U T I L I S A T I O N O F L O W – G R A D E F U E L S I N F L U I D I S E D B E D C O M B U S T O R S

V o l u m e 1

Brian Clifford North

A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 2012

DECLARATION

I declare that this thesis is my own unaided work. It is being submitted for the degree of Doctor of Philosophy to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Brian Clifford North)

……… day of ……………. ………..

ABSTRACT

South Africa has large resources of coal, currently estimated at 33 billion tonnes, the majority of which sits in the Witbank, Highveld, Waterberg and Ermelo coalfields. 250 million tonnes of this are mined annually, of which over 70% is utilised in the domestic market, mostly for electricity and synthetic fuels production. The exported coal (61 million tonnes in 2009) results in large foreign income for South Africa. However, the export market demands coal of a high quality. For many producers to meet this quality (and to meet quality requirements for domestic use), often the coal must be beneficiated to reduce the ash content and increase the calorific value (CV). This results in the generation of waste coal, generally categorised into three main streams, namely discards, duff and slurries. These waste coals represent a financial loss, are often aesthetically displeasing and may result in environmental damage and/or liabilities. It is estimated that in excess of 1 billion tonnes of discard coal has been accumulated.

Fluidised Bed Combustion (FBC) is seen as a key technology to utilise the waste coal in an environmentally acceptable manner. Additionally, co-firing boilers with coal and biomass results in a net reduction in Greenhouse Gas emissions.

This thesis undertook research, development and implementation of FBC technology for the purpose of low grade coal and biomass waste utilisation in South Africa. The research was carried out in an Atmospheric (pressure) Bubbling Fluidised Bed Combustion boiler.

The hypothesis posed is that, due to features of a fluidised bed such as the high “thermal inertia” of the bed and good heat and mass transfer, FBC technology will be able to accommodate fuels of a low grade and of a varying quality.

Duff coal was found to be well suited to utilisation in a Fluidised Bed Combustor, provided that measures are taken to ensure a high combustion efficiency. Despite presenting some materials handling difficulties, duff coal can be transported without a major cost penalty due to its relatively high calorific value.

Bituminous discard coal was also found to be able to be effectively utilised in a Fluidised Bed Combustor. Addition of sorbent to the bed controlled the emission of sulphur oxides, which are generated from the combustion of the sulphur in the coal.

Negative issues with discard coal include transport cost penalties due to its relatively low calorific value.

Anthracite discards, however, were not found to be a suitable fuel for Fluidised Bed Combustors due to low combustion efficiencies.

Coal slurries were successfully burnt, albeit with inherent losses due to the high moisture content. The formation of char-sand agglomerates in the bed allowed some of the coal to have a long enough residence time in the bed to achieve an acceptable combustion efficiency.

Coal and a biomass waste (coffee grounds sludge) were successfully co-fired at pilot-scale level, and an industrial-scale plant was designed based on the research carried out. This has been running successfully in terms of sludge incineration and steam generation for some years.

This research proved that Fluidised Bed Combustion can be employed to utilise a wide range of low grade coals and waste materials, including the over 1 billion tonnes of discarded coal and a range of biomass residues. South Africa could well benefit from the utilisation of these “opportunity fuels”.

Estimates of the potential economic value of discard coal show that 11 000 MW of electricity could be generated using all the current arising discards. This would result in an annual revenue of Rbn 36.7 (36.7 billion South African Rands), which is a total revenue of Rbn 1471 over the 40 year life of the power station. Estimated savings (as compared to utilising conventional coal) of Rbn 5.2 per year and Rbn 207 over plant life could be achieved. If the stockpiles were to be recovered, some 6 000 MW of electricity could be generated from these. This would result in an annual revenue of Rbn 20.6 and a plant life revenue of Rbn 823 Estimated fuel savings are Rbn 2.9 per year and Rbn 116 over plant life. An economic analysis of a discard coal-fired power station located at a mine shows encouraging financial indicators.

Environmentally responsible energy will be the path to follow for the future, and Fluidised Bed Combustion has been proven to be a vital technology to help achieve that goal.

In memory of my parents

Terence Patrick North

and

Olive North

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The visionary initiative of the (then) Department of Minerals and Energy Affairs (DMEA) in funding the construction and operation of the National Fluidised Bed Combustion (NFBC) boiler, which enabled much of the research presented here to be conducted, is applauded.

Many thanks to the mining houses and individuals who supplied the coals to be tested.

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LIST OF SYMBOLS / NOMENCLATURE (Unit)

d_p	Particle diameter (m) (However, note that particle diameter is often quoted in mm)
L	Length (or height) of bed (m)
P	Pressure (Pa, or Nm^{-2})
U	Velocity (of gas) (ms^{-1})
U_{mf}	Minimum fluidising velocity (ms^{-1})
U_t	Terminal velocity (ms^{-1})

GREEK SYMBOLS

ε	Voidage fraction (-)
g	Gravitational constant (ms^{-2})
ρ	Density (kgm^{-3})
ρ_s	Density of solid particles (kgm^{-3})
ρ_g	Density of gas (kgm^{-3})
μ	Viscosity of gas ($kgm^{-1}s^{-1}$)
ΔP	Pressure drop (Pa, or Nm^{-2})

LIST OF ACRONYMS

AFBC	Atmospheric Fluidised Bed Combustion/Combustor
AFT	Ash Fusion Temperature
BFB	Bubbling Fluidised Bed
BFBC	Bubbling Fluidised Bed Combustion/Combustor
Ca/S	Calcium/Sulphur ratio
CAPM	Capital Asset Pricing Model
CCT	Clean Coal Technology
CFB	Circulating Fluidised Bed
CFBC	Circulating Fluidised Bed Combustion/Combustor
CPI	Consumer Price Index
CSIR	Council for Scientific and Industrial Research
CV	Calorific Value
DCF	Discounted Cash Flow
DCS	Distributed Control system
DMEA	Department of Minerals and Energy Affairs
ESKOM	Electricity Supply Commission of South Africa
EPRI	(US) Electric Power Research Institute
ERI	Energy Research Institute
FB	Fluidised Bed
FBC	Fluidised Bed Combustion / Fluidised Bed Combustor
FD	Forced Draught
FGD	Flue Gas De-sulphurising
GCV	Gross Calorific Value
GWP	Global Warming Potential
HHV	Higher Heating Value
HSP	High Sulphur Pitch
ID	Induced Draught
IGCC	Integrated Gasification Combined Cycle
IPP	Independent Power Producer
IRP	(South African) Integrated Resource Plan (2010)
IRR	Internal Rate of Return
ISO	International Standards Organisation
LHV	Lower Heating Value
MCR	Maximum Continuous Rating

MPFBC	Multi Purpose Fluidised Bed Combustion pilot plant
MYPD	Multi-year Price determination
NCV	Net Calorific Value
NERSA	National electricity Regulator of South Africa
NFBC	National Fluidised Bed Combustion boiler
NPV	Net Present Value
NREL	(US) National Renewable Energy Laboratory
PID	Proportional-Integral-Derivative
PF	Pulverised Fuel
PFBC	Pressurised Fluidised Bed Combustion/Combustor
SABS	South African Bureau of Standards
SANS	South African National Standard
TDH	Transport Disengagement Height
TGA	Theromgravimetric Analyser
WACC	Weighted Average Cost of Capital
WMCC	Weighted Mean Cost of Capital
ZET	Zero Emission Technology

1 INTRODUCTION

This thesis covers research, development and implementation of Fluidised Bed Combustion (FBC) technology for the purpose of low grade coal and biomass waste utilisation in South Africa. The research covers three distinct fields of research using different fuel types, namely:

- Combustion of “duff” and discards
- Combustion of coal slurries
- Co-firing of coal and biomass wastes

Each field represents a further progression in the application of the technology to the utilisation of difficult fuels.

The purpose of the research was to investigate the potential for use of low grade fuels in FBCs designed to suit these fuels. In order to accomplish this it is necessary to assess FBC as a suitable technology for the utilisation of these difficult fuels. The hypothesis is that, due to features of a fluidised bed such as the high “thermal inertia” of the bed and good heat and mass transfer, this technology would be able to accommodate fuels of a low grade and of a varying quality.

Although some background information will be given on fluidisation and FBC, the purpose of the research was directed towards the application of FBC rather than detailed consideration of the fundamentals of fluidisation.

This thesis is presented as 2 volumes. This volume, Volume 1, contains the research undertaken to prove the hypothesis stated above.

This introductory chapter of Volume 1 outlines the South African coal situation, highlighting problem areas, a discussion on environmental considerations (biomass firing), the role of Clean Coal Technology (CCT), and a brief discussion on Fluidised Bed (FB) and FBC technology. FB and FBC technology will be discussed in more detail in Chapter 2, the literature review. Analytical and experimental procedures are detailed in Chapter 3, and the results are presented in Chapter 4. An economic assessment of a discard coal-fired FBC power station is presented in chapter 5. Conclusions and recommendations are presented in Chapters 6 and 7 respectively.

Volume 2 is a compilation of some key reports, publications and presentations developed by the author over a number of years prior to and subsequent to the research detailed in this thesis in the field of coal combustion and FBC. They portray the progression of research and development and the expansion of the boundaries of the application of FBC technology. Due to the volume of this work it is provided as a separate document, with its own explanatory introduction.

The research and development detailed in this thesis was undertaken between 1983 and 1995. The issues addressed, namely use of low grade coal and biomass, are still highly relevant today.

1.1 South African Coal Situation

South Africa has large resources of coal. Prevost (2010) reported that South Africa has coal reserves of 33 billion tonnes. 250 million tonnes of this are mined annually, of which over 70% is utilised in the domestic market, mostly for electricity and synthetic fuels production. 61 million tonnes of coal are exported annually which generates a large foreign income stream for South Africa. However, the export market demands coal of a high quality. For many producers to meet this quality (and, indeed to meet quality requirements for domestic use), often the coal must be beneficiated to reduce the ash content and increase the calorific value (CV). This results in the generation of waste coal. This waste coal can be categorised into three main streams, namely discards, duff coal and slurries.

Discards are the high ash fraction. These often also contain relatively high levels of sulphur. Discards have been reported to have a CV in the Range of 11 to 15 MJ/kg (Pinheiro *et al*, 1999; Du Preez, 2001). The amount of discard coal stockpiled in 2009 was reported to be approximately 67 million tonnes (Prevost, 2010).

Duff coal is the fine fraction, nominally -6 mm, generally with a high CV. Historically this was screened out as it was problematic for use on combustion equipment such as chain grate stoker boilers. Due to the prevalent “captive colliery” policy adopted by ESKOM in the 1960’s, it was not used in pulverised fuel (PF) boilers. The practice of disposing of duff has since essentially ceased and it is now being sold to ESKOM and other users.

Slimes or slurries include the finer (nominally -0.5 mm) coal particles which are generated in the mining and beneficiation process. These are too wet to be used in conventional combustion equipment, and cannot be mechanically dewatered to a suitable level. Between approximately 11.3 and 13 million tonnes of slurry, with a CV predominantly in the range of 20 MJ/kg to 27 MJ/kg, were dumped in 2001 (Du Preez, 2001).

This discarded coal represents both a loss of potentially usable energy and an environmental threat due to occasional spontaneous combustion of the heaps. Stockpiles of discard can coal also become a source of acid mine drainage.

It was concern over this waste coal, and in particular the discard dumps, that prompted the (then) Department of Mineral and Energy Affairs (DMEA) to fund the construction and operation of the National Fluidised Bed Combustion (NFBC) boiler (Eleftheriades, 1984). This boiler is described in more detail in Chapter 3. Subsequently additional laboratory and pilot scale research facilities have been developed at the CSIR, and all of these facilities have been utilised in this research.

1.2 Environmental concerns

Despite the fact that South Africa is a non-Annex 1 signatory to the Kyoto Protocol, and is therefore not obliged to reduce its greenhouse gas emissions at this stage, environmental issues are of concern to the country and the industries operating in it.

A key advantage of FBCs is the ability to capture sulphur dioxide emissions “in situ” through the addition of limestone to the bed. The calcium carbonate in the limestone is calcined at the bed temperature to calcium oxide, which then reacts with the sulphur dioxide formed from the combustion of the sulphur in the fuel to form calcium sulphate, or gypsum. This material can be removed and disposed of in an environmentally benign manner.

An advantage often ascribed to FBC is that less nitrogen oxides (NOx) are produced as compared to PF, due to the lower combustion temperature and the possibility of staged combustion. (Utt and Giglio, 2011.) However, claims have been made that FBC produces more nitrous oxide, N_2O, than PF. N_2O is known to have a high global warming potential, 310 times that of carbon dioxide, CO_2. (Global Greenhouse Warming.Com, 2010.) This statement, with proposed ways to minimise the N_2O emissions, has been discussed by many researchers. Lyngfelt et al (1996) concluded that afterburning (burning about 10% of the fuel in the upper part of the combustor) and "reversed air staging" could reduce N_2O emisions significantly. Shen et al (2003) concluded that the char from the coal itself could decompose N_2O, limestone can also promote the decomposition, and co-firing with biomass can reduce N_2O emissions. Valentim et al (2006) made an observation that South Africa should take note of, that inertinite-rich coals produce more N_2O in an FBC than vitrinite-rich coals do. Coda (2012) (who is a research manager – combustion and materials at Foster Wheeler Energia oy, Finland) asserted that large CFBs (particularly those co-firing biomass, as also noted by Shen et al, 2003) have N_2O emissions below 50 mg/Nm^3. NOx emissions reductions are not a focus of the research presented in this thesis, but I believe the issue of N_2O emissions has not been fully resolved, and will continue to be a slight disadvantage to FBC technology.

CO_2 is, by volume, by far the largest contributor to global warming. CO_2 emissions per unit of output (steam and/or electricity) can be reduced by operation at lower excess air levels, which is possible in FBC. However, for combustion of coal, the key operating parameter affecting CO_2 emissions is the steam conditions, which is not specific to FBC. In this respect FBC has lagged behind PF, and past plants have produced more CO_2 than PF power stations. This has been rectified with the recent commissioning of a 460 MW (e) CFBC boiler in the Lagisza power plant in Poland, which operates at supercritical steam conditions (Jantii, 2011; Patel, 2010; Power, 2009; Utt et al, 2009).

South Africa made a commitment to CO_2 emissions reductions at the COP meeting in Copenhagen, namely:

"South Africa will undertake mitigation actions which will result in a deviation below the current emissions baseline of around 34% by 2020 and by around 42% by 2025. This level of effort enables South Africa's emissions to peak between 2020 and 2025, plateau for approximately a decade and decline in absolute terms thereafter."

Source: The Presidency of South Africa, Proposal to Copenhagen COP, 6 December 2009

With an increasing acceptance of the reality of global warming, and that the cause of this is anthropogenic Greenhouse Gas (GHG) emissions, the concept of reducing GHGs by co-firing coal and wastes is gaining popularity. A specific application of this approach formed part of the research in this thesis, where research, development and implementation were undertaken to enable the co-firing of 12 tonnes per hour of a coffee grounds sludge stream, containing 85% water, and coal.

1.3 Clean Coal Technology

As indicated above, there has been a steady incremental increase in the efficiency of coal-fired power stations, both PF and FBC. This reduces the amount of CO_2 emitted per unit of useful energy produced. In terms of greenhouse gas reductions, this essentially ranks them as “cleaner coal technologies”, rather than Clean Coal Technologies, but they are nonetheless a vital interim step on the route towards Zero Emission Technologies (ZETs). An excellent series of reports were produced by the International Energy Agency (IEA) (Henderson, 2003). Technologies such as supercritical PF, pressurised PF, CFBC, Pressurised FBC, Pressurised CFBC, Integrated Gasification Combined Cycle (IGCC), IGCC fuel Cells, hybrid systems and ZETs were considered. The ZETs considered included CO_2 scrubbing from the flue gases using amine scrubbers (Post Combustion Capture) and oxyfuel firing. The general conclusion was that further technical development was required to decrease the risk and cost of such systems. Specifically, the energy penalty associated with CO_2 scrubbing and production of oxygen will need to be reduced. For these reasons, cleaner coal technologies such as FBC, especially when combined with utilisation of waste or “opportunity” fuels, have a clear role to play in the near to medium term future.

1.4 Research objectives and scope

The research detailed in this thesis is the author’s contribution to investigating and expanding the application of FBC technology as applied to the effective utilisation of waste or low grade fuels, and proving that it does indeed have a role to play in the South African energy mix.

The rationale, research objectives and scope, largely drawn from the original research proposal, are detailed in sections 1.4.1 to 1.4.4 below.

This research is intended to ascertain if FBC is a suitable technology for utlisation of low grade fuels, thereby demonstrating that a larger fraction of the coal mined in South Africa can be utilized, rather than dumped on the surface. The ability of South African sorbents to capture sulphur in-situ will also be determined.

It is intended to both explore the boundaries of FBC design and operation and to understand its limitations.

1.4.1 Advantages of FBC

Fluidised Bed Combustion (FBC) is a technology which could potentially utilise these reject coal streams most effectively for the production of heat and power generation (MacGillifray, 1979). Aspects of FBC which suggest that it could be applied in this field include the following aspects:

- There is a high degree of gas/solids mixing in the turbulent fluidised bed, which can assist in the access of oxygen to the carbon and results in high heat transfer rates to steam tubes within the bed.

- The attrition of particles within the bed causes new carbon surfaces to be exposed to the oxidising environment and therefore higher rates of reactivity and consumption.

- Sulphur dioxide emissions can be controlled highly effectively by directly injecting a high sulphur sorbent into the bed (“in-situ” capture).

- The mass of suspended inert material in the fluidised bed acts as a “thermal flywheel” which can accommodate swings in fuel feed rate or quality.

- Combustion occurs at a lower temperature than conventional combustion equipment (in the range 850 ℃ to 950 ℃), which al lows for the use of lower CV, or higher water content fuels at the same excess air levels.

- Such low combustion temperatures also reduce the production of thermal NOx, and they prevent the melting of minerals and ash slag formation, as often occurs in pulverized fuel boilers combusting at temperatures over 1 400 ^{o}C.

Based against the background above, this proposal seeks to undertake research to establish FBC as a feasible, efficient and environmentally sound heat and power generating technology which can assist is reducing the considerable quantities of unwanted waste materials in South Africa. Falling in the broad field of Clean Coal Technology, this thesis specifically targets studies to establish the feasibility of utilising “low grade” including *coally materials* in the form of “*discards*” (high ash, low Calorific Value (CV), often with high sulphur content), “*duff*” (high fines content, but generally with a high CV), “*slurries”* (very fine, high water content) and *biomass waste* in FBCs.

The research will comprise test work in purpose-designed pilot scale fluidized bed test facilities and in an industrial-scale plant (the National Fluidised Bed Combustion (NFBC) Boiler (Eleftheriades and North, 1987) to ascertain the possibility of utilizing low grade coals (discards, duff and slurries) in an FBC, and to determine and optimize the combustion and thermal efficiencies. The combustion and thermal efficiencies will be calculated thorough the use of a computer program written for this purpose. The effect of boiler operating parameters such as re-firing of elutriated solids on the efficiency will be gauged. The reduction of sulphur oxides emissions using South African sorbents will be investigated. Initial test work will be carried out on the combustion of high water content biomass waste with a custom design of a combustor capable of utilising this fuel.

These are all new areas of research which will lead to new knowledge being generated to enable FBC plant to be designed to utilize low grade South African coals and other wastes.

1.4.2 Research questions and hypothesis

Given the unusual low grade nature of South African waste fuels, the following questions are posed:

- Can discard coal be effectively utilized in an FBC?
    - What thermal and combustion efficiencies can be achieved?
    - Can bed defluidisation be avoided?
    - How effectively can the sulphur oxides emissions be controlled?

- Can duff coal be effectively utilized in an FBC?
    - What thermal and combustion efficiencies can be achieved?
    - How does refiring of elutriated solids increase combustion efficiency?
    - Is in-bed firing practical?

- Can coal slurries, or slimes, be effectively utilised in an FBC?
    - What thermal and combustion efficiencies can be achieved?
    - What solids loading can practically be achieved in the slurry?

- Can the dual purpose of waste minimization and energy recovery from biomass waste sludge be achieved in an FBC?
    - Can the biomass be burnt as it arises, or does it need to be co-fired with coal?
    - What is the maximum biomass waste to coal ratio?

It is postulated that FBC will prove to be a suitable technology for low grade fuel utilization. (Although application of FBC will depend on many factors, such as capital cost, fuel cost (incl. transport), environmental constraints and proximity to suitable sorbents.)

1.4.3 Scope of research

This research will include :

- Selection of a variety of fuels including discard coal (including anthracitic discards), duff coal, coal slurries and biomass wastes for testing.

- Development of pilot scale FBC equipment

- Undertaking of extensive experimental/test work on the developed pilot plant facility and the National Fluidised Bed Combustion facility

- Assessment of the results of the detailed analyses with comprehensive theoretical calculations including thermal and combustion efficiencies

- Computerization of a program developed to achieve the above purpose

- Adaptation of the design and operating procedures of a number of full scale FBCs in which various waste fuels are to be used, based upon experience gained during the experimental testing procedures, and

- Summary of the ability of the FBC process to meet a number of environmental concerns with specific emphasis on SOx and CO_2 emissions.

1.4.4 Expected contribution to the body of knowledge

The following contributions may be expected:

- The information gained will enable future decisions regarding the possible use of FBC to utilise the low grade or 'waste' fuels found specifically in South Africa.

- Optimal designs of FBC plant for each type of waste fuel will be established.

- Combustion and thermal efficiencies will be optimized through a better understanding of plant operating parameters.

- A computer programme will be developed which will facilitate faster compilation and assessment of combustion and operating data; this will result in the rapid production of important calculations concerning, inter alia, thermal and combustion efficiencies.

- A number of papers will be written on the research and presented at local and international conferences.

- The knowledge and experience will be disseminated through forums such as advanced university combustion courses, conferences and publications.

To my knowledge, no industrial scale research has been carried out in South Africa to determine the performance of reject/low grade South African coals and waste materials in an FBC. The work presented here is aimed at filling that research gap, to prove the technical viability of burning low grade South African coals and wastes in FBCs and to provide information upon which feasibility studies and optimised combustor designs may be based.

1.5 Key Components of Fluidised Bed Combustors

This section provides the reader with an understanding of the key components of FBC technology, and the importance of designing the plants correctly.

1. Forced Draft Fan (with damper or variable speed drive)
2. Plenum (or Windbox)
3. Distributor
4. Bed
5. Freeboard
6. Heat transfer surfaces
7. Gas de-dusting (cyclones and/or bagfilters)
8. Induced Draft Fan (with damper or variable speed drive) and Stack
9. Feeders (Coal, other fuels, Limestone etc.)
10. Bed Removal and Management System

1.5.1 Forced Draft (FD) Fan

This fan provides the air for both fluidising the bed and for the combustion. It is sized in terms of volume to provide the required amount of air to effect the combustion and to maintain the fluidised bed at the required temperature (effectively by control of the air/fuel ratio, taking into account heat taken up by in-bed heat transfer surfaces and the heat leaving the bed as hot gas). It is sized in terms of pressure to overcome the pressure drop through the plenum and distributor, and through the bed.

1.5.2 Plenum (windbox)

The function of the plenum is to provide the air evenly across the base of the bed. It is conceptually a contained space or box under the distributor, but in reality can be more complex. For example, in CSIR-designed fluidised beds it consists of a cylindrical main plenum with a series of risers and horizontal sparges to distribute the air evenly across the bed.

1.5.3 Distributor

This is conceptually a porous plate or sieve that allows the air to flow upwards but prevents bed material from falling downwards into the plenum. Again, in reality, it is more complex. Most vendors employ stand-pipes with horizontal nozzles. With the CSIR design the stand-pipes are mounted on the horizontal sparges. The correct design of the distributor is critical to the proper operation of the fluidised bed. The nozzles must be designed so that they achieve the objective of allowing the air into the base of the bed but preventing particle back-flow. They must also provide sufficient pressure drop to ensure that the air passes evenly through all pipes and nozzles, rather than preferentially passing through only one portion. This minimum pressure drop has been recommended as approximately 10% (Kunii and Levenspiel, 1977) or 12% (Highley and Kaye, 1983). It should be noted that this minimum pressure drop is required at minimum load, so if a fluidised bed is designed to operate with a 2:1 turndown (ie should be able to operate properly at 50% of its design load) the pressure drop across the distributor at full load will be almost 50% of the pressure drop across the bed. (Pressure drop increases with the square of velocity, so doubling velocity will quadruple the pressure drop from, say, 12% to 48%.)

1.5.4 Bed

As mentioned earlier, the bed is generally composed of sand, at least at initial start-up. After a period of operation the bed will consist of sand, fuel and fuel ash and, if sulphur capture is being employed, fresh and spent sorbent. The depth of the bed is generally dictated by the fuel. If a high quality, graded coal is being used, a shallow bed (in the order of 150 mm) can be employed. Where problematic fuels are being employed, especially when fuel quality swings are possible, a deeper bed is desirable. The bed acts as a “thermal flywheel”, and can accommodate these swings. A deep bed also allows for longer slump (switched off) period (North et al, 1990). A drawback to a deeper bed is a higher pressure drop, requiring a forced draft fan with a higher air delivery pressure, therefore also incurring higher electricity consumption.

The bed can be contained within a refractory wall for hot gas generators and low grade or wet fuels or, for high quality fuels in a boiler application, by a “membrane wall” (panels of heat transfer surface). Additional heat transfer surfaces (discussed below) may be immersed in the bed to effect additional heat removal, to allow operation at the correct temperature and excess air level. The fuel burns within this bed, utilising oxygen from the fluidising air, and liberating heat into the bed.

1.5.5 Freeboard

With a bubbling FBC there is a discernible surface to the bed, and the freeboard is the area above the bed The combustion process can continue in this zone, especially continued combustion of volatile matter released from the fuel. Unless fuel and sorbent are being fed into the bed (which has advantages, but is problematic) they will be fed over the bed, in the freeboard area. Due to bubbles erupting at the surface of a fluidised bed, particles can be ejected from it. These require a time and distance to come to a halt, and then to fall back to the bed. This distance is known as the Transport Disengagement Height (TDH). For BFBCs The freeboard height should be at least greater than the TDH.

1.5.6 Heat Transfer Surfaces

In boiler applications, the purpose of heat transfer surfaces is to raise steam from the heat liberated from the combustion of the fuel. The heat transfer surfaces may be in the bed, they may form the walls of the containment vessel for the bed and freeboard, they may be in the freeboard area and further downstream, or a combination of all three. Saturated steam may be raised or, for power generation, the steam can be superheated or re-heated. As mentioned above, the heat transfer surfaces also maintain the bed at the correct temperature and excess air level.

1.5.7 Gas Dedusting

To prevent the emission to the environment of dust particles entrained in the gases leaving the freeboard and heat transfer section it is necessary to remove the dust. This can be achieved with conventional cyclones and bagfilters. The cyclone ash can contain a significant amount of unburnt carbon, and recycling of this ash to improve carbon utilisation formed part of the research presented in this thesis.

1.5.8 Induced Draft (ID) Fan

The induced draft fan pulls the gases (after cooling through the heat transfer surfaces and dedusting) and vents them through the stack to atmosphere. It also controls the pressure in the freeboard area, either by variable speed drive or dampers, maintaining it slightly below atmospheric pressure.

1.5.9 Feeders

For most fuels, conventional screw-type conveyors can be used to supply a controlled amount of fuels or sorbent to the bed. To limit the number of feeders required, fuel distributers are often also employed. These can be mechanical, such as spreaders or “flingers” (employed in spreader stoker-fired boilers) or non-mechanical such as air-blown spreaders. For feeding sludges or liquid fuels an injection nozzle or lance can be used.

1.5.10 Bed Removal and Management System

It is inevitable, especially when firing low grade or waste fuels, that tramp non-combustible material will also be fed into the bed. This will fall to the base of the bed. If not removed, it will build up and can cause incorrect bed height measurement, and can even swamp thermocouples in the bed, giving an incorrect bed temperature measurement. Additionally, sintering or agglomeration of particles can occur, resulting in similar problems, including a coarsening of the bed which can lead to localised defluidisation. To prevent this, bed material is withdrawn from the bed, generally through cooled screw conveyors. This material can be screened (and crushed if necessary) and the correct size range fed back to the bed through a dedicated feeder or through the fuel or sorbent feeder. Often a make-up amount of fresh bed material will be required, and this can be fed with the recycled material.

2 LITERATURE REVIEW

2.1 Fluidised Bed Technology

If a fluid is passed upwardly through a bed of particles, the pressure drop across the bed will increase with the velocity of the fluid. This pressure drop can be described by the Ergun equation (Kunii and Levenspiel, 1977).

$$\Delta P = \frac{150 \mu U L}{d_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75 \rho_g U^2 L}{d_p} \frac{(1-\varepsilon)}{\varepsilon^3} \qquad \text{(Eqn. 2.1)}$$

As the velocity is increased, a point is reached where the frictional force between the particle and the fluid equals the weight of the particle and the pressure drop equals approximately the weight of the particles in a given section. This is known as the minimum fluidising velocity, U_{mf}. The weight of the bed, and therefore the pressure drop over the bed, is given by

$$\Delta P = L\ g\ (1-\varepsilon)(\rho - \rho_g) \qquad \text{(Eqn. 2.2)}$$

Equating the pressure drop (from the Ergun equation) to the weight of the bed results in an equation which can be used to calculate the minimum fluidising velocity (U_{mf}) (Geldart, 1986).

$$1.75 \rho_g U_{mf}{}^2 + \frac{150(1-\varepsilon)\mu}{d_p} U_{mf} = (\rho - \rho_g) g d_p \varepsilon^3 \qquad \text{(Eqn. 2.3)}$$

Increasing the fluid velocity further does not result in increased pressure drop. At some point, the particles become entrained in the fluid and are carried out of the vessel they were contained within. This is known as the terminal velocity, U_t (Geldart, 1986).

Between these two velocities a discernible bed of solids is present. This is generally known as a dense-phase or bubbling fluidised bed (BFB). Depending on factors such as bed dimensions and particle characteristics, phenomena such as slugging, channelling and jetting can occur, shown in figure 1.1 below (Geldart, 1986).

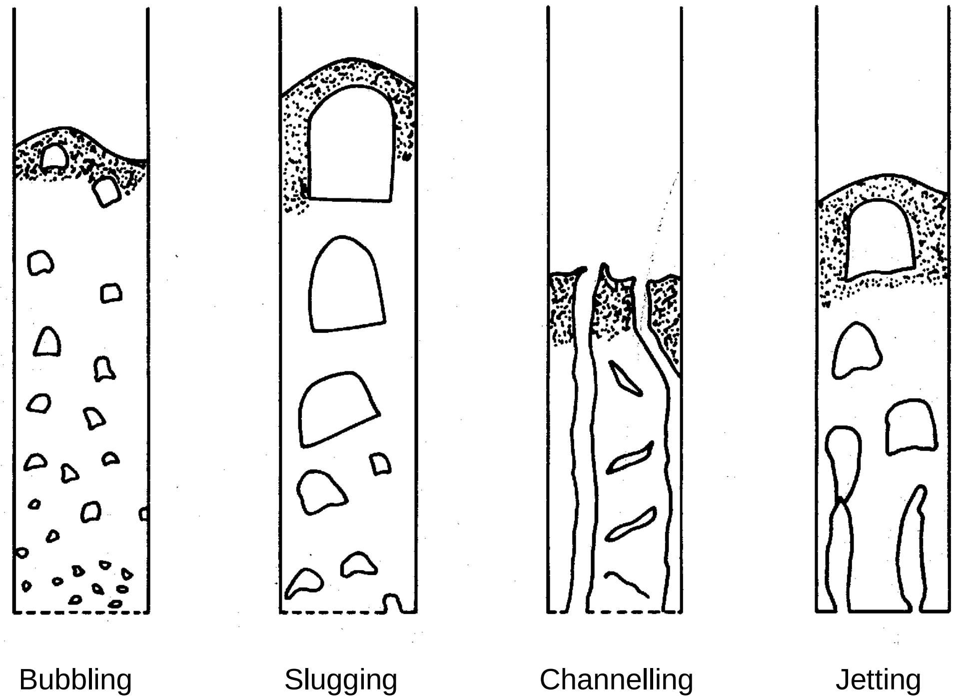

Figure 2.1Types of fluidisation (Geldart, 1986)

At fluid flow rates higher than the terminal velocity of the particles the upper surface of the bed disappears and solids are carried out of the bed with the fluid. This is known as a disperse-, dilute- or lean-phase fluidised bed, with pneumatic transport of the solids (Kunii and Levenspiel, 1977). If a significant fraction of the transported solids are collected in a cyclone and returned to the bed it is said to be a circulating fluidised bed (CFB). Although CFB is now the technology of choice for large-scale combustion equipment, at the time of this research BFB was “state of the art”. All of the research and development indicated in this dissertation was conducted on BFBs.

The term “fluidised bed” does not signify that the bed is in fact a fluid, i.e. that is has become molten, which is a common misperception. It is rather intended to signify that it behaves much like a fluid, for example the surface of the bed will remain horizontal even if the vessel containing it is tilted (Kunii and Levenspiel, 1977).

The following generic advantages and disadvantages of fluidised beds were stated by Kunii and Levenspiel (1977). (Table 2.1 below.)

Table 2.1 Advantages and disadvantages of fluidised beds (Kunii and Levenspiel, 1977)

Advantages	Disadvantages
1. The smooth, liquid-like flow of particles allows continuous automatically controlled operations with ease of handling. 2. The rapid mixing of solids leads to nearly isothermal conditions throughout the reactor, hence the operation can be controlled simply and reliably. 3. The circulation of solids between two fluidised beds makes it possible to transport the vast quantities of heat produced or needed in large reactors. 4. It is suited to large scale operations. 5. Heat and mass transfer rates between gas and particles are high when compared with other modes of operations. 6. The rate of heat transfer between a fluidised bed and an immersed object is high, hence heat exchangers within fluidised beds require relatively small surface areas.	1. The difficult-to-describe flow of gas, with its large deviations from plug flow and the bypassing of solids by bubbles, represents an inefficient contacting system. This becomes especially serious when high conversion of gaseous reactant is required. 2. The rapid mixing of solids in the bed leads to non-uniform residence times of solids in the reactor. For continuous treatment of solids this gives a non-uniform product and lower conversions, especially at high conversion levels. On the other hand, for batch treatment of solids this mixing is helpful since it gives a uniform solid product. For catalytic reactions the movement of porous catalyst particles which continually capture and release reactant gas molecules contributes to the backmixing of gaseous reactant, reducing yield and performance. 3. Friable solids are pulverised and entrained by the gas; they then must be replaced. 4. Erosion of pipes and vessels from abrasion by particles can be serious. 5. For noncatalytic operations at high temperature the agglomeration and sintering of fine particles can necessitate a lowering in temperature of operation, reducing the reaction rate considerably.

Advantages 2, 5 and 6 are of particular importance for combustion. Associated with advantage five is the fact that the ash residue is removed from the surface of the burning particle by the abrasive action of the bed, thereby exposing fresh combustible material. Disadvantage 4 has been a problem in combustion systems, as this gives rise to erosion of heat transfer surfaces.

2.2 Fluidised Bed Combustion Technology

If combustion were to occur in a bed of pure coal particles, the bed temperature would rise to approximately the maximum adiabatic temperature (about 2000 °C). Slagging would occur, as this is above the ash fusion temperature (AFT) of coal. However, if the bed is "ballasted", or diluted, with an inert material, the high heat transfer rates from the particles to the bed and from the bed to immersed heat transfer surfaces allow the bed to operate at lower temperatures (Essenhigh, 1979). Broughton and Howard (1983) make a similar statement, and add that the heat transfer coefficient between a fluidised bed and a surface immersed in it is commonly more than five times as large as between a moving gas stream and a surface. The inert material is generally sand, as it is a readily available material that can withstand the operating temperatures of the FBC. The fluid is air, which both effects the fluidisation and provides the oxygen necessary for combustion.

An FBC typically operates in a range between 750 °C and 950 °C. The lower limit is to avoid unacceptably low combustion efficiencies and the upper limit is to avoid risk of ash melting (Highley and Kaye, 1983). A key advantage of FBCs over conventional combustion equipment is the ability to capture sulphur in the fuel "*in situ*", by the injection of calcareous sorbents. If sulphur capture is employed, the bed temperature should be maintained between 800 °C and 850 °C, as the sulphur capture decreases rapidly over 850 °C (Roberts *et al*, 1983).

A fluidised bed combustor may be operated at atmospheric pressure, when it is referred to as an Atmospheric FBC (AFBC), or at elevated pressures, when it is referred to as a Pressurised FBC (PFBC). Roberts *et al* (1983) give a good review of PFBC systems. In principle PFBC is attractive, because it allows for a higher heat release rate per unit bed area, since more oxygen (on a mass and molar basis) is being supplied per unit area and therefore more coal could be burnt in it. However, PFBC has been problematic, with issues such as feeding solids against the pressure and the larger amount of heat transfer surface required with a concomitant deep bed. Research into PFBC has largely ceased. All the research presented in this thesis has been on AFBC systems.

So, with the flexibility of FBC to utilise low grade fuels, the question is how can this technology be utilised in South Africa to realise the energy potential in waste coal and biomass? Faced with the current reality of rapidly rising primary energy costs and the generally accepted need to reduce the environmental footprint associated with mining and utilising coal it makes sense to use more of the mined coal and to look at more efficient and cleaner ways to utilise it.

The research detailed in this thesis was undertaken to attempt to prove that the energy (and value) in discard coal and other low-grade fuels can be unlocked in an environmentally responsible manner.

2.3 Development of and Research into FBC Technology

2.3.1 Internationally

Development

Hoy (1983) and Howard (1983) attribute the advancement of FBC in the western world to Professor Douglas Elliott. Elliott undertook his work in the 1950's to the 1970's. He presented an inaugural lecture in 1969 after his appointment as Professor of Mechanical Engineering of Aston University in Birmingham. The title of this lecture was "Can Coal Compete? – The Struggle for Power". It is of interest that, over 40 years later, the same question can still be asked, albeit for different reasons.

Historically, new-build and retrofit FBC plants were driven primarily by environmental considerations, principally the reduction of Sulphur oxides (SO_x) and Nitrogen oxides (NO_x) and more efficient fuel utilisation. Examples of BFB retrofits are the Montana-Dakota Utilities plant (Gorrell *et al*, 1987) and the "Black Dog" plant (Follett *et al*, 1987; Goblirsch *et al*, 1987). The Montana-Dakota plant utilised a lignitic coal, and the retrofit from spreader stoker to FBC was intended to improve the combustion and thermal efficiency. Additionally, the opportunity was used to increase the output by about 8%. The Black Dog project, where a pulverised fuel (PF) firing system was replaced by FBC, was intended to reduce emissions. Both retrofits, although now decommissioned, achieved their objectives and provided valuable information for future such plant.

A good discussion on the development of FBC has been given by Koornneef *et al* (2006). (Table 2.2 below.) Historic milestones, from the patent registered by Winkler in 1922 (for the gasification of lignite), through test facilities and programmes in the 1960's, through industrial scale demonstrations in the 1970's, through large scale demonstration and implementation in the 1980's to commercial operation and scale-up in the 1990's and beyond are tabulated. The authors also give the number of BFBC and CFBC boilers installed world-wide at that time (173 and 396 respectively, presented as Figure 2.2) and information on the diversity of fuels fired. A similar history is presented by Szentannai *et al* (2008).

Table 2.2 Important events in the history of fluidised bed combustion (Koornneef et al, 2006)

Year	Event
1922	Winkler patent
1965	Start of the Atmospheric Fluidized Bed Combustion Program (between 1965 and 1992)
1965	First BFB test facility commissioned
1972	First contract awarded for Rivesville
1973	EPI provided the first fluidized bed combustion (FBC) system in the US capable of converting waste biomass into usable energy
1976	BFB Rivesville industrial scale demonstration project
1976	Start of large scale R&D program by ERDA (USA)

Year	Event
1978	European Commission starts supporting FBC technology with demonstration projects until 1990
1979	First CFB industrial scale power plant by Foster Wheeler
1981	First coal fired commercial CFB boiler supplied by Alstrom (now Foster Wheeler)
1981	First commercial BFB fired with biomass as main fuel type supplied by EPI
Mid 1980s	First HYBEX (BFB), Kvaerner
1982	First Lurgi Lentjes CFB is commissioned
1983	First commercial CFB fired with biomass as main fuel type by Foster Wheeler
1986	The Clean Coal Technology (CCT) Demonstration Program started (USA). Ended in 1993.
1988	Large scale (142 MWe net) BFB demonstration project in the USA.
1988	First commercial CIRCOFLUID by Babcock
1990	EU THERMIE (RD&D) programme includes 3 CFB projects, ends 1996
1992	First commercial operation INTREX by Foster Wheeler (CFB)
1994	Model project on CFB implemented in 1994 under Green Aid Programme for Asia-Pacific countries
1994	First CYMIC® Kvaerner (CFB)
1996	First IR-CFB B&W (CFB)
1999	International Energy Agency (IEA) FBC implementing agreement started, now 12 countries are members
2003	First supercritical CFB boiler Lagisza Poland Foster Wheeler with Siemens OTU (once through unit) design. Start-up is planned in 2009

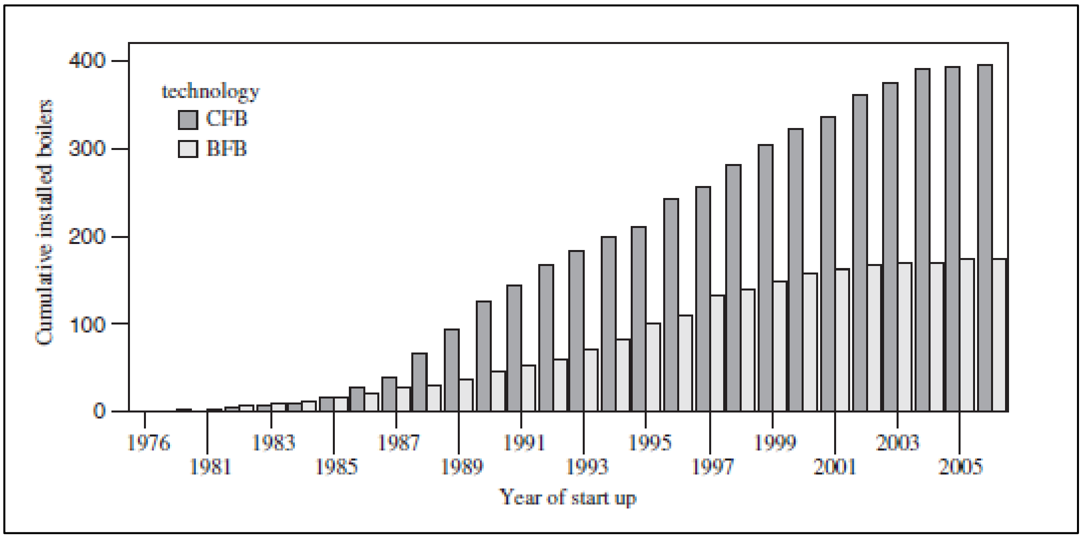

Figure 2.2 Installed FBC plant (from Koornneef, 2006)

BFBC installations flattened off from about the year 2000, whereas growth in CFBC installations remained strong until 2004. With the benefit of hindsight, the flattening off of CFB installations from 2004 could have been an early indicator of the global economic slowdown.

An omission in Koornneef's list of important events, I believe, was the commissioning of two CFBC plants in Tonghae, South Korea, in 1998 and 1999. These were Asia's largest CFB plants, and were designed to burn low-grade anthracite. (Power Engineering International, 1999.) Due to the erosive nature of the anthracite ash, key design features for these plants included a relatively low fluidising velocity and prevention of waterwall erosion through refractory design and application. A rectangular design of the furnace, with an aspect ratio above 2:1, was also included to optimise fuel combustion and sorbent utilisation. This plant has been the subject of subsequent research and development, including co-combustion tests carried out by Kim et al (2006). They reported more stable operation and an increased efficiency with the co-firing of bituminous coal with the anthracite which they concluded was due to an "…improvement of the combustion reactivity of the anthracite through the co-combustion with the bituminous coal…".

Since 2006, a significant event was the commissioning of the Lagiza supercritical FBC in 2009 (Utt et al, 2009; Jantti, 2011). This unit was groundbreaking in terms of both its size and supercritical steam conditions. Since this, Foster Wheeler, the suppliers of the Lagiza plant, have been given notice to proceed with the design and supply of four 550 MW supercritical FBCs. (Jantti et al, 2012.) Supercritical FBCs with a capacity of 800 MWe are a commercial offering today (Utt and Giglio, 2011).

Research

Research investigating the combustion of colliery rejects including high ash discards and slurries has been undertaken. Duffy and La Nauze (1985) reported on trials carried out on a 4.5 MW (th) FBC in Australia. They concluded that FBC was a technically feasible option for the utilisation of high ash Australian coals and coal wastes. Their work, as reported, did not include sulphur capture. Similar studies have been undertaken by Keyser (1983), Pis et al (1991) and others. The results were positive. Interestingly, Keyser effected sulphur capture by injecting lime into the flue gases rather than using limestone in the bed. The reason for this was not reported.

The combustion of coal water slurries in a BFBC has been investigated and proven to be possible (Massimilla and Miccio, 1986; Miccio et al, 1989; Miccio and Massimilla, 1991.) Their key finding was that combustion efficiency was enhanced through the formation of char-sand agglomerates and char-flecked sand. Char-sand agglomerates are formed from the drying and devolatilisation of slurry droplets in the bed. Char-flecked sand can either be formed directly from coal particle adherence to a sand particle, or from the attrition of a char-sand agglomerate. They proposed various mechanisms for the attrition of the char-sand agglomerates into smaller agglomerates, char-flecked sand and eventually into “flying fines” (the “F-phase”). They reported that 75% of the carbon injected into the bed burnt while attached to the bed solids and 10% burnt as carbon fines. 15% was elutriated. They concluded that a key factor in the design of FBC units would be post-combustion of these fines in the freeboard.

Chugh and Patwardhan (2004) investigated the techno-economic feasibility of a mine-mouth power station using processed fine bituminous coal (Illinois No. 5 seam) rejects in a CFBC. The nominal installed capacity of the power station is 25 MW to 35 MW. Their concept was to feed the fine coal to the FBC as a high solids concentration slurry. A great deal of their work involved preparing the fuel, through screening and froth flotation. They were able to produce a slurry which was pumpable at a solids concentration of 55.7%, albeit with a high calculated pressure drop (8.5 kPa per meter in a 150 mm diameter pipe). They elected to use a hydraulically driven piston pump due to this high pressure drop. Combustion tests were undertaken in a pilot scale CFBC. For these tests the slurry was fired at a solids concentration of 51%. They reported combustion efficiencies in the range of 95% to 99.5%. They noted that “The bed ash contained material that was coarser than the coarsest material in the feed.”, and concluded that this was due to agglomeration of particles in the bed ash. Unfortunately they did not describe the nature of these agglomerates, so it is not known if this was due to the formation of char-sand agglomerates (as described by Miccio et al, 1989), or due to partial melting of the coal ash. They concluded that the proposed project was both technically and economically viable.

A “desk top” study was undertaken by Anthony (1995) where he reviewed the utilisation of alternative solid fuels in FBCs throughout the world. His study included the utilisation of petcoke, coal mining wastes (including SA research), paper/pulp, agricultural and industrial wastes. He concluded that FBC was a versatile technology capable of utilising a wide range of fuels, and that petcoke and waste coal are of special economic importance. He indicated that challenges lay in the control of Nitrous Oxide (N_20) emissions and, for some fuels, in the control of slagging or fouling.

Hupa (2004) listed Foster Wheeler and Kvaerner Power (now Metso) CFBC and BFBC projects between 2001 and 2002. 13 CFBC projects were listed, ranging from 44 to 689 MW_{th}. There was a range of fuels: one fired by brown coal (lignite), one by coal and peat, two by coal and petcoke, with the rest being biomass fired or co-fired. 11 BFBC projects were listed, ranging from 36 to 269 MW_{th}, with all being fired by a combination of biomass wastes. This shows the trend towards the application of FBC, and especially of BFBC, to the utilisation of waste and biomass fuels.

Hupa (2004) concluded that although one of the great advantages of FBC was the ability to burn a wide range of materials, unexpected ash behaviour and fouling can occur due to interaction between the ashes of the various fuels. He stated that often the only way to fully understand the firing properties of the fuel mixtures is to test the fuel mixture in a pilot plant or full-scale boiler.

BFBCs cannot compete with CFBC at utility scale. However, many vendors offer mature BFBC technology for smaller scale applications, in particular for firing or co-firing wastes or biomass fuels. Companies that are very active in this field include

Foster Wheeler, Metso, Energy Products of Idaho (now trading as Outotec), Thermax and BHEL. Details of these companies and their respective products can be found on their web sites. Thermax, in particular, has a great deal of experience in burning biomass in BFBCs and has developed a database on the behaviour of these fuels in BFBCs.

Atimtay and Kaynak (2008) conducted pilot scale BFBC test work on a mixture of lignite and peach and apricot stones. The biomass fraction was varied from 0% to 100%. They noted that when burning the peach stones and lignite mixture, from 25% peach stone up to 75% peach stone, the combustion efficiency stayed constant at 98%. When burning Apricot stones at the same ratios. however, the combustion efficiency dropped from 96.9% to 94.68%. Their explanation for this was an inherently lower combustion efficiency for apricot stones because of higher losses in the form of carbon monoxide (CO). They concluded that the stones could be successfully utilised, but the fraction of the stones in the feed should be less than 50% in order to comply with European Union emission limits.

Saidur et al (2011) gave a comprehensive overview of types of biomass, preparation methods and utilisation technologies. This article is an excellent reference for the properties of biomass fuels, such as Proximate and Ultimate analyses, CV, ash constituents etc. They concluded that of the possible combustion technologies, FBC would be the best technology. This was a feasibility study, and did not therefore include combustion data on the fuels. However, the potential for biomass utilisation is great, as they estimate that the power potential of residues from existing agricultural practices is in the region of 42 000 MW of electricity.

Not only can FBCs utilise multiple fuels, they can also produce multiple products. Goldstein et al (2003) reported on an integration of a 150 MWe CFBC with other technologies to utilise waste coal (or discards) while generating steam and/or electricity and building materials.

Castleman and Mills (1995) reported on the operation of a 80 MWe power plant, which incorporates two 180 t/h CFBC boilers. The fuel fired is “GOB”, essentially what would be referred to as Discards in South Africa. The CV of the fuel ranged from 8.4 MJ/kg to 19 MJ/kg. The ash content ranged from 40% to 65%. The thermal efficiency (referred to as boiler efficiency in the paper) was reported as 80%. The plant successfully passed performance testing and went into commercial operation.

Singh and Chauhan (1995) gave an overview of the Indian coal and reject coal situation, the potential to produce electricity from this via FBC power stations and some operating FBCs. The reject coal is of low CV, ranging from 6.7 MJ/kg to 11.3 MJ/kg. The ash content can be as high as 70%. They reported successful utilisation of this fuel in three operating BFBC plants. A thermal efficiency of 79% was achieved. They calculated that the power potential of coal washery rejects is in the region of 1900 MW.

A recent development is the incorporation of "oxy-fuel firing" into FBC design and operation. This is a CO_2 capture technology, and can be applied as a new build or a retrofit. It is essentially closed-loop combustion, where a large portion of the exhaust gases are recycled back through the distributer and into the combustion zone. Pure oxygen is added to these recycled gases to produce a gas stream with an oxygen content similar to air, 21%, but the balance being CO_2 rather than N_2. The result is that the exhaust gases have a very high CO_2 content, which can then be sent for sequestration.

Jia et al (2012) retrofitted and commissioned a pilot scale (0.8 MW_{th} CFBC at CanmetENERGY. Extensive trials were carried out on this unit, and they reported stable operation and the successful utilisation of a range of fuels including coal, petroleum coke and lignite. They also reported poor sulphur capture, but as yet they do not understand why this was so. Further research is being conducted on this.

Foster Wheeler (Hotta et al, 2011) state that oxy-fuel firing is now being developed an option on their CFBC boilers. They offer a a technology, trade-named Flexi-Burn, to provide flexible operation both in normal air mode and in oxy-fuel mode. A 30 MW_{th} boiler is being developed to prove the pilot scale results at a larger scale.

Both CFBC and BFBC are now mature technologies, capable of competing with "conventional" technologies such as PF, but with the added benefit of being able to burn a wide range of fuels, and to reduce gaseous emissions such as SO_2 and NOx.

The research presented in this thesis was aimed specifically at the utilisation of low grade South African fuels in BFBCs.

2.3.2 South Africa

In South Africa, the adoption of FBC technology has lagged behind Europe, the US and Asia.

Although not a deployment of FBC, a notable bold proposal was made by MacGillivray (1979). He proposed that a central FBC power station be built in the Witbank area to produce about 1200 MW of electricity from discard coal delivered from the surrounding mines by conveyor belt.

Research was undertaken at a bench scale by the CSIR in 1983 to 1985. Hamman (1985) investigated the combustion of discard coal in a fluidised bed. His work concentrated on trying to understand the devolatilisation and char combustion characteristics of a duff coal from Tavistock colliery and a discard coal from Rietspruit colliery.

This work was followed up by the National fluidised Bed Combustion (NFBC) project, also at the CSIR (Eleftheriades, 1984). The scope of work undertaken in this project was extensive, investigating the combustion and thermal efficiency of duff and discard coals, and coal slurries. The ability of FBC to capture sulphur oxides (SOx) was also investigated. The coal (duff, discards and slurries) research contained in this thesis was conducted by the author in this test facility.

A number of researchers have investigated the combustion of discard coal in bench scale FBC facilities (Hamman, 1985; Petrie, 1988).

An early attempt at comparing FBC and conventional boilers was undertaken by the CSIR in 1990 (North, 1990). The conclusion was that FBC was not at that time competitive with conventional boilers, due to perceived risk and higher capital and operating costs. These higher costs and perceived risk were in turn due to lack of experience with FBCs. It was forecast that FBC would be applied in niche applications such as “problem fuels”, for 10 to 15 years, but then could become competitive with conventional boilers as adoption of the technology “snowballed”.

The viability of converting a chain grate boiler to FBC was assessed by the CSIR in 1991 (North, 1991). This purely theoretical study proposed various options, including an external BFBC with in-bed steam generation that would increase the total steam output.

An overview of FBC research and development carried out at the CSIR was presented in 2005 (Hadley and North, 2005). This publication covers the industrial plants designed by the CSIR and also the process development work undertaken in pilot and bench-scale facilities. A key conclusion was that invaluable experience can be gained by working as a team with clients.

Concerning sulphur capture, Petrie (1988) conducted batch laboratory scale trials on South African sorbents in a laboratory FBC. His work showed that the physical properties of the sorbents, in particular their friability in the bed at operating conditions, can play a greater role in their efficacy than does the calcium content. The results of industrial scale sulphur capture tests were reported in 1988 (Petrie and North, 1988).

Krupp engineering supplied a semi-commercial fluidised bed to Highveld Steel and Vanadium in 1988. This was a pilot plant, intended to show the feasibility of producing gas from discard coals sourced from the surrounding mines. This project was unfortunately not a success due to low carbon conversion and clinkering which occurred near the oxygen injection nozzles.

Babcock Engineering built a large bubbling FBC boiler at AECI Modderfontein. The purpose of this boiler was to combust the carbonaceous flyash from a Koppers-Totzek gasifier. This flyash was in the form of a filtercake. When it came to commissioning the boiler, the performance of the gasifier was better than expected, with a corresponding lower carbon content. It therefore proved difficult to fire the boiler on flyash alone, and coal was co-fired with it. Subsequently the gasifier, and therefore the flyash, has been discontinued as it was found to be uneconomic and the boiler has continued to fire coal only since then.

Babcock Engineering also built two 80 tph (steam) bubbling FBC boilers at Soda Ash Botswana in the mid 1980's. These were designed to burn the local Morupule coal. This is a commercial coal product. However, a high shale content in the coal led to excessive erosion of the in-bed tubes. A considerable amount of materials research and development was undertaken, which led to achieving an acceptable tube life. These boilers are still operating.

The CSIR designed and supplied a BFBC hot gas generator in 1988. (North et al, 1990.) This BFBC, rated at 14 $MW_{th,}$ utilised duff coal to generate hot gases which were used to dry slag from a blast furnace which was then milled and blended with cement. This project was a technical and commercial research, and received the South African Institution of Mechanical Engineers' Projects and Systems award in 1990.

In 1992/1993 the CSIR designed a BFBC to co-fire a biomass sludge containing 85% moisture with coal to generate 26 t/h of process steam (North and Eleftheriades, 1997). This was a complex design, requiring both theoretical energy balances over the bed, the freeboard and the boiler, and test work before the boiler could be designed confidently. It was successfully commissioned and put into operation in 1994. The project was awarded the South African Institution of Chemical Engineers' Innovation award in 1994.

A BFBC High Sulphur Pitch (HSP) incinerator was designed by the CSIR and supplied to Sasol in 1995/1997. (North et al, 1999.) This FBC was designed to incinerate 2 t/h of a High Sulphur Pitch. The injection of a liquid fuel into the fluidised bed was problematic, and required a great deal of test work to develop a suitable technology. Over 85% of the sulphur was captured *in-situ* though the addition of limestone.

Shortly after the design of the HSP incinerator, a BFBC deodoriser was designed by the CSIR for African Products in Meyerton. (Uys et al, 1999.) This FBC was designed to deodorise an air stream coming off a grain drying system. The chief challenge in this design was using warm air at 100% humidity, and therefore relatively low oxygen content, to fluidise the bed. The plant was successfully commissioned and put into operation.

Scientific Design have supplied a large number of compact FBC Hot Gas Generators to the minerals and agricultural industries. Key features of their design were a fast start-up (through direct gas injection into the bed) and the "Caretaker mode", which allowed the plant to maintain the bed in a hot condition, thereby enabling a rapid start-up even after an extended period of non use. These FBC's have been designed to use good quality, graded coals.

ESKOM commissioned an in-depth feasibility study for re-powering the mothballed unit 7 at Komati power station with a discard coal-fired FBC. This was undertaken by Black and Veatch (Black and Veatch, 2000). The study indicated that the repowering was feasible, with the feasibility depending heavily on the availability of “free” discard coal and the availability of sorbent within about 150km of the power station. However, the decision was made to repower the unit with the original coal combustion technology of PF. This was because at this stage there was still no obligation to reduce sulphur emissions, and the capital expenditure of the repowering back to PF would be less.

Babcock Engineering have recently successfully designed, built and commissioned two BFBCs in KwaZulu-Natal. One, at Sappi Tugela is a retrofit to an existing boiler. It is designed to burn wood waste from the paper mill and coal. The second, at Mondi Merebank (Durban) is a “multifuel boiler”, designed to burn wood and sludge wastes from the paper mill, coal and gas. It also has the capability to re-burn the ash from old coal fired boilers, to improve combustion efficiency and lower the carbon content of the residual waste ash. These boilers utilise a biomass stream that has been partially dewatered through use of clarifiers and presses, and the sludge contains approximately 62% water. In this respect these boilers differ from the research presented in this thesis, where a biomass stream was combusted as it was formed, still containing approximately 85% water. Both of the Babcock multifuel boilers are operating successfully.

Moodley (2007) reported on test work carried out with South African discard coals in a pilot scale BFBC. The coals are referred to as A, B and C for confidentiality requirements. The coals were combusted with and without a specific sorbent. He reported a high sulphur capture (90%) for “Coal A”, over a wide bed temperature range. The Calcium to sulphur ratio was kept constant at 1:1 for all sorbent tests. His work was aimed at determining the performance of different coals with a specific sorbent, whereas the sulphur capture research presented in this thesis determined the performance of various sorbents with the same coal, at a range of calcium to sulphur ratios.

The most recent application of FBC technology in South Africa known to the author is a project which is still underway. A company is installing two BFBC 30 t/h steam boilers in Newcastle, KwaZulu-Natal. (Kruse, 2012.) The design fuel is discard coal which is available locally. Phase 1 of the project is to supply only steam, but in phase 2 it is envisaged that the boilers will be operated as co-generation plant, and electricity will also be generated. The CSIR (and the author) contributed to the process development for this project by conducting FBC test work in pilot plant facilities.

Pilot scale Fluidised Bed research facilities exist at the CSIR, Eskom, Mintek (primarily for minerals treatment), Sasol (for Fischer-Tropsch reaction research), the University of the Witwatersrand, North West University, the University of Pretoria and the University of KwaZulu-Natal. None of these are industrial scale plants.

From this literature review, it is apparent that no industrial scale research has been carried out in South Africa to determine the performance of reject/low grade South African coals and waste materials in an FBC. The research carried out and presented in this thesis is novel, and is still relevant today.

2.4 Author's contribution to FBC and coal research and development

Following is a summary of a selection of reports, papers, publications etc. developed over a number of years in the field of coal utilisation and FBC. They are intended to show a progression, and application of knowledge gained to expand the boundaries of the application of FBC technology.

These are presented in full as Volume 2 of this thesis presented to the University of the Witwatersrand.

An investigation into the comparative results obtained from boiler tests using the direct, indirect and loss methods of calculation

CSIR report CCOAL 8531
Year: 1985
Authors: D Clark and B North
This report shows the generic method to test the performance of a boiler. In this instance it was applied to a "conventional" chain grate stoker fired boiler. This report illustrates the three methods that can be used , namely the direct, indirect and loss

methods. It also illustrates the laborious hand calculations used at the time. It could take up to one day to calculate the results of a test.

A report on an investigation into the combustion of various coals in a chain grate stoker fired boiler

CSIR Report COAL 8514
Year: 1985
Author: B North
This is an example of a report which would be written after a series of tests has been concluded. This series was aimed at investigating the relative performance of pea sized coal versus “smalls” in a chain grate stoker fired boiler, and proved that the efficiency obtained with smalls coal was significantly less than with pea coal. It was carried out in cooperation with the Department of Mineral and Energy Affairs and the Transvaal Coal Owners Association. This research was key in deciding the pricing structure of the two grades of coal.

Boiler test calculation, as used on the chain grate stoker fired boiler (John Thompson Afripak Mk II)

CSIR report ICOAL 8602
Year: 1986
Author: B North
The key item of interest in this report is the presentation of the computer programme written to replace the laborious hand calculations. It gives the user the option of using either the direct or indirect methods, and takes a few minutes to run. A full print-out of input data and output calculations is generated. This programme was used, with minor modifications to include extra ash streams and steam superheat, for the tests on the National Fluidised Bed Combustion boiler.

Special plant features and their effect on combustion of waste coals in a fluidized-bed combustor

1987 International Conference on Fluidised Bed Combustion (FBC Comes of Age)
Year: 1987
Authors: C Eleftheriades and B North
This paper presented some of the very early research carried out on the National Fluidised Bed Combustion boiler. Plant features such as inbed and overbed fuel firing, cyclone grit re-firing, recycling of flue gas and sorbent feeding (to effect sulphur capture) were investigated. An understanding came from this research that each fuel has its own characteristics, and the FBC has to be designed with these in mind in order to optimise efficiency and operability.

Effect of sorbent selection on $S0_2$ emissions from a 10 $MW_{(th)}$ bubbling bed fluidized boiler

4th International Fluidised Combustion Conference
Year: 1988
Authors: J Petrie and B North
Extensive sulphur capture trials were carried out on the National Fluidised Bed Combustion boiler using three different sorbents. The test work was carried out jointly by the CSIR and the University of Cape Town (Energy Research Institute). This research, and the earlier sorbent research indicated in C4, created the knowledge and experience that was later applied in the design of plants using high sulphur fuels and also in calcination plants.

Calcination of Lyttelton dolomite by direct firing with coal in a fluidized bed

CSIR report ENER-C 90006
Year: 1990
Authors: B North and S Saayman
Although limitations were seen with high-ash coal, low grade dolomite and the use of a boiler rather than a purpose-built calciner, this research further expanded the understanding of calcination in fluidised beds. A preliminary design was undertaken for a 100 t/day calcination plant.

Fluidised bed calcination of diatomaceous earth slurry (Project "Sandpiper")

Report generated for Gencor Engineering and Technologies

Year: 1994

Authors: B North and M Heydenrych

This work, and in particular the SEM micrographs of the product, was fascinating. There were many technical difficulties, not the least of which was the very high water content of the diatomaceous earth slurry. The ultra-fine nature of the product and the sodium content were also problematic. Product was produced, but it had to be concluded that a bubbling fluidised bed was probably not the best technology, a circulating fluidised bed would perform better. Extensive modelling showed that thermal management systems such as fluidising air pre-heat could significantly reduce the amount of energy required to calcine the slurry. This research furthered the understanding of both calcination and the feeding of high water content materials into fluidised beds.

Slagment hot gas generator

The Journal of the South African Institution of Mechanical Engineers (Projects and Systems Award edition)

Year: 1990

Authors: B North, A Hamman and C Eleftheriades

The Slagment hot gas generator was the first industrial-scale plant designed by the CSIR. The plant was a 13 MW fluidised bed hot gas generator, which supplies hot gas to a dryer to dry slag prior to milling. It was designed to utilise duff coal, principally because of the (then) low price of such waste coal. It drew on experience gained on the National Fluidised Bed Combustion boiler, and incorporated features such as a low fluidising velocity, a tall freeboard area and the possibility of operating at higher temperatures in order to achieve a high combustion efficiency. (This was a client requirement, as carbon contamination could not be tolerated in the final product, slagment.) Additionally, a deep bed was employed to meet another client requirement that the plant could be shut down for extended periods and re-started without the use of the gas burner. The deep bed could retain enough heat to re-start after a slump of 20 hours. A negative consequence to this was the need for two forced draught fans in series in order to supply fluidising air at a pressure high enough to fluidise the deep bed.

A great deal of learning was obtained from this plant, in particular the design of the air distribution system. The riser and horizontal sparge system was developed for this plant. This was in general very effective, and allowed for bed drainage and use of an under-bed burner for start-up, but it suffered from an unexpected problem, in that the ends of the horizontal sparges (which are in static sand, below the fluidised sand) deformed inwards over time due to continual expansion and contraction from thermal cycling. A re-design to incorporate “shovel ends”, and adding stiffeners to some of the nozzle cap risers successfully solved the problem, and was employed in future designs.

As indicated in the title, this plant received the South African Mechanical Engineers’ Projects and Systems award (category R500k to R1000k) for its innovative design and conformance to demanding client requirements.

Fluidised bed combustion of coffee grounds

CSIR report ENER-C 91071

Year: 1991

Author: B North

This internal report describes the process undertaken to design a fluidised bed combustor to co-fire a biomass sludge with coal to achieve both incineration of the sludge and generation of process steam. It is described in detail in the dissertation, and will not be discussed in detail here.

The design of this plant, which was highly problematic, and indeed was a world-first, was made possible through the accumulated experience gained in burning coal and high water content materials in fluidised beds. Conservative fluidising velocities, a deep bed, an un-cooled combustion zone and a large freeboard area were employed. The need to adequately disperse the sludge over the bed was known from past experience, and injection nozzles based on research into firing slurries were designed and employed. In turn, experience gained from the design of this plant was that in such problematic and high technical risk applications a systematic step-wise approach can reduce the technical (and financial) risk, and can enhance the design and operability of the final plant.

The plant received the South African Institution of Chemical Engineers Innovation award in 1994.

Biomass fluidized-bed combustion boiler; Estcourt, KwaZulu-Natal

Operators training course notes

Year: 1993

Authors: B North and C Eleftheriades

Despite the biomass sludge and coal co-fired boiler being designed to be as "operator friendly" as possible, there was still a need to train the operators in its operation. A large part of this was to introduce them to the concept of fluidisation and fluidised bed combustion, as many had operated boilers, but of chain grate and underfeed stoker designs. The course was extremely successful, and we received very positive feedback from the attendees. This was a change of mode for myself, from researcher to teacher, which in itself was very valuable experience.

Acknowledgement is given to John Thompson Boilers and Skelton and Plumber Controls for their contribution.

Slurry combustion and coal drying in fluidised beds

The Journal of the South African Institution of Mechanical Engineers, March 1994

Year: 1994

Authors: B North and A Engelbrecht

This article combined and presented the experience gained in burning slurries in fluidised bed combustors and in drying coal and even slurries in fluidised beds. The combustion research was carried out by myself, and the coal drying research was carried out primarily by Engelbrecht.

Incineration of a biomass sludge in a bubbling FBC

14th International conference on Fluidized Bed Combustion

Year: 1997

Authors: B North and C Eleftheriades

This paper introduced the award-winning biomass sludge combustion research, design and implementation to an international audience. It was well received, and through this and presentation of subsequent work on fluidised bed deodorising, lead to international contracts for fluidised bed system development.

Design and control of a 12 MW coal-fired fluidised bed deodorising and steam generation plant

15th International Conference on Fluidized Bed Combustion

Year: 1999

Authors: B Uys, B North and C Eleftheriades

This work, not presented in the dissertation, was another example of applying fluidised bed combustion to solve a process problem while supplying plant steam. In this case a coal-fired fluidised bed combustor was fluidised by the air coming from a drying circuit in a maize processing plant. The air was at 100% humidity and was odorous. In order to avoid an excessive energy penalty in approaching the deodorising as a single goal, a system was designed that used the odorous air as the fluidising medium, thereby deodorising it as it passed through the hot fluidised bed, and generated steam from the exhaust gases in a shell boiler. Again, past experience in coal firing and handling high moisture fuels and high moisture content gases played a significant part in designing this plant and, despite it being unique, it was designed, constructed and commissioned well within schedule and budget.

Destruction of a high sulphur pitch in an industrial scale fluidised bed combustor

15th International Conference on Fluidized Bed Combustion

Year: 1999

Authors: B North, C Eleftheriades, A Engelbrecht and J Rutherford-Jones

This “Waste to Energy” project concerned the destruction of 2 t/h of a high sulphur pitch which is generated by Sasol in their Sasolburg plant. The pitch has a high calorific value, and could easily be combusted in a heavy fuel oil type of burner. This was in fact the practice at the time. However, this released high concentrations of sulphur oxides, in the region of 4000 ppm in the flue gases. And the hot exhaust gases were sent straight to atmosphere, with no energy recovery.

Experience gained in firing liquid fuels into fluidised beds and in capturing sulphur through limestone addition was employed to design a plant that effectively incinerated the pitch and captured up to 90% of the sulphur as gypsum. Also, learning from the risk-reduction step-wise approach taken when designing a biomass and coal co-fired fluidised bed boiler, extensive test work was carried out before the final plant was designed. Features such as a deep bed (to allow residence time of the pitch in the bed and to provide a longer residence time of sorbent), a large freeboard to allow full combustion of volatile matter before passing to a boiler and the injection lances were incorporated based on previous experience with problematic fuels.

Since the plant is designed to capture sulphur, the combustion temperature (at 850 ℃) is lower than in a conventional burner-type incinerator, and steam is generated from the off gases it can be claimed that this plant effectively reduces SO_x, NO_x and CO_2 emissions.

Experience gained in bench-scale and pilot-scale fluidized bed processing

Industrial Fluidisation South Africa 2005

Year: 2005

Authors: T Hadley and B North

This paper is a useful summary of the role of test work (which obviously requires test facilities) in successfully designing fluidised bed systems. It covers some of the high-profile developments such as a biomass and coal co-fired boiler and a high sulphur pitch incinerator, but also covers smaller research and development work such as calcination and sulphide roasting, all of which benefited from previous experience and added to the armoury for future designs.

Waste to energy by fluidised bed combustion

Wits Coal Combustion Course, 2010

Year: 2010-10-14 Authors: B North and A Engelbrecht

This presentation is based on two case-studies on waste-to-energy, namely a biomass and coal co-fired boiler and a high sulphur pitch incinerator. These are described in detail elsewhere.

The purpose of including this here is to show that the experience gained over many years is being disseminated, and will hopefully enhance the adoption of fluidised bed technology in South Africa for waste management and energy generation applications.

FB conversion of a chain grate boiler (Phase 1 – feasibility study)

CSIR report ENER-C 91013

Year: 1991

Author: B North

This purely theoretical study was aimed at evaluating if a conventional chain grate boiler could be retro-fitted with a fluidised bed combustor to utlise low grade fuels. Some fluidised bed boilers of a shell-type with internal fluidised beds have been marketed and purchased but, in general, these failed to utilise graded coal effectively never mind high ash or high fines content coal. Various options for an FBC retrofit were considered, including internal and external beds. Space permitting, an external bed is the much better retrofit option, and can even result in additional steam production, if the external bed employs heat transfer (steam generation) surfaces.

Techno-economic evaluation of FBC and conventional boilers

CSIR report ENER_C 90046

Year: 1990

Author: B North

Here an attempt was made to compare fluidised bed and conventional boilers to show that there can be an economic incentive to installing a fluidised bed boiler. Factors included were the cost of fuel, the cost of desulphurising (FGD for conventional boiler, "in-situ" capture with fluidised beds), operability etc. The major conclusion was that for high quality coal there is little incentive to use fluidised bed boilers, as conventional boilers are well-proven and are cheaper due to (relative) mass production. But, reducing coal quality and increased environmental legislation, both of which are a reality, could change the picture significantly.

Techno-economic and environmental review of alternative energy resources (for SA)

CSIR report PTC-05-032

Year: 2004

Authors: Many

This was a large project, which was undertaken for two reasons. The first was the results of the study itself, and the second was the effect it had in bringing together the various disparate energy researchers at the CSIR. Many researchers contributed to the study. My role was as project manager and as author of a section on Clean Coal Technology. The report, at over 300 pages, is too large to include, so only the executive summary and table of contents have been included in Volume 2.

The study showed:

- Coal, despite the negative image it has as a polluting energy technology, must continue to play a large role in the South African Energy mix. We simply cannot ignore the huge asset we have in terms of coal resources. But, modern coal-fired boiler technology such as pulverised fuel and fluidised bed boilers operating at supercritical and ultra-supercritical steam conditions, integrated gasification combined cycle (IGCC) and carbon capture and storage must be considered.

- Solar is the single biggest renewable energy resource that South Africa has. We have the best solar insolation (**in**cident **sol**ar radi**ation**) in the world, and some of our worst sites rival areas in Europe that are currently being developed for solar energy plants. Despite the current high capital cost of solar power stations this must be a high priority for South Africa. It could also become a national industry, in the same manner that Germany and Denmark are benefitting from their proactive approach to wind energy.

- Wind energy is a low-grade and erratic resource in South Africa. However, it should be noted that since this report was written further resource mapping studies have been undertaken, and a study to investigate the establishment of a wind energy industrial sector has also been completed recently by the CSIR.

- Hydropower is a low-level resource in South Africa, but the possibility of bringing power down from the Congo should be considered when greater political stability is achieved in the area.

- Waste-to-energy, and in particular utilisation of municipal solid waste, should receive much more attention than it currently is. Utilisation of discarded agricultural residue alone could meet South Africa’s (admittedly modest) renewable energy targets.

- Nuclear will play a role, but this will probably be dictated more by public opinion than technology.

Investigation into the gasification characteristics of South African power station coals

Pittsburgh Coal Conference (Johannesburg, 2007)
Year: 2007
Authors: A Engelbrecht, B North and T Hadley
This work represents a new direction for the Clean Coal Technology research group at the CSIR, ie coal gasification rather than combustion. The purpose is to understand the behaviour of selected South Africa power station coals in a fluidised bed gasifier. The research has been promising, and shows that gas of a calorific value suitable for utilising in a gas turbine can be produced through relatively mild oxygen enrichment of the fluidising air stream, rather than going to the expensive option of using pure oxygen.

Fluidized bed gasification of selected South African coals

The Journal of the South African Institute of Mining and Metallurgy, May 2010
Year: 2010-10-14
Authors: A Engelbrecht, R Everson, H Neomagus and B North
This is an expansion on the research presented at the Pittsburgh Coal Conference . Again, IGCC is highlighted as a strong technology contender for future power stations. The different coals tested, however, showed significantly different performance in terms of carbon efficiency and gas quality. This is related to properties such as coal rank, with higher rank coals showing reduced reactivity. Thermal shattering of the coal, which correlates with the grindability indices of the coals, also plays a role in carbon utilisation.

Study on the structure and gasification characteristics of selected South African bituminous coals in fluidised bed gasification

Fuel Processing Technology
Year: 2010
Authors: B Oboirien, A Engelbrecht, B North, V du Caan, S Verryn and R Falcon

This research concentrates on the effect of fundamental properties of the coals such as the inertinite and vitrinite maceral content. The microstructural changes that occur in the coal particles over the gasification process are evaluated. Additionally, the role of inert material (ash), linked to the inertinite content, in affecting carbon utilisation is investigated. A significant difference in the behaviour of the coals tested has been seen.

3 EXPERIMENTAL AND ANALYTICAL TECHNIQUES

As indicated previously, the research covers a number of different low-grade fuels. The materials tested, facilities used and the experimental procedures followed to undertake the research are indicated below.

3.1 Materials sampled and tested

The research undertaken in this dissertation included the performance of coal waste products and biomass materials in FBC systems. The materials tested are as follows:

- Boschman's duff
- Tavistock duff
- Greenside discards
- Utrecht anthracite discards
- Biomass sludge (coffee grounds)

Anthracite is a high rank coal with a volatile matter content of less than 10% and is defined by a Vitrinite reflectance of greater than 2 per cent RoVrandom (Falcon, 1986).

The analysis of each material is given in Appendix A and is further discussed in the following chapters.

3.2 Test facilities for large scale test work

The majority of the research discussed in this dissertation was conducted on the National Fluidised Bed Combustion (NFBC) boiler (figure 3.1 below). This was an industrial BFBC scale boiler, funded by the Department of Minerals and Energy and project managed/operated by the CSIR. The primary purpose of this research was to assess the ability of FBC boilers to utilise low grade, or waste, South African coals. A picture of the NFBC boiler and a schematic side view of the NFBC can be seen in Figures 3.1 and 3.2 below

Figure 3.1 The NFBC test boiler

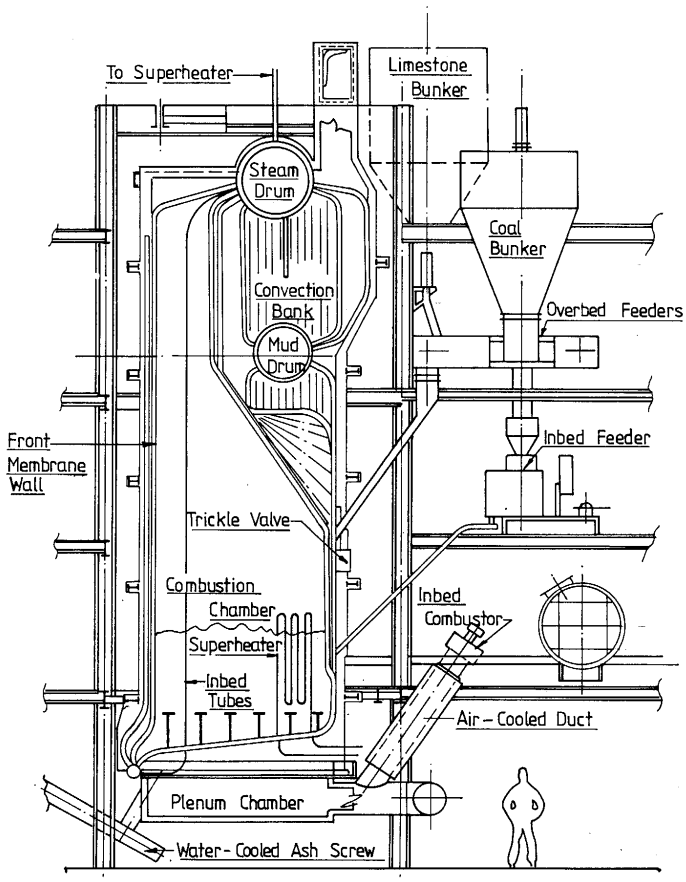

Figure 3.2 Schematic side view of the NFBC boiler

The NFBC is described in detail in the tender document produced by the chosen supplier (Elgin, 1982). Features and details of major components and the control system are given below.

Steam generation: Steam was generated in a two-drum (the steam drum and the mud drum) natural circulation boiler. The steam was superheated using vertical in-bed superheaters. The NFBC was designed to produce 12 t/h of steam from discard and duff coal at a steam temperature of 255 ℃. Sin ce this is a research boiler the steam was not utilised, but was condensed in an air-cooled condenser.

Fluidised bed: The bed was square, with dimensions 3.05 m by 3.05 m. The static bed depth was nominally 800 mm, with an expanded bed depth of up to 1500 mm. The freeboard height was 4.5 m. The bed was divided into five zones for ease of load control. The primary zone was always operational, and the other four could be fluidized as load increased. The superheaters were also included in two of these zones.

Distributor: The distributor was water cooled. Air was supplied to the bed through stand-pipe nozzles located in the fins of the distributor panel.

Start-up system: Start-up was effected by a diesel burner which was fired into the refractory-lined plenum of the primary zone.

FD and ID fans: These were constant speed fans, with air/gas flow being controlled by dampers. The FD fan was rated at 150 kW and the ID fan was rated at 90 kW.

Gas handling and de-dusting equipment: This consisted of primary and secondary cyclones and a bagfilter. Fly-ash could be mechanically returned from the primary cyclone to the bed. Additionally, internal fly-ash recirculation was achieved by employing a trickle valve after the boiler bank. An airheater was situated after the secondary cyclone, before the bagfilter, in which the boiler feed water was heated.

Coal and sorbent feeding: Coal was fed overbed by two screw conveyors. The screw speed was measured and coal feed rate was calculated based on calibration runs. However, the coal feed rate for the purposes of calculation of thermal efficiency was derived from load cells which supported the 15 t capacity coal hoppers. Sorbent was fed from a separate hopper but was blended and fed with the coal in the screw conveyors.

The NFBC was supplied with an in-bed coal feeding system, designed to be able to inject duff coal against the positive pressure below bed height, but this system proved very troublesome and was not employed.

Bulk coal and sorbent storage and handling: Coal was received by rail truck and transferred to a concrete storage bunker of approximately 100 t capacity. Sorbent was stored in a walled-off section of this bunker. The coal was transferred by conveyor to the coal hoppers situated at the boiler. If the coal needed to be crushed it was first sent to a hammer mill to crush it down to below 6 mm.

Control system: The boiler was controlled by a PROVOX Distributed Control System (DCS). This provided great flexibility in the control of the boiler. All valves, dampers etc, could be controlled from the control panel in the control room. All data such as temperatures and pressures were fed back to the PROVOX. These were displayed and trended. All important plant parameters were sent to a PC via an RS232 interface for recording and further processing. Temperatures were measured by type K thermocouples and Resistive Temperature Devices (RTDs). Pressure and differential pressure transmitters were used to monitor variables such as steam pressure and bed pressure drop respectively.

The design operating parameters of the NFBC are given in Table 3.1 below.

Table 3.1 NFBC boiler design operating parameters

Parameter	Unit	Value
Steam Flow	kg/h	12000
Steam conditions		
Pressure	MPa	1.5
Temperature (superheater)	°C	255
Feedwater temperature	°C	95
Bed temperature	°C	780-900
Bed Dimensions	m	3.05 X 3.05
Freeboard Height	m	8
Superheater Area	m^2	2.35
Sulphur Capture	%	80
Boiler Turndown	-	3:1
Boiler Efficiency*	%	80
Freeboard Velocity (max)	m/s	1.9
Flue Gas Exit Temperature	°C	170

* The Boiler (or Thermal) Efficiency is the energy given to the Boiler Feed Water to generate steam as a percentage of the energy in the coal which is fed to the boiler. This is described in detail in section 3.8.4 and in Appendix B.

3.3 Test Facilities for Small Scale Test Work

Where small scale trials were required before proceeding to large scale trials, the CSIR's "Multi Purpose FBC" (MPFBC) was used. The MPFBC is shown in Figure 3.3 below. It was designed by the author to investigate wide fields of FB processing, such as combustion, calcination and minerals processing.

Figure 3.3 The Multi Purpose FBC Pilot Plant

The MPFBC, also a BFBC, has internal bed dimensions of 0.75 m by 0.5 m (bed area 0.375 m^2) and is 4 m high. It is refractory lined, and is not designed to generate steam. A flowsheet of this plant (as set up for trials burning High Sulphur Pitch, (section 4.5.3)) is shown in Figure 3.4 below.

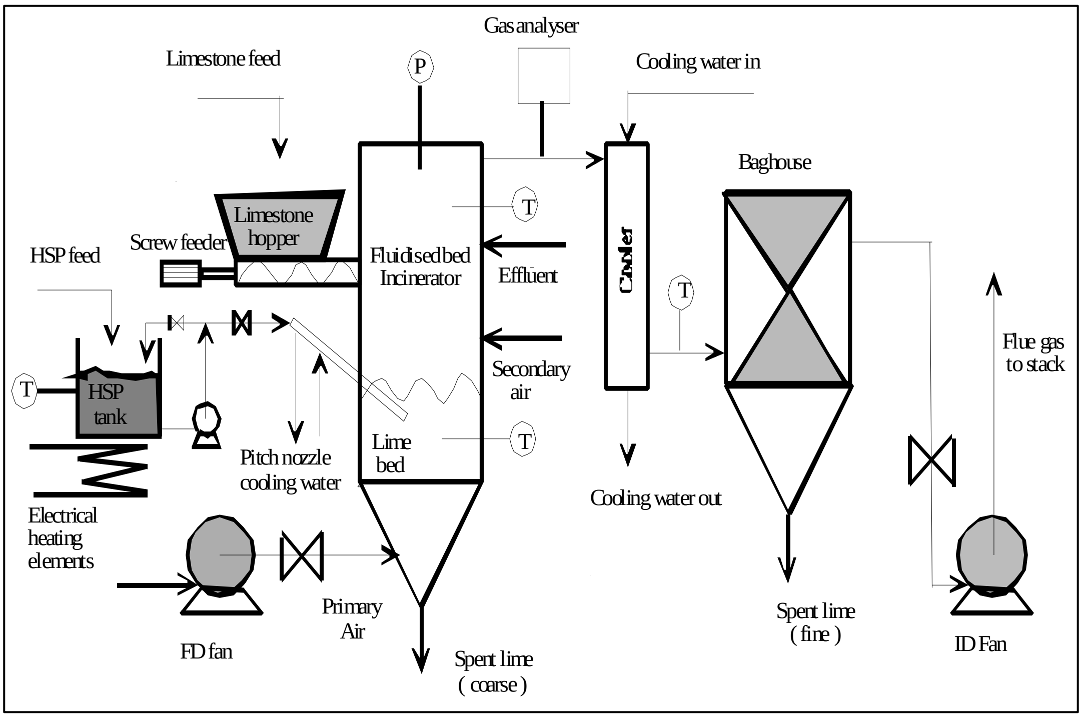

Figure 3.4 Flowsheet of Multi Purpose FBC Pilot Plant

Fuel and sorbent can be fed at two different heights above the bed. Liquids can be injected overbed or inbed. Ash and/or spent sorbent is removed from the bottom of the bed, below the distributor. Flyash is removed from the cooler and the baghouse.

Under combustion conditions, approximately 60 kg/h of coal can be burnt.

Although it is not equipped with a control system as sophisticated as a DCS, all necessary temperatures and pressures are monitored. Temperatures are measured by type K thermocouples and pressures and pressure differentials are measured by manometers.

It is equipped with both forced draft and induced draft fans, and furnace draft is controlled by manually balancing these by adjusting dampers. The fans are capable of fluidising the bed at 2 ms^{-1} at 850 ℃, which equates to approximately 6500 Nm^3/h.

Bed height can be controlled by use of a stand-alone Proportional-Integral-Derivitive (PID) controller.

Bed temperature can also be controlled at a set point my means of a PID controller.

Start-up is by means of direct gas injection through the air distribution nozzles, with an overbed ignition lance.

3.4 Experimental procedure for Thermal and Combustion Efficiency trials (Duff and Discard Coals)

The thermal and combustion efficiency trials are the most frequent tests carried out on the NFBC, and also perhaps the most difficult. The difficulty lies not in the combustion of the coal, but rather in the accurate retrieval of data and samples and adherence to a strict procedure. The test procedure on the NFBC was developed by the author to a point where accurate, repeatable results could be obtained. This procedure is as follows:

A period of time, ranging from one to four days, depending on circumstances such as coal type and test constraints, is taken to set the boiler up on the test coal. The aim is basically to simulate the conditions of the planned test, in terms of bed temperature, recycle ratios, excess air, etc. Once stable conditions have been reached, the boiler is run for the rest of the day in order to ensure that it is stable and also to maintain the bed and heat transfer surfaces at high temperature. At approximately 18h00 on the day on which stable and optimal conditions have been reached the bed is slumped at running temperature.

The bed depth is physically measured the following morning before restarting at 05h00. Because of the relatively deep bed (800 mm to1000 mm) the bed temperature will only have dropped by 100 ℃ to 200 ℃ overnight. The test coal is again fed to the boiler and the bed is brought back up to the required temperature. The boiler is then set to the required conditions and allowed to stabilize. This will generally take 1.5 to 2 hours. The boiler is run for approximately 3 more hours, to ensure "thermal soaking" before the test is started at 10h00.

A test sheet is written out for each test in which all aspects of the test are detailed. This is discussed with the plant superintendent and technicians a day or two prior to the test to ensure that the correct procedure is followed at the start of the test.

Immediately the test starts, the ash streams (Primary Cyclone Drop-out (PCDO), Secondary Cyclone Drop-out (SCDO), Baghouse Drop-out (BHDO) and the bed material) must be diverted from their normal route to a tared bin. The ashes flow to these bins throughout the test and are weighed at the end of the test. The ashes and the coal are sampled every half hour and the samples from each stream are combined to make a representative composite. Where primary cyclone grit re-firing has been employed this recycle stream is also sampled.

Also, immediately on test start, the mass of the coal bunkers, as indicated by four load cells, is noted. Experience has shown that it is necessary to employ load cells as the metering feed screws, although adequate for control purposes, are not sufficiently accurate to provide information on which to base heat and mass balances.

Data is collected throughout the 4 hour test. Data capture is generally started two or three hours before the test starts in order to demonstrate that the boiler was in fact stable and also to help in understanding why a test has for some reason failed.

The test is run on a "hands-off" basis, i.e. no changes are made to feed-rates or any of the other operating parameters. Occasionally, this results in a slight decrease or increase in bed temperature over the test. If this is excessive the test is discontinued.

At the end of the test the ash bins are removed and tared again, the rate of each ash stream being determined by difference. The mass of the coal hoppers is again noted in order to calculate the coal feed rate. The boiler is left to run for a further hour, with the computer still collecting data, by way of a final demonstration of boiler stability.

The half-hourly samples are collected and about half of each combined to form a composite sample for each stream. These composites are submitted to a coal analysis laboratory for standard Proximate, Ultimate, Carbon in ash and other analytical determinations. Some of the half-hourly ash samples are also submitted in order to determine if there has been a drift in the carbon-in-ash figure during the test. Upon receipt of the analyses, the information is processed to provide a complete heat and mass balance.

The above procedure covers one individual test, which is part of a series of tests. This series is designed in advance to demonstrate the effect of one plant parameter, generally also related to steam production (load).

For example, if it is intended to establish what effect grit re-firing has on thermal efficiency, a total of approximately eighteen tests would be carried out. These tests would consist of three repeat tests at three loads with and without grit re-firing.

The plant parameters which were investigated in the current research programme were primary cyclone grit re-firing and bed temperature. Re-firing of the primary cyclone grits gives unburnt carbon a second chance to burn. It is seen as being potentially beneficial for both duff and discard coals; duff coal because of high elutriation of carbon due to its high fines content and discard because of its low reactivity. In practice, it proved difficult when burning high-ash discard coal due to the detrimental effect on bed temperature of such a large amount of relatively cool ash being returned to the bed.

It was reasoned that since South African coals have a higher ash fusion temperature than European coals, it should be feasible to run a fluidized bed at a higher temperature than would be considered normal for those coals. The higher temperature is beneficial because of better reaction kinetics leading to better carbon utilization. Previous work at the CSIR (Hamman, 1985) has shown that an increase of 100 ℃ can decrease burn-out time by as much as a factor of 3.

In addition to the combustion of bituminous discard coal, the combustion of anthracitic discards was studied. The discards were obtained from Rand Mines and were from the Utrecht colliery. The basic test programme carried out on the discards was combustion trials to establish thermal and combustion efficiencies. The format of these trials was identical to that detailed above.

One further trial was carried out on the anthracitic discards, and this was to determine the ease of ignition. This test was considered worthwhile because one of the advantages of a deep fluidized bed is the ability to restart the following morning without using a diesel burner to heat up the bed. If the anthracite discards require a considerably higher bed temperature for ignition than duff or bituminous discards, this may cause problems. The test took the following form.

The boiler was allowed to cool down for a 2 day period. Upon fluidization, the bed temperature was found to be 550 °C. This was further cooled, by fluidizing without coal feed to 450 °C. The diesel burner was used to slowly bring the bed temperature up. Anthracite discards were added at maximum coal feed rate for short periods at discrete intervals of bed temperature. The bed temperature and gas analysis (O_2, CO_2 and CO) were observed closely to determine if combustion had occurred. Once these readings indicated that combustion had occurred, the coal feed was stepped up, again carefully watching the instruments. The result of this test is an indication of the ignition temperature of the discards. This is not an ignition temperature as would be indicated by a thermogravimetric analyser (TGA), but it is felt that the results are more useful than TGA figures as they apply to the real situation in a fluidized bed.

3.5 Experimental Procedure for Sulphur Capture Tests

This research was carried out with the Energy Research Institute (ERI) of the University of Cape Town. It built upon previous research conducted by Petrie (Petrie, 1988). In his initial research, Petrie conducted lab-scale batch sulphation experiments to obtain constants indicative of the efficacy of sorbents. The research reported in this thesis was carried out in the NFBC boiler by Petrie and myself, and was intended to evaluate the sorbents under continuous operating conditions, using discard coals.

The coal used for these tests was a representative discard sample from Greenside Colliery with a typical calorific value of 16 MJ/kg, an ash content of 45-48%, and a sulphur content ranging from 2.6-3.3%. The coal was delivered in bulk by rail, and stored in a concrete bunker. It was crushed in a hammer mill to <6 mm before being transferred to the boiler hoppers.

The sulphur capture trials were aimed at determining the relative ability of three South African sorbents to reduce sulphur dioxide emissions. These sorbents were highlighted in Petrie's previous research as displaying a range of sulphur capture efficacy (Petrie, 1988). They were a dolomite (Lyttelton Dolomite), an inland limestone (Union Lime) and a marine limestone (Bredasdorp lime).

In all tests, the combustor bed depth was kept constant at one metre by continuous removal of bed material. The required operating conditions of bed temperature and excess air were achieved through using design features of the NFBC such as bed zones (Eleftheriades and North, 1987). The required Ca/S ratio was achieved by linking sorbent feed rates to the coal flow set point. Both coal and sorbent flows were metered through calibrated screw feeders, with averaged flows checked against load cells attached to the respective feed hoppers.

Sulphur dioxide, carbon monoxide and dioxide were measured by non-dispersive infra-red monitors, whilst flue gas oxygen was measured by a paramagnetic analyser.

The test structure was relatively straightforward. The combustor was allowed to reach steady state operation, whilst burning coal at the desired conditions of velocity and temperature. Sorbent feed was initiated and stepped up at predetermined levels, until steady state SO_2 had been reduced by between 70% and 90%.

3.6 Test Facilities and Experimental Procedures for Coal Slurries

Coal slurry presented unique challenges and, although the same experimental procedure as for duff and discards was followed in terms of evaluating its performance in the NFBC, the specific methodology followed for obtaining, pumping and burning the slurry is discussed within this section.

3.6.1 Slurry procurement

Only bituminous slurries were considered as the production of anthracite slurries is very low.

In terms of selection, it was decided that the Calorific Value (CV) was the most indicative feature on which to base slurry selection. Ash content and volatile matter content are to a great extent dependent on the CV.

A suitable slurry was then sourced. It was impossible to transport the slurry as it was produced, so it was decided rather to recover the slurry from a slimes dam where it is in the form of a filter cake containing approximately 10% water. This imposed some limitations as the colliery had to be willing and able to retrieve the slurry and load it onto trailers. Also, retrieval of material from what is essentially a dump can lead to the inclusion of “tramp” material such as clay and stones.

The slurry first selected was from Tavistock Colliery, but this proved to be unsuitable for reasons which are discussed in more detail in Chapter 4, section 4.2. Slurry was then obtained from Goedehoop Colliery, and this slurry was used for the test work.

3.6.2 Slurry mixing and pumping trials

The slurry was first mixed by hand in a glass beaker to about 60% solids, to enable visual observation of its rheological nature. This is shown in figures 3.5 to 3.7 below.

Figure 3.5 Coal slurry in glass beaker

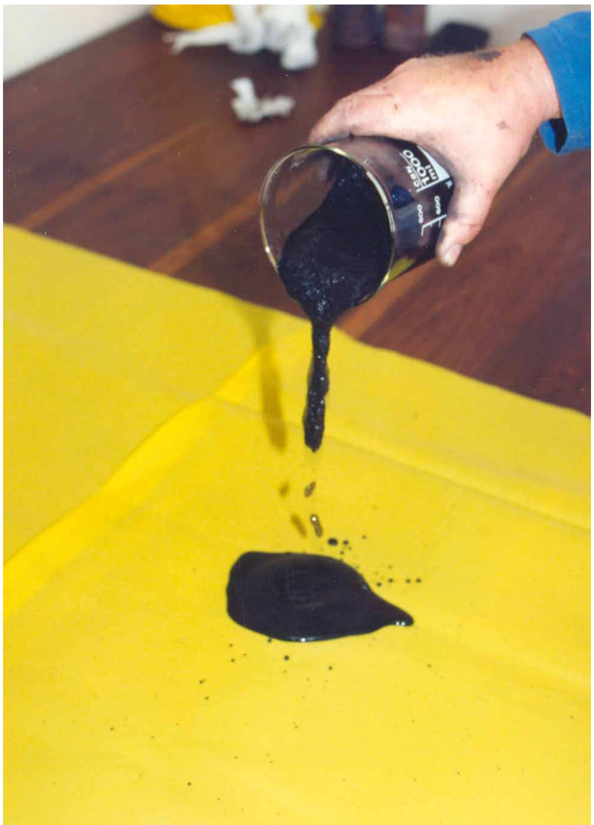

Figure 3.6 Pouring coal slurry

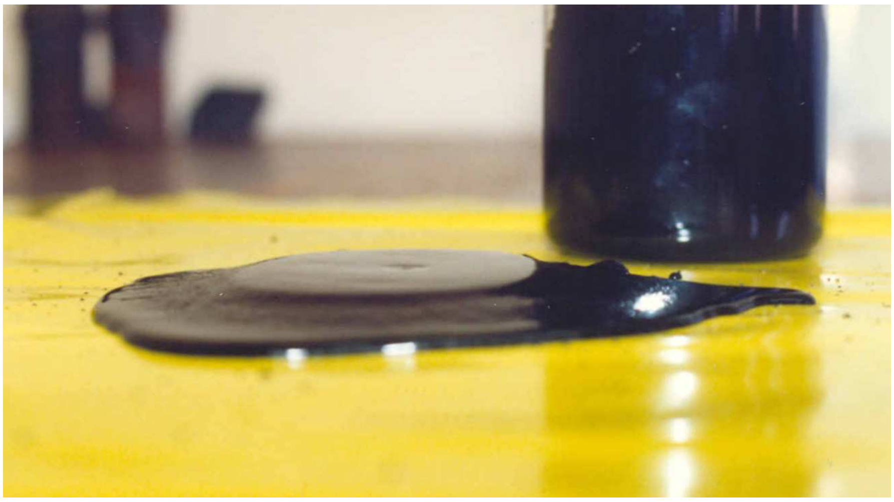

Figure 3.7 Coal slurry after pouring

The slurry exhibited strong thixotropic, or shear-thinning, behaviour.

A cylindrical, conical-bottomed tank of 0.3 m^3 capacity was constructed (Figures 3.8 and 3.9) to perform small scale pumping trials.

Figure 3.8 Small scale coal slurry pumping trials

Figure 3.9 Coal slurry agitated by air injection in small tank

Approximately 150 litres of water were added to the tank. This was agitated by an air sparge at the bottom of the tank, and then dry slurry was added to give the desired slurry concentration as determined by thermal drying. The slurry was removed vertically from a point on the conical section of the tank, and pumped by a 1 ½" Warren-Rupp pneumatically driven, double-diaphragm pump through a section of 19 mm i.d. flexible pipe back into the tank. Slurry pumping and reticulation proved to be trouble-free at this scale.

A slurry injection nozzle was designed and constructed. This is shown below in figure 3.10.

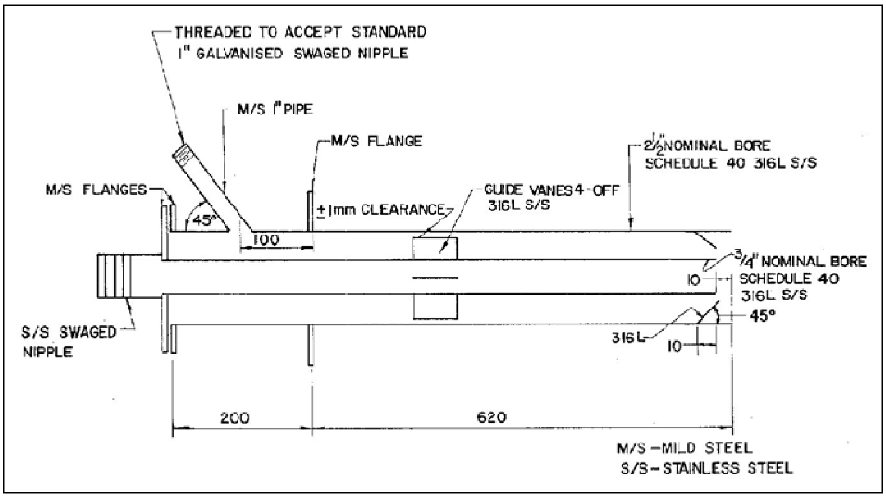

Figure 3.10 Coal slurry injection nozzle

The coal slurry is pumped through the central pipe. Air, either from a compressor or tapped from the FD fan, travels through the annulus. This air serves two purposes. Firstly it keeps the slurry cool, and prevents the water from boiling off. Secondly, it provides some dispersion at the tip. A ring was installed inside the outer tube at the tip of the inner tube to direct the air towards the slurry. (Again, both to cool the tip of the slurry pipe and to create turbulence to promote dispersion.)

Trials were undertaken to assess the effect of using annular air to disperse the slurry at the tip of the injector. Figures 3.11 to 3.13 below show the effect of increasing the flow rate of the annular air.

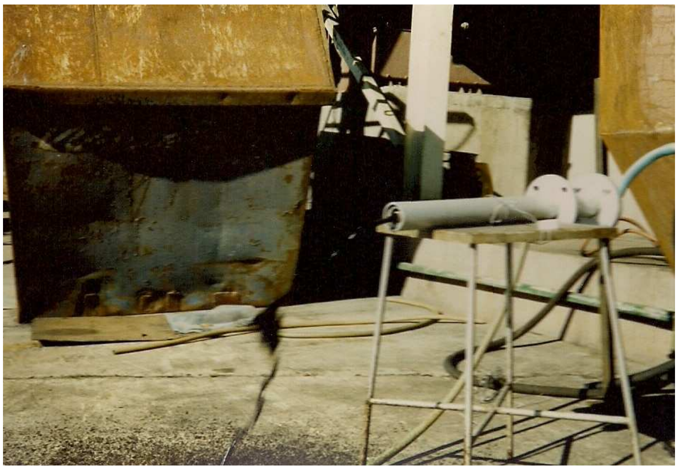

Figure 3.11 Coal slurry injection with low annular air volume

Figure 3.12 Coal slurry injection with increased annular air

Figure 3.13 Coal slurry injection with full annular air

Following the successful completion of small-scale trials, a batch of slurry was mixed in a large tank of approximately 8 m^3 capacity. The internals of this tank can be seen in Figure 3.14 below.

Figure 3.14 Internal view of large coal slurry tank

The slurry was agitated by a 2,2 kW stirrer and by five air sparges (one at the bottom of the tank and four situated on the conical base section). A simple, cheap and effective method was developed to prevent back-flow of slurry into the air delivery lines in the event of air stoppage. A short length of bicycle inner tubing was clamped onto the inlet nozzles. When the air was stopped, the tube collapsed on itself due to the pressure of the slurry, thereby preventing backflow. When air was restarted the tube opened up again.

The slurry was pumped from the tank through a flexible pipe to the boiler, with a controlled amount being fed to the boiler and the remainder being recycled back to the tank. This was done to enable control of the velocity in the pipe, as a low velocity could result in slurry settling out in the pipe and causing a blockage.

Pulsing of the slurry into the NFBC, which was caused by the type of pump used for the trials (a pneumatic double diaphragm pump), was cured by designing and installing a “de-pulser” in the line. This was a closed cylindrical vessel fabricated from 300 mm diameter steel pipe which allowed the pulse induced by the pump to fluctuate the pressure of an air space within it rather than affect the slurry pumping rate.

Factors which were assessed at this stage included:

i) Mixability, or “slurriability”, of the filter cake.

This consisted basically of a visual inspection of the slurry and the amount of solid filter cake left in it. In all trials under this project the slurry was fired in batches of approximately 6 tonnes, and each batch was given enough time to blend fully before pumping. In a continuous system, however, lumps of unblended slurry may cause problems and a more complicated system may be required to ensure uninterrupted operation.

ii) Re-slurriability after long periods without agitation.

If the slurry separates out on cessation of agitation, as may happen during a power failure, the agitator may not be able to re-slurry it. This has implications for agitator design and motor size. It was because of this possibility that the central air sparge was included – this should be able to break up the settled slurry around the agitator and thereby reduce the torque required to turn it. To test this, a 60% solids slurry was allowed to settle for 16 hours before agitation was recommenced.

iii) Effect of slurry lying stagnant in the pipe for short periods.

There is a danger with thixotropic fluids that if it stops flowing in the lines, it may not be possible to restart it again. To test this, the pump was stopped for periods of up to one minute and restarted.

iv) Removal of deleterious “tramp” material.

As mentioned earlier, the slurry was recovered from a slimes dam and contained a certain amount of coarse material (stones, coal, etc.) and clay. The clay should not be a problem (assuming it is fully blended), but the coarse material could block the pipe line. A system was developed as the trials progressed, with modifications being made as necessary.

3.6.3 Coal slurry combustion trials

The coal slurry was fired into the boiler through an injection nozzle, shown in Figure 3.15 below.

Figure 3.15 Coal slurry nozzle mounted in NFBC wall

The slurry was pumped through a central pipe with air flowing in an annular space around it. Under normal operating conditions, the slurry velocity was 1.4 m/s in the overbed nozzle and 0.7 m/s in the inbed nozzles. Air from the start-up booster fan flowed through the annulus between the outer and inner pipes. This air served to keep the nozzle cool and also helped to disperse the slurry at the tip of the nozzle. In addition, compressed air was admitted directly into the slurry line. This also helped with slurry dispersal, and prevented the ingress of hot material into the line in the event of a slurry stoppage (particularly applicable to the inbed nozzles).

When firing the coal slurry the boiler control philosophy had to be altered. The conventional control philosophy is as follows:

1. In the event of a load change (e.g. increased steam demand), the steam drum pressure will change (fall).
2. This change (fall) will be seen by the coal controller and the coal feed rate will be changed (increased) in order to re-establish the drum pressure.
3. The forced draught (FD) air flow will copy the change (increase) to the coal feed rate because both are linked by a preset ratio. The bed temperature can be trimmed by adjusting this ratio.

When the coal slurry was fired, however, the reading from the coal feeders was erroneous because the slurry feed was not monitored directly by the controlling computer. Typically, the drum pressure would rise rapidly when the slurry was fired. The coal feeders, and therefore the FD air flow, would cut back, with the coal feed falling to zero and the FD air flow falling to a preset minimum level. This would generally result in insufficient air for combustion. The control philosophy was therefore changed as follows:

1. The coal feeders were left on automatic and allowed to follow the drum pressure. This meant that as long as the actual drum pressure was higher than the set point no coal would be fed by the coal feeders.
2. The FD fan was given a set point which was altered as necessary to affect such parameters as bed temperature and excess air.
3. In the event of steam pressure fluctuations, the steam pressure set point would be changed in order to ensure that no coal was fed by the coal feeders.
4. Load was altered by adjusting the coal slurry recycle valve and/or the stroke rate of the pump.

Once it had been established that the boiler could be controlled in a satisfactory manner, combustion tests were begun. The procedure adopted for these tests is generally as detailed in 3.5.3 above.

The bed material was inspected in order to ascertain in what form the carbon in the bed was present. Many workers have concluded that when burning slurries or coal-water mixtures, the carbon is present as char-sand agglomerates which are much larger than the individual slurry particle size (Roberts et al, 1982; Arena et al, 1985).

<u>Parameters investigated</u>

The parameters which were investigated were:

- Effect of dual firing (i.e. coal and slurry) on plant operation.
- Effect of solids concentration on efficiency.
- Effect of load on efficiency.

It was also investigated whether the boiler could be restarted after an overnight slump using coal slurry feed alone versus the standard practice of to starting up on coal feed and then switching to slurry feed once the boiler had stabilized.

3.7 Calculations, Test Facilities and Experimental Procedure (Biomass Sludge)

An International food and beverage company with plants in South Africa produces a waste stream of coffee ground sludge from their granulated coffee production plant. This sludge is produced at a rate of 12 t/h and contains, nominally, 85% water. The sludge was being dried and combusted in a self-contained incineration unit. Due to various factors, one of which was high maintenance costs of the incineration unit, the company was keen to investigate alternative means of disposal of the sludge.

The process chosen for extensive investigation was to burn the coffee grounds in an FBC boiler while co-firing with coal. The required output of the boiler (Maximum Continuous Rating (MCR)) was 26 t/h steam, although it was also required that the boiler be able to run at 21 t/h while still consuming all the coffee grounds.

The purpose of this investigation was to evaluate the combustion of such a biomass sludge/coal mixture in an FBC unit in order that the combustion zone could be designed with full confidence. It should be borne in mind that, although many FBC units throughout the world burn wet material, combustion of such a high moisture content sludge is novel, and extensive research and development was required. No other boiler in the world burns coffee grounds sludge as it arises from the processing plant.

There were four distinct stages in the investigation of the combustion of the coffee grounds, namely:

- Theoretical studies
- Small scale combustion trials (including pumping trials)
- Nozzle performance trials
- Large scale combustion trials (including further pumping trials).

These stages are covered in detail below.

3.7.1 Theoretical studies for biomass combustion

The first step was to draw up a composite fuel table, where the relative feed rates and the analysis of each fuel were used to generate the analysis of a hypothetical fuel.

Table 3.2 shows an example. Initially the efficiency selected in this table is an estimation, based on experience with other high moisture content fuels. The analysis thus generated is then used as part of the data input in a heat and mass balance which was conducted using the method described in section 3.7.4 below) over an FBC boiler. From this balance the validity of the assumed thermal efficiency was evaluated. An iterative process followed, until a valid thermal efficiency was found.

Table 3.2 Composite Fuel Table, biomass sludge and coal

Component		Coal	Coffee	Other	Total (Mass)	Composite Fuel
CV	MJ/kg	26.60	3.77	0.00		7.56
Rate	kg/h	2385.00	12 000.00	0.00	14 385.00	14 385.00
C	%	67.70	10.53		2 878.42	20.01
H	%	3.40	0.71		166.59	1.16
O	%	7.00	3.64		603.15	4.19
N	%	1.60	0.01		39.41	0.27
S	%	0.00	0.03		3.74	0.03
Ash	%	14.60	0.08	25.00	357.76	2.49
H_2O	%	5.70	85.00	75.00	10 335.95	71.85
CV (Comp) MJ/kg:		7.56				
Total heat (MJ/h):		108 751				
Thermal efficiency:		54%	Steam produced: 26 000 kg/h			

The thermal balance based on Table 3.2 is shown in Table 3.3. The criterion used to establish the validity of the balance was the "radiation, convection and unaccounted losses" component. This must be greater than zero, and should be in the range of 2% to 4%

Table 3.3 Energy balance over FBC boiler co-firing biomass sludge and coal

Energy stream	MJ/h	%
Heat in fuel	109 326.00	100.00
Heat transferred to steam (thermal efficiency)	58 657.88	53.65
Heat lost in ashes		
Heat lost due to moisture in fuel	5894.25	5.39
Heat lost due to hydrogen in fuel	28 456.35	26.03
Heat lost in dry flue gases	4 274.39	3.93
Heat lost due to humidity of air	4 7 953.58	7.38
Overall accountability	58.28	5.33
	105 294.7	96.31
Therefore radiation, convection and unaccounted losses =	4 031.28	3.69

Having established through the heat and mass balance calculations that the feed rate of coal and biomass sludge are sufficient to produce the required amount of steam, the next step was to perform a similar balance over the bed. This was necessary because it must be known at what excess air level the bed must be run in order to maintain it at the required temperature (900 ℃ to 1000 ℃). It was also possible that the feed rates as calculated could have resulted in an "impossible" situation, with insufficient heat being supplied from combustion to cover the heat losses, the major losses being heat to moisture in fuel and heat to flue gases leaving the bed at the bed operating temperature. The energy balance for the bed is presented in Table 3.4

Table 3.4 Theoretical energy balance over fluidised bed, biomass sludge and coal

Energy stream	MJ/h	%
Heat in fuel	109 326.00	100.00
Heat lost in ashes	6 116.28	5.59
Heat lost due to moisture in fuel	43 000.16	39.33
Heat lost due to hydrogen in fuel	6 458.99	5.91
Heat lost in dry flue gases	46 000.76	42.08
Heat lost due to humidity of air	340.67	031
Overall accountability	101 916.9	93.22
Therefore radiation, convection and unaccounted losses =	7 409.13	6.78

From these theoretical studies, the proposed co-combustion of coffee grounds and coal was assessed as being possible, impossible or borderline.

3.7.2 Small-scale biomass and coal combustion trials

The next step was to carry out combustion trials in the CSIR's MPFB pilot FBC, in order to check if the theoretical figures could be achieved in reality.

It was at first attempted to pump the sludge into the test rig. However, various pumps (including double diaphragm, centrifugal and Mono) were tried with no success. In any event, the nozzle which would have been required in order to maintain reasonable velocities would have been approximately 7mm in diameter. This would almost certainly have blocked. It was decided therefore to feed the biomass sludge through an auger, with the coal being fed through a separate auger.

The coal feed rate was controlled by a PID controller which used bed temperature as its control parameter. The biomass sludge feed rate was controlled by hand, with the feed rate being calculated by weighing the mass of sludge fed to the bed. The procedure was as follows:

- The bed was fluidised, and a diesel burner was used to bring the bed temperature up to 600 ℃.
- Coal was fed, and the temperature brought up to 700 ℃, when the burner was cut off.
- The bed temperature was further increased to 900 °C, and the system was left to run for approximately one hour.
- The coffee ground sludge was introduced slowly, using a slow screw RPM and intermittent feeding.
- The bed cooled down, as was expected from the theoretical studies.
- The oxygen content of the off-gases was noted.
- The coal feed rate was increased to bring the bed temperature back up to 900 ℃
- The coffee grounds and coal feed rates were slowly increased, until the oxygen content of the off gases was in the region of 5% to 6%. This corresponds to an excess air level of approximately 30% to 40%, which is the same as would be expected from a conventionally-fired FBC unit. Note: In this case direct formation of steam in the bed was providing the cooling (and therefore consuming the coal and oxygen) that in bed heat transfer surfaces would do in a conventional FBC boiler.

The operation was difficult, particularly with respect to bridging in the feeder hopper and saturation of the silica gel used to dry the gases before the oxygen analyser, but it was possible to run the unit for a period of approximately two hours, during which time readings were taken of all pertinent data. Despite not achieving a longer duration such as 4 hours the data obtained was used to generate a heat and mass balance over the bed.

The absolute mass rates determined in the theoretical studies could not be achieved. The goal was rather to achieve the coffee grounds to coal ratio at the correct excess air level. Again this is a critical step, because if there is a significant deviation from theoretical behaviour, a borderline case may become impossible. It was also essential to establish how much combustion occurred in the bed, and how much drying occurred in the bed. This has a direct impact on the design of the bed because, if the actual heat balance over the bed showed that there is excess heat, then it would be necessary to install inbed heat transfer surfaces. If, however, there is insufficient heat, then inbed heat transfer could not be included and, in fact, some method would have to be found to reduce heat losses from the bed, for example pre-drying of the sludge.

After optimising the coffee grounds to coal ratio, a test run was undertaken and the data used to develop an actual thermal balance over the bed. An example is given in Table 3.5. Deviations from theoretical behaviour are investigated, reasons postulated and solutions proposed.

Table 3.5 Actual energy balance over small scale FBC, biomass sludge and coal

Energy stream	MJ/h	%
Heat in fuel	453.53	100.00
Heat unavailable from fuel	30.79	6.79
Heat lost in ashes	13.33	2.94
Heat lost due to moisture in fuel	172.99	37.92
Heat lost due to hydrogen in fuel	23.78	5.24
Heat lost in dry flue gases	198.52	43.77
Heat lost due to humidity of air	1.48	0.33
Overall accountability	440.22	97.0
Therefore radiation, convection and unaccounted losses =	13.60	3.0

3.7.3 Biomass nozzle performance trials

Trials were carried out in order to determine what design of nozzle would be required to achieve dispersion of the coffee grounds sludge into a fluidised bed. The basic design of this nozzle was drawn from the experience gained in injecting coal slurries into an FBC. Parameters which were investigated were:

(a) The effect of annular compressed air
(b) The effect of directly injected compressed air
(c) The effect of a deflector at the nozzle outlet

Additional trials were carried out at the client's site. The report produced from these trials can be seen in Appendix D.

3.7.4 Large-scale combustion trials – Biomass sludge and coal co-firing

As a final test of assumptions made during the previous stages, and to provide proof of stable operation, a test was run on a large-scale fluidised bed. The NFBC was used for this test work.

3.8 Analytical and calculation techniques

3.8.1 Coal and ash analyses

The coals were subjected to Proximate, Ultimate and Calorific Value analyses. These analytical techniques are used to enable a mass and energy balance to be conducted over the boiler. (This in turn yields performance indicators such as combustion and thermal efficiency.) The analytical techniques are described in detail by Ergun (1979). They are also detailed in ISO and SABS standards, as indicated below and shown in Appendix A.

The Proximate Analysis (ISO 17246:2005) gives the inherent moisture content (SABS 925), the Volatile Matter content (often referred to as "Volatiles") (ISO 562), Ash content (ISO 1171) and Fixed Carbon (by difference).

The Ultimate Analysis (ISO 17247:2005) gives the content of the elements Carbon (ISO 12902), Hydrogen (ISO 12902), Nitrogen (ISO 12902), Sulphur (ISO 19759) and Oxygen (by difference).

The Calorific Value is a direct measure of the chemical energy stored in the coal and is determined in a calorimeter. (ISO 1928)

A full moisture analysis yields the Superficial, Inherent and Total water content of the fuels (SANS 589; 2005).

The Ash Fusion Temperature (AFT) (ISO 540) is determined by gradually increasing a formed cone of the ash. It is noted at what temperature the tip of the cone starts to deform (the Deformation Temperature, or DT), the temperature at which the sample has melted but remains viscous with a high surface tension (the Hemispherical Temperature, or HT) and the temperature at which the sample flows freely (the Fluid Temperature, or FT).

In order to facilitate the calculation of combustion efficiency, the ash samples were analysed for carbon (char) content. In addition, some ashes were submitted for a full inorganic elemental analysis.

Moisture content of slurries and sludges was calculated by mass loss on drying using an infra-red heated balance. These tests were conducted in-house ("on-line") during the course of the test work.

3.8.2 Gas analyses

Sulphur dioxide, carbon monoxide and carbon dioxide were measured by non-dispersive infra-red monitors, whilst flue gas oxygen was measured by a paramagnetic analyser. Flue gas was filtered to remove particulates before the analyser train.

3.8.3 Slurry viscosity

The coal slurry viscosity was measured using a Haake Rotovisco RV3. The procedure, and results, are reported by Luterek (1988).

From these viscosity determinations, predictions were made of pipeline pressure drop as a function of slurry concentration. This is a notoriously difficult procedure. Moreland (1963) concluded: “Pressure gradients measured in an experimental pipeline carrying a suspension of coal …. could not have been predicted using the viscosities determined in the laboratory” .These predictions were therefore regarded as relative indications only, with the actual case results being of more interest.

3.8.4 Calculation of thermal and combustion efficiencies

Thermal and combustion efficiency calculations are essentially, in chemical engineering terms, a mass and energy balance over the system. The analyses detailed above are used to calculate the energy into the boiler (in the form of chemical energy in the coal) and the energy streams leaving the combustor/boiler (including primarily steam, hot flue gases, moisture (from the air, coal, and from the hydrogen in the coal), unburned carbon in ash and losses due to radiation and convection). The thermal efficiency is the percentage of the energy in the coal that is transferred to energy in the steam. The combustion efficiency is the percentage of carbon that went into the boiler that was combusted, ie that did not come out in the form of solid carbon in ash.

The calculations are generally carried out on a “Direct”, “Indirect” or Loss” basis. The Direct method is the most accurate, and requires measurement of all mass flows, temperatures etc. This is used in this research. Often, in operating industrial boilers, some parameters cannot be measured. If the coal feed rate cannot be measured the Indirect method is employed. If the steam (or water) flow cannot be measured, the Loss method is used. The methods, based on British Standard 845, and a program developed to perform the calculations, are detailed in CSIR report ICOAL 8602 (North, 1986). This report can be found in Volume 2: 3.

A summary example of the major steps in the calculation of the combustion and thermal efficiencies is given in Appendix B. This is based on the data shown for Tavistock duff on Figure 4.3 (at a steam load of 7 t/h, without grit refiring). The analysis of the coal can be seen in Table 4.2.

4 RESULTS AND DISCUSSION

4.1 Combustion of Duff and Discard (including Anthracite Discards) coal – Thermal and Combustion Efficiency

Three coals were tested in the NFBC, namely, Boschmans duff, Tavistock duff and Greenside discards. A full analysis of these coals can be seen in Appendix A and in Tables 4.1, 4.2 and 4.3.

The plant parameters which were varied in order to optimize combustion were the use of primary cyclone grit re-firing and bed temperature. It was also attempted to investigate the effect of inbed firing of coal. These latter trials were abandoned after the unreliability of the inbed feeders repeatedly caused tests to be aborted.

Table 4.1 Analysis of Boschman's Duff

PROXIMATE			ULTIMATE	
H_2O	(%)	2.7	C (%)	64.31
Ash	(%)	18.7	H (%)	3.46
Volatiles	(%)	24.7	N (%)	1.44
Fixed carbon	(%)	53.9	S (%)	0.75
			O (%)	8.64
GCV (MJ/kg)	25.0			

Size (mm)	Fractional	Cumulative
+6	3.6	100.00
-6+4	25.8	96.4
-4+3	5.9	70.6
-3+2	20.8	64.7
-2+1	15.2	43.9
-1+0.5	11.3	28.7
-0.5	17.4	17.4

Ash Fusion Temperature	
DT	1340 ℃
HT	1350 ℃
FT	1390 ℃

Table 4.2 Analysis of Tavistock Duff

PROXIMATE			ULTIMATE	
H2O	(%)	3.9	C (%)	61.51
Ash	(%)	18.9	H (%)	3.15
Volatiles	(%)	25.8	N (%)	1.35
Fixed carbon	(%)	51.4	S (%)	0.66
			O (%)	10.53
GCV (MJ/kg)		24.1		

Size (mm)	Fractional	Cumulative
+10	2.8	100.00
-10+6	32.4	97.2
-6+4	25.3	64.8
-4+2	16.9	39.5
-2+1	8.5	22.6
-1+0.5	5.6	14.1
-0.5	8.5	8.5

Table 4.3 Analysis of Greenside Discards

PROXIMATE			ULTIMATE	
H_2O	(%)	2.8	C (%)	40.78
Ash	(%)	44.1	H (%)	2.63
Volatiles	(%)	19.8	N (%)	0.89
Fixed carbon	(%)	33.3	S (%)	2.77
			O (%)	6.03
G C V	(MJ/kg)	16.5		

Size (mm)	Fractional	Cumulative
+10	2.2	100.0
-10+6	8.9	97.8
-6+4	13.3	88.9
-4+2	20.0	75.6
-2+1	17.8	55.6
-1+0.5	20.	37.8
-0.5	17.8	17.8

Ash Fusion Temperature	
DT	1160 ℃
HT	1230 ℃
FT	1300 ℃
H_2O	
SUP	5.6%
INH	4.0%
TOT	9.4%

4.1.1 Effect of load on thermal and combustion efficiency

The effect of load on thermal efficiency for Boschmans duff and Tavistock duff is shown in Figure 4.1 below. These tests were carried out without primary cyclone grit re-firing.

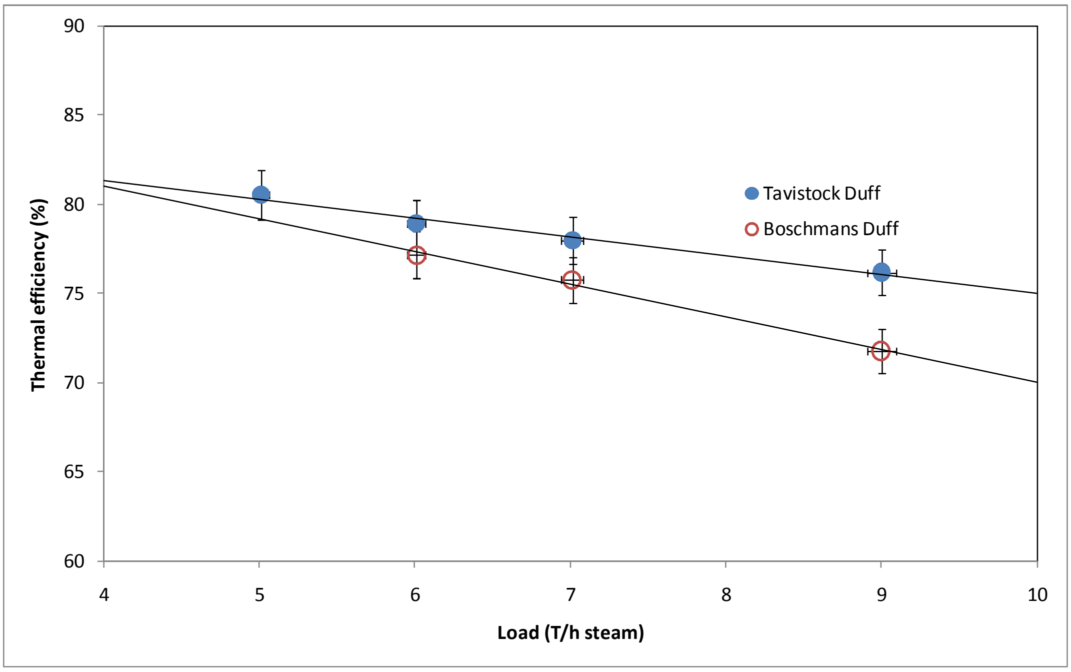

Figure 4.1 Effect of Load on Thermal Efficiency (Duff coal)

As would be expected, the graph shows that thermal efficiency decreases with load. This is essentially due to the fact that at the higher loads, the freeboard velocity is higher and this, in turn, leads to a higher elutriation of unburnt carbon. For Tavistock duff the efficiency fell from 80.6% at 5 t/h steam to 76.4% at 9 t/h steam. For Boschmans duff the efficiency dropped from 77.1% at 6 t/h steam to 71.8% at 9 t/h steam. A further important conclusion can be drawn from Fig. 4.1. The thermal efficiency for Boschmans duff is consistently less than for Tavistock duff, and the disparity increases with increasing load. It is concluded that this is due to the different proportion of fines content in the two coals. From Table 4.1 it can be seen that the fraction of the Boschmans duff that is smaller than 1 mm is 28.7% while Table 4.2 shows that the -1 mm fraction of the Tavistock duff is 14.1%. This explains both the phenomena mentioned earlier, i.e. the higher fines content of the Boschmans duff results in a lower efficiency than with Tavistock duff, and also causes that deficiency to become greater with load as it is at higher loads that fines elutriation becomes more prevalent.

This conclusion is supported by the combustion efficiency in the same tests, presented in Figure 4.2 below, where an identical trend was seen. The combustion efficiency for Tavistock duff dropped from 92.5% at 5 t/h steam to 89.4% at 9 t/h steam. For Boschmans duff, the combustion efficiency dropped from 87.7% at 6 t/h steam to 82.6% at 9 t/h steam.

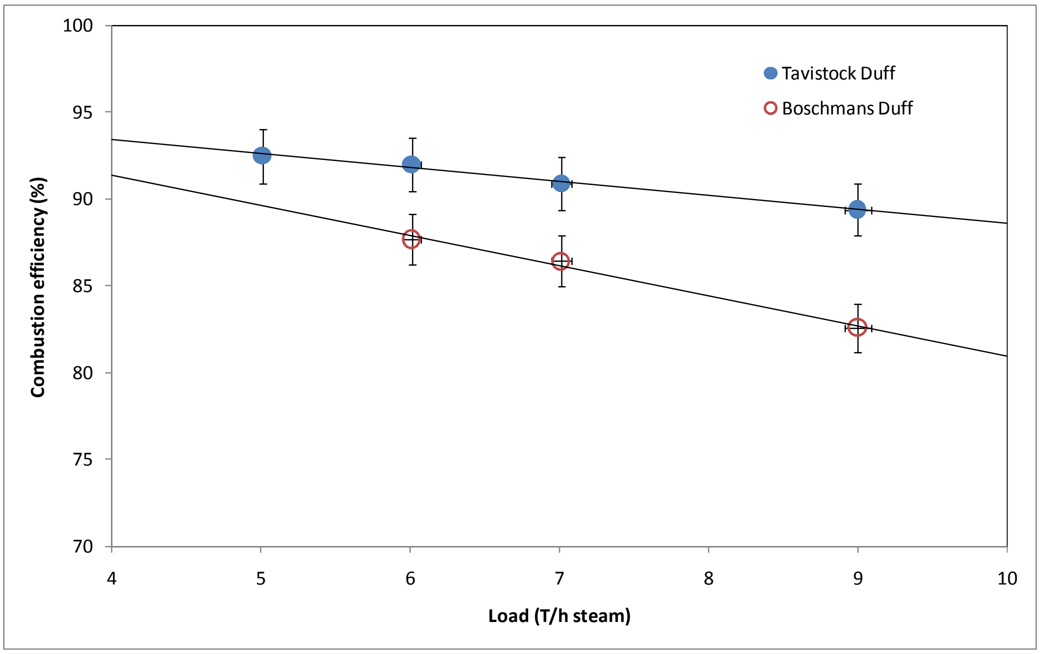

Figure 4.2 Effect of Load on Combustion Efficiency (Duff Coal)

4.1.2 Effect of grit re-firing on thermal and combustion efficiencies

The coals tested for the effect of grit refiring on thermal and combustion efficiency were Tavistock duff and Greenside discards. The results from these coals can be seen in Figures 4.3 and 4.4 respectively. From Fig. 4.3, it can be seen that primary cyclone grit re-firing increases the thermal efficiency by an average of 6% and the combustion efficiency by an average of 6.8%. Of significance is the fact that grit re-firing causes a “flattening” of both trends, i.e. it tends to reduce the detrimental effect of higher loads. This can again be explained by the high fines content. As discussed under 4.1.1, it is elutriation of the fines which causes unburnt carbon losses and this problem is exacerbated by high loads (and therefore higher gas velocities). Recycling of this unburnt carbon considerably increases the residence time in the hot environment of the furnace and therefore improves carbon burn-out.

A combustion efficiency of as high as 98.1% was achieved for Tavistock duff when employing grit recycle at 5 t/h of steam production. This fell to 97.3% at 9 t/h.

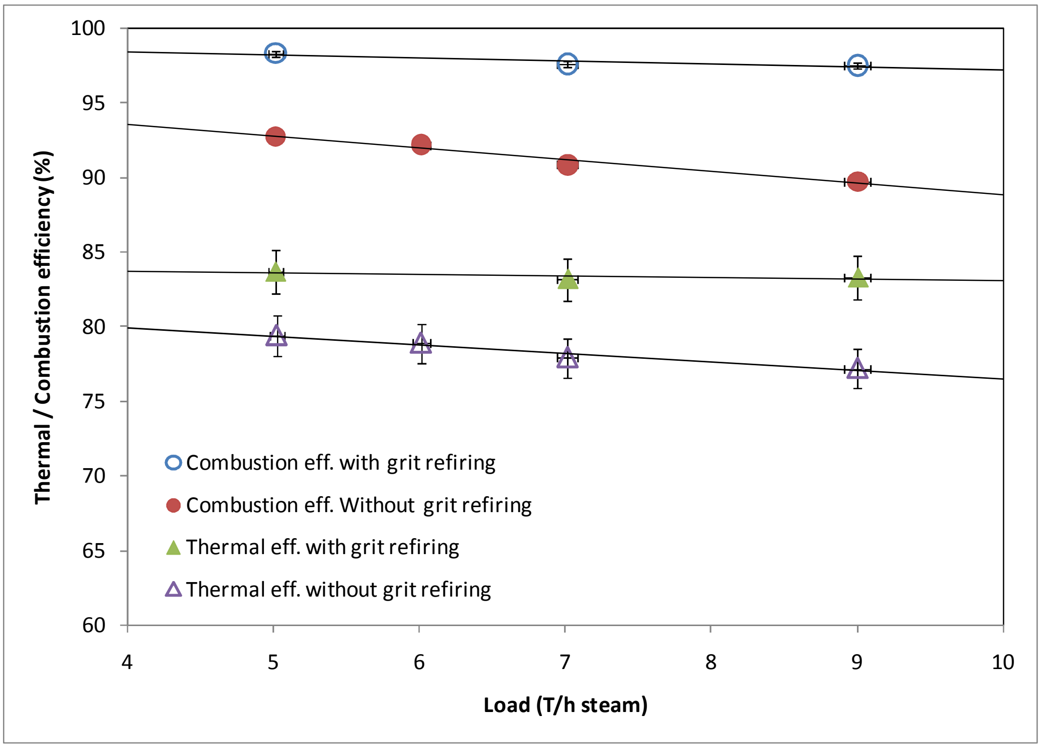

Figure 4.3 Thermal and Combustion Efficiency with and without Grit Refiring (Tavistock Duff)

Fig. 4.4 shows a similar trend for Greenside discards. The thermal efficiency ranged from 77.6% to 74.9% without grit refiring and 8.1% to 80.2% with grit refiring. The corresponding combustion efficiencies were 92% to 89.2% without grit refiring and 95.3% to 93.5% with grit refiring. The improvement is not as marked as was seen for duff coal. With the higher ash content of the discards coal, a relatively larger mass of relatively cool ash was returned to the bed. In order to maintain the bed at an acceptable temperature, it was necessary to run at a lower excess air. This had a negative effect on the combustion efficiency and to a certain extent off-set the beneficial effect of the re-firing of the primary cyclone grits.

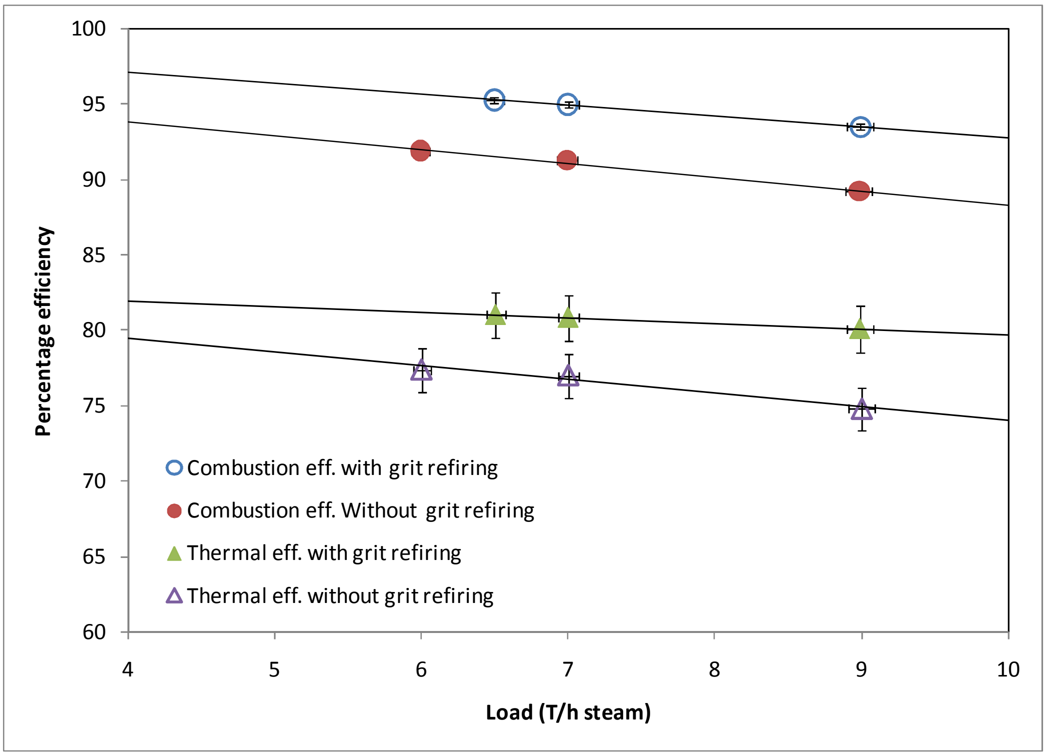

Figure 4.4 Thermal and Combustion Efficiency with and without Grit Refiring (Greenside discards)

4.1.3 Effect of bed temperature on combustion efficiency

A study conducted at the CSIR in 1985 indicated that gains could be made in combustion efficiency by increasing the combustion temperature (Hamman, 1985). Fig. 4.5 shows a synthesis of these results. The burn-out time of a 275 micron particle can be reduced by approximately 70% by increasing the combustion zone temperature from 850 °C to 950 °C.

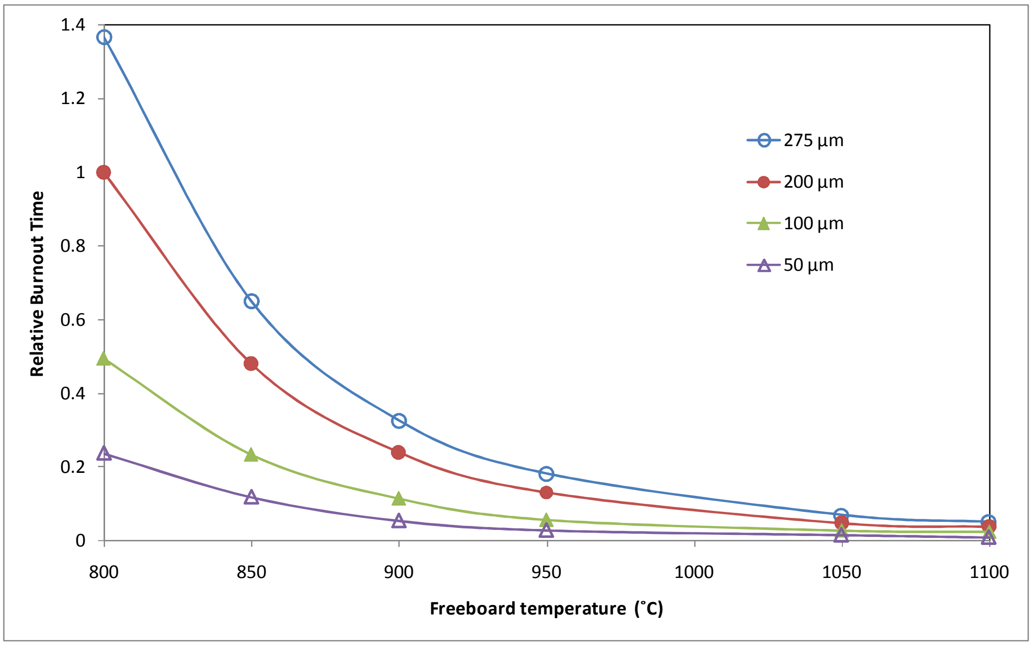

Figure 4.5 Effect of Temperature on Particle Burn-Out Time (Hamman, 1985)

Based on this premise, a series of tests were carried out on Tavistock duff to gauge the effect of a 100 ℃ rise in combustion temperatu re. The results are shown in Figure 4.6.

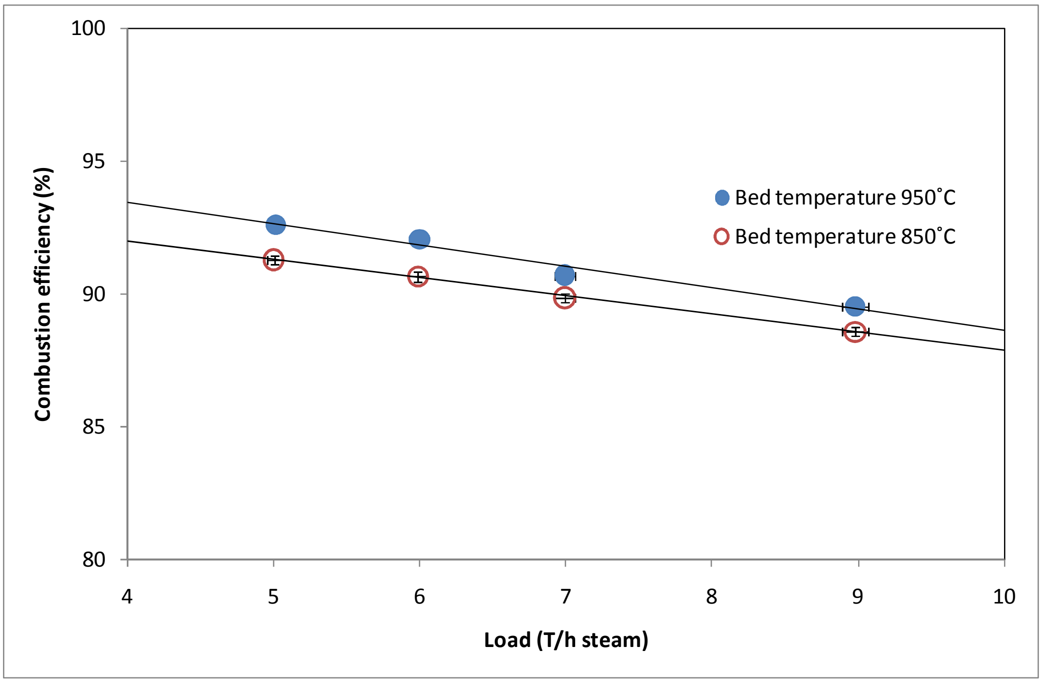

Figure 4.6 Effect of Bed Temperature on Combustion Efficiency (Tavistock duff)

A gain in combustion efficiency of approximately 1% can be seen, and this remains fairly constant with increasing load. There is a slight convergence of the two lines as the load is increased. This is believed to be due to lower residence times becoming the dominant factor influencing burn-out.

4.1.4 Combustion of Anthracite Discards

The coal used for this test work was an anthracite discard from the Utrecht mine. The first test carried out on the fuel was to determine at what temperature it ignited in the NFBC. The procedure detailed in section 3.1 was followed. An analysis of the anthracite discards can be seen in Table 4.4. The low volatile matter content (10.3%) and the high ash content (42.4% (air dried basis)) are of specific concern.

Table 4.4 Analysis of Utrecht Anthracite Discards

PROXIMATE			ULTIMATE	
H_2O	(%)	1.6	C (%)	46.61
Ash	(%)	42.4	H (%)	2.03
Volatiles	(%)	10.3	N (%)	1.44
Fixed carbon	(%)	45.7	S (%)	1.53
			O (%)	4.39
GCV	(MJ/kg)	18.1		

Size (mm)	Fractional	Cumulative
+25	14.9	100.00
-25+18	8.1	85.1
-18+12	20.3	77.0
-12+8	23.3	56.7
-8+5	5.8	33.4
-5+3	6.3	27.6
-3+1	7.1	21.3
-1+0.5	3.8	14.2
-0.5	10.4	10.4

DT	1280 ℃
HT	1330 ℃
FT	1370 ℃
H_2O	
SUP	9.1%
INH	1.5%
TOT	10.5%

A graph of bed temperature and fuel feed rate against time during a start-up is shown in Fig. 4.7.

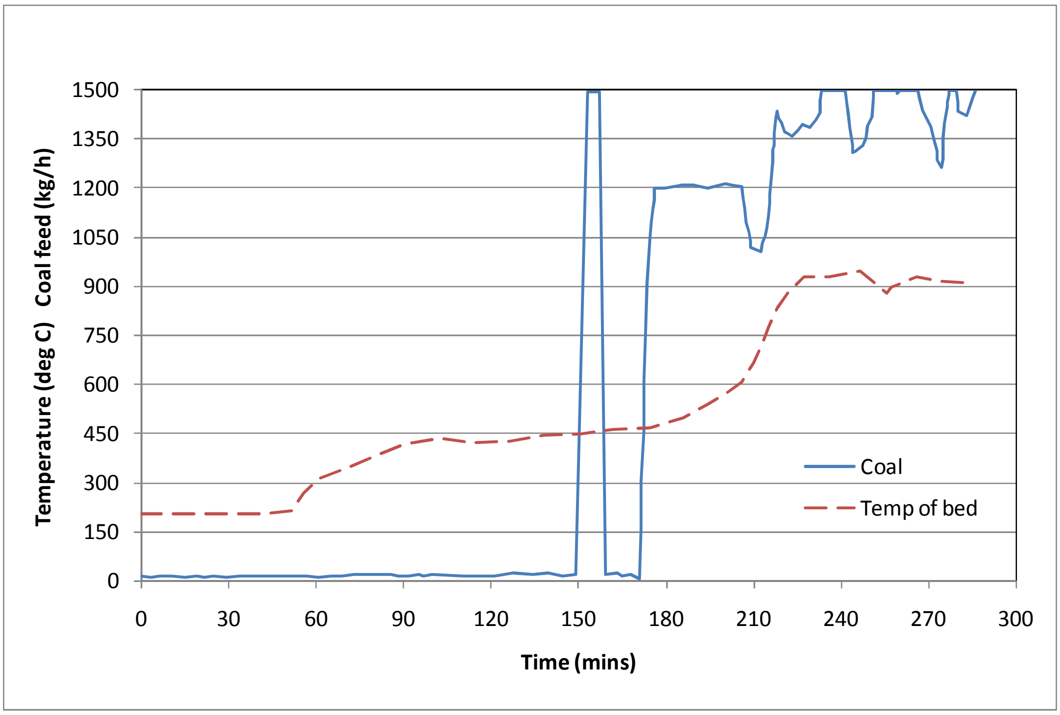

Figure 4.7 Ignition of anthracite discards

A bed temperature of 200 ℃ can be seen for the first 45 minutes. During this period the bed was not fluidized. Upon fluidization the temperature rose rapidly to 425 ℃. This rise was due to a combination of (a) mixing of hot material from the centre of the bed into the lower level of the bed, where the thermocouples are situated, (b) combustion of carbon still present in the bed, and (c) the diesel burner. By 90 minutes the effects of (a) and (b) had disappeared and a steady temperature rise of 0.53 ℃/minute can be seen. A small amount of anthracite was first added at a bed temperature of 450 ℃, with no noticeable effect. Anthracite was again added at a bed temperature of ± 460 ℃, and an increase in the rate of temperature rise to 5.8 ℃/minute was seen. It was at a bed temperature of 600 ℃ that full, stable combustion could be said to have taken place. At this time the rate of bed temperature rise was 18.5 ℃/minute, at which rate it stayed until the bed temperature levelled off at about 900 ℃.

The results show that partial combustion occurs at just over 450 ℃, and stable combustion occurs at about 600 ℃. To be safe, the bed temperature should not be below 600 ℃ when starting up on anthracite discards. Experience at the NFBC has shown that the boiler can be shut down for over twelve hours and the bed temperature will still be above 700 ℃. The anthracite discards should therefore present no problem as far as initial ignition is concerned.

Following the ignition tests, a series of combustion trials were carried out in the same manner as described in section 3.1. No grit recycling was employed during these trials. It proved to be difficult to maintain bed temperature when burning the anthracite. The excess air levels had to be kept relatively low (normally less than 30%) to avoid excessive bed cooling and subsequent loss of ignition.

The result of the combustion trials are presented in Fig. 4.8.

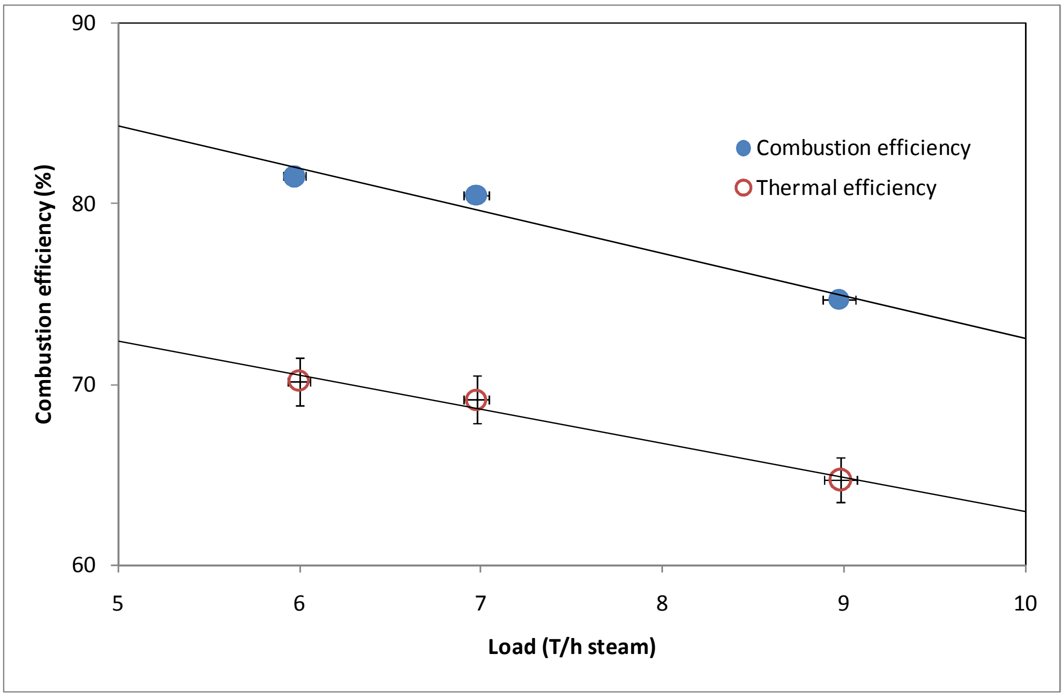

Figure 4.8 Combustion and Thermal Efficiency of Anthracite Discards

The most notable feature of Fig. 4.8 is the low thermal and combustion efficiencies. The thermal efficiency dropped from 70.2% at 6 t/h steam to 64.4% at 9 t/h steam. The combustion efficiency fell from 81.4% to 74.3% over the same interval. This should be compared to the efficiencies for Greenside discards (bituminous) shown in Fig. 4.4, where the thermal efficiency ranged from 77.6% to 74.9% and the combustion efficiency ranged from 92% to 89.2%.

The cause of these low efficiencies for the anthracite discards is a very poor burn-out. This can be attributed chiefly to the low volatile content and the low reactivity of the anthracite.

Particles in the feed which are too fine to enter the bed will be elutriated, as with any other coal. The evidence suggests that with the anthracite fines they do not ignite in the freeboard, and are elutriated still containing a significant portion of their original carbon. Further, burning particles leaving the bed are likely to extinguish. The result of this carbon elutriation was a primary cyclone drop-out which contained over 30% carbon-in-ash. This is very poor, bearing in mind that the feed was a high-ash discard. The total heat lost in the ashes was in the order of 20% of the available heat in the fuel.

This observation is corroborated by Falcon (2012) who has shown in laboratory combustion test work on anthracite and anthracite discards that they are difficult to devolatilise and ignite. Anthracitic coals contains low volatile levels, hence there is difficulty in achieving ignition. Additionally, the carbon matrix in the char produced from anthracitic coal is semi-graphitic, which is a property associated with high rank coals. This leads to a low carbon burn-out. To achieve a higher carbon burn-out high combustion temperatures are required. FBCs are designed to operate at relatively low temperatures of around 850 ℃ in order to enabl e sulphur emissions to be captured *in-situ*, and are therefore not well suited for this type of fuel.

Experience from the Tong-Hae anthracite-fired CFBs in Korea (Kim et al, 2003) showed that combustion efficiency was also low in a CFBC. Boiler modifications including re-injection of ash from the air heater and electrostatic precipitator were installed, which reportedly improved the combustion efficiency. However, Kim et al (2007) continued to try to increase the combustion efficiency by co-firing with bituminous coal.

From these results, it appears that FBC may not be a viable combustion technology for this type of fuel. Or, if anthracite is to be the fuel (as with the Tong-Hae boilers, it may be the only indigenous fuel), the boiler needs to be designed with the unreactive nature of the fuel in mind.

4.2 Sulphur Capture

Research was conducted on the NFBC to determine the ability of three South African sorbents to reduce sulphur emissions when burning discard coal.

Laboratory trials were carried out by Petrie (1988) on a number of sorbents. His work provided parameters to rank the sulphur capture ability of the sorbents. The work reported below, carried out in collaboration with Petrie using the methodology described in 3.5 above, was aimed at verifying the laboratory results at a large scale on three of those sorbents, namely Bredasdorp Lime, Union Lime and Lyttelton Dolomite.

The fuel used for all the research carried out at an industrial scale in the NFBC boiler was Greenside Discards. An analysis of this coal can be seen in table 4.4. The sulphur content was 1.53%.

A typical sulphur dioxide (SO_2) trace from one of the sulphur capture tests can be seen in Fig. 4.9. The series of “steps” are due to the nature of the test procedure as explained in 3.5. The plateaus are the stable period at one calcium to sulphur (Ca/S) ratio. From this graph it is determined what percentage reduction can be achieved for a particular Ca/S ratio.

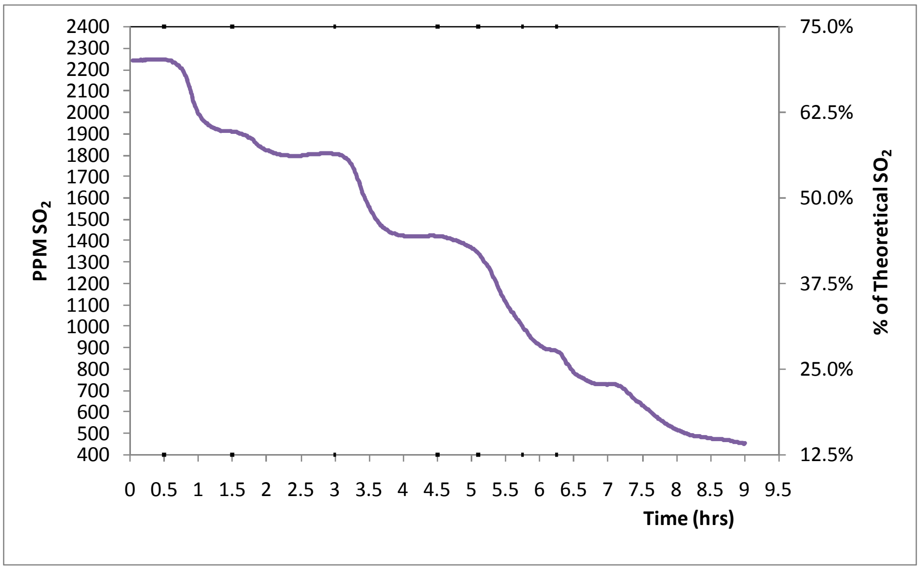

Figure 4.9 Typical SO_2 reduction trace

These data were then used by Petrie to establish the relative performance of the three sorbents. Petrie and North (1988) reported the findings as shown in Figure 4.10 below.

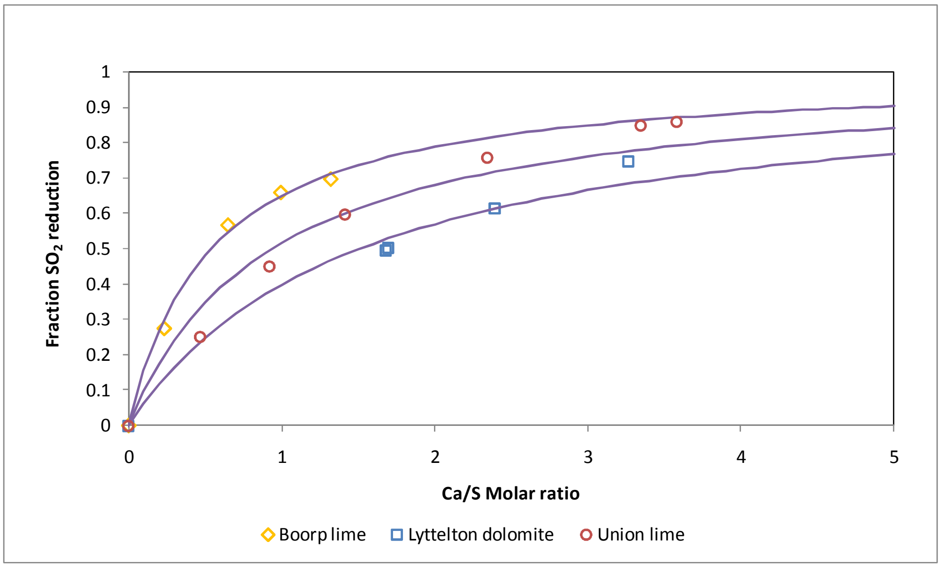

Figure 4.10 Relative performance of the sorbents

Bredasdorp lime is clearly a superior sorbent to the other two. For a given sulphur capture value Bredasdorp lime can be twice as effective as Union lime and nearly 3 times as effective as Lyttelton dolomite. The reason for this is proposed to be the physical nature of the sorbents, and in particular their friability and porosity under bed operating conditions.

Additional factors will affect the choice of sorbent for a particular application, chiefly transport costs. Although Bredasdorp lime is a better sorbent, it would need to be transported to the point of use, which is likely to be nearby the source of the discard coal.

4.3 Coal slurries (procurement, pumping and combustion)

Initially slurry was sourced from Tavistock colliery. This material was of a suitable CV, but unfortunately was much coarser than would be expected with a slurry. Some 15% of particles were greater than 4 mm, with particles up to 8 mm being present. It proved impossible to carry out laboratory trials with this slurry as it was not stable enough (i.e. it was too prone to settling out) for meaningful tests. It was possible to pump a 50% solids slurry, but only for short periods before a blockage occurred in the line. This material may have an application in larger units that require a correspondingly larger-diameter slurry feed line, but it was unsuitable for tests on the NFBC.

Accordingly a second slurry was sourced, from Goedehoop colliery. An analysis is given in Table 4.5 below.

The CV is 24.6 MJ/kg which is within the range of typical South African coal slurries and was therefore considered acceptable for testing. There is very little material larger than 500 micron (0,5mm), and nearly three-quarters is smaller than 355 micron.

Table 4.5 Analysis of Goedehoop Slurry

Proximate		**Ultimate**			
H_2O (%)	2.6	C (%)	60.24		
Ash (%)	20.7	H (%)	3.64		
Volatile matter (%)	26.2	N (%)	1.52		
Fixed carbon (%)	50.5	S (%)	1.00		
		O (%)	10.30		
CV ($MJkg^{-1}$)	24.6				
H_2O		**Size grading**			
Superficial (%)	6.3				
Inherent (%)	4.4				
Total (%)	10.4				
AFT		**Size range (micron)**		**Fractional (%)**	**Cumulative (%)**
DT (°C)	1380				
HT (°C)	+1400				
FT (°C)	+1400		+500	16	100.0
		-500	+425	6	84.0
		-425	+355	6	78.0
		-355	+212	18	72.0
		-212	+106	18	54.0
		-106	+90	7	36.0
		-90	+60	13.9	29.0
		-60	+45	4.6	15.1
		-45	+30	4.1	10.5
		-30	+20	2.9	6.4
		-20	+10	2.3	3.5
		-10		1.2	1.2

4.3.1 Laboratory trials on Goedehoop Slurry

The result of most interest shown in the report of Luterek (1988) is the prediction of pressure drop when pumping the slurry. A flow rate of 3 000 kg/h was assumed, as this was calculated to be the required volume of slurry to fire the NFBC at up to full load. With a 50% solids slurry, a pressure drop of 1.16 bar per metre of pipe was predicted. At 61% solids, the predicted pressure drop had risen to 9.5 bar per metre. This had serious implications for the pumping trials, as the slurry had to be pumped over a distance of 32 m with a pump that cannot give more than 7 bar pressure. Despite this negative indication, it was decided to proceed further with mixing and pumping trials.

4.3.2 Mixing and pumping trials

A 50% solids slurry was mixed in the small air-agitated tank (described in detail in Section 3.5.2). This was found to be much more stable than the coarse slurry had been. The slurry was circulated through approximately 5 m of pipe with apparent ease. The slurry concentration was steadily increased up to about 64% solids and remained pumpable. It appeared that the pressure drop predictions from the laboratory trails were in fact inaccurate. (As mentioned earlier, predicting slurry pressure drop from laboratory trials is a very difficult task.)

A batch of approximately six tonnes of slurry was made up in the large tank. The solids concentration ranged from 60% to 65%, and the slurry was pumped from the tank to the nozzle and then recycled back to the tank through 32 m of pipe. More evidence was seen at this stage of the inaccuracy of the laboratory trials. The line pressure at the outlet of the pump was 1.6 bar when pumping a 65% solids concentration slurry. (Based on the laboratory trials, a pressure drop in excess of 300 bar could have been expected.) The factors detailed under Section 3.5.2 were then assessed, namely:

i) Mixability of the filter cake

The slurry as received was not totally dry and contained a large amount of agglomerated material. These agglomerates took up to one hour to disperse fully into the bulk of the slurry.

ii) Re-slurriability

All agitation was stopped at 16:00 one afternoon. The following morning at 08:00 the material was successfully re-slurried by first opening up the air sparges and then starting the stirrer.

iii) Slurry stagnation in the pipes

The pump was stopped for periods of up to one minute, with slurry flow being successfully re-established on restarting the pump. It was not attempted to extend the period until the slurry went “solid” as it would have been a very large task, if not an impossible one, to clean the line.

iv) Removal of deleterious tramp material

Three forms of tramp material were found in the slurry as received, namely clods of damp slurry, clay, and lumps of coal and stone. The first two did not cause any serious problems as they went into suspension fairly quickly. The lumps of coal and stone, however, did cause frequent blockages. To overcome this, the slurry off-take was moved higher up the conical section and a 100mm cube fashioned from 5mm mesh was secured over the outlet. The large material tended to collect at the base of the tank, and could be removed easily by stopping the central air sparge and opening a 75mm valve at the base. Essentially it was a form of blow-down, similar to that in boilers to keep the dissolved solids concentration at an acceptable level.

4.3.3 Coal slurry combustion trials

Before any combustion tests were performed, a series of familiarization runs were carried out. This entailed firing the slurry overbed and inbed for a period of approximately two weeks, with factors such as bed temperature, excess air and boiler controllability being monitored. It was during this period that the control philosophy was revised as described in Section 3.5.2.

The overbed firing trials in which the slurry was pumped through a single nozzle gave problems in terms of maintaining the bed temperature at an acceptable excess air level. The fly ash was also visibly high in carbon, and it was therefore clear that insufficient coal particles were combusting within the bed. For this reason it was decided to employ inbed firing for all further trials. The overbed trials were carried out with a relatively thin slurry (55% solids). Later qualitative trials with a much thicker slurry (67% solids) gave better results in terms of excess air and reduced carbon carryover. This was almost certainly due to increased generation of char-sand agglomerates. These agglomerates will be discussed in more detail later.

Acceptable combustion conditions were established more easily when the slurry was fired through two inbed nozzles. These nozzles were situated 300mm above the distributor and 400 mm below the static bed surface.

Figure 4.11 shows the trend of some of the important plant parameters during one of these “familiarization” trials. The trend starts at time zero just as the slurry feed was started.

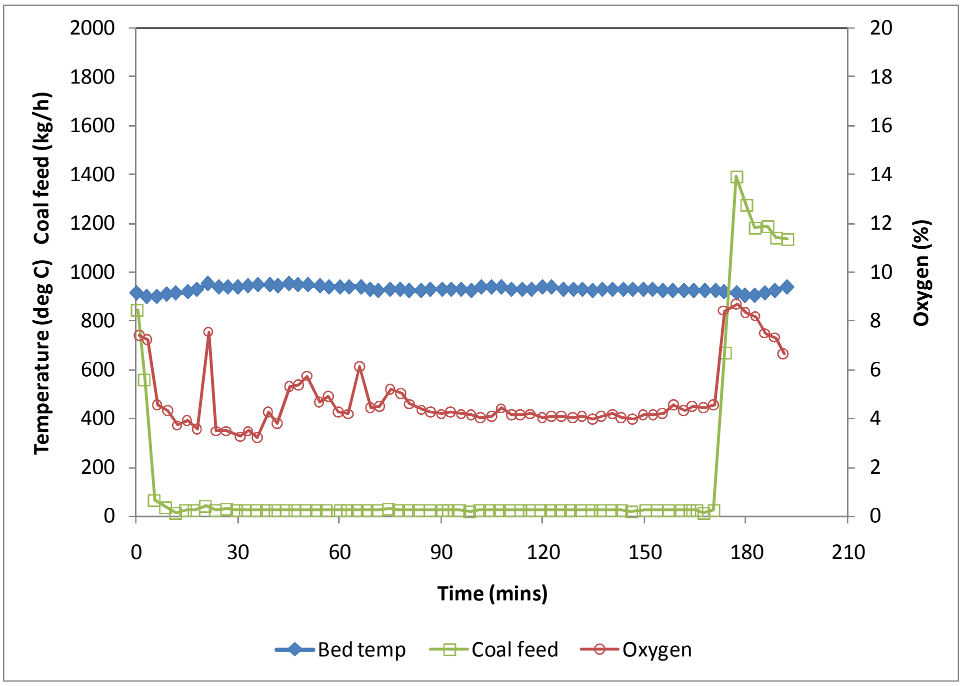

Figure 4.11 Operation on coal slurry

It can be seen that the coal feed dropped off rapidly to zero, as the combustion of the slurry was generating sufficient heat to satisfy the steam demand. The bed temperature stayed fairly stable at approximately 900 ℃ to 930 ℃. The oxygen in the flue gas fell from 8% (60% excess air) to about 4% (24% excess air).

The boiler was run for 2.5 hours on slurry alone, and then the slurry pump was stopped and the control philosophy changed back to normal. This was done in order to ascertain the response of the boiler to such a dramatic change in firing mode. From Figure 4.11 it can be seen that the bed temperature was only very slightly affected. Steam pressure was also held within 2% of the set point (1 520 kPa). This test shows that a suitably designed FBC boiler can operate with both slurry and coal feeds and still be controllable within tight limits.

It was also investigated whether the boiler could be started up after an overnight slump (shut down) on slurry alone (generally it is started on coal and slurry is only fired once the boiler is stable). Figure 4.12 shows the trend of bed temperature and flue gas oxygen concentration with time for the start-up.

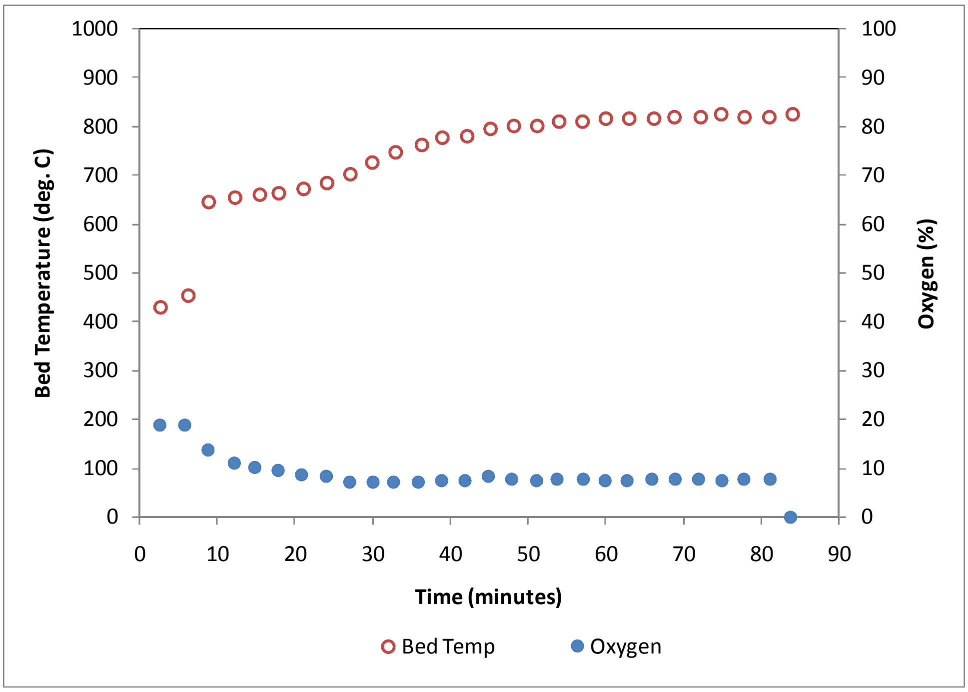

Figure 4.12 Start-up on coal slurry alone

The bed temperature was initially indicated at 400 ℃ when slumped. Upon fluidization, hot material was mixed throughout the bed and a more accurate average bed temperature of 640 ℃ was indicated. This was b rought up to 800 ℃ by firing the coal slurry (without coal) over a period of 40 minutes, after which the slurry pumping rate was cut back slightly. The bed temperature was then slowly increased to the normal operating temperature.

These results prove that the slurry can be combusted while maintaining an acceptable excess air level and bed temperature. This is theoretically very difficult to achieve, as the residence time in the bed of particles of less than 212 micron has been estimated as 1 second, which would result in an extremely low burn-out of only 1% of the carbon (Arena et al, 1985). There must be some mechanism, therefore, that causes the carbon to be present in the bed in particles significantly larger than the parent coal particles which in turn results in a longer residence time. Two mechanisms which have been proposed are char-sand agglomerates and char-flecked sand (Massimilla and Miccio, 1986; Roberts et al, 1982; Arena el al, 1985). The agglomerates consist of relatively large (up to 1cm) clusters of devolatilised coal and sand. These agglomerates are formed while the individual slurry droplets are drying and devolatilising. In this respect the concept of the combustion of coal-water slurries in a fluidized bed differs from the concept of the combustion of commercial coal-water mixture (CWM) fuels in a burner. In the former case, large droplets are desirable, while in the latter case fine atomization is essential.

Massimilla and Miccio (1986) give a discussion on the formation and destruction of these agglomerates. The formation of the agglomerates is promoted when using a high swelling (coking) coal. They studied the attrition of the particles from the agglomerate that is formed (the “A-phase”), through carbon-spotted sand (“S-phase”) to fines which can be elutriated (“F-phase”). Carbon-spotted sand can also be generated directly by small slurry droplets interacting with individual bed particles. From their attrition and fragmentation studies they determined that an agglomerate will break down into individual sand particles in about 5 minutes under oxidising conditions.

A sample of the bed material was taken after an extended period of slurry firing in the NFBC. This was found to contain 3-4% carbon, which was present in the form of char-sand agglomerates, very similar in appearance to those produced in the studies of Massimilla and Miccio (1986). Figure 4.13 shows some of these char-sand agglomerates which have been placed on a standard metric grid in order to indicate size. The char-sand agglomerates are the 8 pieces on the upper half of the figure.

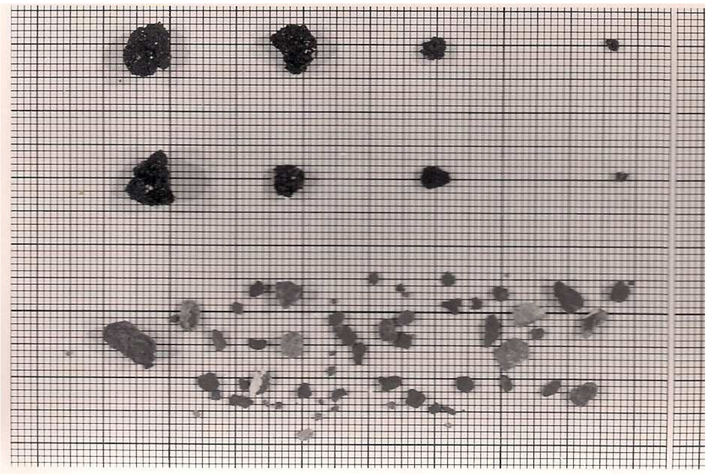

Figure 4.13 Char-sand agglomerates from coal slurry combustion

Also shown, below the agglomerates, is some of the inert (non-carbon containing) bed material. This consists mostly of the ash residue of discard and duff coal which had been fired in the boiler over a period of several months. Although the agglomerates are significantly larger than the rest of the bed material, which would raise concerns of a steadily coarsening bed, Massimilla and Miccio (1986) indicate that the agglomerates fragment back down to the parent bed particles in about 5 minutes. A build-up of coarse material should therefore not be expected. The size of the agglomerates is generally increased by reducing the amount of atomizing air. This is beneficial from a combustion efficiency viewpoint but, if the agglomerates become too large, there is a danger of bed defluidisation (Miccio et al, 1989).

Once it had been proved that the slurry could be burnt autothermally, a series of combustion tests were carried out. These were performed as described in Sections 3.2 and 3.6 above.

Firstly, slurries with a solids concentration ranging from 59% to 64% were fired under similar operating conditions. Data were collected in the normal fashion and the results processed to give a breakdown of the heat losses from the system (i.e. losses due to unburnt carbon, water in the fuel, etc.) and the thermal and combustion efficiencies.

Figure 4.14 shows the effect of solids concentration on heat loss due to water in the fuel.

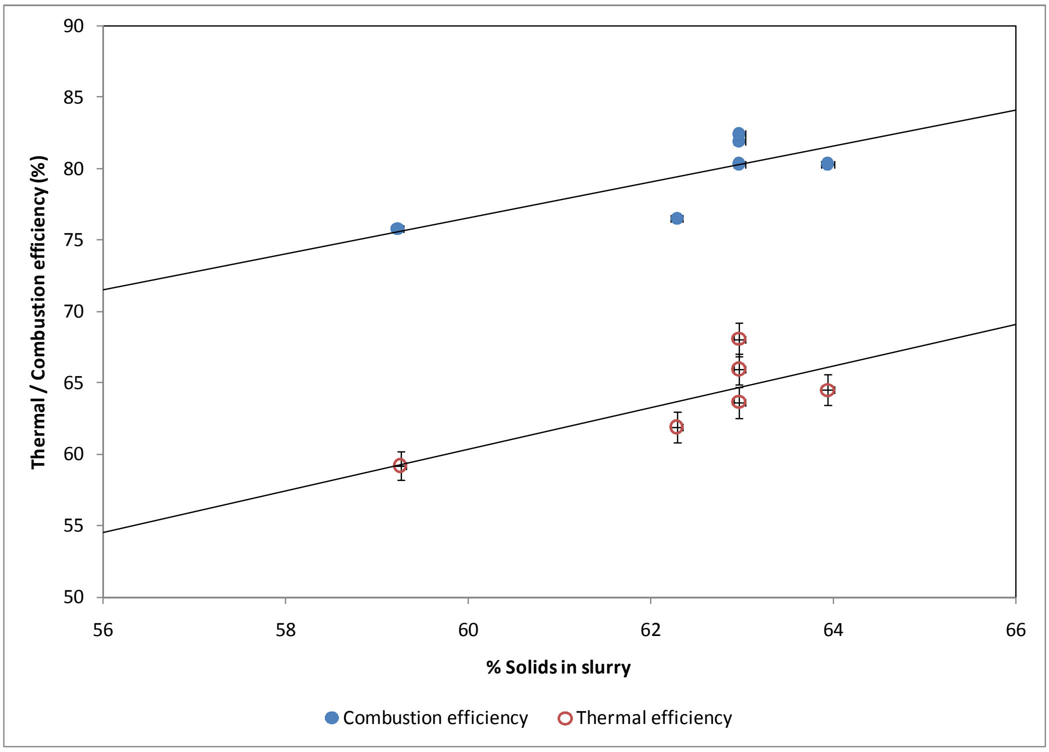

Figure 4.14 Effect of slurry solids concentration on heat loss due to water

Presented in 4.14 is both the heat lost from the entire system and the heat lost from the bed (assuming all the water is driven off in the bed). The former has a direct influence on the thermal efficiency of the system, while the latter would have an influence on the allowable inbed heat transfer surface area if a fluidized bed was to be purpose-designed to burn slurries. It can be seen that when a 60% solids slurry (interpolated from Figure 4.14) is combusted, a 7% penalty in thermal efficiency is incurred (i.e. 8% lost, compared with a normal heat loss of 1% when firing ordinary coal). When the slurry concentration is increased to 67% this penalty falls to 5% (extrapolated from Figure 4.14). This relatively high heat loss due to water is an unavoidable fact when burning slurries.

Roberts et al. (1982) investigated the combustion of coal-water mixtures in a pressurized fluidized-bed combustor (PFBC) and concluded that the heat loss due to water was "not prohibitive". This is due in large part to the fact that the PFBC was part of a combined-cycle power-generation system, in which approximately half the heat lost is recovered due to increased gas flow through the turbine.

Figure 4.15 shows the effect of solids concentration on thermal and combustion efficiency.

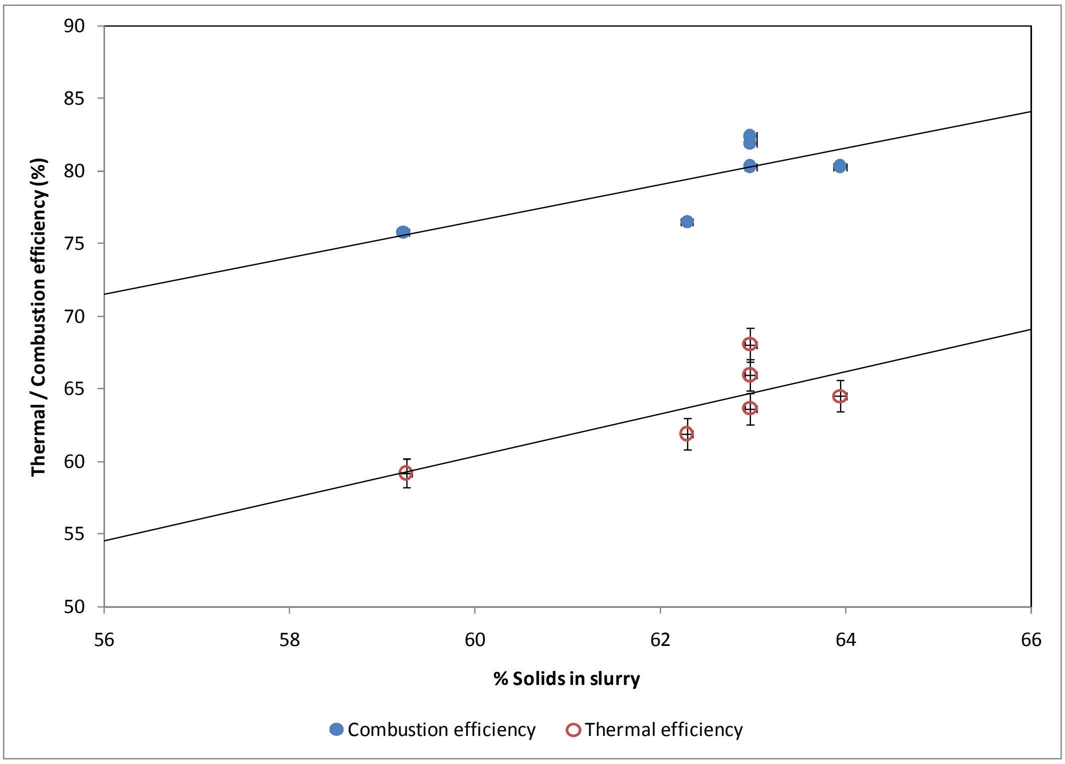

Figure 4.15 Effect of solids concentration on thermal and combustion efficiency

As mentioned above, the water content has a direct effect on thermal efficiency, so the trend seen in Figure 4.15 would be expected. What is also apparent, however, is that a higher solids concentration results in reduced unburnt carbon losses and therefore in a higher combustion efficiency. There is no direct evidence to indicate why this is so, but it is most likely to be due to increased formation of agglomerates with increasing solids concentration.

A maximum thermal efficiency of 67% was achieved. The indications by extrapolation are that, when a slurry is fired in the range of 67% to 68% solids, a thermal efficiency of about 70% may be achieved. This is still however considerably lower than when duff is fired, when thermal efficiencies of up to 80% have been achieved (Eleftheriades and North, 1987).

The lower efficiency is due in part to the unavoidable heat loss caused by water in the fuel, as mentioned earlier. An equally large contributor to the inefficiency, however, is un-burnt carbon losses. The combustion efficiency ranges from 75% to 82%. This is similar to the figures quoted by Miccio et al (1989). However, Roberts et al (1982) quote combustion efficiencies as high as 99%. Although an efficiency as high as this does not appear to be feasible within the system used for the tests reported here, some increase may be gained by optimizing slurry concentration and atomizing air. An expanded, refractory-lined freeboard and primary cyclone ash re-injection would also be of benefit.

A series of tests was carried out in order to determine the effect of load (and therefore fluidizing velocity) on the thermal and combustion efficiencies. In these tests, a slurry of 63 to 64% solids was fired, so discrepancies due to differing solids content are minimal. Figure 4.16 shows the results of these tests. As expected, both the thermal and combustion efficiency decrease with increasing load (and therefore increasing velocity). The effect is not as marked, however, as when duff coal is fired (North, 1989). The fact that the slurry thermal and combustion efficiencies do not drop dramatically with increasing load is due to the formation of char-sand agglomerates which are not as prone to elutriation as the fine parent coal particles.

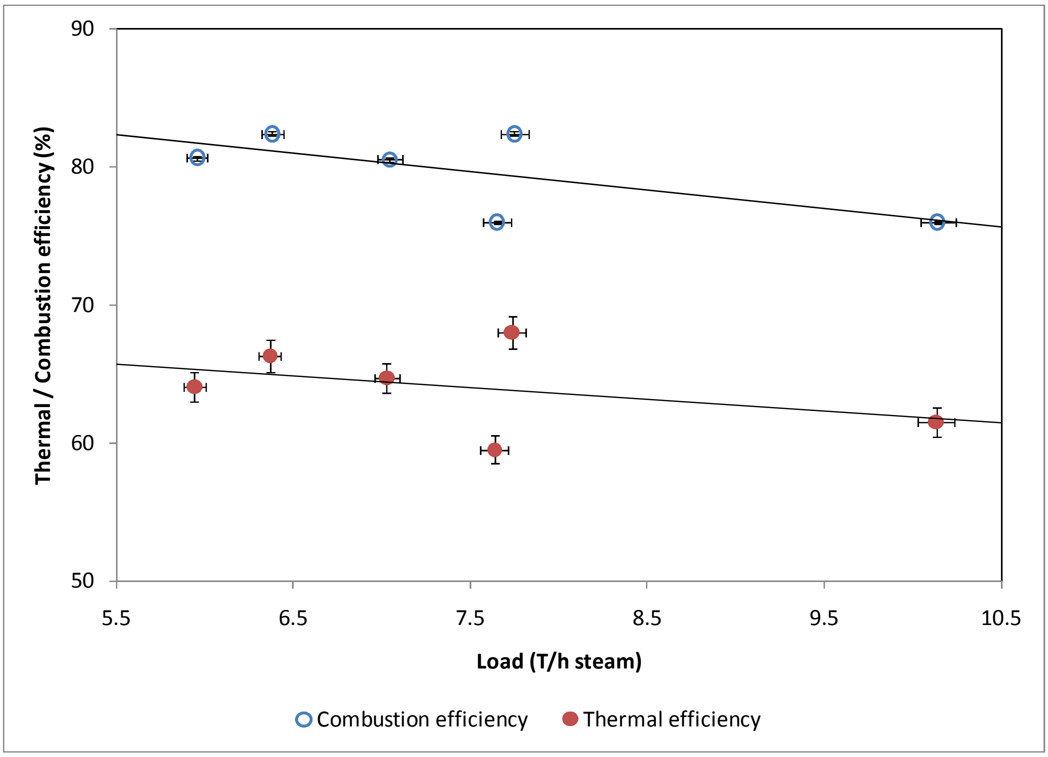

Figure 4.16 Effect of Load (fluidising velocity) on thermal and combustion efficiency firing coal slurry

In conclusion, it is possible to utilise coal slurries in FBCs. The slurries can be pumped at lower pipeline pressure drops than predicted by laboratory tests. The formation of char-sand agglomerates in the bed allows the carbon to have a longer residence time in the bed than would be the case for the parent coal particles, thereby enhancing the combustion efficiency. Stable continuous operation can be achieved, and the boiler can be started up on slurry alone after an extending shut-down period.

However, factors such as location of the slurry versus location of the FBC boiler (with associated transport costs), the inherent penalty due to water content, lifetime of the slurry ponds need to to be considered. Additionally, alternative utilisation methods such as a combination of mechanical and thermal drying and blending into other coal products should be considered.

4.4 Combustion of biomass sludge (co-fired with coal)

4.4.1 Theoretical studies

As explained in section 3.7 above, an iterative process was followed in order to determine what mass of coal is required, in theory, in order to combust the 12 t/h of coffee grounds (which contain 85% water) and raise 26 t/h of steam.

The composite fuel which was derived at the end of this iterative process in illustrated in Table 3.2. Likewise, Tables 3.3 and 3.4 show the theoretical thermal balances over the boiler and the bed respectively. These tables show that, in theory, a composite fuel consisting of 5.03 times as much coffee grounds as coal can be combusted. They also show that, again in theory, the bed will be stable because there is sufficient heat liberated within the bed (from combustion of the fuel) to cover the heat losses from the bed.

Some points need to be noted in connection with the theoretical studies.

(a) They were based on a system employing no heat transfer within the bed. The results validate this basis, as there is a minimal amount of excess heat available in the bed. If heat transfer surfaces were present, then additional heat would need to be generated within the bed. The burning rate of coal in the bed must therefore be increased, with a consequent increase in oxygen consumption. The situation could be reached where there is insufficient excess oxygen in the bed to allow the fuel to burn. This would be a dangerous position to be in, as a very slight change in air or fuel feed rates could cause a switch from a combustion mode to a gasification mode, making control impossible.

(b) The studies were based on the assumption that all of the fuel dries and burns within the bed.

(c) The studies were based on a fluidised-bed operating temperature of 900 ℃ to 1000 ℃.

4.4.2 Small-scale combustion trials

Small scale combustion trials were undertaken in order to establish if a fluidised bed could be run stably while firing it with a coffee ground sludge/coal mixture in the ratio of 5.03:1, the ratio determined in the previous theoretical studies.

The highest coffee ground to coal ratio which was achieved was 4,2:1. The thermal balance over the bed resulting from this run is given in Table 4.6.

Table 4.6 Actual thermal balance, small scale biomass sludge trials

	MJ/h	%
Heat in fuel	453.53	100.00
Heat unavailable from fuel	30.79	6.79
Heat lost in ashes	13.33	2.94
Heat lost due to moisture in fuel	172.99	37.92
Heat lost due to hydrogen in fuel	23.78	5.24
Heat lost in dry flue gases	198.52	43.77
Heat lost due to humidity of air	1.48	0.33
Overall accountability	440.22	97.0
Therefore radiation, convection and unaccounted losses =	13.60	3.0

The figure “heat in fuel” is the total mass of coal and sludge times the weighted gross calorific value (GCV). In order to make the balance hold, an additional figure has to be introduced, i.e. “Heat unavailable in fuel”. This is the fraction of heat available in the fuel which in theory should be evolved in the bed, but in practice is not. It is approximately 7% of the total heat. If the assumption is made that this “loss” of heat arose solely from the coffee grounds burning above the bed instead of in the bed, then it can be calculated that 20.1% of the available heat in the coffee grounds was not evolved in the bed. It is for this reason that it was not possible to reach a ratio of 5:1. This had implications for the design of the planned boiler’s combustion zone. Further, if the worst case is taken, i.e. a ratio of 6:1 when the boiler is producing only 21 t/h steam, a negative heat loss is seen (Table 4.7). This implies that more heat would be lost from the bed than could be generated in it, resulting in loss of bed temperature and, eventually, loss of ignition.

Table 4.7 Thermal balance for extrapolated ratio of 6:1, small scale FBC

	NO DRYING		WITH DRYING	
	MJ/h	%	MJ/h	%
Heat in fuel	513.52	100.00	513.52	100.00
Heat unavailable from fuel	43.43	8.46	43.43	8.46
Heat loss in ashes	14,.9	2.90	14.89	2.90
Heat loss due to moisture in fuel	241.22	46.97	209.52	40.80
Heat lost due to hydrogen lost in fuel	29.02	4.65	29.02	5.65
Heat lost in dry flue gases	199.78	38.90	199.78	38.90
Heat lost due to humidity of air	1.47	0.29	1.47	0.29
Overall accountability	529.82	103.17	498.11	97.00
Therefore radiation, convection and unaccounted losses =	-16.30	-3.17	15.41	3.00

The only way to overcome this situation is to partially dry the coffee grounds before they reach the bed, thus lowering the “heat lost due to moisture in fuel” component and bringing the balance back to a favourable state. The easiest way to achieve this drying is to allow some of the water to flash off in the freeboard.

Such a small amount of water being driven off in the freeboard should not seriously affect the temperature profile there. However, if the process is taken to the extreme, i.e. if all of the coffee grounds are dried and burnt in the freeboard, this will result in a chilling of the gases by almost 300 ℃ which will have serious implications on combustion characteristics and down-stream heat transfer surfaces. It is for this reason that suspension firing, as is sometimes employed with bagasse and wood waste, is not feasible.

4.4.3 Nozzle performance trials

The first nozzle to be tested was a concentric tube type with annular air, similar to the nozzle developed for coal slurry injection. Trials showed that the sludge could be fired through a nozzle as small as 20 mm diameter, provided the reduction from the 75 mm line carrying the coffee grounds was gradual. However, the degree of dispersion achieved was minimal, even when annular air was employed. Direct injection of air into the sludge line proved much more successful, and the sludge could be fired for several meters with a spread of approximately 2 to 3 metres. The sludge was broken up into particles approximately 5mm in size. Interestingly, the particles appeared to have undergone some drying, even though the ambient air temperature was only about 20 ℃. Placing an obstru ction in the patch of the sludge greatly increased dispersion, and a spread of 6 to 10 metres was achieved.

Both these features, i.e. direct air injection and deflector plate, were employed in the nozzle which was built for the trials in the NFBC, although the pipe itself was of a larger diameter (40 mm). Cold trials with the nozzle showed that the dispersion achieved with the smaller nozzle could also be achieved with the large nozzle.

4.4.4 Large-scale combustion trials

In order to further prove the ability of in-flight flash evaporation to swing the thermal balance to a favourable state, trials were carried out in the NFBC facility in Pretoria West.

For the purposes of this test, the NFBC was set up to simulate a “hot gas generator”, or uncooled furnace as closely as possible. This was achieved by blocking off the fluidising nozzles around the periphery of the bed, thereby creating a stagnant slumped zone between the bed and the membrane wall. This limited heat transfer to the wall to a great extent, but it does not remove it altogether. Prior to firing the coffee grounds, trials were carried out to determine what heat was still being removed from the bed by this means, in order that this figure could be included in thermal balances over the bed when firing the coffee grounds.

The most difficult aspect of the trials proved to be the pumping of the sludge. Earlier trials had shown that a 50 mm double diaphragm pump would be able to pump the sludge, however, when running for periods in excess of 10 minutes a solid cake formed in the chamber which prevented further pumping, and in fact caused one of the pistons in the pump to shatter.

Another pump was tried (a lobe type, supplied by Mono), which successfully circulated the solids from and to the 8 m^3 storage tank. Unfortunately, an unforeseen problem occurred when firing the sludge to the boiler. The pump ran for periods of up to 30 minutes but then blocked. It transpired that what was happening was that, due to the high suction head of the pump, the sludge was actually filtering itself and water was preferentially being drawn from the tank. This did not matter when the sludge was being recirculated, but when it was being fired into the boiler, the remaining sludge in the tank gradually became thicker, resulting in the pump blocking. Due to time pressures, however, it was decided to proceed with this pump and cope with these blockages as best as possible.

Despite continued pumping problems, the sludge was fired at a rate of 4 tonnes per hour. During this period the coffee grounds to coal ratio was 2.6:1. However, the excess air level was still high, with the flue gases still containing 8.5% oxygen, so the ratio could have been increased, had continued operation been possible.

To determine what drying, if any, took place in the freeboard, a thermal balance was again generated for the bed. After including the factors mentioned and evaluated earlier (i.e. “heat unavailable in fuel” and “heat to inbed tubes”), a negative heat loss was observed. Since by definition the system did balance (as indicated by the fact that the bed temperature remained stable) it is concluded that the heat losses from the bed were not as great as would occur if all the coffee grounds dried in the bed. This energy “saving” can be equated to approximately 30% of the water being flashed off in the freeboard rather than the bed.

It should be noted that the chief aim of these trials was to maximise the drying in the freeboard, and a great deal of dispersion (by air injection and a deflector plate) was employed. Physical inspection of the furnace after the tests revealed that the degree of dispersion was actually too great, and some coffee grounds had impinged on the tubes of the wall opposite the feeding point. This should be avoided in the planned boiler. There are two beneficial factors which indicate that this should be easily achieved.

1. The planned boiler furnace is much larger than the NFBC furnace (28 m^2 vs 9 m^2).
2. The degree of drying achieved in the NFBC was much greater than actually required (30% vs 13.3%), indicating that a lesser degree of dispersion could be employed.

4.4.5 Implementation – an industrial FBC boiler co-firing coal and sludge

Based on the encouraging test results, a full scale plant was designed, constructed and commissioned. The bed area required at conservative fluidising velocities was 28 m^2. As indicated by the test work, the combustion zone could not contain any heat transfer surfaces, and so it was constructed as a refractory-lined chamber. Figures 4.17 and 4.18 show the refractory walls of the furnace. 4.17 is the wall which houses the coal feeders, and the opening for two of these can be seen. Figure 4.18 shows the wall through which the coffee ground sludge is injected. Three of the four injection points can be seen.

Figure 4.17 Coal feeder wall of the sludge and coal co-fired FBC

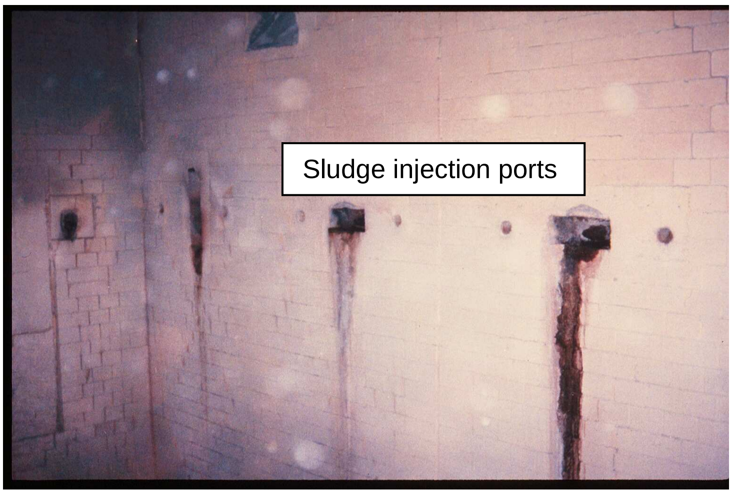

Figure 4.18 Sludge injection wall, of the sludge and coal co-fired FBC

Based on the learning gained with pumping the sludge in the test work and the client's experience with handling the sludge, the pump chosen for pumping the sludge into the FBC for the full scale plant was a wide throat auger-fed mono pump. This pump proved to be ideal for the purpose.

The sludge was delivered to a buffer tank, pumped to the boiler, and injected through the four nozzles. This can be seen in Figures 4.19 to 4.21 below.

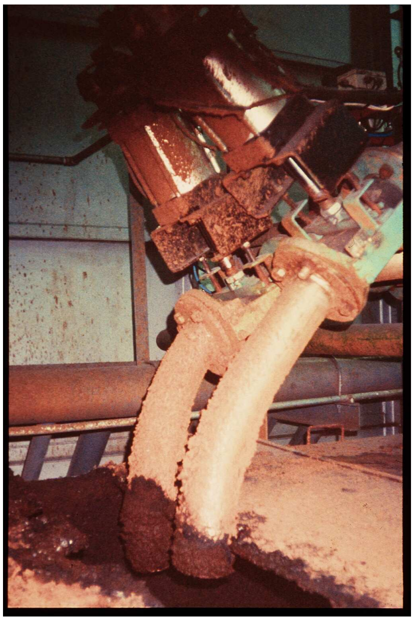

Figure 4.19 Sludge delivery lines (to buffer tank)

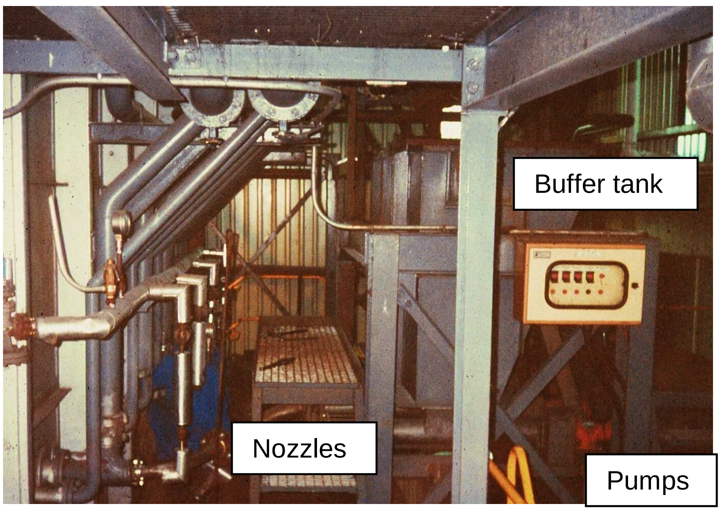

Figure 4.20 Sludge buffer tank with delivery pumps and nozzles

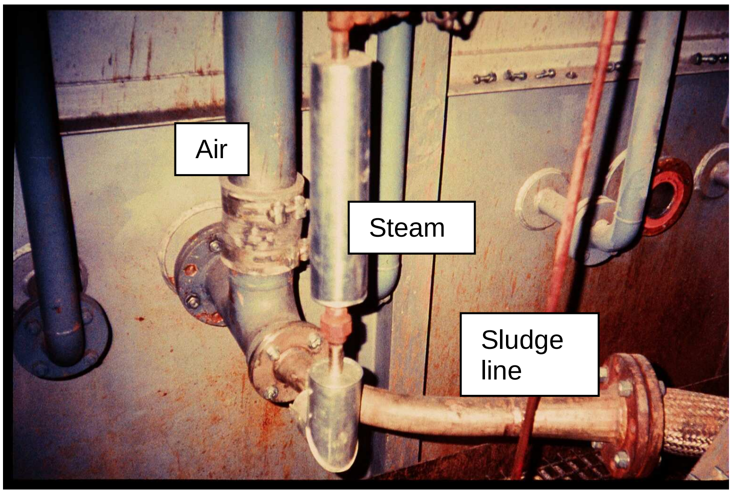

Figure 4.21 Sludge delivery nozzle, on wall of FBC

The design of the nozzle was finalised by undertaking tests on different designs at the client's site. The report produced during these tests is given in Appendix D.

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The main variable between the types of nozzles was the tip, essentially how the sludge was dispersed. All attempts to promote dispersion by some physical constraint at the tip proved futile, as the nozzle would inevitably block. To avoid this, and also to develop a nozzle for which spares could easily be fabricated by the client, a "flattened pipe" was favoured. This concept proved successful during the trials at site. The design was refined through calculating the optimum aspect ratio of the pipe, in conjunction with dispersion air requirements. Theses calculations and results are also given in Appendix D.

The final nozzle design was similar to that used for the coal slurry combustion trials. This had the coffee grounds flowing through a central pipe and air from the forced draught (FD) fan flowing through an annulus. Compressed air or steam was injected into the sludge line to assist in dispersion. The original idea of putting a deflection plate at the end of the nozzle was replaced by an up-turned bottom lip. The top lip was cut back to accommodate this, and to prevent blockages from lumps of chicory which are inevitably present. The nozzle can be seen, removed from the boiler, in figure 4.22 below.

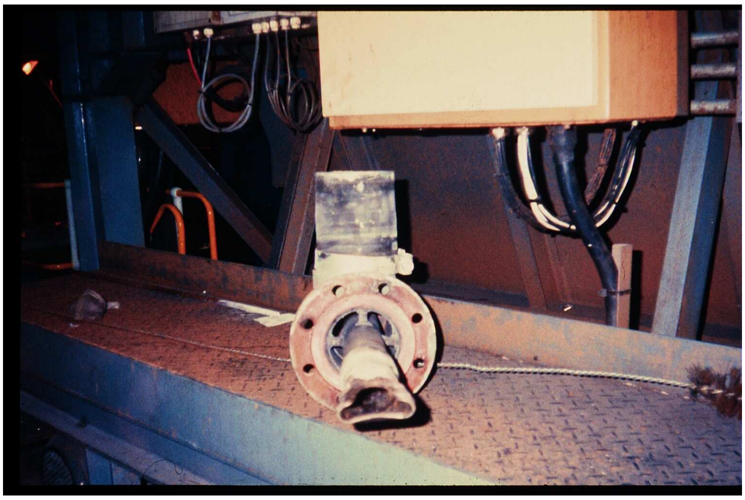


Figure 4.22 Sludge injection nozzle

The coal was fed onto the bed by three feeders. Control of coal flow was by speed of the screw feeders. The coal was dispersed over the bed by spreaders or “flingers”, of the type used in spreader stoker fired boilers. Figure 4.23 below shows the coal feeders.

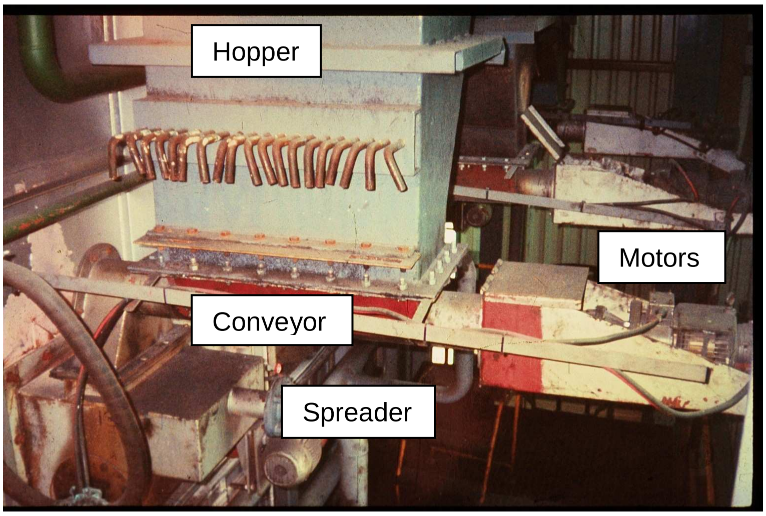


Figure 4.23 Coal feeders

A picture of the boiler, which is essentially a waste heat boiler, and an overall view of the plant, including the boiler section (right hand side) and the gas clean up plant (left hand side) can be seen in figures 4.24 and 4.25 below.

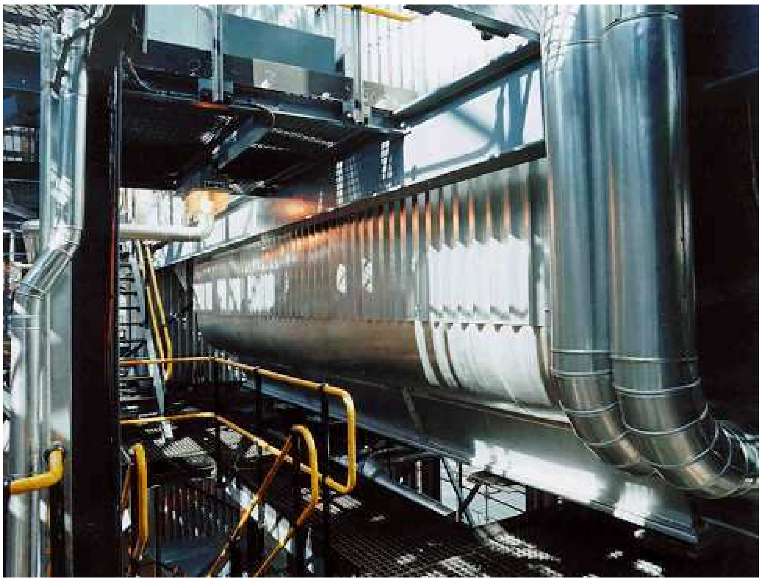


Figure 4.24 Boiler generating 26 t/h of steam

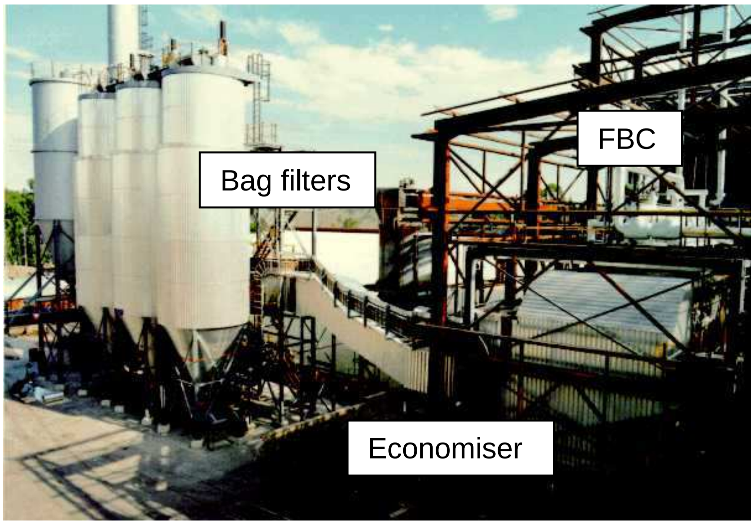


Figure 4.25 Overall view of biomass and coal co-fired FBC plant

In conclusion, through a process of theoretical calculations, test work and full scale implementation it has been proven that coal and biomass sludge can be successfully co-fired in an FBC boiler. The operator of the boiler has enjoyed a high degree of availability and trouble-free operation from the unit, and has disposed of many thousands of tonnes of waste, while generating the required plant process steam.

4.5 Summary of FBC plants designed by the author during research period

Details are given below of FBC plants which have been designed by the author based on experience gained during this research. This serves to highlight the impact that this research had on the development and application of FBC technology in South Africa. These plants have generally been designed for niche applications, with a general theme of “Waste to Energy”. Additional detail of these plants can be seen in Volume 2. (See reference after plant title.)

4.5.1 Slagment Hot Gas Generator (Volume 2: 8)

The Slagment hot gas generator was the first industrial-scale plant designed by the author. It was supplied to the company Slagment, in Vanderbijlpark, South Africa. The plant is a 13 MW fluidised bed hot gas generator, which supplies hot gas to a dryer to dry slag prior to milling.

There were three primary design requirements.

- The fuel would be low-grade duff coal.
- A very high combustion efficiency must be achieved in order to minimise carbon carry-over into the slag.
- The plant should be capable of being shut down (“slumped”) for extended periods and re-started quickly, without requiring the start-up burner to be fired.

Duff coal was the design fuel principally because of the (then) low price of such waste coal. The FBC replaced an existing stoker-fired hot gas generator which required a high quality, graded coal. The design of this plant drew on experience gained on the National Fluidised Bed Combustion boiler, and incorporated features such as a low fluidising velocity, a tall freeboard area and the possibility of operating at higher temperatures in order to achieve a high combustion efficiency.

A deep bed (up to 600 mm deep) was employed in order to ensure that the plant could be shut down for extended periods and re-started without the use of the gas burner. The deep bed could retain enough heat to re-start after a slump of 20 hours. A negative consequence to this was the need for two forced draught fans in series in order to supply fluidising air at a pressure high enough to fluidise the deep bed.

A great deal of experience was obtained from this plant, in particular the design of the air distribution system. A central plenum, main riser, horizontal sparge, stand-pipe and bubble cap system was developed for this plant. This design was in general very effective, and allowed for bed drainage and use of an efficient under-bed burner for start-up. The design, with sets of three standpipes projecting upwards from the horizontal sparge, dictates that the number of bubble caps in one dimension of the FBC must be a multiple of three. The number of bubble caps in the other dimension is generally an even number. The design did however exhibit an unexpected problem, in that the ends of the horizontal sparges (which are in static sand, below the fluidised sand) deformed inwards over time due to continual expansion and contraction from thermal cycling. A re-design to incorporate “shovel ends”, and adding stiffeners to some of the bubble cap stand-pipes successfully solved the problem, and was employed in future designs.

This plant easily met the design requirements and was financially successful for the client, with a short pay-back time due to the low cost of the duff coal. This plant received the South African Institution of Mechanical Engineers’ Projects and Systems award for its innovative design and conformance to demanding client requirements.

4.5.2 Biomass and Coal Co-fired FBC Boiler (Volume 2: 9, 10, 12 and 16)

This plant, designed for a multi-national food company based in Estcourt, KwaZulu-Natal, South Africa, is described in detail in this thesis, as I consider it to be a novel and unique application of FBC technology that required a great deal of innovation and test-work to accomplish.

The plant had two primary functions : to dispose of a waste stream of 12 tph of coffee grounds sludge (which has a moisture content of approximately 85%) and to generate 26 tph of process steam.

This situation was unique in that the coffee grounds had to be fired as they arise. Other FBC plants elsewhere in the world burn coffee grounds that have been dried to some extent. However, the local circumstances prevalent at the time, i.e. relatively expensive cost of capital and relatively cheap cost of energy (coal in this case), led to the decision to burn the grounds wet. This avoided the installation of presses and effluent treatment plant such as multiple effect evaporators.

This approach led to the need for a complex design. The wet coffee grounds cannot burn autothermally, they need to be co-fired with coal. Coal is in any event required to achieve the steam production. The goals were to produce the design amount of steam (26 tph) while minimising the coal requirements and to provide a plant that was easy to operate. This was achieved through extensive calculations and modelling of the system at various loads and coffee grounds firing rates, and through small and large scale test-work.

This FBC was awarded the South African Institution of Chemical Engineer's "Chemical Engineering Innovation" award in recognition of this novel and unique application of FBC technology.

The plant operated successfully and has met all the design requirements.

4.5.3 High Sulphur Pitch Incinerator (Volume 2: 14 and 16)

This is another example of a waste to energy application of FBC which the author designed. Sasol (in Sasolburg, South Africa) produces a stream of High Sulphur Pitch (HSP) as an inherent part of their coal-to-liquids technology. This stream has a high calorific value, similar to oil, but it contains an assortment of chemicals and also a considerable amount of sulphur (in excess of 10%). Incineration is the only viable disposal method for this waste stream. It had been disposed of in a refractory-lined incinerator where the HSP was burnt at a high temperature through a conventional burner. Adequate residence time for full destruction of the organic components was given, and the gases were exhausted though a tall stack. No sulphur reduction measures were taken. At the time, no such measures were mandated. Sasol, however, decided pro-actively to install a new incinerator that would reduce the sulphur emissions.

The technology chosen was an FBC designed by the author. This unit was designed to incinerate both the HSP stream and a High Organic Water (HOW) stream. A key feature of the design was in-situ sulphur capture (85%) through limestone injection into the bed.

Although experience had been gained in firing slurries and wet fuels such as the coffee grounds described above, the combustion of a liquid fuel in the FBC was a considerable challenge. Calculations and exhaustive test-work were required in order to optimise the injection and combustion of the HSP, and effect the sulphur capture.

The final design incorporated six (optionally 12) HSP injection points and 6 HOW injection nozzles. The HSP was injected into the bed using water-cooled lances. This was necessary in order to maximise the amount of in-bed combustion versus over-bed combustion. Limestone was distributed over the bed using two air-swept spreaders. Limestone was delivered to the spreaders by variable speed metering screws. Coal was also fed through these feeders during start-up, to boost the bed temperature up before commencing HSP feeding. The plenum, riser, sparge and bubble cap air distribution system was employed to allow for continuous removal of spent sorbent. This spent sorbent was extracted through water-cooled screws and was further cooled in a fluidised bed cooler before being sent to a storage silo.

The exhaust gases passed though a boiler, where 20 tph of steam was generated, before passing to a bagfilter for de-dusting before being exhausted to the atmosphere.
The plant was commissioned successfully and met the required sulphur reduction target of 85%.

Three major environmental claims are made for this plant.

- Reduction of Sulphur emissions (a reduction of 85% against the original incinerator). This sulphur was captured dry, and avoided the use of water, which is a scarce resource in South Africa. This is a major advantage over conventional Flue Gas Desulphurisation (FGD) plants which utilise considerable volumes of water.
- Reduction of NOx emissions, since the FBC operates at a lower combustion temperature than the original incinerator.
- Reduction of CO_2 emissions, since the plant is producing process steam for the Sasol plant that had previously been generated in a coal-fired boiler.

4.5.4 Fluidised Bed Deodoriser (Volume 2: 13)

Although not a waste to energy plant, this application of FBC nonetheless incorporated the solution to one problem (odorous air) with the benefit of generation of plant steam.

African Products, a large South African company specialising in maize products, was planning a greenfields expansion project. As with the existing plant, steam tube driers were to be employed to dry process and spent grain. From experience, these dryers produce an odour, which some consider to be pungent. The design, therefore, needed to include a means to deodorise the air leaving these dryers.

Similar maize processing plants operating in the USA employ gas burners to incinerate the odorous air. However, gas is not an economically viable solution for South Africa, as gas resources are scant. Coal, on the other hand, is in abundant supply, and is significantly cheaper than gas, oil or electricity for industrial heating and drying applications. The design for this application was a coal-fired FBC, using the odorous air as the fluidising gas.

Although the 48 000 Nm^3/h of gases leaving the dryers are predominantly air, with trace amounts of odorous components, they are also saturated with water vapour. At the dryer exhaust temperature, air holds 58% water vapour. This proved to be the major technical challenge, as there was insufficient oxygen in the stream to burn the coal required to operate the FBC at 850 ℃.

A significant amount of water was removed from the gas stream by passing it through a scrubber. Although the gas is still saturated with water vapour when it exits this scrubber, it is at a lower temperature of 72 ℃, an d therefore only contains 36% water vapour. Some 13 to 16 tph of water are knocked out of the gas stream in this way.

Handling saturated gas is difficult, as any further reduction in temperature will cause water to condense out of the gas stream. Of particular concern was the possibility of having water droplets entering the Induced Draft fan. So to avoid this occurring a steam pre-heater was installed directly after the scrubber to re-heat the gas stream up to approximately 100 ℃.

The odorous air stream was used as the fluidising gas in the FBC (through the plenum, riser and sparge air distribution system). Start-up was by means of an underbed burner, as with the previous plants. Coal was fed through two air-swept spreaders similar to those designed for coal and limestone distribution in the HSP plant.

The hot (deodorised) gases leaving the FBC pass through a shell waste heat boiler to generate 13 tph of process steam. This avoids the use of additional coal being used to generate this steam in the boiler plant.

The plant was commissioned successfully and has been in commercial operation for some time now.

5 ECONOMIC VALUE OF DISCARD COAL

The ability to burn low grade coal is of academic interest only unless there is an incentive to do so. This incentive would generally be economic. What economic value could be gained from utilising existing discard dumps and current arising discards?

This section is presented as first a “screening” assessment, in order to ascertain if there is potentially value in utilising discard coal to generate electricity in an FBC power station, followed by a more in-depth analysis to calculate potential investment indicators such as Net Present Value and Internal Rate of Return, and also to run sensitivity analyses.

A study was undertaken at the CSIR (North, 1990) (Volume 2: 18) to compare FBC and conventional combustion technology such as pulverised fuel (PF) on a technology and economic basis. The report indicated that although FBC had potential advantages over PF, factors such as technology maturity, capital costs, environmental legislation and run-of mine coal quality indicated that FBC was at that time not yet a viable competitor. The report concluded that factors such as reducing coal quality and more stringent environmental legislation could change that picture.

Since then, with both those factors arising, and with the maturity of FBC technology increasing substantially, the picture has indeed changed. The South African Integrated Resource Plan (IRP) (South African Department of Energy, 2010) recognised that FBC will be a part of South Africa’s electricity supply mix, with FBC power plants built, owned and operated by Independent Power Producers (IPPs) coming on-line as early as 2014/2015.

In support of this, project proposals have already been tabled. Anglo American are proposing a 450 MW(e) CFBC power station fuelled by discard coal from dumps at nearby Anglo American mines (Hall et al, 2011). This proposal was in fact tabled at the public hearing of the IRP. Anglo American would not own or operate the power station. They would provide land, discard coal and water. They would also enter into an off-take agreement with the IPP, with the electricity being used to supply Anglo American’s platinum mines. It is estimated that the discard dumps at Kleinkopje, Greenside and Landau collieries will be enough to supply the power station for 30 years. This coal is reported to have a CV of 10 MJ/kg to 15 MJ/kg, containing approximately 50% ash.

The relative capital costs of FBC and PF power stations have converged. Early sources indicate that FBC could have a capital cost approximately 20% higher than PF (Eskom fact sheet, 2007). Recent articles have revealed that the two are on a par (Aziz and Dittus, 2011; Utt and Giglio, 2011, Haripersad, 2010). This is in large part due to the maturity of FBC. FBC power stations being built at present are of a similar size to PF power stations, so the penalty associated with FBC power stations due to them being built at lower capacities has fallen away. Additionally, operation of utility scale FBCs at supercritical steam conditions has been proven (Utt et al, 2009). For the Lagiza Supercritical FBC (Patel, 2009; Utt et al, 2009) a specific capital cost figure as low as USD1300/kW installed capacity was quoted (Luckos, 2011). It should be noted, however, that this was a “brownfield” development, and many costs such as coal handling equipment, offices etc were largely avoided.

Site specifics and emission control requirements will also affect the capital cost of plants. These could also affect non fuel-related operating costs.

The key identifiable factor determining the cost of electricity produced by an FBC power station fired by discard coal versus that produced by a PF power station fired by a higher grade coal is the cost of the coal. It was decided, therefore, to undertake a “screening” comparison of an FBC power station to a PF power station essentially on the cost of the fuel.

5.1 Screening comparison of FBC vs PF based on fuel cost

There are a number of scenarios that can be considered. A primary consideration is whether one uses the discards already stockpiled, or whether one uses the currently arising discards. Also, one needs to consider the cost of the discard coal. An easy, but simplistic, viewpoint is that it is free. However, in reality the use of such low grade coal will result in costs such as reclamation and crushing, and may lead to increased running costs due to having to handle higher ash loads etc.

Koornneef et al (2006) gave an excellent discussion on the development of FBC, and gave a comparison of costs. They state that the fuel cost component of electricity is 29% for PF and 15% for FBC firing discard coal (referred to by them as “scrap coal”). This indicates that, by their research, there is a cost to discard coal – it is not free.

Eskom (2011) indicated that the electricity revenue in the year 01 April 2010 to 31 March 2011 was 40.27 c/kWh. The cost of the fuel, excluding factors such as an environmental levy, use of IPPs and other costs, is indicated as 14.4 c/kWh.

The above inputs were used to estimate the potential value of discard coal. The results are presented below. This is not a rigourous study, it is rather intended to indicate potential value. Many location, fuel, water and sorbent-specific issues need to be evaluated when evaluating such an opportunity. A more detailed economic analysis of a discard coal-fired FBC power station follows this screening comparison.

The value of discard coal, realised through the production of electricity in an FBC power station, was estimated for six scenarios (A to F). The assumptions for each scenario are given below. Discard coal stockpiles and arising discards quantities were obtained from Prevost (2010), fuel cost component figures from Koornneef et al (2006) and the South African electricity value was obtained from Eskom (2011). The calculated values for these scenarios are indicated in Tables 4.8 to 4.13

Scenario A (“Free fuel” and total revenue from sale of electricity) key assumptions:
The existing dumps throughout South Africa are utilised
This is done over 40 years
The average CV of the discards is 13 MJ/kg
Plant availability is 95%
Plant efficiency is 38%
The value (sale price) of electricity is R0.4/kWh

Scenario B (“Free fuel” and total revenue from sale of electricity) key assumptions:
Only the arising discards are used.
Plant life is 40years
Average CV of the discards is 13 MJ/kg
Plant availability is 95%
Plant efficiency is 38%
The value (sale price) of electricity is R0.4/kWh

Scenario C (Savings due to “Free Fuel” vs high-grade) key assumptions:

The existing dumps throughout South Africa are utilised

This is done over 40 years

The average CV of the discards is 13 MJ/kg

Plant availability is 95%

Plant efficiency is 38%

The value (sale price) of electricity is R0.4/kWh

The Fuel component cost of electricity is R0.1475/kWh

Scenario D (Savings due to “Free Fuel” vs high-grade) key assumptions:

Only the arising discards are utilised

This is done over 40 years

The average CV of the discards is 13 MJ/kg

Plant availability is 95%

Plant efficiency is 38%

The value (sale price) of electricity is R0.4/kWh

The Fuel component cost of electricity is R0.1475/kWh

Scenario E (Cost of discard coal included (not Free Fuel)) key assumptions

The existing dumps throughout South Africa are utilised

This is done over 40 years

The average CV of the discards is 13 MJ/kg

Plant availability is 95%

Plant efficiency is 38%

The value (sale price) of electricity is R0.4/kWh

Fuel component cost of electricity (high grade coal in PF) is 29%

Fuel component cost of electricity (discards in FBC) is 15%

Differential fuel savings for discards (14% of electricity value) is R0.0564/kWh

Scenario F (Cost of discard coal included (not Free fuel)) key assumptions

Only the arising discards are utilised

This is done over 40 years

The average CV of the discards is 13 MJ/kg

Plant availability is 95%

Plant efficiency is 38%

The value (sale price) of electricity is R0.4/kWh

Fuel component cost of electricity (high grade coal) is 29%

Fuel component cost of electricity (discards) is 15%

Differential fuel savings for discards (14% of electricity value) is R0.0564/kWh

Tables 4.8 to 4.13 indicate the potential revenue (for Scenarios A and B) and potential savings compared to using high-grade coal (for Scenarios C, D E and F)

Table 5.1 Scenario A – Revenue from Electricity (Dumps)

Scenario A: Utilising existing dumps, revenue from sale of electricity			
Input data	**Value**	**Unit**	**Source**
Amount of discard coal stockpiled	1500	Million tonnes	Prevost, 2010
Period over which discards utilised	40	Years	Assumption
Average calorific value of discards	13	MJ/kg	Du Preez, 2001
Plant availability	95	%	Estimate
Efficiency (coal to electricity)	38	%	Estimate (SC)
Value of electricity	0.4	R/kWh	Eskom, 2011
Output results			
Rate of use of discards	37.5	Million tonnes/yr	
Power plant capacity	6183.41	MW	
Amount of electricity produced	51458.33	GWh/yr	
Value of electricity produced	20.58	Rbn/yr	
Value of electricity produced	823.33	Rbn over lifetime	

Table 5.2 Scenario B – Revenue from Electricity (Arising discards)

Scenario B: Utilising arisings, revenue from sale of electricity			
Input data	**Value**	**Unit**	**Source**
Discards arisings	67	Million tonnes/y	Prevost, 2010
Lifetime of plant	40	years	Assumption
Average calorific value of discards	13	MJ/kg	Du Preez, 2001
Plant availability	95	%	Estimate
Efficiency (coal to electricity)	38	%	Estimate (SC)
Value of electricity	0.4	R/kWh	Eskom, 2011
Output results			
Power plant capacity	11047.69	MW	
Amount of electricity produced	91938.89	GWh/year	
Value of electricity produced	36.78	Rbn/year	
Value of electricity produced	1471.02	Rbn over lifetime	

Table 5.3 Scenario C – Savings due to Free Fuel (Dumps)

Scenario C: Utilising existing dumps, full fuel cost savings ("Free Fuel")			
Input data	**Value**	**Unit**	**Source**
Amount of discard coal stockpiled	1500	Million tonnes	Prevost, 2010
Period over which discards utilised	40	Years	Assumption
Average calorific value of discards	13	MJ/kg	Du Preez, 2001
Plant availability	95	%	Estimate
Efficiency (coal to electricity)	38	%	Estimate (SC)
Value of electricity	0.4027	R/kWh	Eskom, 2011
Fuel component cost of electricity	0.144	R/kWh	Eskom, 2011
Output results			
Rate of use of discards	37.5	Million tonnes/yr	
Power plant capacity	6183.41	MW	
Amount of electricity produced	51458.33	GWh/yr	
Savings in fuel costs	7.41	Rbn/yr	
Savings in fuel costs	296.40	Rbn over lifetime	

Table 5.4 Scenario D – Savings due to Free Fuel (Arising discards)

Scenario D: Utilising arisings, full fuel cost savings (Free Fuel)			
Input data	**Value**	**Unit**	**Source**
Discards arisings	67	Million tonnes/y	Prevost, 2010
Lifetime of plant	40	years	Assumption
Average calorific value of discards	13	MJ/kg	Du Preez, 2001
Plant availability	95	%	Estimate
Efficiency (coal to electricity)	38	%	Estimate (SC)
Value of electricity	0.4027	R/kWh	Eskom, 2011
Fuel cost component of electricity	0.144	R/kWh	Eskom, 2011
Output results			
Power plant capacity	11047.69	MW	
Amount of electricity produced	91938.89	GWh/year	
Savings in fuel costs	13.24	Rbn/year	
Savings in fuel costs	529.57	Rbn over lifetime	

Table 5.5 Scenario E – Partial fuel cost savings (Dumps)

Scenario E: Utilising existing dumps, partial fuel cost savings (Not Free Fuel)			
Input data	**Value**	**Unit**	**Source**
Amount of discard coal stockpiled	1500	Million tonnes	Prevost, 2010
Period over which discards utilised	40	Years	Assumption
Average calorific value of discards	13	MJ/kg	Du Preez, 2001
Plant availability	95	%	Estimate
Efficiency (coal to electricity)	38	%	Estimate (SC)
Value of electricity	0.4027	R/kWh	Eskom, 2011
Fuel component cost of electricity - high grade	29	%	Koornneef et al, 2007
Fuel component cost of electricity - discards	15	%	Koornneef et al, 2007
Differential fuel saving for discards	14	%	Koornneef et al, 2007
Differential fuel saving for discards	0.0564	R/kWh	By calculation
Output results			
Rate of use of discards	37.5	Million tonnes/yr	
Power plant capacity	6183.41	MW	
Amount of electricity produced	51458.33	GWh/yr	
Incremental savings in fuel costs	2.90	Rbn/yr	
Incremental savings in fuel costs	116.04	Rbn over lifetime	

Table 5.6 Scenario F – Partial fuel cost savings (Arising discards)

Scenario F: Utilising arisings, partial fuel cost savings (Not Free Fuel)			
Input data	**Value**	**Unit**	**Source**
Discards arisings	67	Million tonnes/y	Prevost, 2010
Lifetime of plant	40	years	Assumption
Average calorific value of discards	13	MJ/kg	Du Preez, 2001
Plant availability	95	%	Estimate
Efficiency (coal to electricity)	38	%	Estimate (SC)
Value of electricity	0.4027	R/kWh	Eskom, 2011
Fuel component cost of electricity - high grade	29	%	Koornneef et al, 2007
Fuel component cost of electricity - discards	15	%	Koornneef et al, 2007
Differential fuel saving for discards	14	%	Koornneef et al, 2007
Differential fuel saving for discards	0.0564	R/kWh	By calculation
Output results			
Power plant capacity	11047.69	MW	
Amount of electricity produced	91939	GWh/year	
Incremental savings in fuel costs	5.18	Rbn/year	
Incremental savings in fuel costs	207.33	Rbn over lifetime	

Analysis of the scenarios set out in the tables above leads to the following observations:

The current arising discards could generate more electricity than the two power stations currently under construction in South Africa (Medupi and Kusile, rated at 4800 MW each).

The statement made above should be qualified in that this generation capacity would most likely be through a number of smaller power stations, since the discards are generated over a wide area. This is recognised in the SA Integrated Resource Plan (South African Department of Energy, 2010) which envisages IPPs building power stations in about the 400 MW to 500 MW range.

Utilisation of the existing dumps over a 40 year period could add another 6659 MW. (But some of this coal may not be practically recoverable.)

The annual value of the electricity generated, if sold to a customer at the current generation cost, is Rbn 20.6 and Rbn 36.7 for stockpiles and arising discards respectively.

The annual fuel savings compared to firing high-grade coal in a PF power station, if the discard coal is considered as free, would be about Rbn 7.4 and Rbn 13.2 for dumps and arising discards respectively.

If a cost for the recovery and utilisation of discard coal were to be included, annual savings of Rbn 2.9 and Rbn 5.2 could be achieved for dumps and arising discards respectively.

Building a power station is expensive. Even taking the “optimistic” figure of \$1 300 000/MW for the Lagiza CFBC (Luckos, 2011) (at current exchange rates of about \$1 = R8.7, this is R11 310 000/MW), the capacity required to utilise current arising discards would cost over Rbn 100.

5.2 Economic analysis of a discard coal-fired FBC power station

An economic analysis of a discard coal-fired FBC power station was undertaken to provide more concrete indicators of economic viability than the (promising) indications of the screening assessment.

A case study of a 450 MWe station was considered. This is in line with the size of FBC power stations envisaged in the South African Integrated Resource Plan (South African Department of Energy, 2010) and plants being considered by industry (Hall et al, 2011), and is within the proven capacity of efficient, supercritical FBC plants (Utt et al, 2009).

The analysis was undertaken in two components, both of which utilised Excel® spreadsheets. The first is essentially a material and energy balance, in which fuel and sorbent requirements are calculated using input data such as plant size, plant efficiency, fuel CV, Ca/S ratios etc. Additionally, in this component, operating costs, fuel and sorbent transport costs and revenue (from the sale of electricity) are calculated.

The figures calculated in the first component are then used to construct the second component, a Discounted Cash Flow (DCF) analysis. This is used to run sensitivity analyses and to calculate economic indicators such as the Net Present Value (NPV) and the Internal Rate of Return (IRR). The IRR is the discount rate at which a zero NPV is seen, and is essentially a measure, as its name would suggest, of the return that could be made on the investment. Most companies have a “hurdle rate”, and will not consider projects returning an IRR which fall below this. The IRRs (and NPVs) of various projects are also often compared to select the optimal investment out of many possible investments.

Definitions of, and example calculations of, DCF, IRR and NPV can be found in any standard economics or finance book, e.g. Correia et al, 1989.

5.2.1 Calculation of costs (Input parameters)

A list of input parameters, with a discussion and reference (if available) is given below. These values are used as a “base case”, and evaluation of different scenarios and sensitivity analyses then follow.

Plant size: 450 MWe

This is in line with the size of FBC power stations envisaged in the South African Integrated Resource Plan (South African Department of Energy, 2010) and plants being considered by industry (Hall et al, 2011), and is within the proven capacity of efficient, supercritical FBC plants (Utt et al, 2009).

Plant efficiency: 40%

This is not the thermal efficiency referred to previously, but rather the percentage of the energy in the coal that is converted to electrical energy. Utt and Giglio (2011) assumed 40% efficiency for a supercritical CFB. In a prior publication Utt et al (2009) reported an efficiency of 41.6% for the Lagiza power station. Jantti (2011) later reported that an efficiency of 43.3% was being achieved at Lagiza, however, it appears that this may have been calculated on the Lower Heating Value (LHV) (or Net Calorific Value, NCV) rather than the Higher Heating Value (HHV) (or Gross Calorific Value, GCV). It was decided therefore, keeping in mind the low quality discard coal that would be utilised, to assume the relatively conservative figure of 40%.

Capacity Factor: 85%

This is the electricity that is actually produced in a year as a percentage of the electricity that could be produced. It takes into account load following and planned and unscheduled maintenance. The US Electrical Power Research Institute (EPRI) assumed 85% in a study undertaken as input to the South African IRP (EPRI, 2010), and this was adopted in this current analysis. From this more detailed analysis, it appears that the 95% assumed for the screening analysis was optimistic.

Fuel Calorific Value: 13 MJ/kg

This is the same value used for the screening assessment, and is drawn from studies undertaken to assess the inventory of duff and discard coal (Pinheiro *et al*, 1999; Du Preez, 2001).

Fuel Ash content: 45%

Discard coal, both in dumps and being produced, has a wide range of ash content. (Pinheiro *et al*, 1999; Du Preez, 2001, Hall et al, 2011). A figure of 45% was used because it is in good agreement with those quoted by Hall et al (2011) and is similar to the ash content of the Greenside Discards tested in the NFBC (Appendix A of this thesis). The economic calculations are not, however, very sensitive to the coal ash content, as for the purposes of this analysis the coal requirements are calculated from the Calorific Value of the coal rather than the ash content.

Sulphur content: 2.77%

Again, there is a wide range of sulphur contents of both arising discards and those in dumps. A value of 2.77% was used, this being the sulphur content of the Greenside discards tested in the NFBC (Apendix A of this thesis). It is also in agreement with sulphur contents reported by Hall et al (2011). Aziz and Dittus (2011) reported a significantly lower Sulphur content of 1.5% in their study of a CFB power station utilising discard coal from the Delmas coal mine. The economic study is sensitive to the sulphur content of the coal, because this dictates the amount of sorbent required to reduce the sulphur oxide emissions.

Not considered here, but of merit to consider in a real application, is the possibility of beneficiating the discards, particularly those being recovered from dumps, to reduce the sulphur content and therefore sorbent requirements (discussed below). Hall et al (2011) considered this option, whereas Aziz and Dittus (2011) did not.

Required Ca/S ratio: 2.9, 5.3

This is the molar ratio of calcium in the sorbent to sulphur in the coal, with a stoichiometric (1:1) ratio theoretically (but not practically) being able to remove all the sulphur. As shown by the research in the NFBC, the calcium content of a sorbent is not necessarily a good indication of the efficacy of the sorbent, and therefore of the amount required. The physical nature of the sorbent plays a large role. A figure of 2.9 was derived from figures quoted by Aziz and Dittus (2011) for limestone. Utt et al (2009) indicate that 94% of sulphur from a fuel containing 0.6% to 1.4% sulphur could be achieved at a Ca/S ratio of 2.0 to 2.4. It was decided to use the 2.9 quoted by Aziz and Dittus, as a measure of conservatism.

For dolomite (the rationale for use of which is explained below), a Ca/S ratio of 5.3 was used. This is based on the relative performance of Lyttelton Dolomite vs Union lime shown in the research on the NFBC (figure 4.10). This is an estimate, but it is intended to show the effect of sorbent type and source on financial viability.

This is an important parameter, as it dictates the amount of sorbent that will be required, which is a significant operating cost for the plant. It would be of great value if the economic assessment developed here could be linked to a sorbent efficacy model, so that the required Ca/S ratio for a given sorbent can be input, rather than estimated. This will be expanded upon in Section 6, Recommendations.

Calcium carbonate content of sorbent: 30% to 96%

While the selected Ca/S ratio drives the calculation of how much calcium is required, the calcium content of the sorbent then dictates how much sorbent is required. This has implications on both the base cost of the limestone and the transport cost. South African limestones typically have a calcium carbonate content in the range of 85% to 95% (Agnello, 2005). The limestone chosen for this analysis is supplied by Idwala Lime, who operate a limestone quarry in Danielskuil, approximately 700 from the Witbank area. Idwala Lime currently supply the limestone for the CSIR-designed FBC High Sulphur Pitch incinerator operating at Sasol in Sasolburg. (Discussed in section 4.5.3) This limestone has a high calcium carbonate content, at 96%. This equates to a Calcium content of 38.4%, as the molecular weight of calcium carbonate is 100 whereas that of calcium is 40. The product Data Sheet is shown in Appendix C.

An advantage of in-situ sulphur capture in FBC over Flue Gas Desulphurisation (FGD) in pulverised fuel (PF) fired boilers, is that FBC can utilise relatively poor sorbents, including dolomite. Haripersad (2010) (drawing heavily on Agnello, 2005), concluded that the ability of FBC to utilise these lower grade sorbents was a driver towards the adoption of FBC technology. There would be competition with the gold mining industry and the cement industry for the high grade limestones required for FGD on PF plants, whereas there is little competition for low grade limestone and dolomite. Further, he concluded that PF with FGD would become resource constrained in terms of both sorbent and water by 2025. A scenario of using dolomite was therefore also considered in this current assessment.

Fixed operational costs: Rm 181.8/y

This was calculated from the figures quoted by EPRI (2010) for fixed costs of an FBC power station (with limestone addition) as a factor of the installed capacity. (R404/kW-y)

Variable operational costs: Rm 231.53/y

This was calculated from the figure quoted by EPRI (2010) for variable operating costs for an FBC power station as a factor of power sent out in the year. (R69.1/MWh)The costs for an FBC without limestone addition was used, as in this current analysis limestone costs are split out in order to assess their contribution to the costs, and to enable sensitivity analyses to be carried out on the delivered cost of limestone.

Water cost: R390k/y

This was derived from the water consumption indicated by EPRI (2010) (33.3 L/MWh) and an assumed cost of water of R3.50/Ml. Water costs are a relatively small component of the total annual operating costs.

Fuel cost (R123.85/tonne)

This value was essentially “reverse engineered” from the current electricity price and the indication by Koornneef that the fuel component of the cost of electricity for “waste coal” is 15% (Koornneef et al, 2006). Again, in reality, there could be a great range to this value. From experience with the Slagment FBC (section 4.5.1), once a waste (in the case of the Slagment FBC, this was duff coal) starts to be used the owner of that waste starts to ascribe increasing value to it. If the power station developer is also the owner of the mine, this effect will largely be negated.

Utt and Giglio (2011) used a value of \$100/tonne for a 25 MJ/kg coal, and EPRI (2010) used approximately R288/tonne for a 19.2 MJ/kg coal. The cost of the fuel needs to be determined/negotiated and contracted in order to conduct an accurate economic viability assessment. For the purposes of this study, where the specific intent is to show the potential advantage of using waste coal, I believe the approach of using the fuel cost component indicated by Koornneef et al (2007) is valid.

Fuel transport cost: R0.8/km.t

It proved to be difficult to get transport costs from the transport industry itself. An indication of road transport costs was obtained from Blenkinsop (2012). Although not in the transport industry, Blenkinsop is assessing the viability of utility-scale FBC projects in Southern Africa, and is therefore regarded as a reliable source of information. He indicated a range of between R0.80/km.t to R1.20/km.t. The lower limit was taken, this being the transport cost indicated by Idwala Lime (below).

Fuel transport distance: 0km

As the intent is to operate a mine-mouth power station, this will be zero for this current assessment. It has, however, been included in the calculations in order that sensitivity to this figure can be assessed, should a potential application be located away from the mine. Or, perhaps there may be multiple fuel feeds from multiple mines.

Sorbent cost: R403/t

This cost was obtained from Idwala Lime, who operate a limestone quarry in Danielskuil, approximately 700 from the Witbank area. Idwala Lime currently supply the limestone for the CSIR-designed FBC High Sulphur Pitch incinerator operating at Sasol in Sasolburg. (Discussed in section 4.5.3)

Sorbent transport cost: R0.8/t.km

Idwala Lime indicated that the transport cost of their product from the mine to Witbank is R550/t. With the distance being approximately 700km, this equates to approximately 80c/km.t.

Sorbent transport distance: 700 km

A distance of 700km was sued for the analysis, this being the distance from the Idwala Lime mine in Danielskui to Witbank. The sorbent transport distance is however varied in order to gauge the sensitivity of the project viability to this parameter.

Electricity value: R0.5716/kWh

The tariff at which Eskom is allowed to sell electricity is currently a hotly debated subject in South Africa. Proposed tariffs are set out in a Multi-Year Pricing Determination (MYPD) document. The National Energy Regulator of South Africa (NERSA) reviews this, and makes a decision on what it believes is a reasonable tariff increase, based on considerations of the cost of producing electricity and the impact that electricity increases could have on the economy of South Africa.

For the years 2010/2011, 2011/2012 and 2012/2013, an increase of 25.9% for each of these years had been approved by NERSA. (ESKOM, 2012). However, following a "..combined effort by Government and ESKOM to lessen the impact of higher tariff increases on consumers..", the increase for 2012/2013 was reduced to 16%. (ESKOM, 2012). This brings the electricity tariff to 60.66 c/kWh, which includes a 3.5 c/kWh environmental levy. A upper figure of 57.16 c/kWh was therefore derived. It is not clear, however, how much of this value could be realised by an IPP. If the electricity is to be used elsewhere (but possibly within the same company or group), there will be costs associated with transporting the electricity through the Eskom grid. An analysis was therefore run to estimate what the lower limit for the electricity value is that still results in a viable project. The value of the product, electricity, has of course a major impact on viability.

Note, the electricity value indicated above differs from the 40.27 c/kWh assumed in the screening analysis because of the combined effects of the 25.9% and 16% increases that have been applied since this screening analysis was undertaken.

An alternative approach was also taken, i.e. to calculate the cost that electricity would need to be sold at in order to realise an acceptable IRR.

Plant capital cost: R 18410/kW

This is a very important parameter, and unfortunately estimates of this varied. Utt and Giglio (2011) indicate a specific plant cost of $2000 to $2100 per kW installed capacity for supercritical FBC. Tidball et al (2010) showed a range of between approximately $1700/kW and $2600/kW (reported in 2007$). This was a subcontract report written for a National Renewable Energy Laboratory (NREL) contract. EPRI

(2010) indicate a specific plant cost of R16540/kW. This is quoted in South African Rand rather than US $ because the analysis was conducted as input to the South African Integrated Resource Plan. It was decided to use this value (corrected for two years inflation at the average South African inflation rate of 5.5%, giving R18410/kW) because this was a) specifically carried out for a South African scenario and b) specifically considered FBC power stations. Converting to US $ at 8.7 R/$ gives $2120/kW which is within the range indicated by the other researchers.

Depreciation period: 5 years

This is included in the Discounted Cash Flow as a "wear and tear" tax allowance which is allowed on capital expenditure. The allowable depreciation was assumed to be straight line over 5 years. This approach is explained in Correia et al, 1989.

Plant lifetime: 30 years

Although a power station may be kept operating for 40 years or more, the assumption made by EPRI (2010) of 30 years plant life was also used in this analysis. The effect of assumed plant life on NPV was assessed.

Discount rate: 9%

This is a key parameter in an economic analysis. Unfortunately, again, there is a range of values suggested. The discount rate is essentially a return that an investor would have to receive on the investment to warrant it. Generally, the value used here is the Weighted Average Cost of Capital (WACC) (or Weighted Marginal Cost of Capital, WMCC.) This is (simplistically) calculated from the relative weights and contributions of equity, debt and shares that is used to finance the project. (Correia, 1989.) The accurate calculation of the WACC is in itself a science, and can involve the application of a Capital Asset Pricing Model (CAPM) (Nel, 2011). Power (2004) asserts that "The Cost of Capital is a price, a price for a "share" of risk sold by a company.". As such, factors such as where a company's head office (in this case Anglo American) is listed can significantly affect it.

For the purposes of this analysis it was decided to use available figures for the WACC for the only current electricity utility in South Africa, Eskom. However, even with this narrowed focus, a range was obtained. BUSA (2009) states that the WACC proposed by ESKOM (10.3%) was possibly high, and a value of 8% may be more realistic. Mokoena (2010) states that ESKOM's WACC is 8.16%. Mining Weekly (2012) quoted Dick Kruger, SA Chamber of Mines techno economic assistant adviser, as saying that "..the 10.3% applied by the utility..." "..should be as much as three percentage points lower..". It was decided to adopt a figure towards the middle of this range, namely 9%.

Tax rate: 28%

This is the standard tax levied on companies by the South African Revenue Service. (SARS, 2012)

Inflation: 5.5%

Inflation is a variable figure. Historically South Africa has seen periods of high inflation, whereas more recently inflation has been lower, and more stable. Bruggemans (2011) shows a current inflation rate (2012) of 5.6%, and forecasts 5.5% and 5.9% respectively for 2013 and 2014. The figure of 5.5% forecast for 2013 was assumed for this study. It was further assumed that this would hold steady over the analysis period. An inflation rate for each future year could be incorporated into the DCF, but this would complicate the analysis, with uncertain added value. In any event, the more important consideration is how much more or less than the Consumer Price Index (CPI) inflation other parameters will be, such as fuel price, transport price etc.

Coal, water and transport cost inflation: 7.5% (2% above CPI)

An assumption was made that energy-related costs would rise at a rate above inflation. Coal is an energy product, water has a high electricity component to its price (due to pumping requirements) and transport obviously requires fuel and/or electricity.

Limestone, fixed operational and variable operational costs: 5.5% (equal to CPI)

These commodity or equipment type costs are assumed to inflate in line with the CPI.

Electricity price inflation

The general belief that electricity price increases would continue to be well above inflation has proven to be valid, with the release of Eskom's Multi-year Price Determination 3 (MYPD3) document. Engineering News (2012) report that increases of 16% have been requested in MYPD, which was released on 22 October 2012. As with previous MYPD submissions this will still need to be reviewed by NERSA, but for the purposes of this analysis an increase of 16% per year was assumed for the first 5 years, with increases of CPI plus 2% thereafter.

Discussion on material and energy balance and DCF

The material and energy balance, including calculation of costs, of the base case is shown as Table 5.7 below. In order to test the material and energy balance, input data was derived from the information presented by Aziz and Dittus (2011) and the same output in terms of fuel and sorbent requirements etc. was obtained. It was therefore concluded that the material and energy balance was sound.

The DCF table produced from this data (plus additional input such as inflation estimates) is presented in Table 5.8.

Table 5.7 Material and Energy Balance, Base Case

Input data					
Plant specifications			**Annual Costs**		
Output	MW(e)	450	Fixed operational costs	MR	181.80
Efficiency	%	40.0%	Variable operational costs	MR	231.53
Load factor	%	85%	Water	MR	0.39
			Other	MR	0.00
			Sub total	MR	413.72
Fuel specifications					
CV	MJ/kg	13			
Ash content	%	50%	**Fuel and sorbent costs**		
Sulphur content	%	2.8%	Fuel cost	R/t	123.85
			Fuel Transport cost	R/t.km	0.80
			Fuel transport distance	km	0.00
Sorbent specifications			Sorbent cost	R/t	403.00
Reqd Ca/S ratio	-	2.9	Sorbent transport cost	R/t.km	0.80
CaCO3 content	%	96%	Sorbent transport distance	km	700.00
Calculated requirements, costs and income					
Fuel required	Mt/yr	2.320			
Sorbent required	Mt/yr	0.607			
Fuel cost	MR/yr	287.289			
Fuel transport	MR/yr	0.000			
Sorbent cost	MR/yr	244.454			
Sorbent transport	MR/yr	339.687			
Total sorbent cost	MR/yr	584.141			
Electricity value	R/kWh	0.5716			
Electricity income	MR/yr	1915.26			

Table 5.8 Discounted Cash flow Table, Base Case

Input values			**Inflation**		**% above CPI**	**Calculated NPV**	
Specific capital cost	$m/MW	2.12	CPI	5.5%	-	10 years	1502.62
Rand/$ exchange	R/$	8.70	Coal cost	7.5%	2.0%	20 years	14137.91
Specific capital cost	Rm /MW	18.41	Limestone cost	5.5%	0.0%	30 years	30714.80
Installed capacity	MW	450.00	Transport cost	7.5%	2.0%		
Actual plant cost	Rm	8284.25	Water cost	7.5%	2.0%		
Depreciation period	Yrs	5.00	Fixed Opex	5.5%	0.0%		
Plant lifetime	Yrs	40.00	Variable Opex	5.5%	0.0%		
Discount rate	%	9.0%	Electricity 1st 5 yrs	16.0%			
Tax rate	%	28.0%	Electricity thereafter	10.5%	5.0%		

Discounted cash flow table (Rm)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	20	25	30
Costs																			
Capital	8284.245																		
Coal		287.29	308.84	332.00	356.90	383.67	412.44	443.37	476.63	512.37	550.80	592.11	636.52	684.26	735.58	790.75	1135.22	1629.75	2339.72
Coal Xport		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Limestone		244.45	257.90	272.08	287.05	302.84	319.49	337.06	355.60	375.16	395.79	417.56	440.53	464.76	490.32	517.29	676.07	883.60	1154.83
LS Xport		339.69	365.16	392.55	421.99	453.64	487.67	524.24	563.56	605.82	651.26	700.11	752.61	809.06	869.74	934.97	1342.27	1927.00	2766.46
Water		0.39	0.42	0.45	0.49	0.52	0.56	0.60	0.65	0.70	0.75	0.80	0.87	0.93	1.00	1.07	1.54	2.22	3.18
Fixed Opex		181.80	191.80	202.35	213.48	225.22	237.61	250.67	264.46	279.01	294.35	310.54	327.62	345.64	364.65	384.71	502.79	657.13	858.85
Var Opex		231.53	244.27	257.70	271.88	286.83	302.60	319.25	336.81	355.33	374.87	395.49	417.24	440.19	464.40	489.95	640.34	836.90	1093.79
Total costs		1285.15	1368.38	1457.13	1551.78	1652.71	1760.37	1875.20	1997.70	2128.39	2267.83	2416.62	2575.39	2744.84	2925.69	3118.73	4298.24	5936.60	8216.83
Revenue																			
Electricity		1915.26	2221.70	2577.17	2989.52	3467.85	3831.97	4234.33	4678.93	5170.22	5713.09	6312.97	6975.83	7708.29	8517.66	9412.01	15505.79	25544.96	42083.97
Before tax Pr	-8284.25	630.11	853.32	1120.04	1437.75	1815.13	2071.60	2359.12	2681.23	3041.83	3445.26	3896.35	4400.43	4963.45	5591.97	6293.28	11207.55	19608.36	33867.13
Tax		176.43	238.93	313.61	402.57	508.24	580.05	660.55	750.74	851.71	964.67	1090.98	1232.12	1389.77	1565.75	1762.12	3138.11	5490.34	9482.80
After tax Pr		453.68	614.39	806.43	1035.18	1306.90	1491.55	1698.57	1930.48	2190.11	2480.59	2805.37	3168.31	3573.68	4026.22	4531.16	8069.44	14118.02	24384.34
Depreciation		463.92	463.92	463.92	463.92	463.92													
DCF	-8284.25	841.83	907.59	980.94	1062.00	1150.91	889.36	929.18	968.85	1008.39	1047.83	1087.17	1126.45	1165.66	1204.83	1243.98	1439.84	1637.24	1837.88
NPV (Rm)	-8284.25	-7442.42	-6534.83	-5553.89	-4491.89	-3340.98	-2451.62	-1522.44	-553.60	454.79	1502.62	2589.79	3716.24	4881.90	6086.73	7330.71	14137.91	21928.33	30714.80

5.2.2 Calculation of cost of electricity

Although the DCF table is really designed to enable different scenarios, and indeed different projects, to be evaluated against each other, it is possible to calculate the cost of electricity, or the value that electricity would need to be sold at, in order to make the project viable. Or, put another way, the minimum cost the venture could sell electricity at. In order to do this, a “Hurdle rate” of 20% was selected. A hurdle rate is the minimum IRR that an investor would consider worthwhile pursuing further. The hurdle rate is not a fixed number, it will vary from investor to investor and can be effected by the real or perceived risk of the project. Information was obtained from a company, Distributed Energy Generation, which is currently establishing a discard coal to steam boiler (Liebenberg, 2012). A range was given in this communication, from the late teens (for “institutional investors”) to the early twenties (for “private investors”). The average was taken, i.e. 20%.

The DCF is used to calculate the required cost of electricity by setting the IRR to 20% and using Excel’s “Goal seek” function to calculate an electricity price that would return a zero NPV after 30 years. For the purposes of this analysis the cost of coal was held steady at R123.85/t, as the calculated coal cost at 15% of the electricity revenue, based on studies conducted by Koornneef et al (2007), would vary with the electricity price. An electricity price of 49.9c/kWh was arrived at.

This price is very sensitive to the chosen hurdle rate. For example, should an investor adopt a hurdle rate of 22%, an electricity price of 55.3c/kWh would be required. An even more conservative investor, adopting a hurdle rate of 24%, would require 61.1c/kWh.

5.2.3 Calculation of financial indicators (Output parameters)

Financial indicators were calculated using the DCF. These were calculated for the “Base Case” and also used to run sensitivity analyses on the following parameters:

- Plant capital cost
- Cost of coal
- Transport distance of sorbent
- Electricity price (at project start)
- Electricity price increase

NPV and IRR (Base Case)

The after tax NPV at 10, 20 and 30 years and the IRR (30 year plant life) were calculated using the DCF table constructed using the above input parameters. The full DCF analysis/table can be seen in Table 5.8 above. The output results are shown in table 5.9 below.

Table 5.9 Financial Indicators, Base Case

Indicator	Value	Units
NPV (10 Years)	1502	Rm
NPV (20 Years)	14138	Rm
NPV (30 Years)	30715	Rm
IRR (30 Years)	22.64	%

This appears to be a worthwhile investment opportunity, warranting further investigation, with an IRR of 22.64%. As discussed above, investors would adopt a “hurdle rate” of about 20%.

Sensitivity Analysis

As discussed above, these figures were arrived at using a number of input parameters. Although these were justified and substantiated to the best of my ability, it is worthwhile to check the sensitivity of the results to variations in the input parameters. These will be evaluated below, and the results displayed graphically. There are essentially an infinite number of variations, but an approach of varying one key factor while holding the rest steady was adopted in order to highlight the impact of that factor alone.

Plant capital cost: The common way of expressing the specific plant capital cost of a power station is in $/kW installed capacity, as power stations are a “global commodity”. A specific plant cost of $2120/kW installed was used, based on information gathered by EPRI (2011). The literature, however, showed a range of values. Tidball et al (2010), showed costs of up to $2600/kW installed. A range of plant capital cost was taken from $1600/kW to $2800/kw, and the IRR calculated. Table 5.10 shows the trend of NPV and IRR with specific plant cost, which is represented graphically in Figure 5.1.

Table 5.10 Effect of specific plant cost on NPV and IRR

		Financial indicators			
		NPV10	NPV20	NPV30	IRR
Specific capital cost, $/kW	1600	3083	15718	32295	26.1
	1800	2470	15106	31683	24.5
	2000	1858	14493	31070	23.28
	2200	1245	13881	30458	22.21
	2400	633	13268	29845	21.28
	2600	21	12656	29233	20.47
	2800	-592	12043	28620	19.74

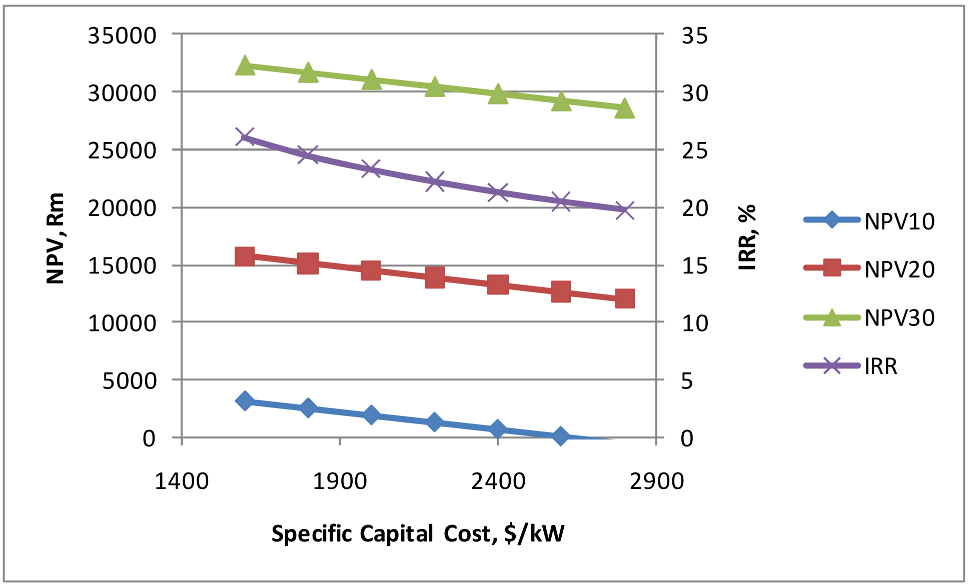


Figure 5.1 Effect of specific plant cost on NPV and IRR

The IRR is very sensitive to the specific plant capital cost, and falls from 26.1% to 19.74% as the specific plant cost rises from $1600/kW to $2800/kW. At a hurdle rate of 20%, the project would be considered marginal at a capital cost in excess of $2600/kW.

Cost of coal: The cost of coal was calculated using information from Koornneef et al (2006) indicating that the fuel cost component of the cost of electricity for "waste coal" is 15%. However, estimates varied, as indicated previously, with Utt and Giglio (2011) taking $100/t as a value. In this current analysis, the coal will be purchased in South African Rands. The cost of the coal was varied from zero to R900/t. Table 5.11

shows the trend of NPV and IRR with specific coal price, which is represented graphically in Figure 5.2.

Table 5.11 Effect of coal price on NPV and IRR

		Financial indicators			
		NPV10	NPV20	NPV30	IRR
Coal cost, R/t	0	3287	17476	35404	24.8
	100	1846	14781	31618	23.05
	200	405	12085	27831	21.33
	300	-1035	9390	24044	19.63
	400	-2476	6695	20256	17.96
	500	-3917	4000	16469	16.29
	600	-5358	1305	12682	14.64
	700	-6799	-1390	8895	12.98
	800	-8239	-4086	5107	11.31
	900	-9680	-6780	1320	9.61

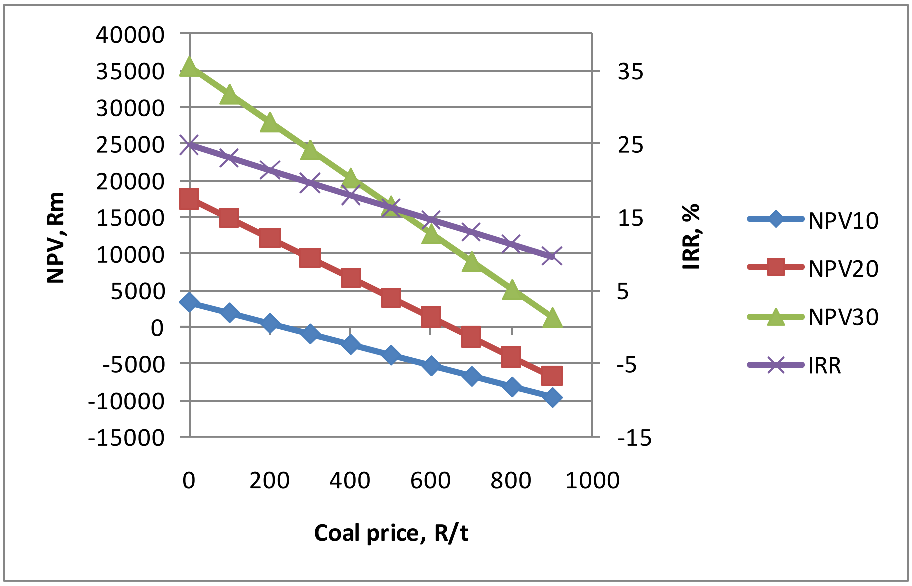


Figure 5.2 Effect of coal price on NPV and IRR

The cost of coal has a large effect on the viability of the project. From zero cost up to R200/t, the project still shows an IRR over the hurdle rate of 20%. At R300/t, the IRR is 19.63%, marginally below the hurdle rate. The 10 year NPV also becomes negative. At R700/t the 20 year NPV also becomes negative. The indication is that this project cannot afford a coal price in excess of approximately R300/t.

Transport distance of sorbent: In order to evaluate the sourcing of sorbent, the effect of transport distance (and therefore cost) was assessed. For the base case, a distance of 700km was taken. For this sensitivity analysis a range of 0km to 1000km was used. Table 5.12 shows the trend of NPV and IRR with sorbent transport distance, which is represented graphically in Figure 5.3. This analysis could also be used to assess the options of sourcing a low grade sorbent near to the power station or a high grade sorbent further away. For this to be of value, however, a full understanding of the efficacy of the sorbents would be needed.

Table 5.12 Effect of sorbent transport distance on NPV and IRR

		Financial indicators			
		NPV10	NPV20	NPV30	IRR
Sorbent transport distance, km	0	3612	18085	36261	25.2
	100	3311	17521	35468	24.83
	200	3010	16957	34676	24.46
	300	2708	16393	33884	24.09
	400	2407	15829	33092	23.73
	500	2105	15266	32299	23.36
	600	1804	14702	31507	23
	700	1502	14138	30715	22.64
	800	1201	13574	29923	22.28
	900	900	13010	29130	21.92
	1000	598	12446	28338	21.56

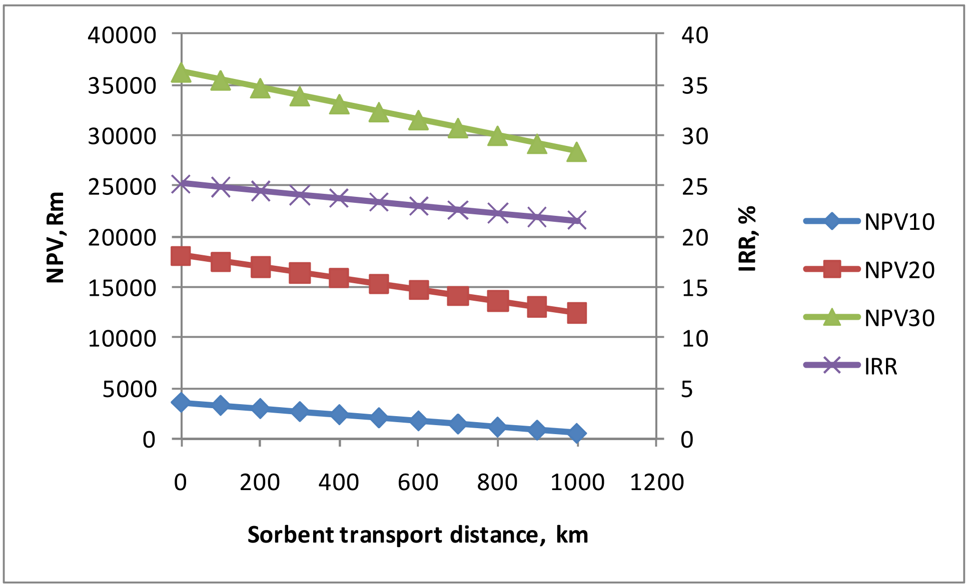


Figure 5.3 Effect of sorbent transport distance on NPV and IRR

Although the IRR at a transport distance of 1000km, at 21.56%, is still above the hurdle rate, an investor should investigate sorbent sourcing options, an exercise that will be carried out later in this section.

Electricity price (at project start): A value of 57.16c/kWh was derived for the base case analysis as described above. There is however significant doubt in the accuracy of that figure, as it depends on factors such as charges to “wheel” the electricity through the existing grid, which would lower the effective revenue earned. There are also indications that it could be higher. Tore Horvei, who was involved in feasibility studies of this kind in southern Africa, indicated that the value of electricity could be 85c/kWh (Horvei, 2012). In order to gauge the sensitivity of the project to the electricity price it was varied from 30c/kWh to 90c/kWh. Table 5.13 shows the trend of NPV and IRR with electricity price, which is represented graphically in Figure 5.4.

Table 5.13 Effect of electricity price on NPV and IRR

		Financial indicators			
		NPV10	NPV20	NPV30	IRR
Electricity price, c/kWh	30	-5084	-618	6389	12.73
	40	-2659	4815	15345	16.82
	50	-233	10248	24302	20.32
	60	2191	15681	33258	23.53
	70	4617	21114	42215	26.2
	80	7042	26547	51171	29.2
	90	9467	31980	60128	32.34

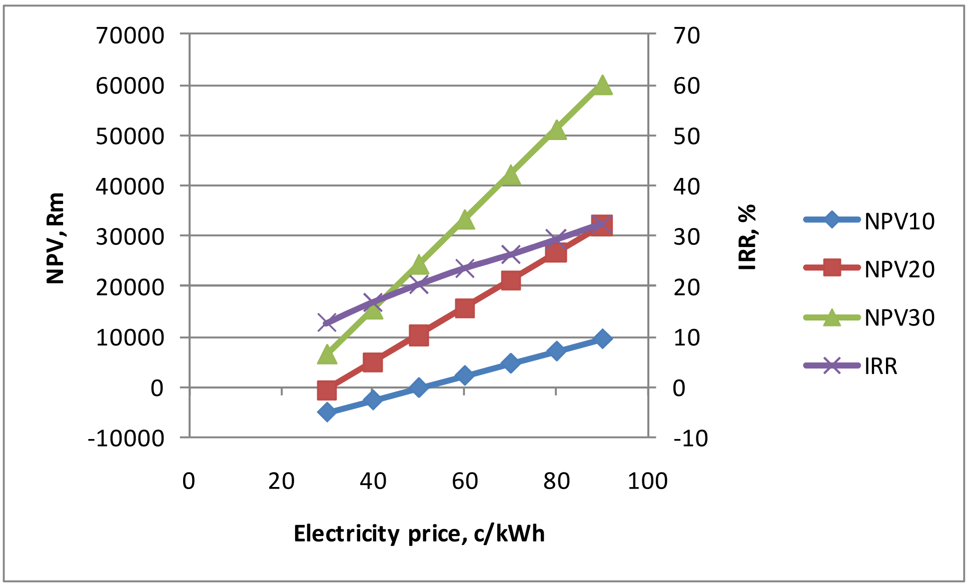


Figure 5.4 Effect of electricity price on NPV and IRR

The electricity price has a marked effect on the viability of the project. At 30c/kWh to 50c/kWh the project shows a negative NPV after 10 years. The IRR hurdle rate of 20% is only achieved at approximately 49c/kWh. At the higher electricity prices, a high IRR is seen, in excess of 30%. The conclusion that can be drawn from this is that a potential IPP needs to understand clearly how much revenue will be effectively gained through the sale of electricity, as project viability is very sensitive to this parameter.

Electricity price inflation: The electricity price inflation was broken into 2 periods – the first five years and thereafter. This was done because of the understanding that the MYPD3 is based on a 5 year period over which a constant increase of 16% has been requested (Engineering News, 2012), but that SA industry (and residential electricity consumers) cannot realistically bear increases of that nature indefinitely (Mining Weekly, 2012). This introduces a slight complication in evaluating the effect of both the short term increases and the longer term increases. It was decided to look at the scenario of a range of electricity increase between 12% and 16% over the next 5 years (as discussed above, NERSA still has to review this requested price increase) and at an increase fixed at CPI inflation plus 3% thereafter, and an additional scenario of increases of 16% over the first 5 years and increases ranging between CPI inflation and CPI plus 5% thereafter. Table 5.14 shows the trend of NPV and IRR with electricity price inflation over the next 5 years, which is represented graphically in Figure 5.5. Table 5.15 shows the trend of NPV and IRR with electricity price inflation in the longer term, which is represented graphically in Figure 5.6.

Table 5.14 Effect of electricity price increase in first 5 years on NPV and IRR

		Financial indicators			
		NPV10	NPV20	NPV30	IRR
Increase, %	12	-506	6822	14742	18.37
	13	-130	7684	16068	18.98
	14	254	8568	17430	19.59
	15	648	9474	18826	20.19
	16	1050	10404	20258	20.79

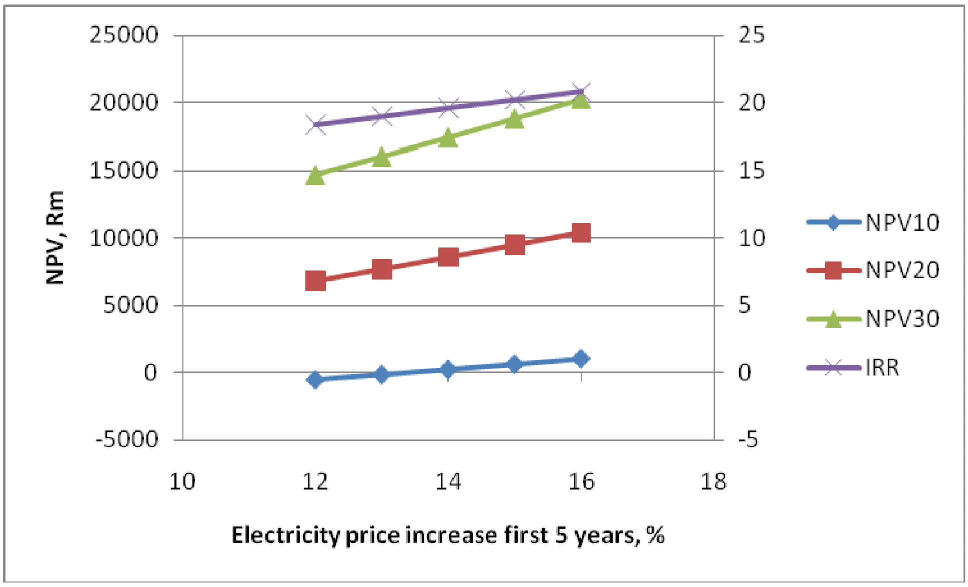


Figure 5.5 Effect of electricity price increases in first 5 years on NPV and IRR

This shows that, with an assumed future electricity price increase of CPI inflation plus 3%, the project only exceeds the hurdle rate of 20% at a 5 year electricity increase above 15%.

Table 5.15 Effect of long term electricity price increases on NPV and IRR

		Financial indicators			
		NPV10	NPV20	NPV30	IRR
Increase over CPI, %	0	412	5871	9305	17.58
	1	620	7256	12448	18.73
	2	833	8763	16072	19.79
	3	1050	10404	20258	20.79
	4	1274	12191	25101	21.73
	5	1502	14138	30715	22.64

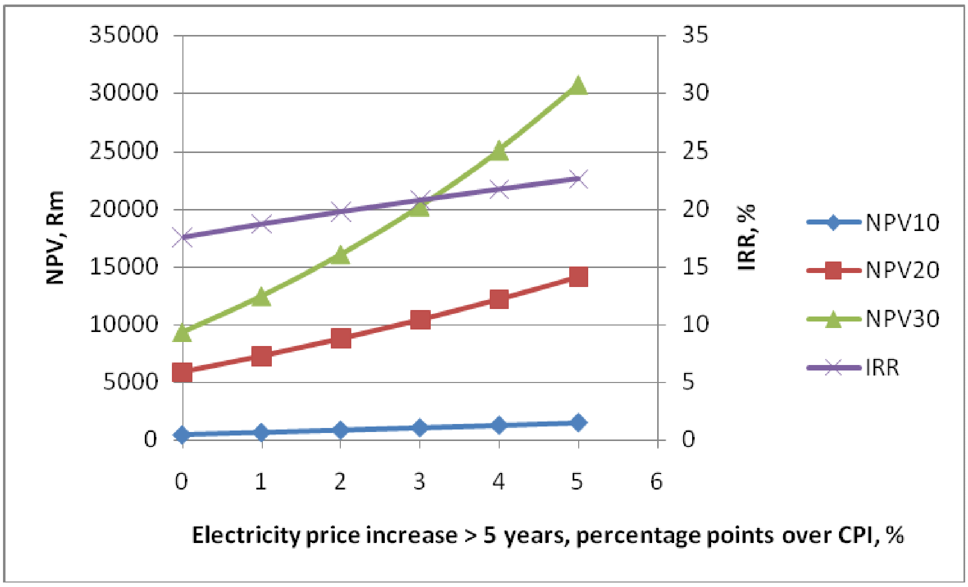


Figure 5.6 Effect of long term electricity price increases on NPV and IRR

This shows that, even with an electricity price increase of 16% per year for the next 5 years, the IRR only exceeds the hurdle rate at future increases in excess of CPI inflation plus 2%. This again shows how sensitive the project is to current and future electricity prices.

Sorbent source: In order to gauge the sensitivity of the project to the sorbent source, five scenarios were considered.

S1: Indwala limestone with a 2.9:1 Ca/S ratio (Base case)
S2: Indwala limestone with a 2.5:1 Ca/S ratio
S3: Bredasdorp limestone with a 2.2 Ca/S ratio
S4: Lyttelton dolomite (from the Centurion mine) with a 5.3 Ca/S ratio
S5: Lyttelton dolomite (from the Marble Hall mine) with a 5.3 Ca/S ratio

The selection of the Ca/S ratio is acknowledged as being an estimate. The base case of 2.9 follows the figure used by Aziz and Dittus (2011). The second scenario is really a “what if”, and is intended to see the effect of a lower Ca/S ratio being possible. The third scenario, Bredasdorp limestone at a Ca/S ratio of 2.2, is based on the much higher efficacy seen with this sorbent compared to the other sorbents tested in the NFBC. Scenarios 4 and 5 are intended to show the effect of sourcing local dolomite. The Ca/S ratio of 5.3 is derived from the relative performance of this sorbent as compared to Bredasdorp limestone in the tests conducted in the NFBC.

The sorbent cost was obtained by contacting the mines, and the transport distance was obtained using “Google Maps”.

The input data are given in Figure 15.6

Table 5.16 Sorbent source input data

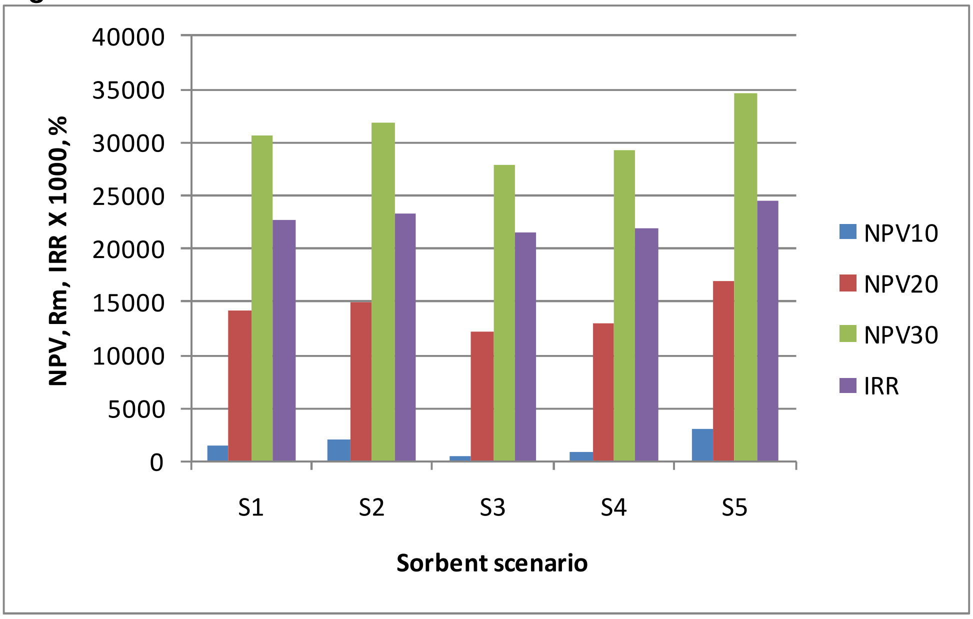
		Source	Cost, R/t	Distance, km	CaCO3, %	Ca/S
Sorbent scenario	S1	Indwala High Ca/S	403	700	96	2.9
	S2	Indwala Low Ca/S	403	700	96	2.5
	S3	Bredasdorp	100	1611	85	2.2
	S4	Lyttelton Dol (Cent)	100	120	30	5.3
	S5	Lyttelton Dol (MH)	155	142	85	5.3

The economic indicators are shown in Table 5.17. These are represented graphically in Figure 5.7.

Table 5.17 Financial indicators for sorbent source scenarios

		Financial indicator			
		NPV10	NPV20	NPV30	IRR
Sorbent scenario	S1	1502	14138	30715	22.64
	S2	1987	15015	31913	23.21
	S3	555	12201	27797	21.45
	S4	865	13040	29284	21.91
	S5	3017	16929	34586	24.46

Figure 5.7 Financial indicators for sorbent source scenarios



As would be expected, scenario 2 shows better financial indicators than scenario 1, the base case. This is due to less sorbent being required, 523 000 t/y vs 607 000 t/y.

Scenario 3, using Bredasdorp limestone, shows the worst indicators of the scenarios. Although it is the best performing sorbent, the transport costs are very high.

Scenario 4 is interesting. Although a low calcium content dolomite has been used, the financial indicators are only marginally lower than the base case. This is because of the short distance over which the dolomite needs to be transported, thereby reducing transport costs.

Scenario 5 shows the benefit of using a high-calcium sorbent which is available relatively close to the site of the power station (the source of the discard coal). The financial indicators are significantly higher than the base case, with an IRR of 24.46% vs 22.64%.

This analysis shows the need to assess multiple sorbent sources, to determine which will result in the lowest running cost for the power station. Inherent in this is a need to know the efficacy of the sorbent, i.e. what Ca/S ratio will be required. It must be stressed that in the above analysis this ratio was estimated.

6 CONCLUSIONS

For ease of reference, the scope and objectives of this research are summarised below.

The general purpose of the research was to establish if FBC can be effectively applied in South Africa to the utilisation of low grade coals such as discards, duff and slurries, and waste biomass.

The research questions were as follows:

- Can discard coal be effectively utilise in an FBC?
- Can duff coal be effectively utilised in an FBC?
- Can coal slurry, or slimes, be effectively utilised in an FBC?
- Can the dual purpose of waste minimisation and energy recovery from biomass waste sludge be achieved in an FBC?

An additional aspect addressed was an economic analysis of generating electricity through the combustion of discard coal in a CFBC power station.

The hypothesis was that FBC will prove to be a suitable technology for low grade fuel utilisation.

This research has proven that FBC is indeed a versatile technology capable of utilising a wide range of fuels, including low grade fuels such as discards, duff, coal slurries and high moisture biomass sludges on an industrial and commercial scale. It should however be noted that FBC is not a “one size fits all” technology. It has been shown through this research that the FBC plant should be designed with the specific fuel type in mind in order to optimise the performance of the combustor/boiler in terms of combustion (carbon utlilisation) and thermal (useful heat derived from the fuel) efficiencies. In the case of wet fuels, the amount of heat transfer surfaces present in the bed area must be limited but correct, or it may become impossible to burn the wet fuel due to low excess air levels. At the other end of the spectrum, when burning dry fuels, heat transfer must be incorporated or the combustor will operate as a hot gas generator, with a high excess air value and therefore low thermal efficiencies. Conclusions specific to the four types of fuels tested during this research (coal discards, coal duff, coal slurry and biomass sludge) are discussed below.

6.1 Coal discards

This research proved that coal discards can be burnt with relative ease in an FBC, with combustion and thermal efficiencies in the range of 95% and 80% respectively. The main obstacle to utilising this fuel was found to be fuel preparation and bed maintenance. The fuel needs to be crushed, nominally to <6mm, in order to prevent feeding large lumps of stone into the bed. The bed needs to be drained on a continuous or batch system, with large material being rejected and the fine material being fed back to the bed. The bed and distributor design therefore needs to be able to accommodate this requirement. This can be achieved through the inclusion of multiple drain points in a flat plate distributor or through using a sparge and riser arrangement which allows the bed material to be removed in a bulk flow manner from the base of troughs below the distributor.

Discard coal generally contains elevated levels of sulphur. To comply with environmental regulations sulphur dioxide emissions must be reduced. One of the key advantages of FBC is the ability to capture sulphur "in situ" by utilising a sorbent such as limestone or dolomite. It has been shown that sulphur emissions can be effectively reduced by utilising local sorbents. Further, it has been shown that different sorbents achieve markedly different levels of sulphur reduction. Limestone performs better than dolomite. To achieve a reduction of 80% a calcium to sulphur ratio of 2.5:1 was required for Bredasdorp lime, but to achieve the same reduction with Lyttelton dolomite would require a ratio of about 6:1. It should also be noted that all limestones do not display the same efficacy, and the physical nature of the limestone plays a key role in its ability to capture sulphur. A friable limestone, such as the Bredasdorp Limestone (a marine deposit), performs better than a non-friable limestone such as Union Lime (an inland deposit.) An interesting observation was that between 15% and 30% of the sulphur was in fact captured by the calcium in the coal ash itself.

These findings on South African discard coal combustion are echoed by international research, development and implementation. Castleman and Mills (1995) reported on the successful design and operation of a 80MW CFBC burning “GOB” (a mix of all the rejects from the plant). Thermal efficiencies of 80% were achieved. Sulphur reductions of 95% were achieved using a Ca/S ratio of 2.2 to 2.3. Singh and Chauhan (1995) conducted pilot scale BFBC tests on a range of Indian reject coal, and reported thermal efficiencies of 79%. They also estimated that 1900 MW of electricity could be generated from coal rejects in India.

Anthony (1995) surveyed a number of FBCs utilising alternative fuels. He concluded that many countries have experimented with the use of FBC to burn coal rejects, and that this technology is ideally suited to this class of fuel. He did, however, also note that cost advantage of reject coal can be outweighed by additional costs associated with extraction and processing of the fuel.

The 460 MWe supercritical CFBC installed at Lagiza (Poland) by Foster Wheeler (Jantti, 2011) was a landmark in the development of the technology, due to both the size and the steam conditions. The CFBC was designed to burn bituminous coal from 10 local coal mines, with a range of CV (18 to 23 MJ/kg), moisture content (6 to 23%) and sulphur content (0.6 to 1.4%). Successful commissioning and operation was reported. Following on from this success, Foster Wheeler are currently building four 550 MWe supercritical boilers in Korea (Jantti, 2012). These are being designed for even lower grade coal, down to a CV of 14.2 MJ/kg.

Combining my own successful utilisation of South African discard coal with international research, development and implementation, it can be stated that the technology is proven. It is no longer a question of whether discard coal can be burnt in an FBC, the question is is it economically viable to do so. A number of IPP projects based on discard coal-fired CFBC power stations are currently being investigated in South Africa. It is not clear yet whether they will proceed to implementation. My economic analysis presented in Chapter 5 indicates that there is financial merit in such a project, returning an IRR of 22.6%. However a prospective investor should, and would, evaluate this investment opportunity against others. For example, a mining house might determine that investing in mining equipment, or the extension of a mine, may provide a better return on investment.

One discard coal to energy project is underway in South Africa (Kruse, 2012). Phase one of this project entails generating 60 t/h of steam by burning discard coal in two 30 t/h BFBCs. The steam will be sold to a nearby industry. Phase two will include cogeneration of electricity. Many of the recommendations made from the research undertaken in the NFBC, such as situating the boilers at the discard dumps rather than trying to transport the coal, were followed.

Anthracitic discard coal did not, however, perform well in the tests conducted in the NFBC. Poor combustion, and therefore thermal, efficiencies were achieved. This is largely to be expected, given the nature of the fuel (Falcon, 2012). Difficulties were also seen with burning discard coal in CFBC boilers designed for this fuel in Korea (Lee et al, 2003). Interventions such as boiler re-design and co-firing with bituminous coal have improved the situation somewhat. A project in progress, a 330 MWe supercritical CFBC being built in Novocherkasskaya (Russia) will use a range of fuels including anthracite, bituminous coal and coal slurry (Jantti, 2012). Commissioning is due in 2014, and the performance of the boiler when burning anthracite will be of great interest.

Based on my research, it is concluded that anthracite discards are not a suitable fuel for BFBCs. CFBCs have reported some success in utilising this fuel, but combustion efficiencies are still reported as low, and research is being conducted to improve this.

6.2 Duff coal

This research proved that duff coal could be burnt with high combustion and thermal efficiencies. A potential problem with duff coal is low carbon efficiencies due to fine unburnt material escaping from the combustion zone. With a BFBC, re-firing of the ash collected in the primary cyclone was shown to significantly improve the combustion efficiency, by about 5 percentage points. It is likely that other design features such as an expanded or lengthened freeboard zone could achieve similar results. Recycling of cyclone ash is inherent in CFBCs.

It is difficult to draw comparisons with international experience specifically on duff coal, as duff and discards together are referred to as rejects. Additionally, duff coal was somewhat unique to South Africa, due to the “Captive Colliery” approach adopted by ESKOM. Duff coal, with a high CV, can be utilised in a PF boiler, albeit with handling problems with wet coal.

One very successful application of BFBC technology to burn duff coal in South Africa was a 14 MW_{th} BFBC designed by the CSIR for Slagment in Vanderbijlpark (North et al, 1990). This plant was designed based on the research undertaken in the NFBC.

6.3 Coal slurry

This research has demonstrated that it is possible to burn a slurry composed of ultrafine coal particles in an FBC. The slurry proved to be easily pumpable, even at a solids concentration of 67%, despite lab-scale viscosity measurements predicting that it would be extremely difficult. A pressure drop of 1.6 bar was seen over a 32 m length (0.05 bar/m) of 19 mm i.d. flexible pipe. This was at variance with the laboratory measurements, the results of which suggested that the pressure drop could be in excess of 300 bar. Early problems with blockages due to stones and lumps of coal were solved by installing a strainer over the slurry outlet and removing large material from the bottom of the tank through a 75 mm valve. Pulsing of the slurry into the FBC, which was simply caused by the type of pump used for the trials (a pneumatic double diaphragm pump) was cured by installing a “de-pulser” in the line. This was a closed cylindrical vessel which allowed the pulse induced by the pump to fluctuate the pressure of an air space within it rather than affect the slurry pumping rate. Other pumps such as centrifugal types could provide a continuous stream, but issues such as erosion still need to be investigated.

A thermal efficiency of 67% was achieved when firing a slurry containing 63% solids. Combustion efficiencies ranged from 78% to 81%. Although not as high as efficiencies seen with discards and duff, it is still surprisingly high, as the slurry has a very high fines content, which would suggest difficulty in burning the fuel and low combustion and thermal efficiencies. The mechanism by which the slurry remained in the fluidised bed was through the formation of char-sand agglomerates. The formation and destruction of these agglomerates in a BFBC was extensively researched by Masssimilla and Miccio (1986). These researchers reported combustion efficiencies as high as 95%. This was, however, using a slurry with a solids content of 70% and using a coal with a high swelling index (which would promote the formation of the char-sand agglomerates). The South African slurry tested in the NFBC, from Goedehoop colliery, is not a swelling coal. It has a swelling index of about 1.5. It would be expected, therefore, that the formation of agglomerates would not be as effective as would be the case with the high swelling coal.

Chugh and Patwardhan (2004) reported on the successful combustion of a coal slurry in a pilot scale CFBC. They achieved a combustion efficiency in the range of 95% to 99.5%. The mine from which the coal was produced is not indicated, and it therefore cannot be established if it was a high swelling coal. They observed a coarsening of the bed, reporting particles that were larger than the parent coal particles. Unfortunately they did not investigate, or report, if this coarsening was due to the formation of char-sand agglomerates or due to the nature of the coal ash. From the combustion efficiencies achieved, and comparing them to the results of the research carried out in the NFBC and reported in this thesis, it is clear that CFBC is a more effective technology in utilising coal slurries than BFBC.

The slurry that was tested in the NFBC was not a naturally occurring product. A coal-washing plant will generally produce slurry with a 50% solids content. Based on the test work in this research it is believed that this could, with difficulty, be burnt in the NFBC. It would entail running the system at very low excess air levels in order to keep the bed hot because at 50% solids concentration, 18% of the heat in the fuel is used up in evaporating the water it contains. Based on experience gained testing the combustion of high water content fuels it can be stated that a purpose-designed unit with low, or even no, heat transfer area within the bed would be able to burn a 50% solids slurry autothermally, albeit at a low thermal efficiency. It may be that this lower efficiency is of no great consequence as burning the slurry may simply be an alternative disposal method to dumping and its primary purpose may not be to efficiently generate a large amount of useful heat. Avoidance of the need for extensive slurry ponds is of value in itself. Another alternative is that the slurry could be pumped to the boiler in a lean state (50% solids) and thickened up to about 65% in a cyclone at the boiler itself. Milling of a portion of the slurry (possibly using jet milling) in order to produce a bi-modal particle size distribution could produce a product that is closer in nature to a Coal-Water Mixture (CWM). Higher solids contents could be reached due to the small particles occupying the interstices of the larger particles. Economics would again be the key. Further technical and economic research is required in this field.

6.4 Biomass sludge

This research proved that a BFBC can utilise a very high water content biomass sludge co-fired with coal. Experience showed that most of the issues discussed above for coal slurries also applied to biomass sludge. In fact, it was the experience gained with coal slurries that gave confidence to investigate and demonstrate the combustion of this difficult fuel, biomass sludge. Features such as the absence of heat transfer surfaces in the bed area and the use of a large refractory-lined freeboard area were again essential. By incorporating these features, and raising steam in an external waste heat boiler, combustion of a composite fuel containing in excess of 70% water was achieved.

Again, however, economics must be considered. At the time of undertaking the biomass sludge research, energy was relatively cheap and capital (borrowing) was relatively expensive. It made sense, therefore, to burn the sludge as it arose, and not incur the expense of presses and multiple effect evaporators to reduce the press water. In times of expensive energy and cheaper capital, it may well be viable to install the press and evaporator equipment. This would need to be evaluated on a case-by-case basis. The degree of dewatering would have a direct effect on the boiler design, especially the inclusion of heat transfer surfaces in the bed area.

Studies were conducted on the economics of utilising these problematic (sometimes referred to as "opportunity") fuels in the past. However, the economic landscape globally and in South Africa has changed in recent times and it is recommended that this aspect should be revisited. The economic analysis developed here for the utilisation of discard coal could be a good basis for a study involving the source, nature, moisture content etc. of wastes.

Due to the costs associated with moving low calorific value material, it is likely that utilisation will be decentralised and at low volumes. BFBC could find a niche here, due to lower capital costs and simpler operation than CFBC. Pascual Pena (2011) drew a similar conclusion. He produced a "Technology selection matrix", which gave a broad indication of when grate technology, BFB technology or CFBC technology should be considered the most appropriate. BFBC's niche was in small to medium (capital cost) applications with low to medium steam conditions. CFBC was clearly the technology of choice for utility-scale applications.

6.5 General

The research covered in this thesis was conducted on a BFBC boiler. This technology has been proven to have a niche in smaller waste-to-energy projects. Pascual Pena (2011) concurs, and he concluded that "BFB technology offers good performance in terms of efficiency, fuel flexibility, emissions, and especially in regard to the installation and maintenance costs, being in some cases a better solution than that offered by other technologies". The information gained on the combustion of low-grade fuels in the NFBC is of great value in terms of their relative performance in FBCs, both BFBC and CFBC. However, discard coal-fired power stations of the size envisaged by the Integrated Resource Plan (IRP) (South African Department of Energy, 2010) will be based on CFBC technology. Economic and environmental decisions will need to be made, which will require absolute performance information, which can only be gained from a well-designed CFBC pilot plant. Boiler manufacturers no doubt have such pilot plants at their disposal, but a publically accessible CFBC pilot plant in South Africa to undertake test work and build up a database on the performance of fuels and sorbents would be of immense value to potential IPPs and to the nation.

In evaluating the economics of putting up an FBC power station fuelled by low grade fuels such as discard coal, the cost of the fuel will need to be determined in terms such as Rands per GJ delivered, and the sorbent in terms such as Rands per tonne of sulphur removed, rather than the traditional measure of Rands per delivered tonne. This would be required in order to take transport costs, the CV of the fuel and the efficacy of the sorbent into account. Test work would most likely be required to determine the sorbent efficacy.

There is potentially great economic value in utilising discard coal dumps and arising discards to generate electricity. A significant portion of South Africa's projected additional electricity demand could be supplied in this way. It is estimated that current arising coal discards could generate approximately 11 000 MW of electricity. Utilising the existing stockpiles over a 40 year period could generate an additional 6 000 MW. Taking into account that discard coal is not a "free" fuel, fuel savings in the region of R3 bn to R5 bn per year are estimated for utilising stockpiles and arising discards respectively. The total revenue from electricity sales is estimated at R823 bn and

R1471 bn over the power station lifetime for stockpiles and arising discards respectively.

A detailed economic analysis shows that a discard coal-fired CFBC power station could return an IRR of 22.6%. There are, however, many scenarios to be considered, many of which cause the IRR to fall below the adopted hurdle rate of 20%. Site-specific information, such as the true cost of fuel, cost and transport cost of sorbent and the efficacy of the sorbent etc., can be used as input to the economic analysis to evaluate options for such a power station.

Low-grade fuels can be effectively utilised in FBC boilers. This concept has been proven. Based on this outcome, the opportunities indicated in the IRP should be capitalised upon by IPPs, and significant reductions made in discard dumps and arising discards while contributing much-needed electricity to the South African grid.

This approach would have the following benefits:

- Reduction in the amount of coal discarded on the surface, thereby reducing a visible eye-sore

- Extending the lifetime of our finite coal reserves

- Minimising the emissions of greenhouse and acid gases formed by spontaneous heating and combustion of coal discard piles

- Eliminating the ground water pollution often found with discard coal dumps

- Providing energy from materials that are currently discarded and have already been mined/recovered, thereby eliminating the energy required to, and environmental damage caused by, mining coal for utilisation.

Environmentally responsible energy will be the path to follow for the future, and Fluidised Bed Combustion is a vital technology to help achieve that goal.

7 RECOMMENDATIONS

A wide range of materials which are currently regarded as wastes in South Africa should be re-considered as fuels. These include low-grade coal, agricultural waste, industrial waste etc. A producer of and/or a potential user of such fuels should undertake a thorough review to determine the optimal technology to derive maximum benefit from these wastes. Economic benefit may be gained through recovery of materials contained in a waste stream before energy recovery through combustion. And there are a host of technologies that should be considered for energy recovery, such as anaerobic digestion (Land-Fill Gas), rotary kilns (such as used in the cement industry), fermentation etc. (North and Engelbrecht, 2010.) FBC, as demonstrated through the research presented in this thesis, and through subsequent applications, definitely has a key role to play in Waste-to-Energy projects.

Although a versatile technology, FBC must not be regarded as a “one size fits all” technology. The FBC must be designed to the nature of the fuel or fuels to be utilised in it. The calorific value of the fuel, reactivity, moisture content, size, friability, contaminants (Sulphur, heavy metals etc.) and fixed carbon versus volatile content all need to be taken into consideration. Some general recommendations, based on the experience gained during this research, for design features for utilisation of types of fuels in a Bubbling FBC boiler follow:

Fuel type: High CV, granular, non-friable, dry. (E.g. graded coal.)

The following FBC design features can be incorporated to enhance utilisation of this type of fuel.

- A shallow bed (150 mm to 200 mm) can be considered.
- A high fluidising velocity (with a maximum of about 3.0 m/s) can be used. Therefore a relatively smaller bed area will be required.
- In-bed heat transfer required (to remove nominally 50% of useful energy).
- “Water wall” (membrane) freeboard zone can be employed.
- Over-bed feeding with spreaders, or flingers, can be employed.
- Sulphur content must be known to estimate sorbent requirements.
- In general, this can be a compact design.

Fuel type: High CV, fine, dry (E.g. Duff coal)

The following FBC design features can be incorporated to enhance utilisation of this type of fuel.

- A shallow bed can be considered
- Low fluidising velocity
- In-bed heat transfer required.
- Lower area of freeboard refractory lined, upper area water wall.
- Expanded freeboard.
- Re-firing of elutriated fines.
- Sulphur content must be known to estimate sorbent requirements.
- Materials handling problems, before feeding to the boiler, must not be under-estimated.

Fuel type: High CV, fine, wet (E.g. Coal slurries)

The following FBC design features can be incorporated to enhance utilisation of this type of fuel.

- A deep bed should be used, to provide thermal inertia to accommodate fuel quality and moisture content swings.
- Low fluidising velocity. But, the degree of formation of char-sand agglomerates should be tested, as formation of these agglomerates can allow higher velocities to be used.
- Low in-bed heat transfer surface area. (Where possible, though, maximise solids content, which would then lead to a higher requirement for in-bed heat transfer surfaces).
- Lower area of freeboard refractory lined, upper area water wall.
- Expanded freeboard
- Re-firing of elutriated material
- Over-bed feeding with nozzles designed and tested for the material. In-bed feeding can be considered, but it is advised to have these nozzles enter the combustion zone above bed height for ease of maintenance/repair.
- Secondary (over-bed) air may be required.
- Sulphur content must be known to estimate sorbent requirements.
- Evaluate the economic benefit (or burden) of reducing the water content, bearing in mind the released water may need to be treated.

Fuel type: Low CV, coarse, dry (E.g. coal discards)

The following FBC design features can be incorporated to enhance utilisation of this type of fuel.

- A deep bed should be used, to provide thermal inertia to accommodate fuel quality swings.
- Some in-bed heat transfer will most likely be required, if the CV is in excess of 5 MJ/kg. A trade-off between efficiency and absence of in-bed tubes (thus avoiding tube wastage issues) should be considered.
- "Water wall" (membrane) freeboard zone can be employed.
- Over-bed feeding with spreaders, or flingers, can be employed.
- Fuel will need to be crushed, to approximately -6mm, to avoid build-up of coarse inert material in the bed.
- Bed drainage and management is vital.
- Sulphur content must be known to estimate sorbent requirements. Sorbent source and efficacy must also be known.

Fuel type: Low to medium CV, high moisture content, high volatile content (eg agricultural and food processing residues)

The following FBC design features can be incorporated to enhance utilisation of this type of fuel.

- A deep bed should be used, to provide thermal inertia to accommodate fuel quality and moisture content swings.
- With very high moisture content (in the region of 65% to 70%), in-bed heat transfer should not be employed. For lower moisture contents some in-bed heat transfer will most likely be required. A trade-off between efficiency and absence of in-bed tubes (thus avoiding tube wastage and maintenance issues) should be considered.
- Lower area of freeboard refractory lined, upper area water wall.
- Expanded freeboard. (To allow for burn-out of volatile matter, and to conform with temperature and residence time legislation pertaining to incineration, should this be applicable.)

- Over-bed feeding with nozzles designed and tested for the material. In-bed feeding is not advised, due to the likelihood of blockages and the difficulty of working on in-bed feeders during operation.
- Secondary (over-bed) will be required.
- Sulphur content must be known to estimate sorbent requirements. (Sewage sludge, for example, contains a significant amount of sulphur.)
- Not considered in this thesis, but the chemical analysis of the material, especially the alkali metals content, must be known. Alkali metals are known to cause bed agglomeration. Preventative measures, such as using kaolin slurry spray, can be used to prevent this, but of course add to the running costs of the plant.
- Evaluate the economic and environmental benefit (or burden) of reducing the water content, bearing in mind the released water will need to be treated.

As a general recommendation relating to the design of an FBC, unless the fuel, its characteristics and its performance in an FBC are well known, test work should be undertaken in a pilot plant. Some problems, such as fouling and bed agglomeration, can take days to become apparent, so the test work should be extensive. Additionally, especially when contemplating fuels that may contain contaminants, samples of ash as produced under actual combustion conditions are generally required as part of the Environmental Impact Assessment. The pilot plant trials would provide this.

An economic analysis has shown that there is potential financial merit in constructing a discard coal-fired CFBC power station near a source of the discard coal. Many site-specific variables need to be accurately determined in order that the output of this analysis is also accurate. One valuable addition to this analysis would be to incorporate a sorbent efficacy database. For the analysis presented in this thesis, sorbent efficacy (as reflected in the required Ca/S ratio) has been estimated from the research on the NFBC and from published information. If the efficacy of local sorbents was known, it would remove some uncertainty from the results of the economic analysis. Ideally the various sorbents should be tested in a pilot scale CFBC, but there may also be merit in simulating this environment in batch experiments.

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APPENDIX A: SUMMARY OF COAL ANALYSES

APPENDIX A: Analysis of Coal and Biomass sludge

Analyses of coal and biomass – Moisture, Proximate, Ultimate, Calorific Value and Ash Fusion Temperature

ANALYSIS	Applicable Standard	Boschmans Duff	Tavistock Duff	Greenside discards	Utrecht Anthracite Discards	Goedehoop Slurry (ad)	Biomass Sludge (Coffee grounds)
MOISTURE	SANS 589						N/A
Sup (%)		2.4	1.8	5.6	9.1	6.3	
Inh (%)		2.2	4.6	4.0	1.5	4.4	
Total (%)		4.5	6.3	9.4	10.5	10.4	
PROXIMATE							
H_20 (%)	SABS 925	2.7	3.9	2.8	1.6	2.6	5.7
Ash (%)	ISO 1171	18.7	18.9	44.1	42.4	20.7	14.60
Volatiles (%)	ISO 562	24.7	25.8	19.8	10.3	26.2	N/A
FC (%)	By diff.	53.9	51.4	33.3	45.7	50.5	N/A
ULTIMATE							
C (%)	ISO 12902	64.31	61.51	40.78	46.61	60.24	67.70
H (%)	ISO 12902	3.46	3.15	2.63	2.03	3.64	3.40
N (%)	ISO 12902	1.44	1.35	0.89	1.44	1.52	1.60
S (%)	ISO 19759	0.75	0.66	2.77	1.53	1.00	0.00
O (%)	By diff.	8.64	10.53	6.03	4.39	10.30	7.00
GCV (MJ/kg)	ISO 1928	25.5	24.1	16.5	18.1	24.6	26.60
AFT	ISO 540						N/A
DT (°C)		1340	1290	1160	1280	1380	
HT (°C)		1350	1390	1230	1330	+1400	
FT (°C)		1390	1400	1300	1370	+1400	

Analysis of Coals – Fractional Particle Size Distribution

Size Distribution	Boschmans Duff		Tavistock Duff		Greenside discards		Utrecht Anthracite Discards		Goedehoop Slurry		Biomass Sludge (Coffee grounds)
	mm	%	mm	%	mm	%	mm	%	microns	%	N/A
	+6	3.6	+10	2.8	+10	2.2	+25	14.9	+500	16.0	
	-6 +4	25.8	-10 +6	32.4	-10 +6	8.9	-25 +18	8.1	-500 +425	6.0	
	-4 +3	5.9	-6 +4	25.3	-6 +4	13.3	-18 +12	20.3	-425 +355	6.0	
	-3 +2	20.8	-4 +2	16.9	-4 +2	20.0	-12 +8	23.3	-355 +212	18.0	
	-2 +1	15.2	-2 +1	8.5	-2 +1	17.8	-8 +5	5.8	-212 +106	18.0	
	-1 +0.5	11.3	-1 +0.5	5.6	-1 +0.5	20.0	-5 +3	6.3	-106 +90	7.0	
	-0.5	17.4	-0.5	8.5	-0.5	17.8	-3 +1	7.1	-90 +60	13.9	
							-1 +0.5	3.8	-60 +45	4.6	
							-0.5	10.4	-45 +30	4.1	
									-30 +20	2.9	
									-20 +10	2.3	
									-10	1.2	

APPENDIX B: EXAMPLE CALCULATION OF COMBUSTION AND THERMAL EFFICIENCIES AND ERROR ANALYSIS

Calculation of combustion and thermal efficiencies

The following calculation is an example of the method to calculate the combustion and thermal efficiencies for a boiler test. Following the example is an estimation of the possible errors in the results.

The input data required to perform the calculations is indicated in Table C.1 below. This is based on the data shown for Tavistock duff on Figure 4.3 (at a steam load of 7 t/h, without grit refiring). The analysis of the coal can be seen in Table 4.2.

Table B.0.1 Input data for calculation of thermal and combustion efficiencies

Parameter	**Unit**	**Value**
Coal feed rate (as-fired)	kg/h	862
Coal calorific value (air dried)	MJ/kg	24.1
As-fired coal moisture content	%	6.3
Air-dried coal moisture content	%	3.9
Steam rate (at conditions)	kg/h	6035
Steam Conditions		
Temperature	℃	247.9
Pressure (abs)	kPa	1490
Boiler Feedwater Temperature	℃	70
Flue gas temperature	℃	173
Flue gas CO_2 content (dry basis)	%	11.72
Ambient air temperature	℃	30
Ambient air rel. humidity	-	
Ash product	Rate (kg/h)	Carbon in Ash (%)
Primary Cyclone	133	30.9
Secondary Cyclone	2	25.2
Baghouse	51	9.9
Bed	20	3.2

Calculation of combustion (carbon) efficiency

Carbon into boiler:

Carbon into boiler = Coal feedrate times carbon content of coal (adjusted for moisture content)

862 *((100+3.9)/(100+6.3))*(61.51/100) = 518 kg/h

Carbon contained in ashes:

Carbon in ash = ash stream production rates times carbon content of ash streams

(133*(30.9/100)) + (2*(25.22/100)) + (51*(9.9/100)) + (20*(3.2/100)) = 47.3 kg/h

Therefore carbon combusted (converted to CO_2) = 518-47.3 = 470.7 kg/h

Percentage of carbon combusted (**combustion efficiency**) = 470.7*100/518 = 90.9%

Potential heat in unburnt carbon = Mass of unburnt carbon times CV of carbon = 1549 MJ/h

Sensible heat in ashes = mass times enthalpy (obtained from Liley and Gambill, 1973) = 38 MJ/h

Calculation of flue gas volume

The mass of carbon combusted to CO_2 (from above) = 470.7 kg/h

Molecular weight of carbon = 12

Therefore the number of mols of carbon = 470.7/12 = 39.2 = number of mols of CO_2 produced per hour.

The volume occupied by one mol of gas (normal conditions) = 22.4 Nm^3

Therefore the volume of Carbon Dioxide produced = 22.4*39.2 = 878.64 Nm^3/h

The Carbon Dioxide concentration in flue gas = 11.72%

Therefore the volume of (dry) flue gases (normal basis) = 878.6/(11.72/100) = 7497 Nm^3/h

The composition of the flue gas (O_2, N_2 etc.) is calculated by mass balance.

The volume of water contained in flue gases (primarily from moisture and hydrogen in coal) = 364 Nm^3/h

Therefore the volume of wet flue gases = 7497+364 = 7861 Nm^3/h

The energy content of dry flue gases = gas flowrate times enthalpy times temperature (referenced to 25 ℃) = 7861*(1.39/21000)*(173-25) = 1617 MJ/h

(Enthalpy calculated from published heat capacity correlations (Liley and Gambill, 1973).)

Calculation of Heat content of steam ("Useful heat").

The heat given to steam (sensible, latent and superheat, at process conditions is obtained from pulished water and steam data (Spirax Sarco, 2012) = 2.624 MJ/kg

The steam flowrate = 6035 kg/h

Therefore the energy given to steam = 2.624*6035 = 15836 MJ/h.

The fuel energy input to the boiler is the coal feedrate times the calorific value of the coal (adjusted to as-fired moisture content), i.e.

862*24.1*(100+3.9)/(100+6.3) = 20305 MJ/h

The thermal efficiency is the percentage of the energy in the coal given to raise steam, i.e. 100*15836/20305 = 78%.

Note, the expression “Steam production From and At 100 ℃” is often used when describing boiler output. This is essentially a way to relate the thermal rating of a boiler to a steam output. The energy required to raise 1 tonne of steam at 100 ℃ from water at 100 ℃ at a pressure of 101.325 kPa is 2256.7 kJ/kg. (Spirax Sarco, 2012). This is the latent heat of evaporation at these conditions. In practice, however, boiler feed water will be pumped to the boiler at a temperature less than 100 ℃, and the b oiler will operate at a pressure well in excess of atmospheric pressure. Many boilers are also designed to superheat the steam. The total energy given to the steam is calculated as the sensible heat to raise the water to boiling point, plus the latent heat, plus superheat (if applicable). The output, in terms of tonnes of steam “From and At 100 ℃” is the ratio o f the total energy given to the steam divided by the energy required to raise 1 tonne of steam From and At 100 ℃ (2256.7 kJ/kg, or 2.2567 MJ/kg).

A typical small boiler such as the one used for early research (Volume 2: 1 and 2) is rated at 3.2 tonne/hour steam. This is again on a From and At 100 ℃ basis. So the energy given to the steam is 2256.7*3200 = 7221440 kJ/h, or 2 MW.

This convention can lead to confusion, and has led to people buying boilers that are underrated for their requirements, but it is still a prevailing convention.

For the example being followed above the steam output on a From and At 100 ℃ basis is therefore the ratio of energy given to raise the steam to the energy required to raise 1 t/h of steam From and At 100 ℃, i.e. 15836/2.2567 = 7017 kg/h (7 t/h).

The mass and energy balances thus derived are given in Table 3.7 below.

Table B.0.2 Output of Energy and Mass Balances

Parameter	**kg/h**	**%**
Carbon in fuel	518	100
Carbon in ashes	47.3	9.1
Carbon combusted (Carbon Efficiency)	470.7	90.9
	MJ/h	**%**
Energy in (fuel)	20305	100
Energy to steam (Thermal Efficiency)	15836	78
Energy in gases	1617	8.0
Potential Heat in ashes	1549	7.6
Sensible heat in ashes	190	0.9
Heat lost to H_2O (latent at 25 °C)	714	3.5
Radiation and Convection losses (assumed)	406	2.0

Error analysis

With the nature of the test work undertaken, single intensive tests rather than many tests, it is not possible to carry out a statistical analysis of the data. The approach taken was rather to calculate the possible error in a reported value based on the possible error in the data that is used to calculate it.

For the thermal efficiency, which is the percentage of the energy in the coal which is given to raise the steam (i.e. the ratio of energy in steam / energy in coal), the input data that can affect the calculated result are:

- Coal:
  - Feedrate
  - Calorific Value
- Steam:
  - Flowrate

- o Temperature
- o Pressure
- o Boiler Feed Water (BFW) temperature

The likely error and the effect of an error on the calculated thermal efficency in these parameters in shown in Table B.3 below.

Table B.0.3 Errors and effect of errors on calculated results

Parameter	Value (as per example calc.)	Units	Error (source)	Units	Effect of positive error on calculated thermal eff.	High value	Low value	Effect on energy	Units
Steam									
Flowrate	6035	kg/h	1 (1)	%	Positive	6095	5975	Direct	
Temperature	247.9	℃	1.5 (2)	℃	Positive	249.4	246.4	0.00243 (a)	MJ/℃
Pressure	1490	kPa	0.1 (3)	%	Negative	1491.5	1488.5	0.004 (a)	MJ/kg
BFW temperature	70	℃	1.5 (2)	℃	Negative	71.5	68.5	0.00419 (a)	MJ/℃
Coal									
Feedrate	862	kg/h	0.03 (4)	%	Negative	862.3	861.7	Direct	
AD CV	24.1	MJ/kg	0.12 (5)	MJ/kg	Negative	24.22	23.98	Direct	

Source and discussion on error values

- Spirax Sarco and consideration that steam flow is calibrated against BFW flow
- National Instruments (Themocouple suppliers)
- Spirax Sarco (Steam equipment suppliers)
- Load Cell systems (ULP range of load cells)
- SABS coal laboratory, Secunda
- Standard steam tables

The thermal efficiency was recalculated using high energy in steam over low energy in coal and low energy in steam over high energy in coal to give the upper and lower calculated efficiency respectively. This shows that the possible error in the thermal efficiency is plus or minus 1.7% of the calculated value. This is indicated by a vertical error bar on the graphs showing thermal efficiency. The error in the steam flow rate is essentially the error in the measurement of that value, i.e. 1% as indicated above. This is indicated by horizontal error bars.

Although it was of value to consider each contribution to error thoroughly, it is clear that the two main contributors are the coal feed rate and the calorific value of the coal.

Repeating this exercise with the other coals showed that the same possible error (1.7%) applies to the results for tests carried out on Boschman’s duff and Goedehoop slurry. For Greenside discards, however, the absolute (versus relative or percentage) error of 0.12 MJ/kg on the calorific value resulted in a slightly larger total error, due to the lower calorific value of that coal. The error for Greenside discards was plus or minus 1.9%, also indicated by vertical error bars.

The possible error in carbon in ash determinations is 0.2 percentage points. This figure was obtained from Alan Johns, manager of the Witlab coal analysis laboratory. (Johns, 2012.) This calculates directly through as a 0.2% error in calculated carbon efficiency. This error has been shown as a vertical error bar. The steam flow rate has the same error as indicated above, again indicated by a horizontal error bar.

APPENDIX C: SORBENT ANALYSES AND OTHER INFORMATION

PRODUCT DATA SHEET

LIMESTONE FOR INDUSTRIAL APPLICATIONS

Issued 26/01/2010

Description: Blue / grey high quality natural calcitic limestone, having a fine-grained crystalline structure, tough particles, crushed and screened to a variety of sizes.

Other names : Calcite, Calcium carbonate, agricultural lime, stock feed, feed lime.

Chemical formula : $CaCO_3$.

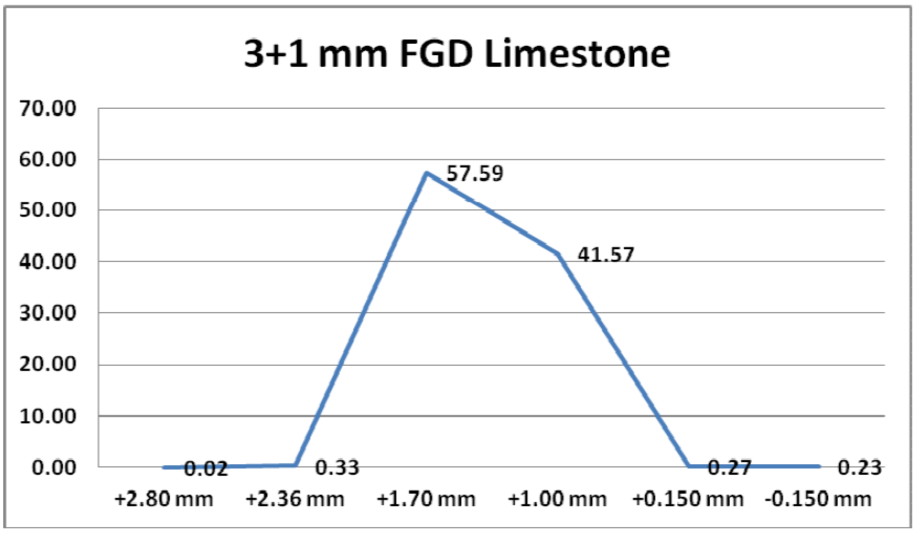
Typical chemical analysis :

$CaCO_3$	96%
$MgCO_3$	1,5%
SiO_2	1.7%
Fe_2O_3	0,2%
Al_2O_3	0,2%
MnO_2	0,6%
Acid insolubles	1,5%
1000° C Ignition loss	43%

Physical characteristics :

Bulk density	approx 1,65 t / m^3
Repose angle	40° off horizontal
Surface Moisture	< 5%

Particle size : -3+1 mm - See below Average size distribution



Packaging : Supplied in bulk only

Transport mode : Approximate tons per load.

Road	Rail	
Tons	Truck type	Tons
	BA / CA	54
35	B	44
	DZ	44
Tipper	Bogies	

Storage : These products are not perishable and have unlimited "shelf-life". Storage may be on stockpiles, or in bins or silos. Finer grades are preferably stored under cover to avoid wind losses and contamination by rainwater.

Safety : Limestone is a non-hazardous natural material, and no special precautions are required in handling the products.

Applications :

1. A fluxing agent in steelmaking, extractive metallurgy, foundries and glass manufacture.
2. A source of calcium in the fertiliser and general chemical industry.
3. A flue gas desulphurising agent.

Analysis supplied for Lyttelton Dolomite (Marble Hall mine) (November 2012)

Supplied by Infrasors Holdings Ltd.

Typical chemical makeup at Marble Hall is:

$CaCO_3$	79.4 to 91%
$MgCO_3$	6.3 to 17%
SiO_2	<4%
Al_2O_3	<0.75%
Fe_2O_3	<1%
Mn_2O_3	<0.5%
K_2O	0.03%
SO_3	<0.03%
H20	<1%
LOI	42.5

APPENDIX D: BIOMASS SLUDGE NOZZLE TEST REPORT AND NOZZLE DESIGN

Report on Coffee Grounds Nozzle Tests Carried Out at Client's Factory

Dates of Tests - 4/5 May 1993

Purpose of Tests

To determine the best nozzle configuration for achieving the desired throw, spread, and dispersion of coffee grounds over the bed of the furnace.

Equipment

1) One variable speed positive displacement pump, capable of delivering a maximum of 4 t/h of coffee grounds against a maximum pressure of 5 bar. The pump used for the test was the actual pump to be used on the job.
2) One nozzle assembly comprising the coffee grounds pipe, cooling air annulus, compressed air connection, and braided hose for coffee grounds supply.
3) A test rig comprising a structural steel frame with a mounting attachment for the nozzle assembly.
4) A number of nozzle tips of various shapes and sizes, and threaded for mounting on to the end of the coffee grounds pipe.
5) Pipes and fittings for the connection of the pump to the nozzle assembly.

Arrangement of equipment

The pump was mounted underneath one the existing coffee grounds storage tanks, the inlet of the pump being connected to the bottom of the tank via a gate valve.

The rig was positioned on the ground slab in a convenient space adjacent to the storage tank, so that the nozzle had an available throw distance of just over six meters, and a spread width of about three meters. The nozzle was fixed in the rig horizontally and at two meters above the ground slab.

The discharge of the pump was connected to the inlet of the nozzle assembly by a short run of steel piping. A rubber hose was used to connect the compressed air connection to the nearest supply point. A gate valve was incorporated into the compressed air connection to the facilitate control.

Procedure

The intended procedure was to test each of the tips individually and in various combinations for a short period of time, at full and half load, both with and without compressed air, and to note their performance in terms of throw and spread in each case.

This procedure was followed in general, though initially it was not possible to achieve full speed from the pumps, and it soon became obvious that the smaller tips would block up so they were not tested.

Day one 4/5/93

The first series of tests were carried out in the evening of 4/5/93, and the nozzles tested were those that had been especially fabricated for the tests. Refer DRG C3960-730-086. Due to incorrect wiring of the motor, the pump speed for these tests was limited to approximately 120 rpm which corresponds to about 2 t / h coffee grounds below. The results were as follows.

Results series one tests

Tip combination	Comments
N2	Smooth non turbulent flow, throw about 2 m. Blocked within a few minutes by a particle of about 15 mm diameter. Not tested with air.
Open ended	Without air – smooth non turbulent flow, very short throw, very little dispersion. No blockages. With air – adequate throw but lumpy spasmodic dispersion, and grounds tended to block up in line.
N1	Without air – smooth non turbulent flow, throw about 1 m. With air – throw about 3 m, dispersion quite good but spasmodic with tendency to clog then clear.
N1 + T1	Without air – short throw, wide spread but poor dispersion. Started to clog after a few minutes.
N1 + T2	With air – initially good throw and dispersion, partial blockage causing uneven flow, then complete blockage after about 5 minutes. Not tested without

	air.
T2	Ditto
N3	With air – initially good throw and dispersion, but blocked completely after about 30 seconds by 25 mm particle. Not tested without air

At this time it was decided that there was no point in testing the N4 nozzle since it was obvious that it would rapidly block. Instead, a piece of pipe with a flattened end was tried, and as the results were encouraging, it was decided to carry on with this type of configuration on the next day. It was also decided to change the air connection so that it entered tangentially to the flow, as it was felt that the right angled connection to the coffee grounds line was causing a back up problem.

Day two 5 / 5/ 93

Five nozzles were made up, all based on the flattened pipe and principle refer fig 2.
The first three had simple rectangular throats, S1 measuring 65 * 23 mm, S2 measuring 65 * 19 mm, S3 measuring 14 * 68 mm.
S4 had a slight figure of eight shapes measuring at 59 mm across * 10 mm at the waist.
S5 was initially hammered into a quarter moon shaped opening, then a semi circular cut out was made in the outer space, and the inner surface was curled slightly inwards.
In addition to the above, the connection for the compressed air was made tangential to the coffee grounds inlet pipe. Refer fig 1.
The wiring of the pump motor was corrected for this series of tests and they were all carried out at full load i.e. 4 t/h.

Results of series two tests

All of the nozzles displayed good throw. spread, and dispersion characteristics when operated with air, the only actual blockage occurring on nozzle S4.
It was noted however, that consistency of the coffee grounds appeared to be much better than the batch used on the previous day's test. It was generally more homogeneous, there were less solid particles present, and the particles were smaller.
In view of this, it was felt that nozzle S3 could well have blocked up had it encountered the sort of particle that had been evident in the coffee grounds of the previous day.
All of these nozzles except S5 had a tendency to "dribble" slightly at the exit point, which created a build up of material at the point immediately below the tip.
S5 had a slight but definite upward trajectory which created an excellent throw and dispersion characteristic.
All the nozzles were highly responsive to compressed air flow. The air valve was initially opened about a half turn, and thereafter only very minor adjustment were required to achieve optimum results. Once achieved there did not appear to be any deterioration of performance with time.

Discussion and Conclusions

1. Nozzles N1, N2, N3, T1 and T2 are not practical due to their tendency to block rapidly. The possibility of screening out the larger particles was discussed, but due to the further complications that this introduces into the system, it was felt that this would only be considered as a last resort.

2. In order to achieve the required throw and dispersion it is essential that a thinning or atomising medium be used. The compressed air used on the test proves to be ideal for this purpose, especially when introduced tangentially into the coffee grounds. However, the client has expressed his expressed reluctance to use compressed air due to an already critical supply situation. The alternatives were discussed:

   a) Steam - This could be tapped off the steam drum and piped to the nozzles without great difficulty and the required flow would be minimal. Also, since the moisture is already in it's gaseous form the absorption of heat and hence loss of efficiency would be minimal. There would be some problem however, in reducing from drum to nozzle pressure, i.e. from 2000 kPaG to about 3 kPaG. This would involve a fairly sophisticated pressure reducing station which would incur high capital and maintenance cost, and would likely be very noisy.
   b) Combustion air – This could be tapped directly from the outlet of the second stage F/D fan, or from a convenient point on the cooling air supply to the nozzles. The calculated pressure of the air at the F/D fan outlet is 18 kPaG when running at full load, this being the pressure required to force air through the distribution nozzle and the head of sand in the bed of the furnace. The calculated pressure of the coffee/air mixture in the nozzle just upstream of the exit point is approx 3 kPaG therefore there should be quite sufficient pressure available for dispersion. Pressure reduction from 18 kPaG to 3 KPaG can be achieved by means of a simple stop valve as was done in the test. It must be noted that combustion air passes into the furnace at various other points such as the coal spreader, the secondary air ports, and the cooling air to the coffee grounds nozzles. All of these lines incorporate wafer valves, and will need to be kept almost closed

to prevent air bypassing the bed, and hence creating insufficient back pressure.

c) Blower air – This would involve installing a separate blower to provide air to the nozzles. This would achieve the same results as the combustion air, but would provide an independent and constant flow of air to the nozzles even at low boiler load. Offsetting this advantage is the cost of providing and installing a pair of blowers, i.e. One operating and one standby.

It is concluded that all three options are feasible but the cheapest is the combustion air, and we will proceed on this basis. Since however this option has not been tested, and cannot be tested until commissioning stage, it is recommended that the customer install compressed air points local to the nozzles as an emergency measure.

3. Of the “flattened end” type nozzle, the most effective was nozzle S5 and will proceed with this design. A distinct advantage of this nozzle is that it is directional to some extent, i.e. it can be orientated such that the two other nozzles discharge horizontally away from the walls of the furnace, whilst the two inner nozzles discharge upwards

<u>Summary</u>

The test proved that satisfactory throw, spread and dispersion of the coffee grounds can be obtained form nozzle type S5 when mixed with tangentially supplied compressed air. Manufacture will proceed on the basis of this design. But air will be supplied from the discharge of the second stage F/D fan.

Design of biomass nozzle and calculation of air requirements

A series of calculations were carried out to design nozzles that could theoretically throw the coffee grounds sludge to the mid-point of the bed. The grounds will disperse (and in fact it is desirable that they do), but it was assumed that equations of motion would describe the average trajectory of the coffee grounds.

Two fixed parameters were the width of the bed and the height above the bed that the nozzles would be placed.

The width of the bed was 6.14m, therefore the nozzle should be designed to throw the coffee grounds sludge 3.07m before it hits the surface of the bed.

The nozzles were to be mounted 2.5m above the bed (essentially as high as they could, bearing other constrictions in mind).

Other considerations in the design of the nozzles were:

- If possible standard pipe (nominal 50mm diameter) should be used, but if necessary fabricated nozzles could be considered.
- The preferred final design would achieve the required throw without the need for compressed air injection into the slurry, but, if necessary, compressed air volumes would be calculated.
- The coffee grounds sludge contains some particles (chunks) of chicory, which can be up to 3 or 4 mm cubes, so the tip of the nozzle needs to be designed to avoid these causing blockages.
- Calculations were at first carried out assuming some degree of inclination of the nozzle would be possible (i.e. angling the nozzle upwards to increase the throw of the sludge), but it transpired that this would be impossible, chiefly due to the thickness of the refractory wall, so only horizontal nozzles were considered.
- The total sludge firing rate is 12 t/h, i.e. each nozzle is designed for 3 t/h

Calculation of cross sectional area of nozzle to achieve throw

Basic equation of motion used: $s = ut + \frac{1}{2} at^2$

Where:

s = distance travelled (in this case the vertical distance down to the bed, 2.5 m)

u = Initial velocity (in this case zero, as the sludge has no vertical motion)

t = time (seconds) to fall to the bed (parameter to be calculated)

a = acceleration (in this case acceleration due to gravity, 9.81 m/s^2)

Therefore

$2.5 = 0t + ½*9.81*t^2$

$t^2 = 2.5/(4.905)$

t = 0.714 seconds

To calculate the velocity at which the sludge would need to leave the nozzle to travel to the mid-point of the bed, the same equation is used. In this calculation the parameters are:

s = distance travelled (horizontal distance to mid-point of the bed, 3.07m)

u = Initial velocity (Parameter to be calculated, in m/s)

t = 0.714 seconds (as calculated above)

a = acceleration (in this case zero (frictional drag assumed to be negligible))

Therefore

3.07 = u*0.714

u = 4.3 m/s (horizontal velocity)

Assuming the sludge has a density close to water (as it is 85% water):

Sludge volumetric flowrate is $3m^3/h$, or 0.00083 m^3/s

Nozzle diameter to achieve 4.3 m/s = 0.00083/4.3 = 0.00193 m2, or 193 mm^2

Conclusion: to achieve an average throw to the midpoint of the bed (without any air assistance) the tip of the nozzle must have an area of at most 193 mm^2 Can this be achieved using a standard (nominal) 50mm diameter pipe (with flattening to reduce the cross sectional area)?

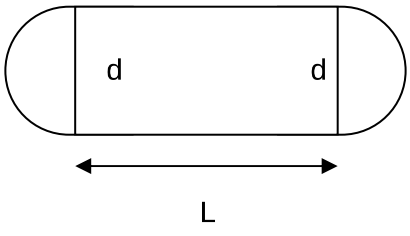


Figure D.0.1 Flattened 50mm pipe (no dimensions)

Figure D.1 above represents a flattened 50 mm pipe. The dimensions indicated are d, the diameter of the (approximately) semi-circular ends and L, the length of the mid section (approximately a rectangle).

To calculate L and d

The internal perimeter of this shape must be the same as that of the original (nominal) 50 mm (ID) diameter pipe, as the metal itself will not be stressed. (For the pipe schedule chosen, the actual diameter D = 52.5 mm)

The internal perimeter of a 52.5 mm ID pipe is $\pi D = \pi * 52.5 = 165$ mm

The internal perimeter of the flattened pipe is $\pi d + 2L$

Therefore $\pi d + 2L = 165$

Therefore $L = (165 - \pi d)/2$

The area of the flattened pipe is $\pi d^2/4 + Ld$

Substituting for L:

Area = $(\pi d^2/4) + d(165 - \pi d)/2$

Rearranging

Area = $82.5d - \pi d^2/4$

The area must be 193 mm^2, therefore

$193 = 82.5d - \pi d^2/4$

Rearranging:

$d^2 - 105d + 246 = 0$

Solving this quadratic equation,

d = 2.41 mm

Therefore L = 78.7 mm

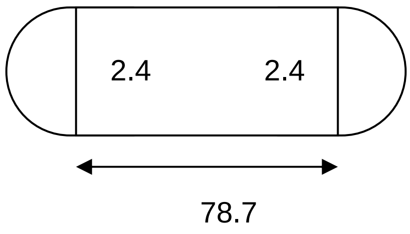


Figure D.0.2 Flattened 50 mm pipe with dimensions

With a height (d) of 2.4 mm, from the practical consideration of the nozzle having to allow passage of chicory lumps this design cannot work.

Having accepted that a larger opening will be needed to allow chicory particles to pass through without causing blockages, it was calculated what air would be required to give sufficient velocity to the sludge when passing through a nozzle with a larger cross sectional area.

Calculation of assistance air requirements

From above, the area of the nozzle can be represented in terms of only the dimension d

Area = 82.5d – $\pi d^2/4$

If d is chosen to be 7.5 mm

Area = 574.6 mm^2

Since the volumetric flowrate of the sludge per nozzle is 3 m^3/h, or 0.00083 $m^{3/}s$, the velocity of the sludge at the tip of the nozzle would be (volumetric flow rate)/(area)

Sludge velocity = .00083/(574.6/1000000) = 1.44 m/s

From the equations of motion, with a time of flight of 0.714 seconds, the distance travelled before hitting the surface of the fluidised bed would be

s = ut

s = 1.44 * 0.714 = 1.03m (which is insufficient)

To achieve the required 3.07m throw, the velocity at the tip of the nozzle must still be 4.3 m/s. Therefore the actual volume must be

Volume = Velocity time area = 4.3 * 574.6/1000000 = 0.00247 M^3/s = 8.89 M^3/h

The assistance air requirement is the difference between the required total volume and the actual volume of the sludge.

Assistance air volume = 0.00247 – 0.00083 = 0.00164 m^3/s

Compressed air requirements are by convention indicated in cubic feet per minute (cfm).

0.00164 m^3/s = 3.47 cfm

Since there are 4 nozzles the total air requirement would be 13.9 cfm.

The air requirement for a range of aspect ratio nozzles was calculated as above and is presented in table D.1 below.

Table D.0.1 Assistance air requirements for various nozzle designs

Height (d) (mm)	Area (mm^2)	Air req. per nozzle (cfm)	Total air req. (cfm)	Velocity without air (m/s)	Throw without air (m)
2.41	194	0	0	4.3	3.06
7.5	575	3.47	13.87	1.45	1.04
10	746	5.03	20.13	1.12	0.80
12.5	909	6.51	26.03	0.92	0.65
15	1061	7.89	31.58	0.79	0.56
17.5	1203	9.19	36.76	0.69	0.49
20	1336	10.4	41.6	0.62	0.45
22.5	1459	11.52	46.07	0.57	0.41
25	1572	12.55	50.19	0.53	0.38
27.5	1675	13.49	53.94	0.50	0.36
30	1768	14.34	57.35	0.47	0.34