.58	1.6	86	84
4	0.62	1.8	87	84
Unit	**4**	**Mill**	**D**	

Pipe	**Velocity pressure**	**Static pressure**	**Temperature**	**Atmospheric pressure**
	kPa	**kPa**	**◦C**	**KPa**
1	0.58	1.5	92	84
2	0.38	1.4	92	84
3	0.42	1.5	90	84
4	0.32	1.4	92	84
Unit	**4**	**Mill**	**E**	
Pipe	**Velocity pressure**	**Static pressure**	**Temperature**	**Atmospheric pressure**
	kPa	**kPa**	**◦C**	**KPa**
1	0.4	1.2	85	84
2	0.58	1,0	83	84
3	0.72	1	86	84
4	0.7	0.9	85	84
Unit	**4**	**Mill**	**F**	
Pipe	**Velocity pressure**	**Static pressure**	**Temperature**	**Atmospheric pressure**
	kPa	**kPa**	**◦C**	**KPa**
1	0.88	1.9	93	84
2	0.84	1.9	92	84
3	0.78	1.9	93	84
4	0.72	1.7	95	84

6.4.2 PF sampling results

Table 6.5 shows the calculated mill data using data collected during PF sampling. Equation 6.3 to Equation 6.5 are used to calculate parameters in Table 6.5.

$$\boldsymbol{Density\ of\ air\ (kg/m^3)} = \frac{\boldsymbol{P_s}}{\boldsymbol{RT}} \tag{6.6}$$

where P_s = absolute static pressure in duct ($P_{measured}$ +$P_{atmosphere}$) pascal, R= gas constant of 287J/kg.K and T= temperature in Kelvin (^oC+273.15).

$$\boldsymbol{Air\ velocity\ (m/s)} = \sqrt{\frac{\boldsymbol{2\Delta P}}{\boldsymbol{\rho}}} \tag{6.7}$$

where ΔP = differential pressure across pitot tube (kPa) and ρ= air density at the measuring point (kg/m^3).

$$\boldsymbol{Air\ flowrate\ (kg/s) = \rho \times v \times A.} \tag{6.8}$$

where ρ= density of air at the pitot traverse point (kg/m^3), v=velocity of air (m/s) and A= total area of duct (m^2).

Table 6.5: Mill calculated data

	Unit	**Mill**	**D**	
	Coal flow	Air flow	Temperature	Velocity
	kg/s	**kg/s**	**◦C**	**m/s**
1	1	2.9	92	32
2	1.5	2.2	92	26
3	2.2	2.5	90	27
4	1	2.1	92	24
5	**5.7**	**9.7**		
	Unit	**Mill**	**E**	
	Coal flow	Air flow	Temperature	Velocity
	Kg/s	**Kg/s**	**◦C**	**m/s**
1	1.3	2.4	85	26
2	1.2	2.7	83	32
3	1.4	3.2	86	36
4	1.3	3.2	85	35
	Unit	**Mill**	**F**	
	Coal flow	Air flow	Temperature	Velocity
	Kg/s	**Kg/s**	**◦C**	**m/s**
1	1.4	3.6	93	39
2	1.6	3.3	92	38
3	1.4	3.4	93	37
4	1.6	3.2	95	36
5	**6**	**13.5**		
	Unit	**Mill**	**C**	
	Coal Flow	Air flow	Temperature	Velocity

	Kg/s	**Kg/s**	**◦C**	**m/s**
1	2.3	3.1	84	33
2	1.5	3	87	34
3	2	2.9	86	32
4	0.9	3	87	33
	Unit	**Mill**	**B**	
	Coal flow	Air flow	Temperature	Velocity
	kg/s	**kg/s**	**◦C**	**m/s**
1	1	2.9	92	32
2	1.5	2.2	92	26
3	2.2	2.5	90	27
4	1	2.1	92	24
	Unit	**Mill**	**A**	
A	**Coal flow**	**Air flow**	**Temperature**	**Velocity**
	kg/s	**kg/s**	**◦C**	**m/s**
1	1	2.5	94	27
2	1.1	2.3	88	27
3	1.1	2.6	88	29
4	1.1	2.3	89	26

6.4.3 PF fineness results

The sieving procedure calculates the percentage of the total sample passing 300,150,106 and 75µm sieves. A 50g sample of pulverised coal is placed on stacked 300,150,106 and 75 µm sieves, shaking these sieves on a shaker for twenty minutes. This was followed by calculating the percentage passing through each sieve using a 50g sample. Equation 6.6 to Equation 6.9 shows the calculation procedure.

$$\%\ \boldsymbol{passing\ through\ 300\ \mu m\ sieve} = \frac{\boldsymbol{50-m_1}}{\boldsymbol{50}} \times \boldsymbol{100}\% \tag{6.9}$$

Where m_1 is the mass of particles retained on a 300 µm.

$$\%\boldsymbol{passing\ through\ 150\ \mu m\ sieve} = \frac{\boldsymbol{50-(m_1+m_2)}}{\boldsymbol{50}} \times \boldsymbol{100}\% \tag{6.10}$$

Where m_2 is the mass of particles retained on a 150 µm.

$$\%\boldsymbol{passing\ through\ 106\ \mu m\ sieve} = \frac{\boldsymbol{50-(m_1+m_2+m_3)}}{\boldsymbol{50}} \times \boldsymbol{100}\% \tag{6.11}$$

Where m_3 is the mass of particles retained on a 106 µm.

$$\%\boldsymbol{passing\ through\ 75\ \mu m\ sieve} = \frac{\mathbf{50-(m_1+m_2+m_3+m_4)}}{\mathbf{50}} \times \mathbf{100}\% \quad (6.12)$$

Where m_4 is the mass of particles retained on a 75 µm.

Table 6.6 shows the PF fineness results. Appendix S and T show the load lines produced from oversize particles retained on all the sieves after pulverised fuel fineness determination. The load lines are compared to the target.

Table 6.6: Pulverised fuel fineness results

A Mill	Sieves % passing			
Sieves	300	150	106	75
Mill pipes				
1	99.6	89.8	78.2	64.6
2	100	95	87	79
3	99	93.2	83.8	69.8
4	99.6	84.4	66.6	55
B Mill	Sieves % Passing			
Sieves	300	150	106	75
Mill pipes				
1	99.2	90.4	79.6	65
2	99	90.2	78.8	66
3	99.6	93.4	84.8	69.4
4	98.6	83.6	67.4	52.6
C Mill	Sieves % Passing			
Sieves	300	150	106	75
Pipes				
1	99.4	91	80	64.8
2	100	93.6	84.6	75.4
3	99.6	89.8	77.6	62.2
4	100	95.8	89.6	82
D Mill	Sieves % Passing			
Sieves	300	150	106	75

Mill pipes				
1	99.8	95.2	88.6	76.8
2	99.8	90.6	80	69.2
3	99.6	90	76.6	59.6
4	99.8	96.4	89.4	81.2
E Mill	Sieves % Passing			
Sieves	300	150	106	75
Mill pipes				
1	99.6	91.6	80	62
2	100	90.6	78.8	68.6
3	99.2	91.6	81	70.2
4	99.2	85.8	74.4	63.2
F Mill	Sieves % Passing			
Sieves	300	150	106	75
Mill pipes				
1	100	90.8	80.2	66.2
2	100	91.4	81.4	71.2
3	99.8	94.4	85.8	73.6
4	99.8	91	79.8	68.4

6.4.4 Mill pulverised fuel regression lines

The regression lines for the mills were done and comparison of the line slopes indicated variation in mill load lines. The regression lines are shown by Appendices C1-C6 .. The results show the variation in the slope of the regression lines.

Table 6.7: Results of a regression analysis for Mill A.

Pipe	**Sieve in µµ**	**Passing**	**Residue**	**100/R**	**Log(100/R)**	**Log.log(100/R)**	
1	75	75.17	24.83	4.027	0.605	-0.218	
2	106	89.45	10.55	9.479	0.977	-0.010	
3	150	97.15	2.85	35.088	1.545	0.189	
4	300	99.45	0.55	181.818	2.260	0.354	

	X=Sieve log(x)	Y=log.log(100/R)	xy	x^2	Y^2	**Slope of line m**	0.936
1	1.8751	-0.218	-0.409	3.516	0.048	**Intercept of line c**	-1.924
2	2.0253	-0.010	-0.021	4.102	0.000	**R**	0.972
3	2.1761	0.189	0.411	4.735	0.036	r^2	0.945
4	2.4771	0.354	0.877	6.136	0.125		
SUM	**8.5536**	**0.315**	**0.858**	**18.489**	**0.209**		
N	4						

Table 6.8: Results of regression analysis for Mill B

Pipe	**Sieve in µm**	**Passing**	**Residue**	**100/R**	**Log(100/R)**	**Log.log(100/R)**	
1	75	65.71	34.29	2.916	0.465	-0.333	
2	106	80.25	19.75	5.063	0.704	-0.152	
3	150	91.58	8.42	11.876	1.075	0.031	
4	300	98.45	1.55	64.516	1.810	0.258	
	x=SIEVE log(x)	y=log.log(100/R)	xy	x^2	y^2	**Slope of line m**	**0.975**
1	1.8751	-0.333	-0.624	3.516	0.111	**Intercept of line c**	**-2.133**
2	2.0253	-0.152	-0.308	4.102	0.023	**R**	**0.992**
3	2.1761	0.031	0.068	4.735	0.001	r^2	**0.983**
4	2.4771	0.258	0.638	6.136	0.066		
SUM	**8.5536**	**-0.196**	**-0.226**	**18.489**	**0.201**		
N	4						

Table 6.9: Result of regression analysis for Mill C

	Sieve in µm	**Passing**	**Residue**	**100/R**	**Log(100/R)**	**Log.log(100/R)**	
1	75	58.59	41.41	2.415	0.383	-0.417	
2	106	76.07	23.93	4.179	0.621	-0.207	
3	150	91.45	8.55	11.696	1.068	0.029	

4	300	99.7	0.3	333.333	2.523	0.402	
	x=SIEVE log(x)	y=log.log(100/R)	xy	x^2	Y^2	**Slope of line m**	**1.364**
1	1.8751	-0.417	-0.782	3.516	0.174	**Intercept of line c**	**-2.964**
2	2.0253	-0.207	-0.419	4.102	0.043	**R**	**0.999**
3	2.1761	0.029	0.062	4.735	0.001	r^2	**0.998**
4	2.4771	0.402	0.996	6.136	0.162		
SUM	**8.5536**	**-0.193**	**-0.143**	**18.489**	**0.379**		
N	4						

Table 6.10: Results of regression analysis for Mill D

	Sieve in µm	**Passing**	**Residue**	**100/R**	**Log(100/R)**	**Log.log(100/R)**	
1	75	68.6	31.4	3.185	0.503	-0.298	
2	106	80.7	19.3	5.181	0.714	-0.146	
3	150	91.3	8.7	11.494	1.060	0.026	
4	300	99.53	0.47	212.766	2.328	0.367	
	X=SIEVE log(x)	Y=log.log(100/R)	x.y	x^2	Y^2	**Slope of line m**	**1.111**
1	1.8751	-0.298	-0.559	3.516	0.089	**Intercept of line c**	**-2.389**
2	2.0253	-0.146	-0.296	4.102	0.021	**R**	**1.000**
3	2.1761	0.026	0.055	4.735	0.001	r^2	**0.999**
4	2.4771	0.367	0.909	6.136	0.135		
SUM	**8.5536**	**-0.052**	**0.109**	**18.489**	**0.246**		
N	4						

Table 6.11: Results of regression analysis for Mill E

Pipe	**Sieve in µm**	**Passing**	**Residue**	**100/R**	**Log(100/R)**	**Log.log(100/R)**	

1	75	68.61	31.39	3.186	0.503	-0.298	
2	106	86.27	13.73	7.283	0.862	-0.064	
3	150	96.05	3.95	25.316	1.403	0.147	
4	300	99.89	0.11	909.091	2.959	0.471	
	x=SIEVE log(x)	y=log.log(100/R)	Xy	x^2	y^2	**Slope of line m**	**1.265**
1	1.8751	-0.298	-0.559	3.516	0.089	**Intercept of line c**	**-2.642**
2	2.0253	-0.064	-0.130	4.102	0.004	**R**	**0.996**
3	2.1761	0.147	0.320	4.735	0.022	r^2	**0.991**
4	2.4771	0.471	1.167	6.136	0.222		
SUM	**8.5536**	**0.256**	**0.798**	**18.489**	**0.337**		
N	4						

Table 6.12: Results of regression analysis for Mill F

Pipe	**Sieve in µm**	**Passing**	**Residue**	**100/R**	**Log(100/R)**	**Log.log(100/R)**	
1	75	67.72	32.28	3.098	0.491	-0.309	
2	106	83.39	16.61	6.020	0.780	-0.108	
3	150	94.71	5.29	18.904	1.277	0.106	
4	300	99.51	0.49	204.082	2.310	0.364	
	X=SIEVE log(x)	Y=log.log(100/R)	x.y	x^2	Y^2	**Slope of line m**	**1.113**
1	1.8751	-0.309	-0.579	3.516	0.095	**Intercept of line c**	**-2.367**
2	2.0253	-0.108	-0.219	4.102	0.012	**R**	**0.992**
3	2.1761	0.106	0.231	4.735	0.011	r^2	**0.983**
4	2.4771	0.364	0.901	6.136	0.132		
SUM	**8.5536**	**0.053**	**0.333**	**18.489**	**0.251**		
N	4						

6.4.5 Pulverised fuel Isokinetic sampling results discussion

The velocities of primary air and coal mixtures are measured in the pulverised fuel pipes. The pulverised fuel flow velocities have maximums and minimums that are required during operation of the mill. The Power Utility pulverised fuel velocities are:

- conveying pipes feet per second minimum load 60-64. The conversion factor is 1ft = 0.3048m;
- design is 89-96 feet per second;
- minimum load pulverised fuel air mixture velocity is 18.288 - 19.507m/s and the design maximum is 27.127 – 29.26 m/s; and
- the burner nozzle flow velocities are 18.897 m/s minimum and design 35.052 m/s.

The mill pulverised fuel sampling tests were carried out and the following result was calculated from the test data. The main aims of sampling pulverised fuel from pipes are:

- coal flow through the mill;
- air flow through the mill;
- particle carrying velocities;
- pulverised fuel mass flow and distribution;
- mill performance evaluation; and
- pulverised fuel fineness.

The mill pulverised fuel and air mixture velocities calculated from the data measured in the pipes are:

- pipe 1 = 27 m/s;
- pipe 2 = 27m/s;
- pipe 3 = 29 m/s; and
- pipe 4 = 26 m/s.

The pulverised fuel fineness distribution to each pipe, the 75 µm sieve under sizing:

- pipe 1 = 64.6%;
- pipe 2 =79%;
- pipe 3 = 69.8%; and
- pipe 4 = 55%.

The coal flow in each pipe kg/s:

- pipe1 = 1.0 kg/s
- pipe2 = 1.1 kg/s
- pipe 3 = 1.1 kg/s and
- pipe 4 = 1.1 kg/s

The mill pipe velocity is at maximum flow at a load of 4.3 kg/s and the pulverised fuel fineness is below design value 64.6%, passing in Pipe 1 and 55% in Pipe 4. The two pipes (2 and 3) are 79 and 69.8% respectively. The fineness distribution is not the same in the four pipes. The coal distribution in the pipes is 1.0 kg/s in Pipe 1 and 1.1 kg/s in Pipes 3 to Pipe 4.

The average fineness from the mill is 67.1%, this is lower than the design value of 70% through the 75µm sieve.

The mill operating velocities are above the minimum pulverised fuel settling velocity:

- Mill F = 37.5 m/s
- Mill E = 32.25 m/s
- Mill D = 27.25 m/s
- Mill = 28 m/s

The mills on Unit 4 at Power Utility X are operating at velocities higher than the maximum of 27m/s - 29 m/s.

The regression for pulverised fuel fineness was done and the slope of the lines are shown by Appendices C1-C6. The regression checks are shown by appendices B1-B4.

The regression lines gradients for the mills are as follows:

- Mill A = 0.936;
- Mill B = 0.992;
- Mill C = 1.364;
- Mill D = 1.111 and
- Mill E = 1.265

6.5 Conclusion

The mill pulverised fuel sampling has been done and the distribution in pipes determined. The fineness of the pulverised fuel in pipes has been found to differ. This is due to the mill operating at high pulverised fuel air velocities. The high velocities' result in changing the cut velocity of the mill and coarser particles are entrained in the high velocity air. Mill A on Unit 4 operates in relation with the other four mills.

The mills' classifier angles settings are at 40-degrees instead of 35-degrees, as was used in acceptance testing. Changing the gradients of the mill's regression lines impacts on mill load lines, mill output and pulverised coal fineness.

The pulverised fuel fineness has impact on the mill capacity. The graph above shows the impact of coal fineness on mill capacity.

7 Mill power consumption and heat balance Excel spreadsheets

7.1 Introduction

The aim of this study is to perform an investigation of the effect of coal feedstock property variation on the vertical spindle coal pulverising mill performance to facilitate optimal plant performance. The purpose of this chapter is to develop two Excel spreadsheet programs that calculate mill power consumption and mill heat balance, respectively.

7.2 Mill power consumption

Mill operation uses electric power which is part of the power generated from the unit. This power, if not controlled, could exceed the design value. Values of power consumption above design reduce the power sent out to the customer. The power consumed by milling plants during power generation is part of the efficiency calculation input data. A high input of mill power consumption reduces the efficiency of the generating unit.

The mill power consumption Excel program is developed using the following equations: 2.22, equation 2.23, equation 2.24, and equation 2.25. The program input parameters are:

- Primary air flow rate;
- primary air temperature;
- primary air pressure;
- pulverised fuel fineness %; and
- force on each grinding ball.

The program results are: mill frictional factor, mill power-draw, cut velocity and cut diameter. The input parameters are varied from upper to lower values to evaluate the effect on mill power-draw, mill frictional factor, cut velocity and cut diameters.

7.3 Mill power consumption Excel spreadsheet results

The data in table were calculated by the Excel spreadsheet. The calculated data is compared to Power Utility data calculated by the spreadsheet. The spreadsheet is calibrated with mill data and mill dimensions. Using this program, calibration to the mill data impacts the accuracy of the output data. The parameters in are in Table 7.1.

Table 7.1: Mill power-draw results

Parameter		Calibration data	Power Utility X data
Frictional coefficient		0.124	0.0687
Mill power-draw	kW	268.03	202.05
Mill specific power-draw	kWh/t	2.51	1.823
Cut velocity	m/s	27.91	27.91
Cut size diameter	mm	12.30	12.30
Inlet diameter	m	6.91	3.456
Tangential velocity	m/s	10.58	42.36

7.3.1 Grinding table speed

The grinding table speed was varied from 5 to 37.9 rpm on the Excel spreadsheet to check the impact of changing table speed to the parameters: frictional coefficient, mill power-draw, cut velocity, cut size diameter, inlet dimeter and tangential velocity. The mill power-draw increased as the mill speed increased. The other parameters showed no change.

Table 7.2: Grinding table speed results

Description	Units					
Test Number		1	2	3	4	5
Grinding table speed rpm	rpm	37.9	30	20	10	5
Frictional Coefficient	µ	0.124	0.124	0.124	0.124	0.124
Mill Power Draw	kW	268.03	212.16	141.44	70.72	35.36
Mill Specific Energy Consumption	kWh/t	2.51	1.98	1.32	0.66	0.33
Cut Velocity	m/s	27.91	27.91	27.91	27.91	27.91
Cut Size Diameter	mm	12.30	12.30	12.30	12.30	20.87
Inlet Diameter	m	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.58	10.58	10.58	10.58	10.58

7.3.2 Primary air temperature

The primary air temperature impacts the mill drying capacity. The primary air temperature for Grootvlei is 245ºC and changes in temperature impact the performance of the mill in coal drying. The Excel spreadsheet temperature of the primary air was varied from 200ºC to 302ºC to investigate whether mill parameters are impacted by the variation of primary air temperature. The primary air temperature impacts mill power-draw that increased from 35.36 to 268.03 kW. The cut velocity and cut diameter both increase as the temperature of the primary air increases.

Table 7.3: Primary air temperature

Description	**Units**					
Test Number		1	2	3	4	5
Primary air temperature ^{O}C		302	245	240	230	200
Frictional Coefficient	µ	0.124	0.124	0.124	0.124	0.124
Mill Power-draw	kW	268.03	212.16	141.44	70.72	35.36
Specific Energy Consumption	kWh/t	2.513	1,989	1.326	0.663	0.331
Cut Velocity	m/s	27.91	27.91	24.90	24.41	22.96
Cut Size Diameter	mm	12.30	9.39	9.09	8.60	20.87
Inlet Diameter	m	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.58	9.53	9.44	9.26	8.71

7.3.3 Primary air pressure

Primary air pressure causes the flow of air from a high to low pressure region. The amount of pulverised fuel carried to the burners is determined by the air pressure and the quantity passing through the mill. On the Excel spreadsheet, the primary air pressure was changed from 70 kPa to 107.7 kPa, the impact noted. Mill power-draw increased with an increase in primary air pressure, cut velocity reduced with an increase in primary air pressure, cut size diameter reduced with an increase in primary air pressure.

Table 7.4: Primary air pressure

Description	**Units**					
Test Number		1	2	3	4	5
Primary air pressure	kPa	107.6	100	90	80	70

Frictional Coefficient	µ	0.124	0.124	0.124	0.124	0.124
Mill Power-draw	kW	268.03	212.16	141.44	70.72	35.36
Mill Specific Energy Consumption	kWh/t	2.51	1.98	1.32	.66	.33
Cut Velocity	m/s	27.91	27.91	37.54	42.90	42.90
Cut Size Diameter	mm	12.30	13.23	16.79	19.31	20.87
Inlet Diameter	m	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.58	11.39	14.24	16.27	16.27

7.3.4 Number of balls in the mill

The E-type Babcock mill has ten balls for coal pulverisation and balls are added as they wear around the mill operating cycle. The ball size impacts on mill grinding performance when the ball sizes are reduced during coal pulverisation. On the Excel spreadsheet the number of balls were changed from 6 to 10 and the impact noted. The parameter affected by ball numbers is the mill power-draw. The mill power-draw increased with the increase in number of mill balls.

Table 7.5: Number of mill balls

Description	**Units**					
Test Number		1	2	3	4	5
Number of balls	n	10	9	8	7	6
Frictional Coefficient	µ	0.12	0.12	0.12	0.12	0.12
Mill Power-draw	kW	268.04	241.23	214.42	187.62	160.821
Specific Energy Consumption	kWh/t	2.51	2.27	2.01	1.75	1.50
Cut Velocity	m/s	27.91	27.91	27.91	27.91	27.91
Cut Size Diameter	mm	12.30	12.30	12.30	12.30	20.87
Inlet Diameter	m	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.59	10.59	10.59	10.59	10.59

7.3.5 Grinding table coal feed rate

Grinding table coal feed rates change according to the load demand on the mill. Parameters were checked by changing the coal flow rate to the mill. The mill power-draw increased with the increase in coal feed rate.

Table 7.6: Grinding table coal feed

Description	**Units**					
Test Number		1	2	3	4	5
Grinding Table Feed	t/h	42	30	20	10	5
Frictional Coefficient	µ	0.12	0.09	0.06	0.03	0.02
Mill Power-draw	kW	268.03	193.00	129.53	65.20	32.71
Mill Specific Energy Consumption	kWh/t	2.51	2.53	2.54	2.56	2.57
Cut Velocity	m/s	27.91	27.91	27.91	27.91	27.91
Cut Size Diameter	mm	12.30	12.30	12.30	12.30	20.87
Inlet Diameter	m	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.59	10.59	10.59	10.59	10.59

7.3.6 Mill grinding pressure

Table 7.7: Grinding pressure on mill balls

Description	**Units**					
Test Number		1	2	3	4	5
Grinding pressure on each ball	kN	54.5	50	40	30	20
Frictional Coefficient	µ	0.12	0.09	0.06	0.03	0.02
Mill Power-draw	kW	268.03	177.06	95.07	35.89	12.00
Mill Specific Energy Consumption	kWh/t	2.51	2.32	1.87	1.41	.94
Cut Velocity	m/s	27.91	27.91	27.91	27.91	27.91
Cut Size Diameter	mm	12.30	12.30	12.30	12.30	20.87
Inlet Diameter	m	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.59	10.59	10.59	10.59	10.59

7.3.7 Primary air flow

The load on the mill is determined by the air flow and the coal flow. The primary air is used for drying the pulverised coal and transporting the pulverised fuel to the burners. On the Excel spreadsheet, primary air was increased from 15 t/hr to 19.1 t/hr and the impact on mill parameters noted. Primary flow rate change impacts the cut velocity, cut diameter and the tangential velocity. The parameters increase as the primary air flow is increased.

Table 7.8: Primary air flow rate

Description	**Units**					
Test Number		1	2	3	4	5
Primary air flow rate	t/h	19.1	18	17	16	15
Frictional Coefficient	µ	0.124	0.124	0.124	0.124	0.124
Mill Power-draw	kW	268.04	268.04	268.04	268.04	268.04
Mill Specific Energy Consumption	kWh/t	2.51	2.51	2.51	2.51	2.51
Cut Velocity	m/s	27.91	27.91	24.84	23.38	21.92
Cut Size Diameter	mm	12.30	12.30	12.22	12.18	20.87
Inlet Diameter	M	6.91	6.91	6.91	6.91	6.91
Tangential Velocity	m/s	10.58	9.97	9.42	8.87	8.31

7.3.8 Classifier blade angle setting

The Power Utility mills are equipped with static classifiers. The classifiers have blades that impact the spin on moving, pulverised fuel particles during classification. The optimum angle setting of these blades impacts the fineness of the pulverised fuel and the mill output. The mill classifier blades were changed on the Excel spreadsheet and the impact noted. The settings were changed from 10 to 45-degree angle setting. The tangential velocity changed with the change in blade angle setting.

Table 7.9: Classifier blade angle setting

Description	**Units**					
Test Number		1	2	3	4	5
Classifier blade angle setting	Degrees	45	40	25	15	10
Frictional coefficient	µ	0.124	0.124	0.124	0.124	0.124
Mill Power-draw	kW	268.04	268.04	268.04	268.04	268.04
Mill Specific Energy Consumption	kWh/t	2.513	2.513	2.513	2.513	2.513
Cut Velocity	m/s	27.91	27.91	27.91	27.91	27.91
Cut Size Diameter	mm	12.30	12.30	12.30	12.30	20.87
Inlet Diameter	m	6.91	6.05	-1.07	5.28	-4.41

7.4 Mill power consumption Excel spreadsheet result’s discussion

The cut velocity and cut diameter increase as the air increases due to temperature. When cut velocity increases, pulverised fuel classification coarse particles entrainment to the burners occurs. The reduction in pulverised fuel fineness results in flame instability.

The grinding table coal feed rate impact is that the mill power-draw increases recirculation load. The recirculation load is coal feed, mill classifier rejects and elutriator rejects. The recirculation load increases with the coal flow rate increase.

Mill grinding pressure impacts mill power-draw increases, with the increase in frictional forces.

The primary air flow impacts on mill power-draw and the cut velocity and cut diameter. The high primary air flows entrain coarse particles of pulverised fuel to the burners. The mill output reduces with coarse particle entrainment, increasing the feed flow results and causing a mill power-draw increase.

Classifier blades angle settings impact pulverised fuel classification and fineness of said pulverised fuel. Optimum position is determined by pulverised fuel sampling and grading. The optimum fineness determines the position of the classifier setting.

7.5 Mill heat balance

The purpose of this section is to develop a heat balance Excel spreadsheet program, that calculates mill heat balance.

The heat balance of the mill can be used to evaluate mill parameters during operation. The heat balance evaluation enables the assessment of the mill drying constraint that exists during operation. The parameters that impact on the drying capacity of the mill are moisture content of coal and the primary air temperature. The Power Utility X design’s coal moisture content is 10% total moisture. Should moisture content of coal value more than 10%, (coal drying is not a constraint) the mill output is reduced due to the extended time of drying the coal. The mill heat balance evaluates the energy going into the mill and the energy out of the mill.

7.6 Mill heat balance Excel spreadsheet results.

The heat balance Excel spreadsheet was modelled using Equations 2.10 to 2.21. Table 7.9 shows the mill heat balance Excel spreadsheet results. Figure 7.1 shows the mill heat balance.

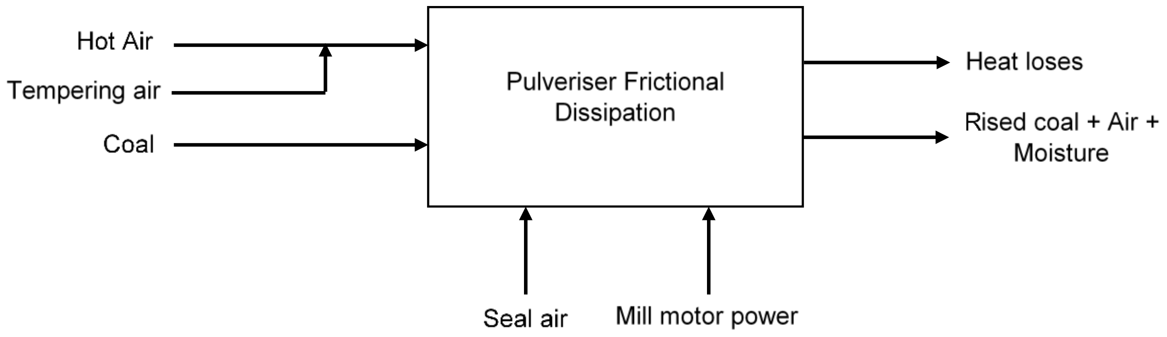

Figure 7.1: **Mill heat balance schematic presentation**

Table 7.10: **Mill heat balance Excel spreadsheet results**

Description	**Units**	**Quantity**
Specific Heat Of Coal	kJ/kgK	1.2
Specific Heat Of Air	kJ/kgK	1.0035
Enthalpy of Saturated Liquid	kJ/kg	398
Enthalpy of Change of Phase	kJ/kg	2269.8
Enthalpy of Saturated Vapour	kJ/kg	2667.8
Enthalpy of Saturated Liquid at mill inlet	kJ/kg	100
Mill Power converted to heat	Kw	125.989
Seal Air flow	kg/s	3
Mill Power converted to heat	kJ/kg	
Parameters Input		
Coal flow	kg/s	6.8
Primary air flow	kg/s	10
Primary air temperature	^{0}C	245
Primary air temperature to Kelvin	K	518
Total moisture of coal	%	8
Inherent moisture of coal	%	5.6
Surface moisture of coal	%	2.4

Ambient temperature	^{O}C	23
Ambient air temperature converted to Kelvin	K	296
Coal Temperature		34
Coal temperature converted to Kelvin	K	307
Mill outlet temperature	^{O}C	84.1
Mill outlet temperature converted to Kelvin	K	357.1
Calculations of Parameters of energy in		
Energy of coal in	kJ/kg	2304.71
Energy of moisture in	kJ/kg	54.4
Energy of primary air in	kJ/kg	5198.13
Energy of Seal air in	kJ/kg	891.108
Total Energy In	kJ/kg	8448.34
Calculations of Parameters of energy out		
Energy of coal out	kJ/kg	2680.82
Energy of inherent moisture	kJ/kg	355.56
Energy of inherent moisture	kJ/kg	73.76
Energy of surface moisture	kJ/kg	435.39
Energy of primary air out	kJ/kg	3583.5
Energy of Seal air out	kJ/kg	1075.05
Total Energy Out	kJ/kg	8204.08
Heat Balance		
Energy Total in	kJ/kg	7514.30
Energy Total out	kJ/kg	8204.08
Energy Difference	kJ/kg	689.78
Total Energy available		
Energy Consumed	kJ/kg	4620.581
Energy Suspense	kJ/kg	335.244
E suspense/E available ratio	+- 0.05	0.06764
Total energy available	kJ/kg	4955.82

7.6.1 Discussion of results

The heat balance Excel spreadsheet calculates the heat input to the mill for drying the pulverised coal and the heat output of the mill. The total energy input to the mill was calculated to be 7514.30 kJ/kg.

The total energy available was calculated and the value is 4955.82kJ/kg

The energy consumed by the mill is calculated by finding the difference between mill total energy out and energy of primary air out. The consumed energy was evaluated to be 4620.58kJ/kg.

Energy suspense is calculated by taking the difference between total energy available and energy consumed. The energy suspense calculated value is 335.24 kJ/kg.

The energy available is calculated by adding the energy of primary air in and mill power, converted to heat. The mill's available energy is 4955.82 kJ/kg.

The design ratio of energy suspense/energy available is +/- 0.05. The Excel spreadsheet model gave an actual ratio of 0.067.

7.6.2 Conclusion

The mill's pulverised fuel drying capacity is within design. The ratio of suspense energy and energy available is 0.067, compared to the standard of 0.05. The moisture content of the coal supply to the station is below 10%. The temperature of the primary air is 245ºC, which is also the heat available to dry the coal. The mill's pulverised fuel leaks need repair to prevent loss of the heat in the primary air.

7.7 Load simulations

Load simulations were carried out on the mills to compare three sets of data:

- Simulated coal flow/air flow;
- sampled coal flow and air flow; and
- control panel indicated coal and air flow.

. Appendix D shows the results of the load simulations.

The operator uses the coal flows indicated on the panel, the load simulations checked the correctness of the instruments and the actual load in the plant. The measured data compared with simulated and control room indications, which can be used as a check on control instrumentation.

Mill load line evaluation is done by measuring the coal flow and the air flow.

7.7.1 Discussion of results

The comparison of simulated, sampled and control room loads provided a check on these parameters. Unit operators rely on control room indications and when these are out of calibration, decisions made based on these indications impact plant performance. Process engineers, with the use of simulation Excel spreadsheets, can determine the loads on the mills.

7.7.2 Conclusion

Load simulations were done and compared with sampled loads and control room indications. The comparison provided data for accuracy of the isokinetic coal sampler and control room indications.

8 Conclusions and recommendations

The present investigation of this dissertation was aimed at performance optimisation of vertical spindle coal pulverisers. A detailed literature review was done to get an understanding of principles of operations of the vertical spindle coal pulverisers. The literature review provided data and information on vertical spindle coal pulverisers on processes and associated components operations. The challenges associated with coal properties variation on pulverisers operations were analysed in detail.

In order to optimise the performance of vertical spindle coal pulverizers, the operating parameters should be monitored. The operational aspect of the mill must be understood in order to relate the fundamental principles of operation to the vertical spindle coal pulverizers. The performance optimisation of the vertical spindle coal pulverizers was investigated and to achieve optimisation, the following was carried out:

Plant tests were conducted at Power Utility X Unit 4 mills A-F to evaluate plant performance as related to fineness distribution, mill bias, mill throughput, mill outlet temperature, power consumption, and reliability and pulverized fuel settling velocity.

Laboratory tests were conducted to determine coal fineness, calorific value of coal, Hardgrove Grindability Index, Abrasion Index, ash and moisture content.

Abrasive Index was determined at the station and compared with the design coal. The coal supply to the station comes from several mines. Contractually, the coal is blended to have ash and calorific values within the contract upper- and lower limits. The values obtained during the test show that the coal is abrasive. Abrasion Index shows that the coal can remove materials on pipes, coal chutes and the mill during the coal grinding process impacting on mill maintenance. The impact of a high Abrasive Index is the high cost of maintenance of the associated plant milling, plant ducting and pipes handling the coal.

Hardgrove Grindability Index was determined at the station using station equipment. The finding was that the Hardgrove Grindability Index of the coal supply to the station is not constant. The test consisted of thirty samples representing thirty days of coal supply. The HGI was varying as indicated by Figure 6.2. The coal with a high HGI is easy to grind and that with a low HGI is difficult to grind. The HGI of coal has an impact on the mill output. The HGI is not additive (ACARP, 1988:1-8) when coal is blended with coal of a different HGI.

The calorific value of coal was determined at the station and the trend showed the variation of Calorific values of coal during the period of supply. The mills are designed to deliver the required coal throughput for boiler energy required. Change in calorific value of coal means change in energy content of the coal. When a low calorific value is experienced, the impact on the mill is twofold. Low calorific value of coal means energy content is low; more coal is required to match the load requirement. The second impact is that the mills grind more coal to match the energy requirements. Mills are designed to provide 7kg/s of coal at full load at the designed calorific value of coal.

Moisture content was determined at the station and the finding was that the moisture content of coal during the dry season is less than 10%. The mill carries four functions at once: grinding of coal, drying, classification and transportation of the pulverized coal to the burners. The drying of the coal is impacted by the moisture content of coal and the inlet temperature of primary air to the mill. The mill design and operating primary air temperature was evaluated and is still operating as designed at the 245ºC inlet temperature. The mill outlet temperatures were observed to be 84ºC. The mill drying capacity is operating as designd when coal moisture content is less than 10%. During the rainy season the wet coal management system ensures that moisture content of coal on the stockpile is controlled by the drainage system.

The fineness distribution of pulverized coal, pulverized fuel burner distribution, mill bias, mill throughput, mill outlet temperatures, power consumption and pulverized fuel settling velocities tests were carried out. The findings were that fineness is not evenly distributed in the pipes leading to the burners. The unit mass in pipes is not evenly distributed, some pipes are carrying less fuel. The pipes with less fuel than air are operating lean. The pipes that are carrying more fuel than air ratios recommended are said to be operating rich. The preferred ratios are those that are termed ‘stoichiometric ratios’.

The velocities m/s in pipes of pulverized fuel were determined and analysed. The station design fuel air velocities are 18.86 m/s minimum velocity. The mills operating below minimum velocity will have fuel settling around bends, as velocity reduction occurs due to low pressure. On the other hand, the maximum operating velocity design is 29.19 m/s. Velocities above the maximum design values impact the mills, having coarser fuel particles carry-over to the burners.

The wear rate of mills, pipes and ducting is proportional to the velocity of air carrying particles (Gill, 1984: 347-353)

Coal feed rate to the mill is achieved by using a coal feeder. The station in question still uses a table coal feeder. The table coal feeder has a table that has waffles to assist in feeding coal to the mill. The feeding mechanism has a plough mechanism that is provided to plough an amount of coal to the mill, depending on the amount of coal required. The plough action coupled with the feeder speed regulation is meant to deliver the required coal. This system has been fixed in position and the feeder uses the speed to deliver the coal required by the mill to match the energy on the boiler. The mechanism opens and closes the gap of angle of coal repose on the table. When more coal is required, the plough increases the angle of cutting coal and the reverse is true when coal reduction is required. The plough mechanism operates in tandem with the speed of the coal feeder. The increase in coal feeder speed is supposed to increase the coal feed to the mill. The investigation finding was that the feeder plough is now fixed and the coal quantity feed to the mill is only increased or decreased by the coal feeder speed.

Mill control during operation is achieved by monitoring the following parameters:

- Coal flow.
- Air flow, primary air differential pressure.
- Mill inlet temperature.
- Mill outlet temperature.
- Mill recirculation load - mill differential pressure.
- Tempering air.

The mill outlet temperatures are controlled by regulating the coal flow and amount of tempering air that is introduced to the primary air at the inlet, reducing temperature to desired value.

The investigation found that the mills are operating at a temperature of 84^{o}C as the outlet temperature and 245^{o}C as the inlet temperature. The mill drying capacity is controlled within the design limits.

The control of primary air differential pressure and mill differential pressure, provide data for mill load line. This load line is used for checking the operating of the mill.

Two Excel spreadsheets were developed using equations in Chapter 2 and these spreadsheets were used to evaluate mill heat losses and the effect of varying operating parameters on a mill. Using these spreadsheets, assumptions are made on the steady state operations of the mill. The mills are operating at equilibrium conditions and the mill dimensional parameters are not changing during operations.

A mill power consumption spreadsheet was used to assess the effect of varying operating parameters on the mill. The parameters that varied were:

- Primary air temperature;
- coal feed rate;

- pressure on the mill balls;
- primary air pressure;
- mill rotation speed;
- fineness of pulverised coal; and
- mill classifier settings.

The impact on mill power draw was noted and changing operating parameters can be done when optimisation has occurred.

The spreadsheet on mill heat balance and mill power consumption are usable for monitoring coal pulveriser performance

8.1 Recommendations

Mill performance monitoring and optimisation programs improve mill output and operating load lines, optimal operation reduces operating and maintenance costs.

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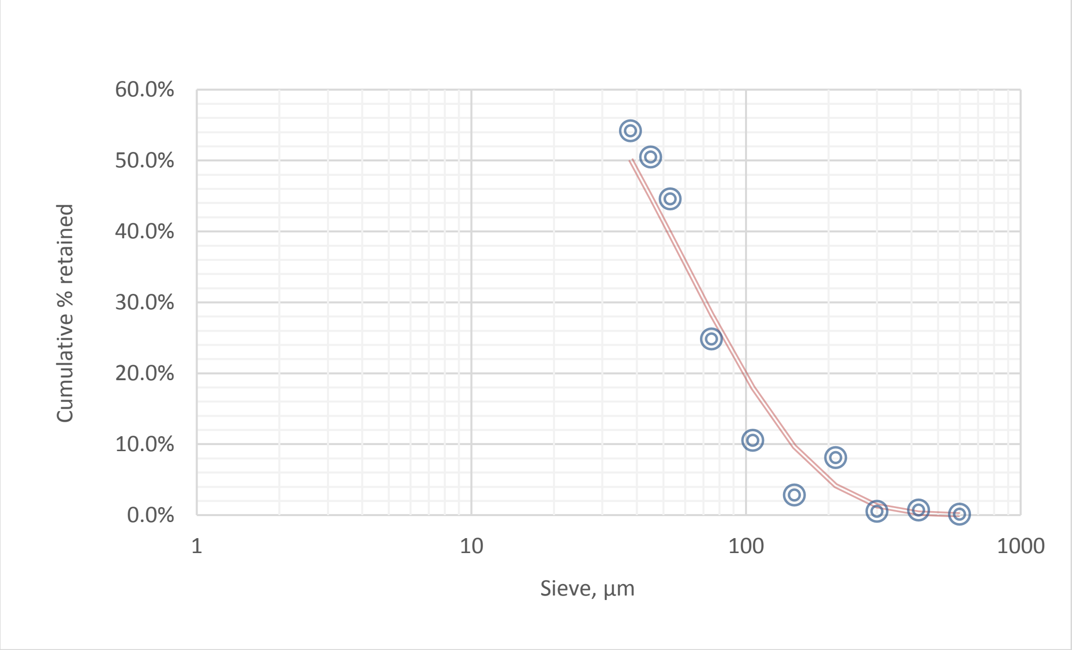
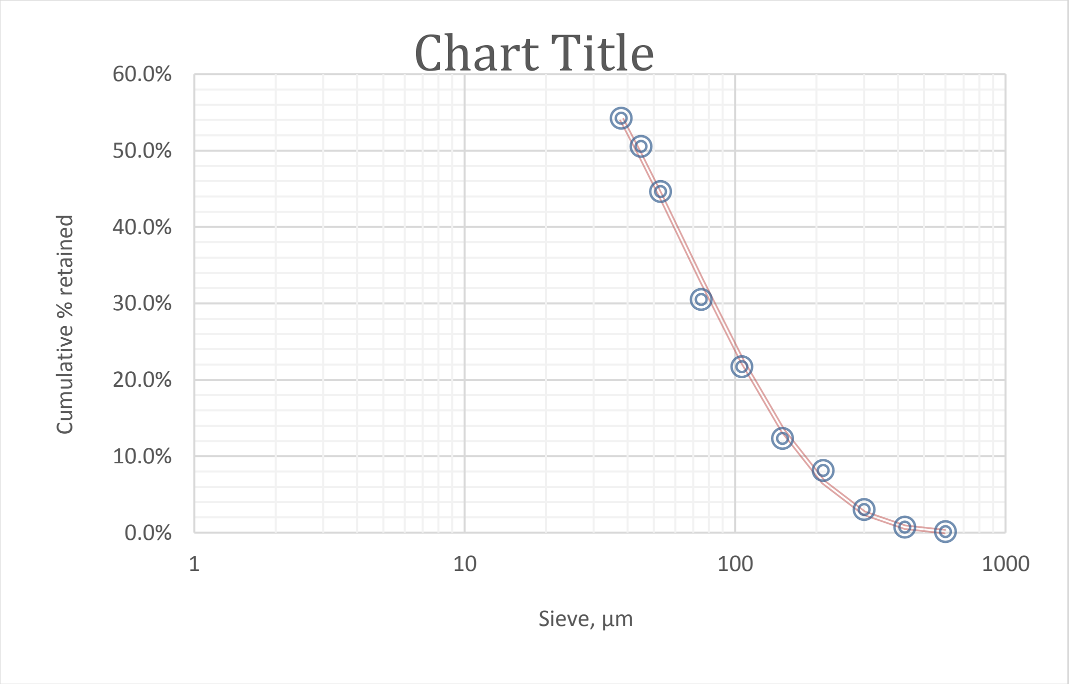
Appendices

Appendix A: Hardgrave Grindability Index machine (ACARP)

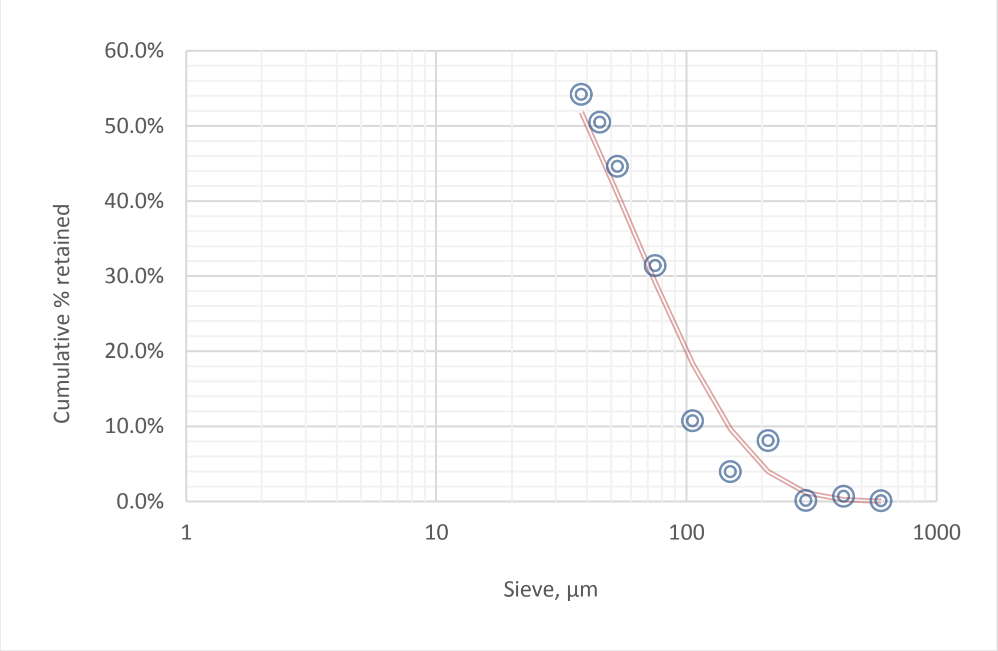
Appendix B1: Mill A Rosin Rammler regression check



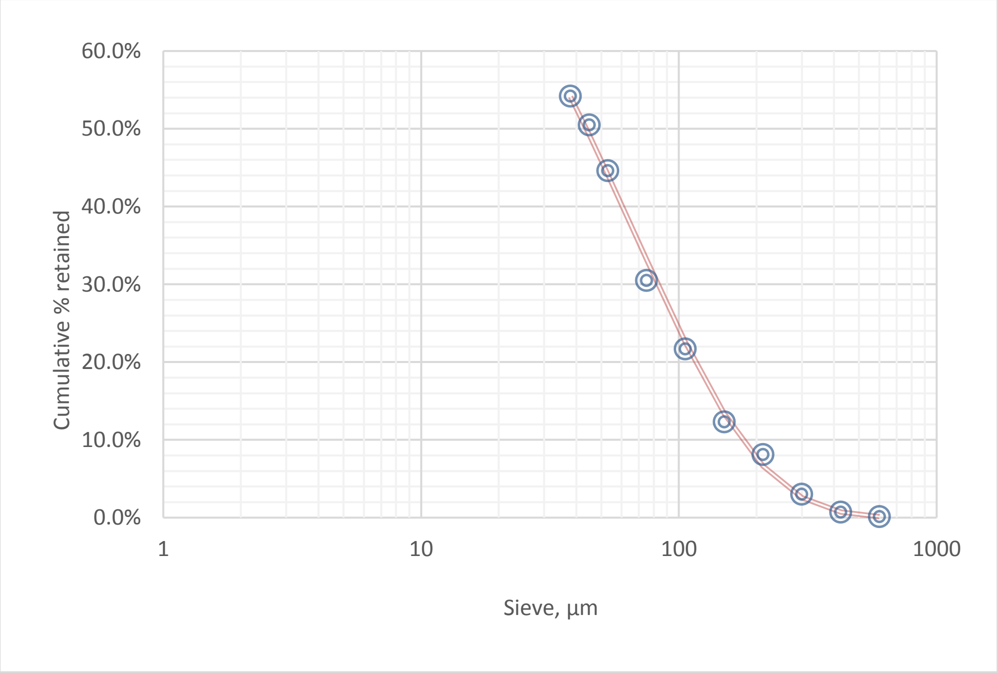
Appendix B2: Mill C Rosin and Rammler regression check



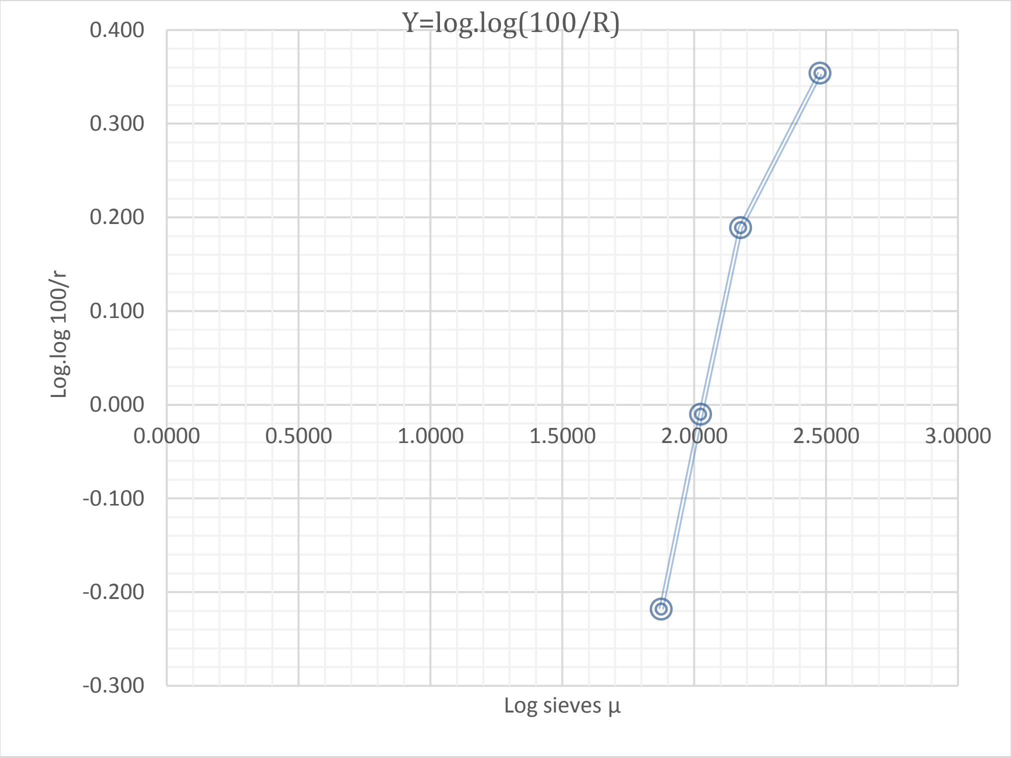
Appendix B3: Mill E Rosin and Rammler regression check.



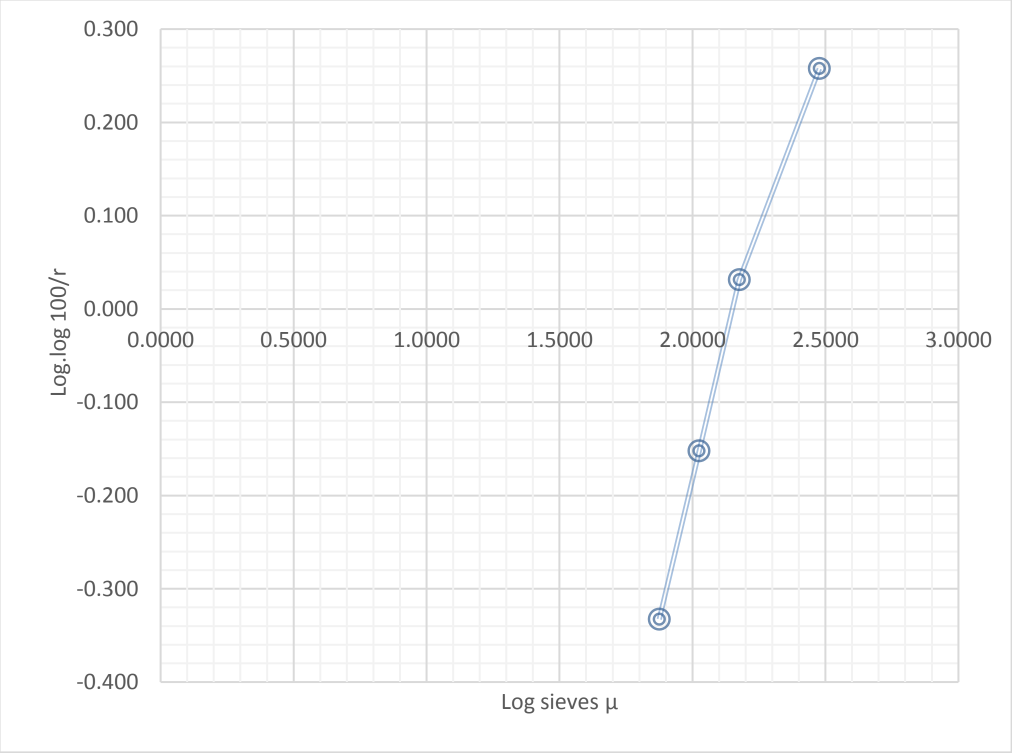
Appendix B4: Mill D Rosin and Rammler regression check



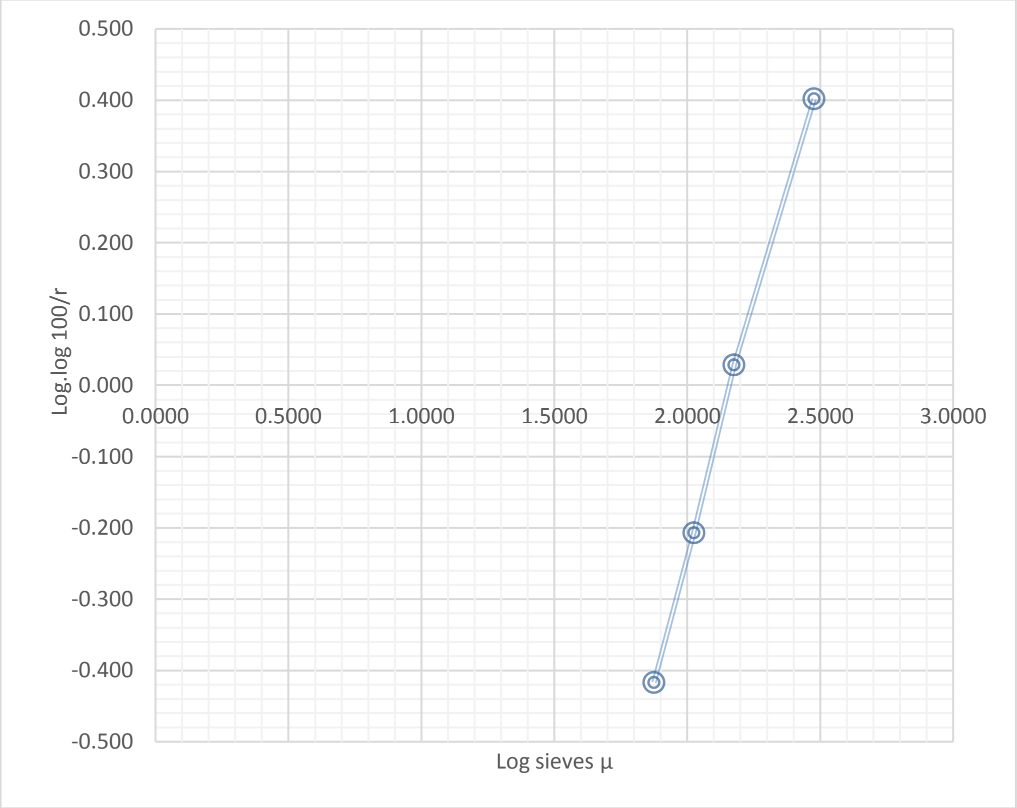
Appendix C1: Mill A PF regression line



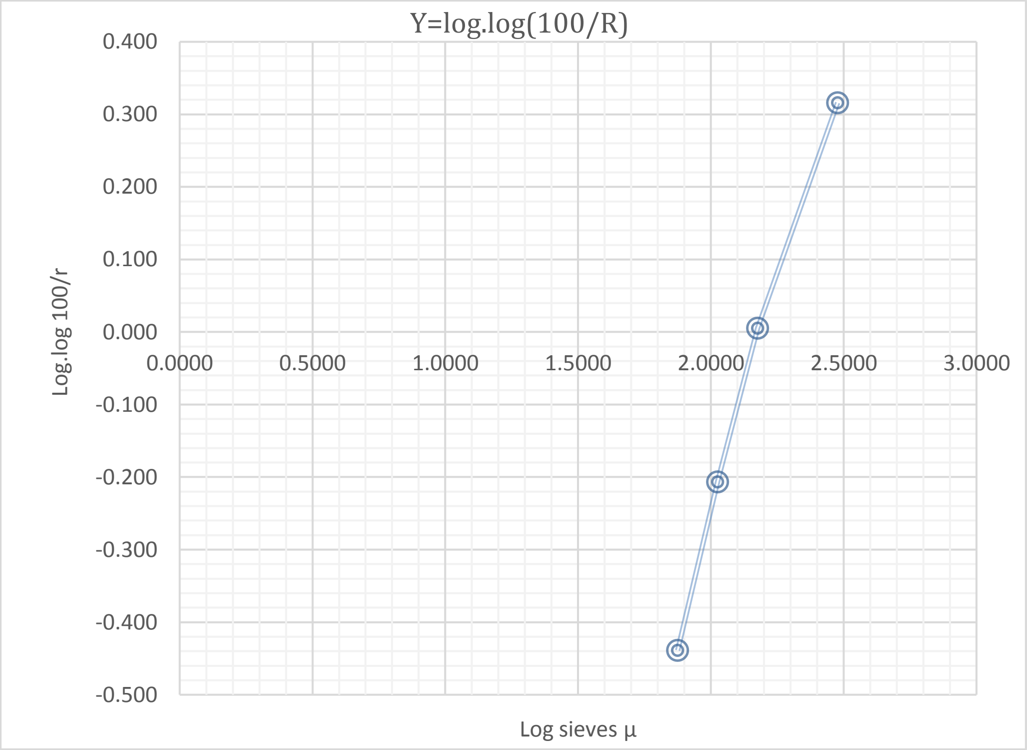
Appendix C2: Mill B PF regression line



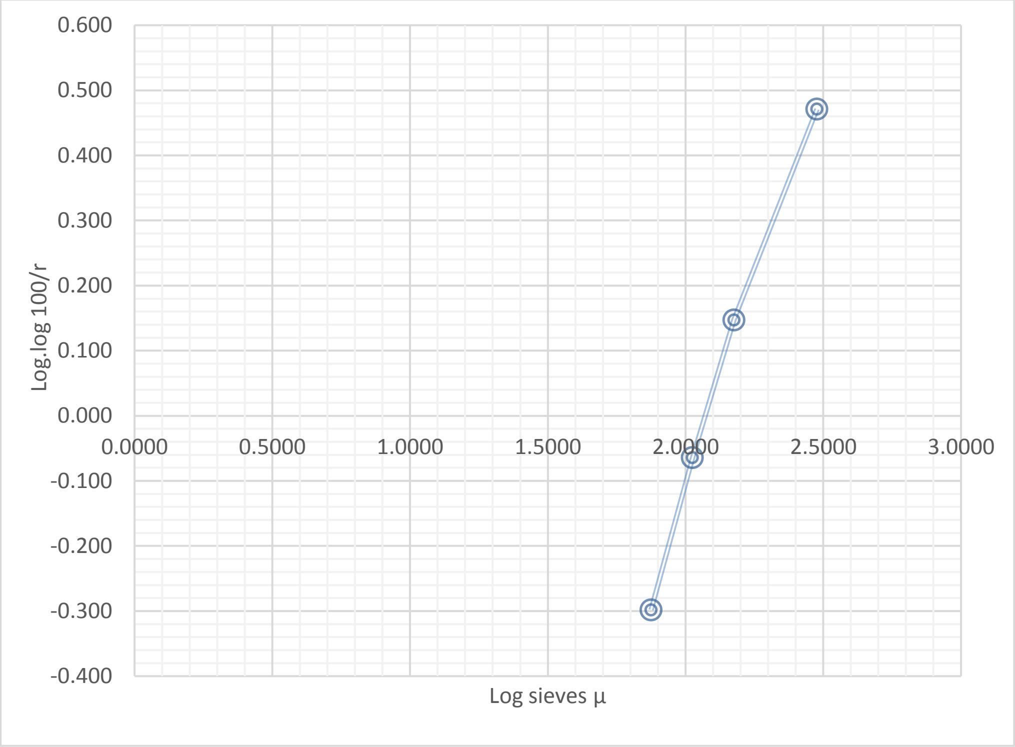
Appendix C3: Mill C PF regression line



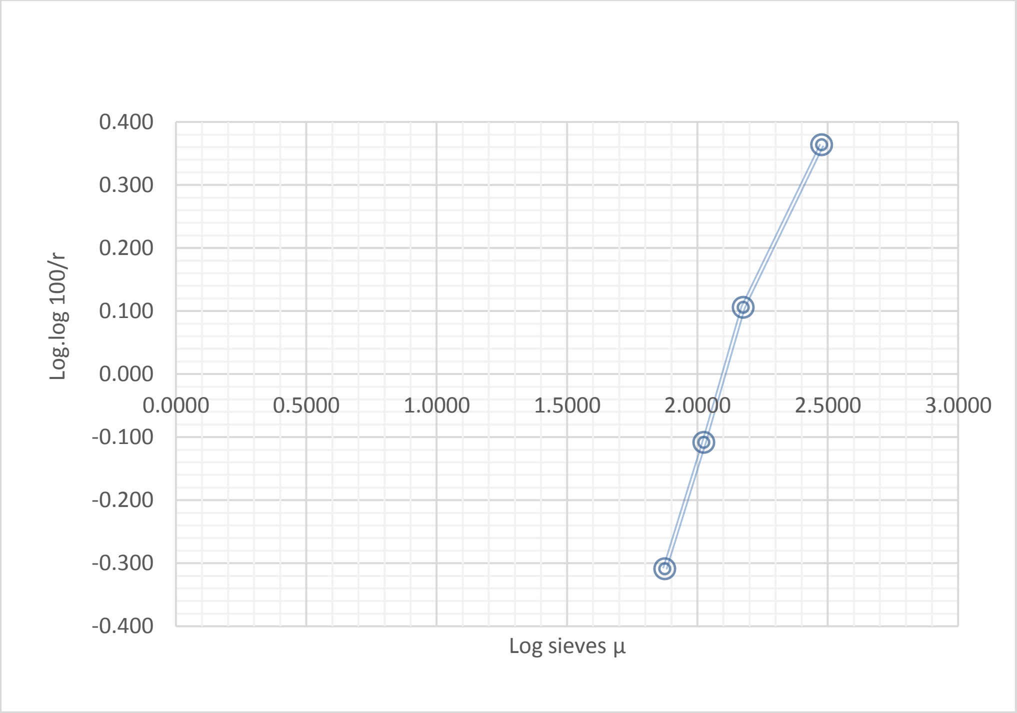
Appendix C4: Mill D PF regression line



Appendix C5: Mill E PF regression line



Appendix C6: Mill F PF regression line

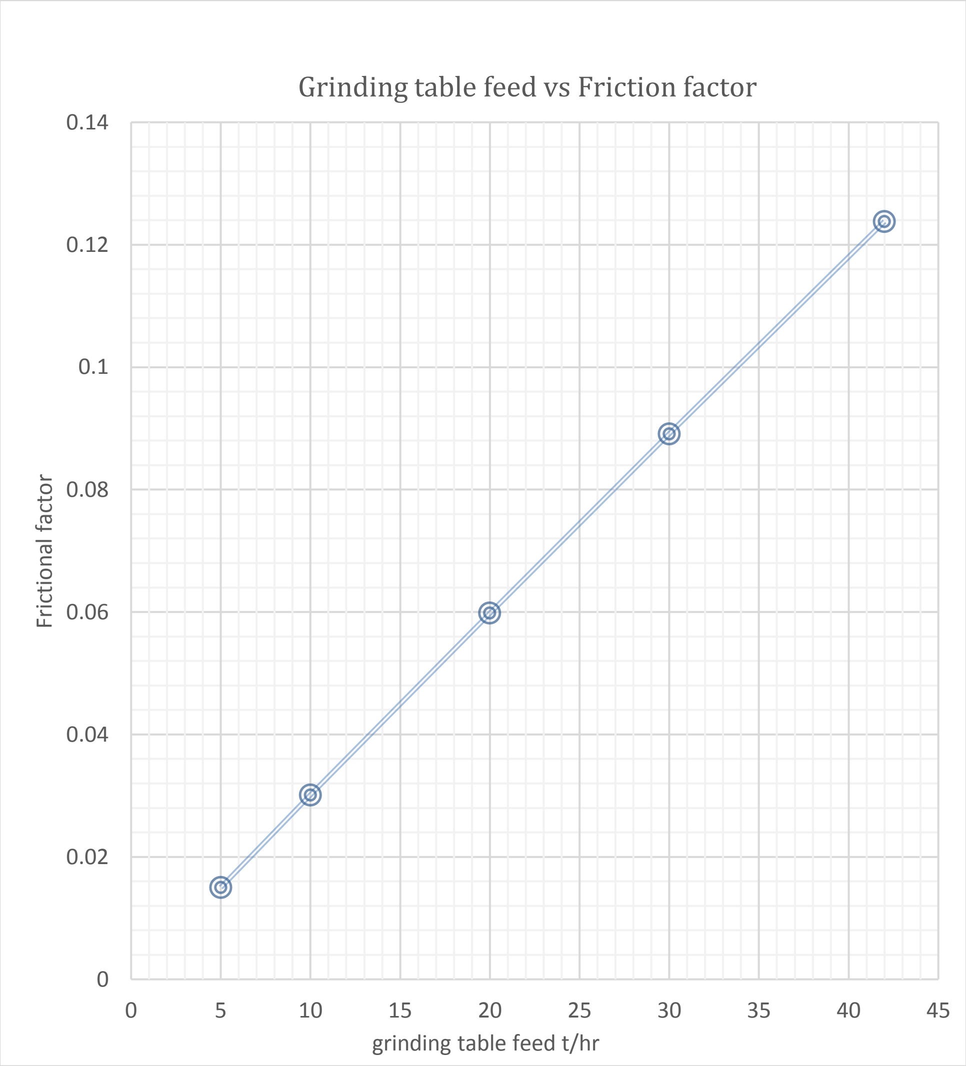


Appendix D: Validation of simulated load

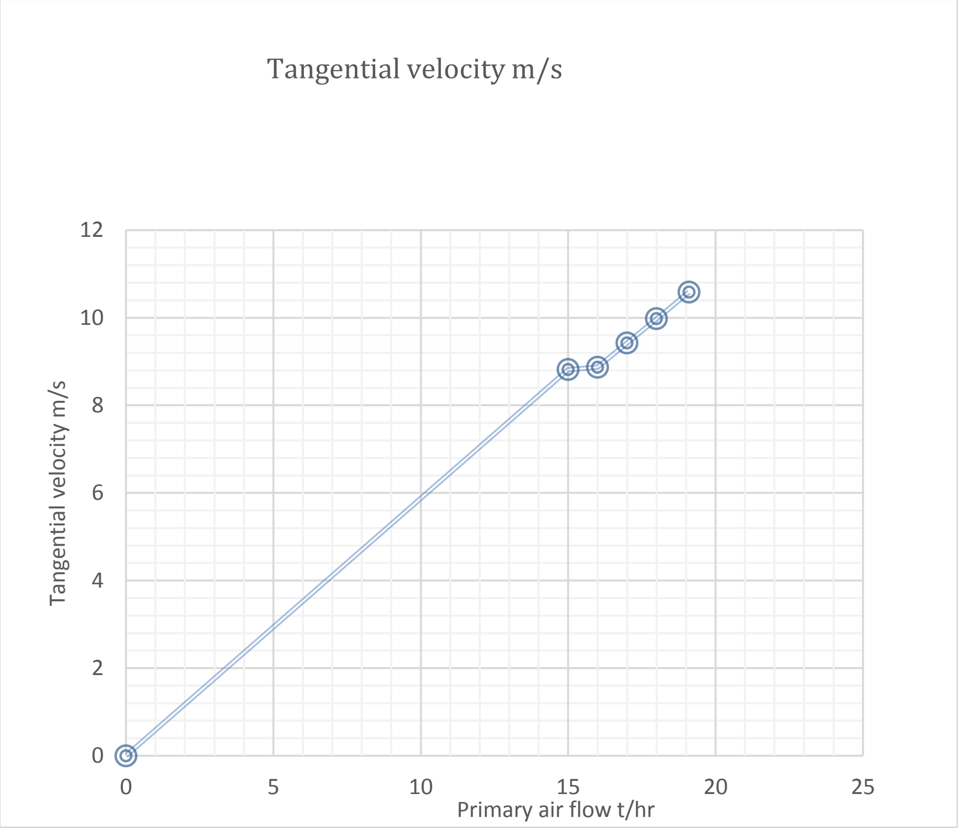
	Validation of simulated load									
	Simulated			**Sampled**			**Panel**			
Test NO.	Coal Flow	Air Flow	Density	Coal Flow	Air Flow	Density	Coal Flow	Air Flow	Density	Mill
	Kg/s	Kg/s	Kg/m3	Kg/s	Kg/s	Kg/m3	Kg/s	Kg/s	Kg/m3	No.
1	6.10	9.80	933.67	6.8	9.8	897.5	6.8	10.5	897.5	A
2	6.37	10.24	975.44	7	10.1	961.1	6.4	10.5	961.1	B
3	6.34	10.19	970.94	6.7	12	954.1	7.5	10.50	954.1	C
4	6.22	10.00	952.514	5.8	9.7	925.8	7.5	10.5	925.8	D
5	6.10	9.80	933.673	5.1	11.6	897.5	6.9	10.5	897.5	E
6	6.4	10.29	979.97	6	13.4	968.2	7.4	10.5	968.2	F
7	4.61	7.42	988.916	3.2	8.1	982.3	-	7.5	982.3	A
8	5.01	8.05	1006.56	4.8	11.4	1010.6	4.9	8	1010.6	B
9	5.49	8.82	979.97	5.7	10.5	968.2	6.1	9	968.2	C
10	5.44	8.74	970.945	4.2	10.3	954.1	4.9	9	954.1	D
11	4.92	7.91	988.916	4.3	11.9	982.3	4.7	8	982.3	E
12	5.21	8.37	984.491	2.3	7.6	975.3	7.5	8.5	975.3	F
13	6.10	9.80	933.6	6.8	10	897.5	4.1	10	897.5	A
14	5.13	8.25	970.95	3.6	8.2	954.1	4.2	8.5	954.1	A
15	6.63	10.65	1015.2	6.8	10.3	1024.7	6.3	10.5	1024.7	A
16	6.66	10.71	1019.54	7	9.5	1031.8	6.5	10.5	1031.8	A

17	5.39	8.67	1019.55	5	8	1031.8	4.5	8.5	1031.8	A
18	6.66	10.71	1019.54	6.4	9.2	1031.8	6.5	10.5	1031.8	A
19	5.39	8.67	1019.5	5.1	8.3	1031.8	4.5	8.5	1031.8	A
20	6.66	10.700	1091	6.1	10.4	1031.8	6.4	10.5	1031.8	A
21	5.39	8.67	1019.54	5.2	8.5	1031.8	4.5	8.5	1031.8	A
22	6.66	10.71	1019.5	7.1	11.1	1031.8	6.4	10.5	1031.8	A

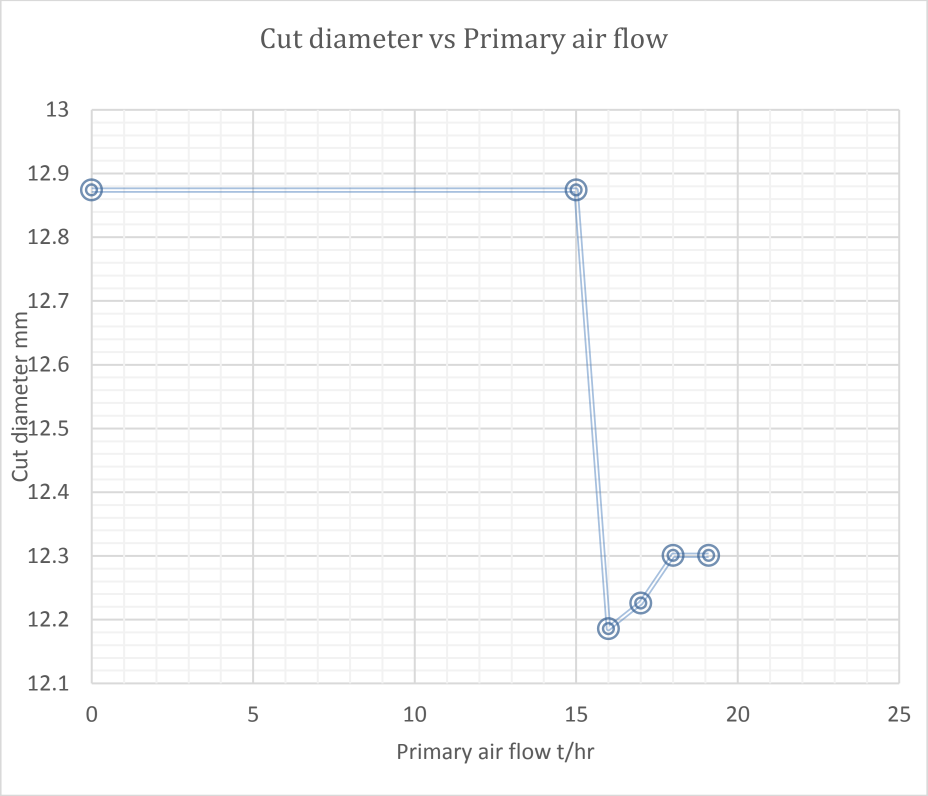
Appendix E: Grinding table feed vs friction factor



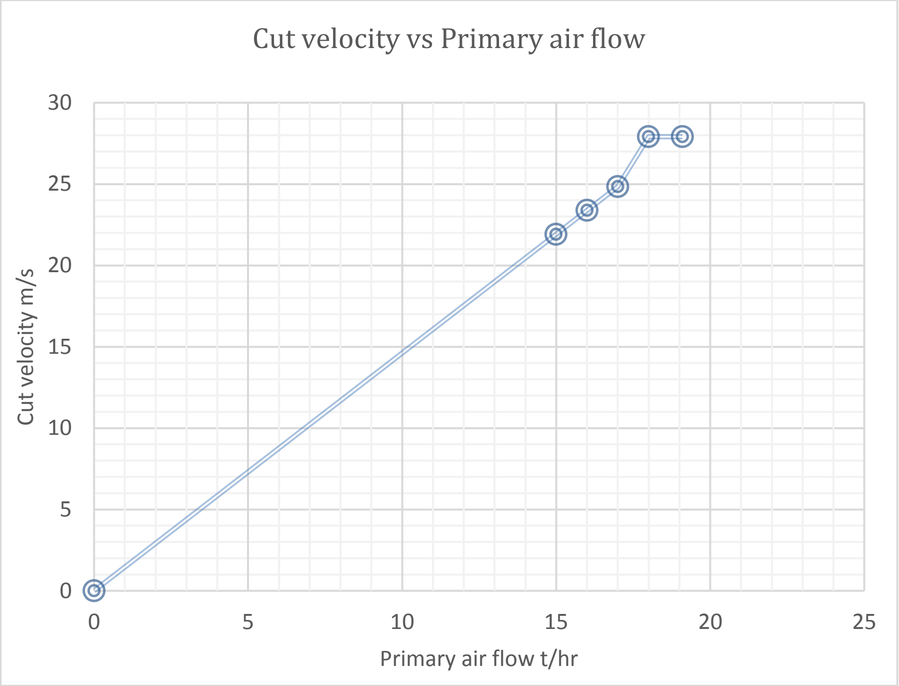
Appendix F: Grinding table feed vs frictional factor



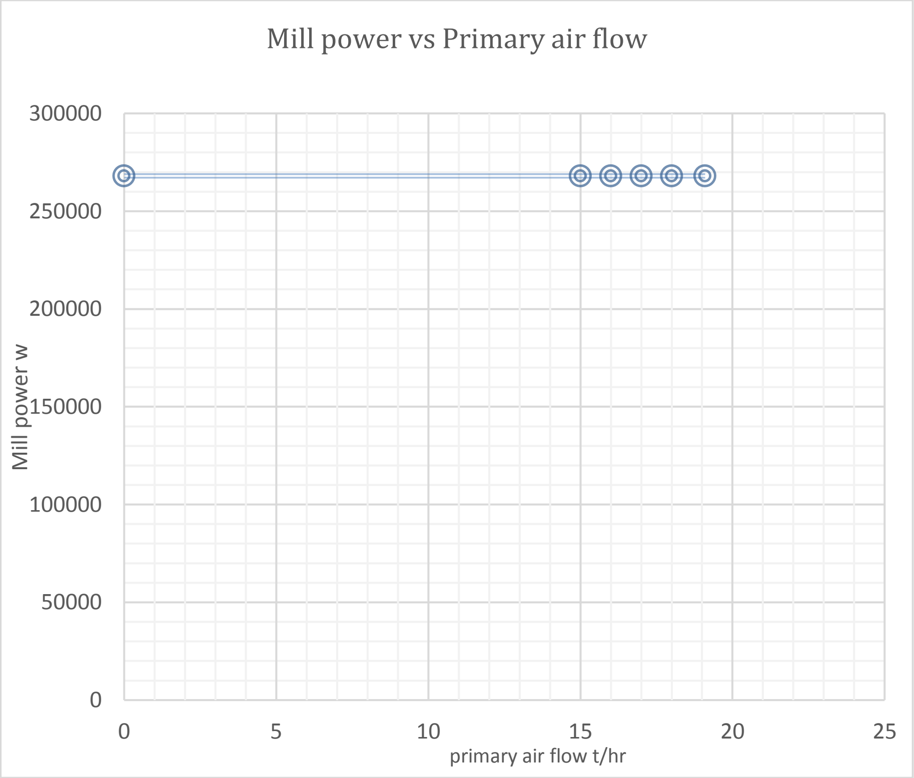
Appendix I: Cut diameter vs air flow



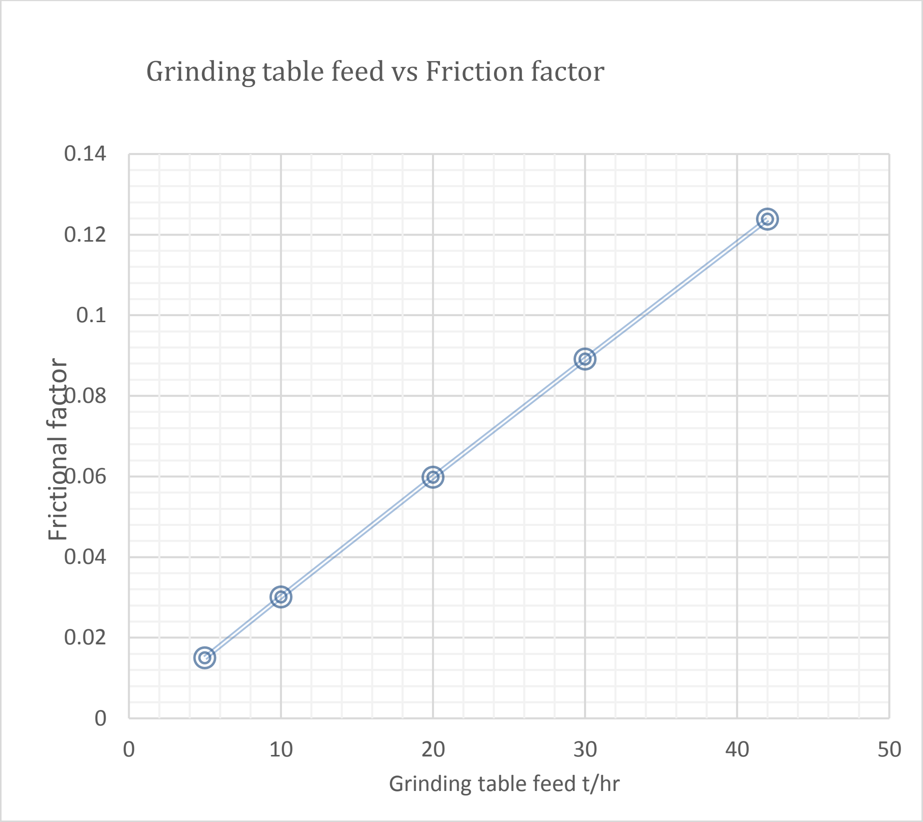
Appendix J: Cut velocity vs primary air



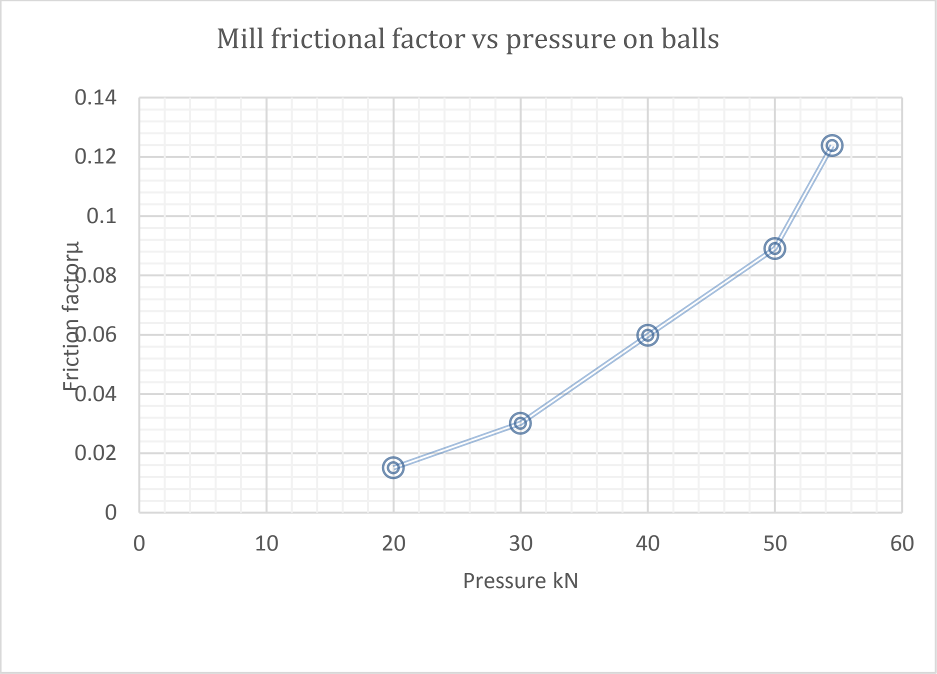
Appendix K: Mill power vs air flow



Appendix L: Grinding table feed vs friction factor.

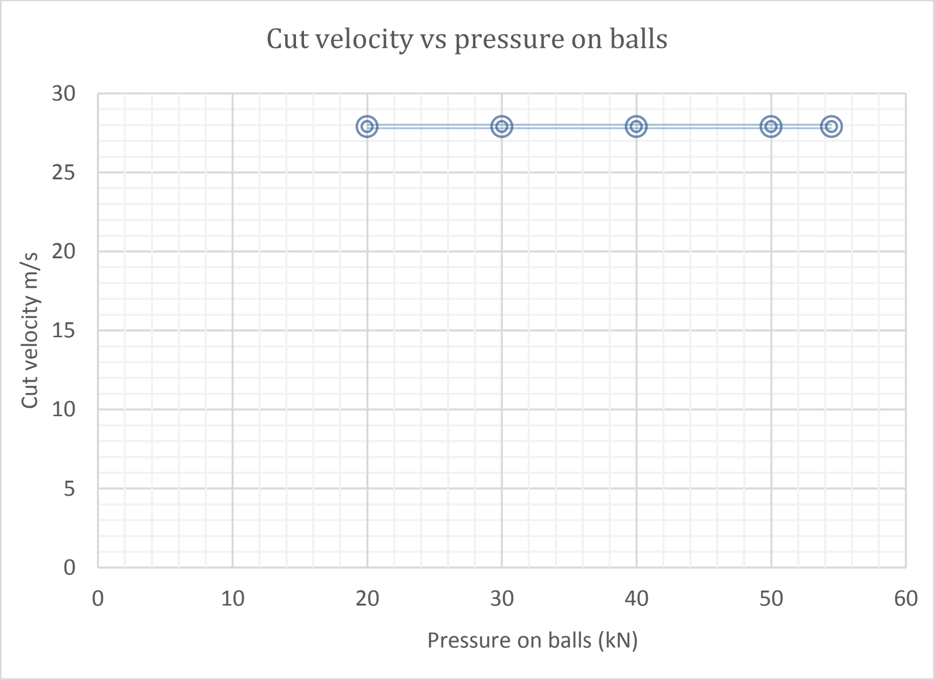


Appendix M: Mill frictional factor vs pressure on balls

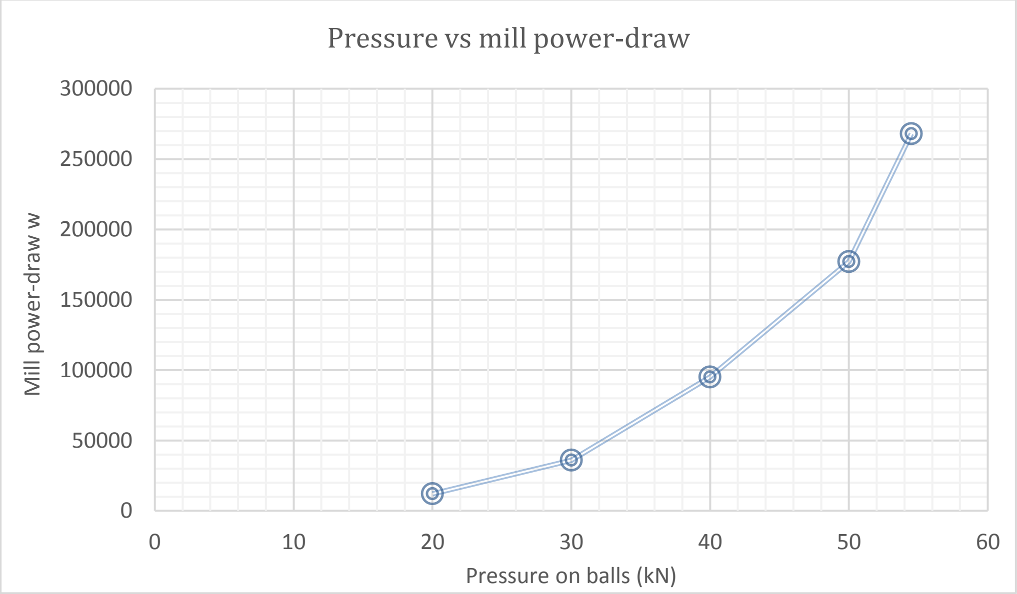


Appendix N: Mill loading pressure vs mill power-draw

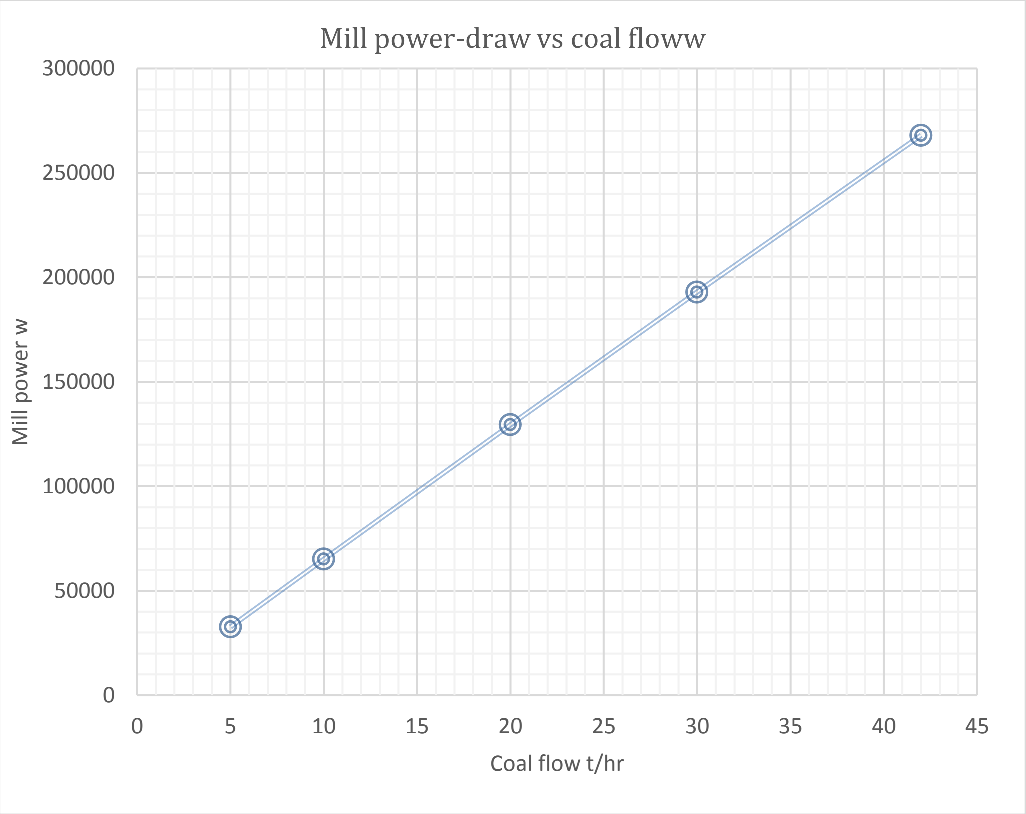
Appendix O: Cut velocity vs pressure on balls



Appendix P: Pressure vs mill power-draw



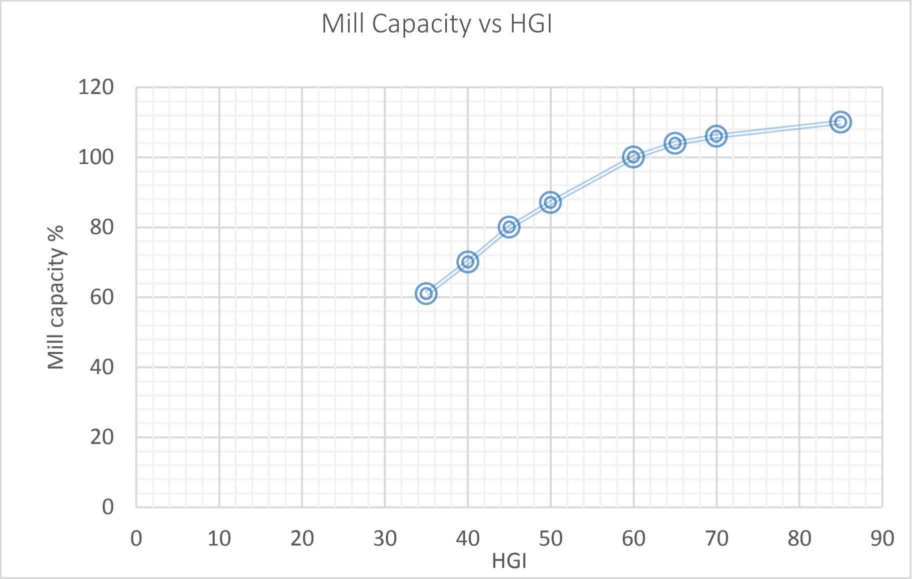
Appendix Q: Mill power-draw vs coal flow



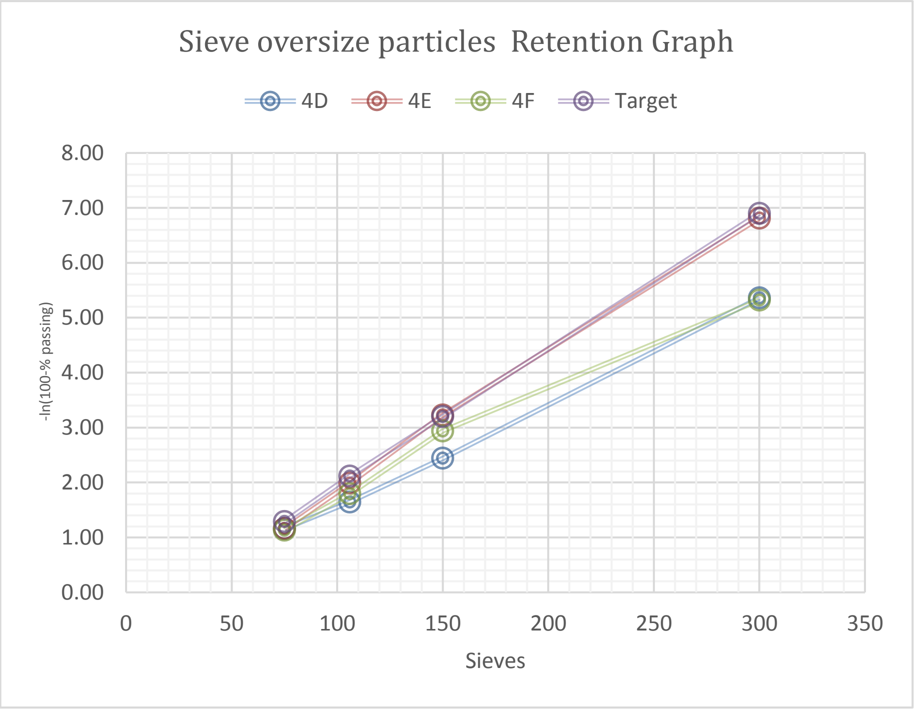
Appendix R: Electrical vibrating sieve shaker (Industrial Laboratory)

The apparatus above is the sieve shaker used during pulverised fuel is being graded. The sieves stacked on each other as 300,150,106 and 75 µm sieves, sample placed on sieve 300µm. When shaking the size distribution is spread across the sieves. The percentage of pulverised fuel passing and retained are calculated after the shaking is completed.

Appendix R: Mill capacity vs HGI (ACARP2008:3-4)



Appendix S: Sieves retention Graph



Appendix T: Sieves retention Graph