CHAPTER TWO – LITERATURE REVIEW

In this chapter the literature review relates to the characterisation of coal for beneficiation with different technologies described. In Section 2.1 the background to coal mineralogical methods and techniques employed in the research are described. In Section 2.2 the background to coal liberation functions are given with an account of the impact the degree of mineral matter liberation and grade could have on coal beneficiation or subsequent utilisation. In Section 2.3 the background to coal processing equipment and plant design is given with an explanation of the significance of the respective equipment in industry. Section 2.4 and 2.5 provide background to the origin, significance and release of specific trace elements in coal during utilisation. Section 2.6 and 2.7 concludes the chapter with an account of economic and life cycle impacts that thermal coal production involves.

2.1 Coal Mineralogy

Falcon and Snyman (1986) highlight the most abundant minerals in South African coals; these are clays, carbonates, sulphides, quartz and glauconite. The minerals found in SA coals are typically composed of high proportions of clay (kaolinite in particular, which makes up on average 80% of the mineral suites), pyrite and carbonate minerals (calcite, dolomite and siderite). Clays occur as nodules and granular lenses, all entrained within the organic matrix. Pyrite occurs as fine to coarse nodules and in cleats. Carbonate minerals range from small ‘flecks’ and nodules of various sizes within the organic matrix to large crystalline forms in cleats and fractures cutting through layers of macerals within the seams. Phosphorus bearing minerals like apatite occur as sub-microscopic grains in some coals. The shape, sizes and nature of these minerals determine the degrees of difficulty in liberating them in order to upgrade coal in the beneficiation process.

2.1.1 Mineralogical Analysis

A review of the main techniques or methods of mineral quantification, distribution and liberation analysis employed namely XRD and QEMSEM analytical techniques are given in Section 2.1.1.
**X-Ray Diffraction**

Every mineral has a unique X-ray diffraction (XRD) pattern that is dependent upon the crystal structure, and to a minor degree upon the composition of the mineral. The patterns are obtained by X-ray diffraction, and are used to identify the minerals present and to determine the quantities (Petruk\(^a\), 2000). Although long established as a definitive tool for mineral identification, XRD has generally been regarded as having a limited value for quantitative determination of mineral proportions (Ward, 2002). Variations in mineral crystallinity, preferred orientation in the sample mount, and differential absorption of X-rays by the minerals in the mixture, for example, may affect the XRD pattern produced. Several methods have been developed on a semi-quantitative basis, to study the minerals in coal samples. These methods have mainly been based on powder diffraction patterns.

The XRD outsourced [by XRD Consulting] test work in this instance was prepared for (XRD) analysis using a back loading preparation method (Verryn, 2011). The samples were analysed with a PANalytical X’Pert Pro powder diffractometer with X’Celerator detector and variable divergence and fixed receiving slits with Fe filtered Co-K\(\alpha\) radiation. The phases were identified using X’Pert Highscore plus software.

The relative phase amounts (weight percentage) were estimated using the Rietveld method (Autoquan Program). The full profile of an XRD pattern provides considerably more information for mineral quantification than the intensities of particular diffractogram peaks. The Rietveld method has developed a formula to give the intensity at any point in the diffraction trace of a single mineral, with information on how to refine relevant crystal structure and instrumental parameters by least-squares analysis of the profile (Ward 2002).

**QEMSEM**

The QEMSEM Quantitive Evaluation of Minerals by Scanning Electron Microscopy was developed by (CSIRO) Commonwealth Scientific and Industrial Research Organisation in Australia to analyse ores and mill products with respect to mineral processing (Petruk\(^b\), 2000). The instrument uses the back scattered electron images to obtain particle outlines that serve as frames for analysis of each grain. Each
identified point is recorded in a file and displayed on the (CRT) Cathode-Ray Tube screen by a colour which represents the mineral. Calculations of the data with respect to mineral image processing are performed automatically, and no further image analysis is performed. Conversely, the QEMSEM performs the analysis unattended with a high degree of confidence in the results.

Ward (2002, pp. 135) describes the method ‘This technique determines the association of chemical elements at individual points on a coal polished section from the output of several X-ray analysers directed at each point in a controlled scan under the SEM (Scanning Electron Microscope). The element association at each point is then processed through a species identification program to determine, from the elements present, the mineral or mineral group represented at that particular data point. Data from numerous points such as in the scan are integrated to give a volumetric assessment of the relative proportions of the different minerals or element-associations present in the coal sample.’

Mineral quantities are determined using either an area or a linear intercept analysis. The area analysis involves counting the number of pixels that it takes to cover the area of the detected features with the binary images of each mineral. The linear intercept analysis involves measuring the intercept length across each feature in the binary images of each mineral (Petruk\textsuperscript{b}, 2002).

According to Ward (2002) the image analysis functions, such as determination of size and shape distributions, can also be applied to the mineral particles in the coal using the (QEMSEM) technique. In addition a generally low level of inter-laboratory reproducibility has been found particularly for clay minerals such as kaolinite. Size distributions of particles and/or mineral grains are determined by measuring each feature using either an area measurement or a linear intercept measurement to define the proportion of particles or of mineral grains in each size range. The diameter of the particle or mineral grain feature is used to define the size (Petruk\textsuperscript{b}, 2000). Mineral liberations are determined by measuring the area of the host particle and of the inclusion inside the host particle, and calculating the area of inclusion to a percentage of the host particle as the degree of liberation (Petruk\textsuperscript{b}, 2000). Fandrich \textit{et al.}, (2003) indicated that materials with predominantly organic components and
hence with very low atomic numbers, such as coal, are not conducive to liberation analysis with electron microscopy systems. Light optical microscopy systems such as the MACE®300 offer solutions to characterising coal particles based on the light reflectance and texture of the organic phases or macerals. Combining the identification and phase discrimination capabilities of both measurement principles through image fusion techniques can offer comprehensive liberation analysis solutions for coal, incorporating both maceral and mineral matter. In the research test work undertaken, Anglo Research employed a similar method in the identification of macerals in the Waterberg Upper Ecca samples. Data which contain maceral–mineral association data, in particular comparative microlithotype data, can provide new information for process optimisation. Subsequent prediction of coal utilisation performance and the definition of new coal quality levels can be realised.

2.1.2 Mineralogical Impact on Physical Properties Affecting Coal Processing

In this section the impact of the physical properties of coal particles have on coal preparation plant performance are discussed. In industry, definite correlation between some minerals with discard or residue management, product quality control and reagent consumptions were established. The physical parameters that will be discussed include:

i. Moisture
ii. Specific Gravity
iii. Structure and breakage
iv. Size composition
v. Friability or size stability
vi. Abrasiveness
vii. Clay and shale
viii. Coal petrography

The mineral and maceral content do not only affect the processing of the clean coal, but also that of the ROM raw coal in a coal preparation plant. The greatest contributor is the mineral content influencing the physical properties of the coal. Especially in terms of Coal Handling Preparation Plant (CHPP) plant power
consumption, a high degree of mineral content could result in increased power consumption. The main minerals in coal are given in Table 4. Mineral matter properties and their implications are discussed in the following sections (Snyman and Botha, 1993).

**Table 4: Principal minerals in coal (Ward, 2002)**

<table>
<thead>
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<tbody>
<tr>
<td>Silicates</td>
<td></td>
<td></td>
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<tr>
<td>Quartz</td>
<td>SiO₂</td>
<td>2.65</td>
<td>Calcite</td>
<td>CaCO₃</td>
<td>2.71</td>
</tr>
<tr>
<td>Chaledony</td>
<td>SiO₂</td>
<td>2.65</td>
<td>Aragonite</td>
<td>Ca₃(PO₄)₂</td>
<td>2.95</td>
</tr>
<tr>
<td>Clay minerals:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Al₂Si₂O₅(OH)₄</td>
<td>2.6</td>
<td>Ankerite</td>
<td>(Fe₂Ca₂Mg)₂CO₃</td>
<td>2.9-3.1</td>
</tr>
<tr>
<td>Illite</td>
<td>K₃Al₂(Si₄Al₂)O₁₀(OH)₆</td>
<td>2.76</td>
<td>Siderite</td>
<td>FeCO₃</td>
<td>3.76-4.25</td>
</tr>
<tr>
<td>Smectite</td>
<td>Na₂[(Al₄Si₂Mg₂)O₁₀(OH)₂]</td>
<td>2.3-3</td>
<td>Dawsonite</td>
<td>NaAl₂CO₃(OH)₃</td>
<td>2.436</td>
</tr>
<tr>
<td>Chlorite</td>
<td>(Fe₃MgAl₂)₂Si₄O₁₀(OH)₆</td>
<td>2.6-3.4</td>
<td>Strontianite</td>
<td>SrCO₃</td>
<td>3.7</td>
</tr>
<tr>
<td>Interstratified Clay minerals</td>
<td></td>
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<tr>
<td>Feldspar</td>
<td>K₂Al₂Si₄O₁₂</td>
<td>2.6</td>
<td>Alstonite</td>
<td>BaCa₂(CO₃)₃</td>
<td>3.706</td>
</tr>
<tr>
<td>Na₂Al₂Si₄O₁₂</td>
<td>2.6</td>
<td>Sulphates</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Ca₅Al₂Si₄O₁₂</td>
<td>2.74</td>
<td>Gypsum</td>
<td>CaSO₄·2H₂O</td>
<td>2.31-2.33</td>
<td></td>
</tr>
<tr>
<td>Tourmaline</td>
<td>Na₂Al₂B₂Si₂O₁₀(OH)₆</td>
<td>3.02-3.26</td>
<td>Bassanite</td>
<td>CaSO₄·1/2 H₂O</td>
<td>2.7</td>
</tr>
<tr>
<td>Analcime</td>
<td>Na₂Al₂Si₄O₁₂·H₂O</td>
<td>2.3</td>
<td>Anhydrite</td>
<td>CaSO₄</td>
<td>2.9</td>
</tr>
<tr>
<td>Clinoïdolite</td>
<td>(NaK)₂Si₂Al₄O₁₂·2H₂O</td>
<td>2.1-2.2</td>
<td>Barte</td>
<td>BaSO₄</td>
<td>4.2</td>
</tr>
<tr>
<td>Heulandite</td>
<td>Ca₅Al₂Si₂O₁₂·6H₂O</td>
<td>2.2</td>
<td>Coquimbite</td>
<td>Fe₃(SO₄)₂·9H₂O</td>
<td>2.12</td>
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<tr>
<td>Sulphides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS₂</td>
<td>4.95-5.1</td>
<td>Natrojarosite</td>
<td>NaFe₃(SO₄)₂(OH)₆</td>
<td>3.1</td>
</tr>
<tr>
<td>Marcasite</td>
<td>FeS₂</td>
<td>4.72</td>
<td>Thenardite</td>
<td>Na₂SO₄</td>
<td>2.67-2.7</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe₇S₈</td>
<td>4.5-4.65</td>
<td>Glauberite</td>
<td>Na₂Ca₂(SO₄)₂</td>
<td>2.7-2.8</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>ZnS</td>
<td>3.9-4.1</td>
<td>Hexahydrate</td>
<td>MgSO₄·6H₂O</td>
<td>1.76</td>
</tr>
<tr>
<td>Galena</td>
<td>PbS</td>
<td>7.6</td>
<td>Tschermigite</td>
<td>NH₄Al₂(SO₄)₆·12 H₂O</td>
<td>1.65</td>
</tr>
<tr>
<td>Stibnite</td>
<td>SbS</td>
<td>4.5-4.6</td>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millerite</td>
<td>NiS</td>
<td>5.37</td>
<td>Anatase</td>
<td>TiO₂</td>
<td>3.88</td>
</tr>
<tr>
<td>Phosphates</td>
<td></td>
<td></td>
<td>Rutile</td>
<td>TiO₂</td>
<td>4.25</td>
</tr>
<tr>
<td>Apatite</td>
<td>Ca₁₀(FPO₄)₆</td>
<td>3.1-3.2</td>
<td>Boehmite</td>
<td>Al₂O·OH</td>
<td>3.3-3.07</td>
</tr>
<tr>
<td>Crandallite</td>
<td>Ca₁₀(PO₄)₂(OH)₂·H₂O</td>
<td>2.78-2.92</td>
<td>Goethite</td>
<td>Fe(OH)₃</td>
<td>3.3-4.3</td>
</tr>
<tr>
<td>Gocezite</td>
<td>Ba₁₀(PO₄)₂(OH)₂·H₂O</td>
<td>3.32</td>
<td>Crocrite</td>
<td>PbCrO₄</td>
<td>5.9-6.1</td>
</tr>
<tr>
<td>Goyazite</td>
<td>Sr₁₀(PO₄)₂(OH)₂·H₂O</td>
<td>3.16-3.28</td>
<td>Chromite</td>
<td>(Fe₂,Mg)₂Cr₂O₇</td>
<td>4.5-4.6</td>
</tr>
<tr>
<td>Monazite</td>
<td>(Ce,La,Nd)PO₄</td>
<td>4.6-5.4</td>
<td>Claustralite</td>
<td>PbSe</td>
<td>7.6-8.8</td>
</tr>
<tr>
<td>Xenotime</td>
<td>(Y,Er)PO₄</td>
<td>4.4-5.1</td>
<td>Zircon</td>
<td>ZrSO₄</td>
<td>4.6-4.7</td>
</tr>
</tbody>
</table>
2.1.1.1 Moisture

Clay minerals in coal, predominantly kaolinite, have a substantial impact on the product moisture obtained and general dense medium processing considerations. Clays in general remain saturated and hold moisture in the coal. ROM coal is normally saturated with moisture, even though it can appear to be dry and dusty when crushed. Fine particles with high clay content, during dense medium processing, affects the dense medium rheology properties including stability and viscosity of the medium. The filtration of fine coal with high clay content is also a challenge and generally results in higher filter product moistures. The moisture percentage can be constant for a given mine and is a characteristic of the rank. From the viewpoint of utilisation, moisture (whether inherent or surface) is considered as an impurity, it replaces potential energy in proportion to the amount of water present. However, the washing process can benefit from the moisture, since the washing process replaces the ash-forming impurities. The product moisture in most cases, however, has very strict customer restrictions.

2.1.1.2 Specific Gravity

Mineral Specific Gravities are given in Table 4. The specific gravity of the impurities associated with coal is of primary importance, since they affect the coal-cleaning methods. The distribution of the mineral matter inside the organic matrix is also important. Microlithotypes, especially carbominerite, is discussed in more detail later in the thesis in Appendix F and Section 4.8. Shale, clay and sandstone have a specific gravity of about 2.6 in their pure form. Carbonaceous shale ranges from 2.0 to 2.6, depending on the quantity of the carbonaceous material. Gypsum, kaolin and calcite have specific gravities of 2.3, 2.6 and 2.7 respectively. Coal’s specific gravity can range between 1.23 to 2.00 depending on the ash content and the percentage moisture content, rank and maceral composition. The specific gravity of coal can also be determined with physical methods.
2.1.1.3 Structure and breakage

Coal breakage starts at the coal face during mining and continuous segregation of coal particles occurs during each step following preparation and ultimately handling at the utilisation phase. The extent, size and shape of the pieces into which coal breaks are determined by the major system of vertical cleavage planes and roughly by the uniform network of planes of weakness (joint cracks or planes), (Snyman, 1994). Low-volatile bituminous coals are very friable due to the development of the joints and cleats present.

2.1.1.4 Size composition

The method of mining has a direct impact on the sizing of the coal. Blasting patterns during opencast coal mining, and pick arrangement on a continuous miner cutter head are examples of factors influencing the amount of fines generated in the ROM material.

2.1.1.5 Friability or size stability

Coal is relatively friable, and fines generation with handling is evident. The relative friability of different coals is of great importance in preparation because the greater the proportion of the finer sizes in the feed to the washing plant, the greater the total preparation costs. The tendency towards friability (breakage on handling) depends to a certain extent on toughness, elasticity, fracture characteristics and strength. The relation between friability of coal and its rank affect its tendency to heat or combust spontaneously. According to Falcon and Falcon (1983) friability is related to the ‘capacity to crumble’ and refers to the compressibility of the coal. Falcon and Falcon (1983) found that low rank coals with high moisture and low porosity tend to be friable. These coals will also be more prone to oxidation.

2.1.1.6 Abrasiveness

The abrasiveness of coal is largely related to not only the type and size distribution of the minerals in the coal, but also the microlithotypes in the coal (Falcon, 1983). Coal has generally been recognised as an abrasive material. The abrasive wear is
accredited more to the impurities associated with coal than to coal substances themselves. Removal of impurities by cleaning should consistently reduce the abrasiveness.

2.1.1.7 Clay and shale

One of the major contaminants of raw coal is clay or shale, they add significantly to the physical properties of the coal and it causes operational difficulties associated with disintegration in particle size during cleaning, which affects the washery-water clarification, as well as dewatering and the drying of fine sizes of coal. It also causes contamination and increased viscosity of dense-medium suspensions. Clay minerals could also cause difficulties with the filtration of froth products and tailings. The handling and disposal of rejects is complicated with the addition of filtered tailing fines.

Firth et al. (2011) explained that for feed medium densities of less than 1.4, the stability of the medium is greater with increasing amounts of non-magnetic material, but the relative amounts of clay and fine coal play a minor role. This effect increases as the feed medium density is decreased, as would be the case with lower grade export or ESKOM quality coal production. The separation density for a Dense Medium Cyclone (DMC) decreases with increasing medium stability, for a given medium density.

This cut point density and medium stability relationship dependence could affect a cleaning circuit’s performance if the amount of nonmagnetic material varies significantly due to:

- Changing feed rate,
- Out of seam dilution,
- Use of stockpiled raw coal,
- Change of clay & shale characteristics in a seam, or
- Poor subdivision in multi-circuit plants.
2.1.1.8 Coal petrography applied to preparation

Coal preparation processes are dependent upon the differences in physical properties between the coal components or macerals. The petrographical composition of the coal influences the ease, and hence the cost, of extracting the coal from the minerals, as the occurrence and association of macerals making up the lithotypes have a definite relationship to the power required to mine the coal. The amount of power required differs from each lithotype, with fusain requiring the least power for breakage, vitrain requiring twice as much power, clarain three times and durain seven and a half times (Falcon and Falcon, 1983).

In the processing of any other valuable mineral, it is vitally important that the mineralogy of the ore body is well understood at the earliest possible opportunity. According to Falcon and Falcon (1983) in the case of coal, it is necessary to establish not only such parameters as the hardness, crushability and washability before design work on the plant commences, but it will also become equally important to have a detailed insight into the quality of the products. In assessing product quality, microscopic analyses of coal should be included, i.e. the evaluation and quantification of the organic and inorganic constituents, and their degree of intergrowth - a fact that will assist in determining the potential liberation characteristics of a coal, including the possible increase in yield for a specific product.

Snyman and Falcon (1986) illustrated the relationship between certain coal parameters and the petrographic constituents of coal. For example, Snyman confirmed what has been long established for North Atlantic, vitrinite-rich coals, that the correlation between the specific macerals and the percentage of volatiles (on a dry, ash-free basis, or dry, mineral matter free basis) was good. A good correlation of mineral matter to the physical quality parameters such as the Hardgrove Grindability index (HGI) was found. The HGI of a coal depends on its elemental composition, rank, and on the degree of cohesion between the different maceral and mineral grains of which it is comprised.

Besides influencing the quality parameters relevant to the successful utilisation of a coal, macerals themselves exhibit behaviour critical to successful and efficient
mining and beneficiation. In Table 5 some inherent physical and chemical properties of the macerals are compared. Physical characteristics of macerals, such as breakage, hardness and compressibility, affect mining efficiency, for instance the wear on the picks of an underground continuous mining machine and the substantive generation of fines. Also, the relative density of macerals affects the product quality characteristics, given the manner in which they react to dense medium beneficiation. Such may result in one or other product suitable for a particular application. For example, Cronauer and Swanson (1991) stated that both vitrinite and liptinite liquefy well with the latter somewhat slowly, and that inertinites liquefy to only a limited extent. In coal beneficiation, not only are minerals separated from the organic constituents, but there is also separation of the macerals.

**Table 5: Displaying the main macerals with their inherent properties and characteristics (Falcon and Falcon, 1983).**

<table>
<thead>
<tr>
<th></th>
<th>LIPTINITE</th>
<th>VITRINITE</th>
<th>INERTINITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile Content</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Aliphatic Structure</td>
<td>Very High</td>
<td>Medium</td>
<td>-</td>
</tr>
<tr>
<td>Aromatic Structure</td>
<td></td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td>Chemical Composition</td>
<td>Hydrogen Rich</td>
<td>Hydrogen + Oxygen Rich</td>
<td>C+O+rich (Oxygen tightly bound)</td>
</tr>
<tr>
<td>Relative Density</td>
<td>1.1</td>
<td>1.3</td>
<td>1.4-1.6</td>
</tr>
<tr>
<td>Compressibility</td>
<td>-</td>
<td>1-10</td>
<td>20-40</td>
</tr>
<tr>
<td>Breakage</td>
<td>Elastic</td>
<td>Brittle</td>
<td>Solid, Dense</td>
</tr>
<tr>
<td>On heating:</td>
<td>Devolatilises</td>
<td>Devolatilises</td>
<td>+ Swells</td>
</tr>
</tbody>
</table>

With traditional dense medium (Dense Medium Cyclones, Wemco Drums, Drewboys, LARCODEMS, Tri-Flow Separators, Dyna-Whirlpools) and gravitational (jigs, spirals, shaking tables, teeter-bed separation) methods, particles are largely separated based on specific gravity and size. The flotation of ultra-fine (-150 µm) coal has proven to exhibit potential in enhanced concentration of specific macerals. Though these so-called conventional methods are able to up-grade coals in terms of maceral separation, more advanced beneficiation methods which separate on the basis of particle surface chemistry, optical characteristics and reflectance could provide for upgrading to more purified forms of these macerals. Relatively new, dry beneficiation developments from a South African perspective include optical sorting (X-Ray Transmission) for coarser sized feed material and tribo-electrostatic separation for fine material where the possibility of identifying and beneficiating to
upgrade specific maceral content could be achieved. Such new technologies require a more advanced approach to the characterisation of coal.

Recent research in flotation by Pineres et al., (2009) has indicated that the control of frother concentration and pH could allow for the selective upgrade of vitrinite content of Columbian coals. Test work conducted by Hower et al., (1997) using electro-static separation on Kentucky and Illinois No. 6 coals and Bada et al. (2010) writing on South African coals found that there was enrichment of the vitrinite in the product and an increase in the non-reactive maceral and mineral contents in the tailings. Recent research by Strydom (2010) utilised petrographic analysis to characterise coal and torbanite (oil shales) for subsequent separation by XRT Dry Sorting. The separation of torbanite and coal, which cannot be successfully achieved with traditional dense medium beneficiation, was achieved with success on the coarse size feed material at both pilot and commercial scale.

2.2 Liberation Functions of Coal & Associated Minerals

The term ‘liberation’ or ‘the degree of liberation’ refers to one of the most fundamental concepts in mineral processing, to give an estimation of the degree of selective grinding and sharpness of separation. The Oxford dictionary definition of liberation is ‘to set free from’. In other words, set valuable fractions in ore free from waste fractions in order to separate the two fractions. In coal processing, this entails the liberation of the organic or maceral from the inorganic constituents (minerals) and to estimate the limits of demineralisation and desulphurisation which depend on the degree of mineral matter liberation. Coal contains inherent and extraneous mineral matter. Inherent mineral matter is mineral matter intimately mixed with the coal, these are the minerals that were present in the original vegetation from which the coal was formed, as well as finely divided clays and similar materials carried into (for example) a swamp by water or wind (England et al., 2002). Coals contain varying quantities of such intimately mixed clays (England et al., 2002). The liberation of coal from inherent mineral matter is difficult and crushing and preparation does not liberate the coal from its inherent mineral matter. The grade of the coal is affected greatly if there is an abundance of these minerals.
Extraneous mineral matter consists of dirt bands, lenses in the seam, shales, sandstones and intermediate rocks introduced into the ROM (Run of Mine) feed. These are mainly contaminants from the roof and floor of the seam. Most of this material is free (not part of coal matrix), and easily removed by coal preparation techniques. In some cases the dirt is strongly attached to the coal, but can almost be freed completely from the coal by finer crushing (Falcon and Falcon, 1983). Coarser sizes tend to have greater amounts of the extraneous mineral matter, than finely ground coal, due to less liberation.

Therefore, coal can be liberated easily from extraneous mineral matter but not from inherent mineral matter. In coal processing the term liberation, its definition and distinction is even more complicated. To support this statement one can simply refer to the degree of variation that occurs in coal mineralogy.

In gold, for instance, the gold in itself is more of a single component or metal liberated from the gangue, after purification and subsequent electrowinning almost pure gold can be obtained. In other words the gold is sold as almost pure gold in the market. In direct contrast, coal rank, grade and type varies from product to product in coal as a bulk commodity.

*Figure 16: Illustrating the coal formation with rank classification (after Spurr, 2006).*
At first glance it would seem that this would only simplify the marketing and beneficiation of coal, but it doesn’t. A common interpretation is that coal is sold as an unknown amount of heterogeneous organics with some inorganic material with which the organic burns to give a required heating value. This perspective cannot be totally adhered to. Coal rank in Figure 16 signify different coals and are just one of the determining factors that influence the market price and which coals are beneficiated at the end of the day. It is far more complicated than anticipated.

The analysis technology especially in terms of mineralogy allows us to have a better understanding of what coal and its constituents really are in other words the ‘make-up’ of a particular coal. For this purpose, the analysis of coal has enjoyed some great advances in the past decade. The analysis is not only related to heating value, moisture and ash analysis, but nowadays a more detailed analytical or chemical analysis is required by the customer. A few examples of how mineral matter influence are (Snyman and Botha 1989):

1. The abrasiveness of coal for example is evidently increased by high mineral matter content. Hard minerals like pyrite and quartz, especially if they are coarse grained, enhance the abrasiveness of coal.
2. Modern boilers and gasifiers today use pulverised coal as a fuel. Any molten coal ash impinging onto the furnace or gasifier walls will solidify thus adversely affecting the transmission of heat. This phenomenon is known as slagging, and generally coals with low ash fusion temperatures have high slagging potential.
3. Species, elements and compounds like alkalies, organic sulphur, phosphorus, boron and chloride in the coals being used, form complex deposits on super heaters and air heater-tubes leading to corrosion, which causes a drop in boiler efficiency. This phenomenon is known as fouling.
4. Finely dispersed pyrite, and minerals containing calcium, sodium and potassium may act catalytically during gasification, while titanium may poison commercial catalysts.
5. Toxic elements such as nitrogen and sulphur that are concentrated in stack emissions constitute a threat to the environment.
6. High alkali metal content in coking coals lowers the mechanical strength during blast furnace operation.

7. Coals with a high lime content, result in basic slag formation. This further result in titania loss to the slag when smelting ilmenite.

8. Coal with a high sulphur and phosphorus content is undesirable in the metallurgical industry. These elements report to the metal and lead to its contamination. In steelmaking sulphur entering the steel results in "Hot shortness", while phosphorus causes "Cold shortness".

It can be seen that the mineral matter of the clean or product coal plays a very significant role for the customer. Not only from a process perspective, but also from an environmental and sustainable development perspective, these new analysis trends have to be incorporated.

In this thesis liberation test work undertaken, liberation curves were derived using Mayer curve estimates (based on Dryzmala, 2007) and King (1990).

Dryzmala (2007) indicated that the conventional Mayer curve is not suitable for analysis of upgrading when the content of useful components in the feed is high (as is the case with ash content being downgraded). Then, recovery of the remaining material (here ash) vs. yield should be plotted as per Figure 17.

![Mayer Curve evaluation for coal (by Dryzmala, 2007)](image)

**Figure 17: Mayer Curve evaluation for coal (by Dryzmala, 2007)**
King et al., (1990 & 1998) have contributed extensive work on the identification of liberation functions. In the King et al., (1990) paper liberation functions were derived for fine fractions of various RSA coals. Here it was found that the M-curve for various coals could be well characterised by the following equation:

**Equation 3:** M-curve equation, King and Birtek (1990), originally derived by Meyer.

\[ Z = A Q^B \exp(C Q) \cdot D Q \]  

Where 
- \( Z \) = Ash Content per 100 units of Feed
- \( Q \) = Yield (% by mass) or Cumulative Yield
- \( A, B, C, D \) = Characteristic parameter for various coal fields

The instantaneous ash content and the derivation of the parameters are further discussed in Chapter 6. A similar method to derive the Liberation Index (LI) can be seen in Chapter 6.

From King (1998), Figure 18 shows geometrically what increased liberation functions would entail and an evaluation at 20 % ash. The area A-B-F-A would indicate the Liberation Index of the particular material.
Figure 18: Illustrating the geometrical characteristics of the M-curve derived by King (1990) and the approach at a 20 % ash content.

The Mayer/M-curves from the literature are applied in the study to the conventional Ash content in the coal, calorific value, various minerals, macerals and trace elements in the coal. From the curves the A,B,C,D parameters are obtained and Liberation indices derived.

2.3 Coal Plant Design and Equipment Selection

ROM coal may be beneficiated at various levels ranging from level 1, which involves essentially no beneficiation, up to the level of chemical cleaning (level 5), which implies a very thorough beneficiation of the coal. The cost of beneficiation also increases exponentially from level 1 to level 5. The 5 generic levels of beneficiation are briefly described in Figure 19 (adapted from Leonard (1991) and Suman and Singh, 1989):
Figure 19: Illustrating different levels of beneficiation. Adapted from Leonard (1991).

**Level 1:** This is a very basic level of beneficiation consisting of size reduction and classification with some attendant removal of refuse and mine dilutions such as pieces of timber, stray machine parts etc., which can cause problems with downstream processing equipment. Level 1 beneficiation is practiced on essentially all coal burned. The calorific recovery or energy recovery from the ROM coal heating value is about 100 %. However, there is essentially no reduction in the mineral impurities present in the coal.
Level 2: This involves level 1 preparation and wet beneficiation of the coarse coal fraction only. The fines fraction generated in the process is generally collected and shipped ‘as is’ with the product coal. Calorific energy recovery at this level of treatment is generally high (>90 %), but there is little to no reduction in the mineral impurities in the coal.

Level 3: This involves level 2 preparation and beneficiation of all coal down to the 1 mm size fraction. The -1 mm material in most instances in South Africa is discarded in contrast to the Northern Hemisphere where the coal is either dewatered and shipped with the plant product or disposed of as refuse, provided environmental legislation permits such disposal. Calorific recovery is generally good (>80 %), and there is significant reduction in the sulphur and impurities in the coal.

Level 4: This involves a full scale or thorough beneficiation of the coal. Level 4 cleaning can usually yield several coal product streams containing varying levels of sulphur and mineral impurities in the coal. The ultra-clean fraction with the lowest sulphur and mineral impurities is generally routed to metallurgical operations. The intermediate streams are known as middlings and are mainly suitable for power station steam generation purposes.

Level 5: In South Africa this level of beneficiation typically involves froth flotation of size fractions minus 150 to zero microns. This level also includes chemical beneficiation, chemical addition (surfactants, coagulants), filtration, briquette making and pelletisation. This level of beneficiation includes beneficiation routes with a high operating expenditure and level of economic complexity.

In general level, coal beneficiation levels 1 to 4 have limitations in that these processes can only remove the extraneous mineral species from the coal and inorganic sulphur (mainly pyritic). Common beneficiation processes are unable to remove the organic sulphur from the coal. Level 5 with advanced processing allows for the reduction in inherent mineral matter and even organic sulphur.

The modern trend for plant lay-outs are small, open plants with less equipment. This entails simplified operation, lower maintenance and operation costs, easier maintenance and operation, lower civil costs and easy access for rigging. The introduction of LARCODEMS (Large Coal Dense Medium Separators) has been
especially successful in South Africa at various Witbank coalfield collieries. DSM cyclones (Dutch State Mine’s cyclones) are still the most preferred method for medium to fine coal beneficiation. Teeter beds made an appearance and proved to be a possible improvement on spiral concentrators. A recent installation at Navigation Colliery has proven successful. The return of Jigs should also be noted, recent advances in India have proven very successful. Although dense medium separation in South Africa still dominates, there is an indication that re-evaluation of its application in South Africa can possibly be considered. Figure 20 shows a comparison between washabilities of typical South African and Indian coals. However, the common use of jigs favoured in India has a rather different objective. Given that a relatively poor yield for coking coal product is compensated for by the use of the entire jig discard as a saleable steam coal product (Kamall, 2001). The same method might be applicable and could be employed in South Africa.

Figure 20: Illustrating the washability densimetric comparison between typical South African, Indian and German coal. (Kamall, 2001)

2.3.1.1 Plant Design

The type of processing equipment for coal preparation plants is chosen primarily on the basis of the following (note this is a basic approach):

1. The size range of the material to be treated (see Figure 21).
2. The material characteristics (friability, abrasiveness, contamination).
3. The SG of the material to be treated (based on the washability analysis). Also taking into account Near Gravity Material and possible density differentials, for example 10 points (i.e. 0.1 RD) for Dense Medium Cyclones.
4. The propensity for acid generation, especially for closed water circuit plants.
5. The propensity for spontaneous combustion.
6. The condition of the coal (weathering and possible oxidation).
7. The optimum size range, based on liberation test work and epm performance prediction in a particular size range (see Figure 22 for the yield influence from near gravity material). Generally treating coarse material with coarse coal separators results in lower epm’s indicating improved separation efficiencies. Finer PSD feed material should be more liberated and result in lower % NGM and hence higher corresponding yields.

![Diagram](image)

**Figure 21:** (Dryzmala, 2007), Optimal range of particle size for separation by different separation methods. *low intensity (LI), ** high intensity (HI), *** high gradient magnetic field (HG))

Figure 21 indicates that dry separation can in fact be conducted on the total PSD spectrum. Figure 22 illustrates the yield influence from predicted epm’s at various
Near Gravity Material (NGM) percentages. Furthermore the epm’s for different dense medium and size class applications are summarised in Table 6.

Figure 22: Epm performance of separators on various feed size distributions, Leonard (1991).
Table 6: Commonly used separation units and their performance for various size fractions. Note that the epm values and the SG range are deduced from the author’s experience in CHPP plants, rather than from literature Leonard (1991) exclusively.

<table>
<thead>
<tr>
<th></th>
<th>epm</th>
<th>Ultra-fines</th>
<th>Fine +0.15-1mm</th>
<th>Medium +1-20mm</th>
<th>Coarse +20mm</th>
<th>Typical RD Range</th>
</tr>
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<tbody>
<tr>
<td><strong>Baths</strong></td>
<td></td>
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<tr>
<td>Wemco</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.026 1.30-2.00</td>
</tr>
<tr>
<td>Drewboy</td>
<td></td>
<td>-</td>
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<td>-</td>
<td>0.030 1.30-2.10</td>
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<td>Teska</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.030 1.30-2.00</td>
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<tr>
<td><strong>Flow Separators</strong></td>
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</tr>
<tr>
<td>DSM Cyclone</td>
<td></td>
<td>-</td>
<td>0.035</td>
<td>0.028</td>
<td>0.028</td>
<td>1.30-2.00</td>
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<tr>
<td>Tri-flow separator</td>
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<td>-</td>
<td>-</td>
<td>0.045</td>
<td>0.035</td>
<td>1.30-2.00</td>
</tr>
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<td>LARCODEMS</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.011</td>
<td>0.011</td>
<td>1.30-2.00</td>
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<tr>
<td>Three-product cyclone</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.014</td>
<td>0.014</td>
<td>1.30-2.50</td>
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<tr>
<td><strong>Jigging</strong></td>
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<tr>
<td>ROM Jig</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>0.035</td>
<td>1.80-2.0</td>
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<tr>
<td>Batac</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.13</td>
<td>0.095</td>
<td>1.80-2.0</td>
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<tr>
<td><strong>Gravity Separators</strong></td>
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<tr>
<td>Spirals</td>
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<td>-</td>
<td>-</td>
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<td>Reflux Classifier</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.40-1.70</td>
</tr>
<tr>
<td>Teeter Bed Separator</td>
<td></td>
<td>-</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>1.35-1.70</td>
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<tr>
<td>Water Only Cyclones</td>
<td></td>
<td>-</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>1.60-1.70</td>
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<tr>
<td><strong>Dry Separation</strong></td>
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<tr>
<td>XRT Sorting</td>
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<td>-</td>
<td>-</td>
<td>0.6</td>
<td>0.4</td>
<td>1.70-2.00</td>
</tr>
<tr>
<td>FGX Separator</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.38</td>
<td>0.26</td>
<td>1.80-2.00</td>
</tr>
</tbody>
</table>
2.3.2 Maximum Utilisation of Resources

The maximum utilisation of the remaining resources will have to entail highly efficient separation of coal and minerals down to zero microns. To achieve this objective, sharp separation at coarse sizes will have to be followed by equally sharp medium size separation followed by optimised fines and ultra-fines beneficiation. In terms of flotation in South Africa, Multi-Cell flotation has proven very successful on lower quality coals, for example in the Witbank area. In areas like Tshikondeni flotation products are coking coal quality, where excellent froth flotation plant yields are obtained. An increased yield factor in all separation areas must be taken into account. The higher the yield, the more tons produced. This requires accurate operational control, especially in terms of density. The more tons produced in South Africa, the higher the share will be in the world coal market. However product quality must not be compensated and hence quality control remains very important. Fine coal beneficiation either by spirals or the more efficient Teeter-bed method seems likely to be improved even more. The retreatment of the discard dumps in South Africa is already underway; here down-to-zero wash and fine to ultra-fine beneficiation technology will play a major role.

According to Leonard (1991), the traditional primary interest of the coal preparation engineer is process design, operation, and maintenance to produce an acceptable product that can be sold at the greatest possible profit. Leonard’s (1991) opinion is that it is the attention to the potential value of coal that is sometimes neglected. The basis for any unrealised potential derives from the coal seam itself. An improved understanding of what constitutes the bulk quality of coal through the maceral and mineral distribution and content of the product is therefore required.

In the US, a ‘seam to steam’ strategy is being used where the strategy is to utilise fine coal in the form of coal water fuel (CWF), also referred to as coal water slurry (CWS), Cronauer and Swanson (1991). This concentrated suspension of coal fine coal in water is required to obtain 65-70 % coal, and not exceed a viscosity of approximately 60 cP (centipoise). This is then used directly for combustion power generation. The slurry is pumped to the utilisation facility. This system through fine
liberated coal cleaning provides the optimum yield and energy recovery of the mined coal.

2.3.2.1 Crushing

Coal has very distinctive physical properties which could influence the choice of crushing method, crushing efficiency and the extent of further downstream processing. These properties include hardness, friability, compressive strength and abrasiveness (England et al., 2002). The hardness can be up to 54 VHN (Vickers Hardness). The compressive strength can vary from 13.8 – 47MPa for +50-100 mm with the friability of bituminous coal being 43 % (result from 3 hours tumbling). The abrasiveness of the coal is directly dependable on the quality of the coal. If the % ash for instance is high, the amount of gangue in the sample is high. Coal with high amounts of gangue (especially sandstone and pyrite) will show much higher abrasiveness. Variability of the physical properties can therefore be attributed to variable gangue content.

ROM Coal Crushing

Crushing of ROM coal is done to reduce the feed to plant top size and to allow for improved liberation for subsequent beneficiation. Currently Jaw Crushers, Mineral Sizers (Double Roll Crushers) and Rotary Breakers are prominent in industry.

Figure 23: Illustration of Rotary Breaker operation (after Wills 2011)
The rotary breaker due to its method of autogenous crushing and screening allows for upgrading of the crushed breaker product. Rotary Breakers allow for autogenous crushing of ROM coal while involving upgrading of the material. This is done by utilising the friability properties of the coal and gangue minerals. Coal is friable and will pass through the sieves. The rocks are hard and not friable and will pass the allotted sieve size, and will be discarded as rock.

Figure 24: Illustration of a Bradford type Rotary Breaker (Wills, 2011)

The successful application of the double roll crusher is becoming increasingly evident in modern day coal operations.
Some of the benefits of using the Shumar Double Roll Crusher include:

- Maximise Desirable Coal Size
- Reduce Fines Generation
- Reduce Crusher Segment Wear
- Less Energy required than other application

Mineral Sizers have similar benefits and are widely used in industry today.

Jaw crushers are still used widely in industry for ROM coal, typically following rotary breakers or in some instances in sequence as primary and secondary crushers.
Crushing of Product

Coal products can be considered easy to crush. The higher the quality of the product (the lower the ash content) the easier the product should be to crush. Low grade export and ESKOM type thermal products could be considered harder to crush. In South Africa, there are mainly two types of coal product crushers used, namely Single Roll Crushers (Figure 28) and American Ring-Roll Crushers (Figure 29).
2.3.2.2 Screening

Dry Screening

The dry screening of ROM coal has become increasingly relevant in the coal preparation industry today. Dry screening although not as efficient as wet screening, does allow for a dry product. In the case of the addition of raw screened product to the overall product mix an improved lower moisture content and hence heating value of the product is achieved.
Dry screening, especially for ROM coal has become increasingly relevant in the South African coal industry. The dry screening application is especially effective in the case of screening out the raw fines and adding it directly to the product, in conjunction with destoning of the coarse fraction. In the case of producing low grade export with relatively high quality ROM, this process proves very effective in reducing product moisture and through that optimising the Net As Received Base calorific value and the air dried yield.

The Bivi-TEC’s unique dual-vibratory screening process minimises clogging and blinding of the screen openings to save downtime and increase productivity (de Korte, 2008). The screen box is accelerated approximately to 2g's while the screen mats can receive up to 50g's, this acceleration and high frequency screening allows for minimal blinding.

### 2.3.2.3 Dense Medium Separation

Dense medium separation is the most common beneficiation method employed in Coal Handling & Preparation Plants (CHPP) in South Africa today. The basic purpose of dense medium beneficiation is particle separation on the basis of mass or specific gravity. With coal representing the lighter particle by mass in the general SG range of 1.3 to 1.8 and the minerals (gangue matter) being the heavier particles by mass in the general SG range of 2.0 and higher.
The combination of the organic and mineral matter in particles influences the overall bulk particle density to determine their behaviour during dense medium separation, either reporting to the floating or sinking material. Near-gravity material (NGM) is traditionally defined as coal and mineral matter particles that are within ±0.1RD of the separation density attained in dense medium separation. South African coals are known to have a high degree of near gravity material which results in poorer separation efficiency (England et al., 2002). Being low vitrinite material the bulk of South African coal will be partitioned in the higher density fractions, in contrast to the high vitrinite coals from the Northern hemisphere (Laurasian coals), where the bulk of the material will be in the low density (1.30-1.40) fractions.

To achieve a high sharpness of separation for medium to fine coal, most industry identifiable units are Dense Medium (Dutch State Mine) Cyclones. Dense medium cyclones are still popular in almost every country where coal is mined. There have been many valuable minor improvements on the original Dutch State Mine design, including involute feed entry, larger vortex finders, and significant improvements in construction materials. The classic cylindro-conical shape remains the most commonly used throughout the world. LARCODEMS have been proved to be successful for the treatment of coarse coal to even as small as 0.5 mm, although in South Africa, 12 mm is the smallest treated size.

The derived designs include the Dyna-Whirlpool separator, the Tri-Flo separator, the LARCODEMS, the Swirl Cyclone, and the Vorsyl separator. Of these systems, those which accept feed at atmospheric pressure, separate from the separation medium, are considered to be more efficient. These systems, which include the Dyna-Whirlpool, Tri-Flo and LARCODEMS systems, all use a separating vessel which is cylindrical along the complete axis. In Dyna-Whirlpool, Tri-Flo and LARCODEMS systems the coal is gravity fed. The Tri-flow and LARCODEMS are popular for destoning applications. Destoning of ROM for South African domestic power station feed will become more prominent in the future especially with coals of low export potential due to the reserve location and geography.

Advantages of dense medium separation:

- Sharp separation (Near Gravity material has less of an impact on coal processing efficiency).
- Lower primary misplacement.
- Process control easier.

Disadvantages of dense medium separation:

- Relatively High CAPEX & OPEX.
- Large footprint.

In Figure 31 it can be seen that the separation efficiency of baths at larger feed particle sizes is better (lower epm’s) than that of dense medium cyclones treating finer feed material.

![Figure 31: Illustrating the predicted epm's of dense medium cyclones and baths respectively with varying feed sizes (Wills and Napier-Munn, 2006).](image)

(A) Coarse Coal Size Dense Medium Beneficiation (+20mm particles and stoning operation)

Examples of coarse dense medium beneficiation equipment includes the following: Wemco Drum, Wemco Cone, Chance Cone, Drewboy Bath, Tromp Bath, Teska
Vessel, Norwalt Bath and the Daniels Bath. The most frequently used up to recently being the DMS drum. The application of dense medium drums up to the present, has shown fairly good results in terms of efficiency and throughput, but is expensive to operate and maintain. The maintenance and replacement of drums is also difficult and requires a long downtime. Examples of increased maintenance items are liner, chain and complete drum replacement. Skirting wear also contributes to lower efficiencies and higher maintenance costs. The use of drums also requires larger plants to sustain their massive operation. The overall application of the LARCODEMS and large-diameter DSM cyclones, rather than DM static baths or vessels, will allow a much increased range of size fractions, typically 100-15mm and 75-5mm respectively, to be processed. This will permit reduction in the number of operating units and transfer between units and a reduction in equipment with a substantial amount of mechanical moving components.

Table 7: Coarse coal dense mediums separators. Illustrations from Wills and Napier-Munn (2006) and de Korte (1997).

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drewboy</td>
<td>The Drew-boy is still used widely in South Africa. They are typically used in destoning applications and are quite popular. Drew-boy circuits are known to be able to operate at high RD’s in excess of 1.80 without extensive operational problems.</td>
</tr>
<tr>
<td>Norwalt</td>
<td>Norwalt separators are not common in South Africa anymore. Bank Colliery 5 seam plant had the last installation, similar performance can be obtained compared to a Drewboy’s, but Norwalt separators tend to be more maintenance intensive.</td>
</tr>
<tr>
<td>Wemco Drum</td>
<td></td>
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</tbody>
</table>
Wemco drums are still used commonly in South African CHPP plants. They are mainly used in export operations and can achieve good epm’s and relatively high operating RD’s. In de-stoning plant circuits operating at high cutpoint RD’s, Drew-boy separation units tend to be preferred currently above Wemco drums.

(B) Medium Coal Size Dense Medium Beneficiation (-20mm+3mm)


<table>
<thead>
<tr>
<th>UNIT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Medium Cyclone</td>
<td>Dense Medium Cyclones developed by Dutch State Mine are used extensively in the South African coal processing industry. A high sharpness of separation for medium to fine coal with Dense medium cyclones can be achieved. There has been extensive research and subsequent improvements made on the original Dutch State Mine design, including involute feed entry, larger vortex finders, and significant improvements in construction materials (Wills 2006). In recent years the application of large</td>
</tr>
</tbody>
</table>
Dense Medium Cyclones have become increasingly popular in Australia and South Africa.

### Dyna-Whirlpool

The Dyna-Whirlpool separates on a similar basis to Dense Medium Cyclones and were developed in the United States. The application of Dyna-Whirlpools in South Africa is limited; its effectiveness has been surpassed by the Large Diameter Dense Medium Cyclone, LARCODEMS and the Tri-Flo Separator.

### Three-product Cyclone

The Chinese 3-product cyclone consists of a cylindrical dense medium vessel, similar to a LARCODEMS, with a conventional dense medium cyclone bolted to the rejects outlet of the primary unit. The cyclones can be either pump-fed or gravity-fed.

### Tri-Flow Separator
The Tri-Flo separator can be described as two Dyna Whirpool type separators in series.

The Tri-Flo separator can provide two stage separation in a single unit.

The device can be operated with two media of differing densities in order to produce two separate sink products of individual controllable densities, this allows for subsequent re-crushing and processing as described in Wills (2006).

**LARCODEMS Separator**

LARCODEMS are generally defined as low cost dense medium separators. They were originally developed to simplify the design of dense medium plants, being capable of efficiently and economically treating a similar size range of raw coal as the Baum jig but with more flexibility of cut-point and greater efficiency.

The three main features of the separator include the use of dense medium, centrifugal forces and separate inlets for mineral and medium. Dense medium is necessary in order to obtain high efficiencies and to give variable
relative density separation. Centrifugal forces make the separator efficient for finer, smaller sized less than 10mm. The use of separate inlets for medium and mineral eliminates difficulties of pump feeding the mineral and reducing breakage of larger sized particles. The material that is only of a slightly higher density than the medium tends to be carried to the separator wall and then to the vortex tractor.

<table>
<thead>
<tr>
<th>Vorsyl Separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Vorsyl separator is not used extensively in South Africa. The Vorsyl separator generally can deliver separation efficiencies similar to conventional DSM Cyclones. According to a report by Cronauer (2001) in the United States, the Vorsyl separator is less sensitive to minor fluctuation in design parameters like feed pressure and vortex finder dimensions.</td>
</tr>
</tbody>
</table>
2.3.2.4 Jigging

In the past, jigging in South Africa has proven very unsuccessful in thermal coal applications. The last operational Jigging plant closed in 1976 where high quality Witbank No. 5 Seam were processed to produce a 13.5 % ash premium, and low phosphorous content product (England et al., 2002). In the event of high near gravity feed material the jigging process does not give high yields of high quality products like coking coal. Through modern developments and technology Jigging might claim a valuable place in the future of South African coal processing. Figure 32 illustrates a modern Batac Jig, which is the most frequently used in the world, along with the ROM Jig. In India Jigging proved successful, but generally for the purpose of obtaining low yield coking coal and selling the discard as steam coal. According to Sanders et al. (2002), ROM Jigs (see Figure 33) require little processing water and no water treatment plants, sufficient downgrades for product coals can be achieved in the process. Sanders et al. (2002) also determined that upon evaluation Jig circuits (ROM Jigs and Batac Jigs) incur lower capital and working costs than conventional dense medium processing circuits.
There are negative design and operation factors to be taken into consideration when installing Jigs:

- Cannot produce wide range of product quality.
- Cannot handle high percentage near gravity material (+25% causes problems).
- Bigger more expensive plant.
- Higher power requirement hence higher electrical power costs.
- More equipment so higher maintenance costs.
- Bigger plant so higher civil engineering costs.
- Higher manning requirement.
The main benefit that jigs could bring to the market is processing without a dense medium i.e. magnetite and lower water requirements. The use of magnetite is very costly; normally a loss of 0.5-1 kg/ton coal processed is acceptable. In destoning operations therefore the use of Jigs is mostly applicable, depending on the coal characteristics.

2.3.2.5 Dry Processing

Dry processing has an important future in South Africa, especially considering the water restrictions. Dry separation could prove to be cheaper than wet processing (Dwari and Rao, 2007), but has definite limitations which could result in product loss. At present the application of dry processing is mainly for destoning applications, but in the case of high cutpoint SG requirements, could even be suitable for the low grade export market.

Based on the paper by Dwari et al., (2007) various characteristics of ore can be utilised during dry coal processing.
The advantages and disadvantages of dry processing can be summarised as follows:

Advantages

- Low product Moisture (increased heat value).
- Small footprint.
- Process not complicated & less equipment required.
- Destoning application.

Disadvantages

- Throughput challenges (especially Optical Sorting).
- Low separation efficiency for high near gravity feed.
- Compressed air required - FGX (Fluidised Gas Separation).

Mainly coarse dry coal beneficiation applications exist in South Africa, but there is current and older research undertaken in the areas of dry fine coal beneficiation through Electrostatic separation (Bada et al., 2011) and Magnetic separation (Trindade, 1974).
Coarse Coal Dry Processing

Only two dry separation units are considered in this thesis, namely the FGX separator and the X-ray sorter. It is the opinion of the author that dry dense medium separation will be in the forefront of coal preparation in the future, but currently has limited industrial application.

Fine Coal Dry Processing (Minus 1 mm)

In the test work undertaken by Bada et al., (2010) it was found that upgrading coal fines could be achieved, and more especially sulphur reduction. A substantial application could be in the potential upgrading to optimal low ash and high vitrinite products.

Trindade et al., (1974) found that magnetic separation could be applied successfully, but that the process is very sensitive to feed particle size and that in some instances magnetic susceptibility could not be induced. Sulphur reduction was however achieved.
**Table 9: Illustrating the main dry separation units in industry today. (de Korte, 2008 & Von Ketelholdt, 2010)**

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGX Separator</td>
<td>FGX separators typically achieve density separations of higher than 1.85 RD. Current destoning or deshaling exists in the Witbank coalfield for domestic coal production.</td>
</tr>
<tr>
<td></td>
<td><img src="image1" alt="FGX Separator Diagram" /></td>
</tr>
<tr>
<td>XRT Sorter</td>
<td>X-ray sorters have been applied in small scale domestic power station production. The major constraint remain throughput of these separators. Research is still ongoing and these separators have a definite future in the processing of South African coal.</td>
</tr>
<tr>
<td></td>
<td><img src="image2" alt="XRT Sorter Diagram" /></td>
</tr>
</tbody>
</table>

Practical combustible recoveries of both electrostatic and magnetic separation compared to theoretical potential, unfortunately remain low.
2.3.2.6 Fine Coal Processing Developments

In the paper by de Korte and Bosman (2007) it was illustrated that the improved separation efficiencies using Fine DSM cyclones on 3 x 0.5 mm material fines could be achieved compared to the conventional Spiral separation. It is known that spirals cut a small SG range of between RD 1.60 to 1.70 and that fine cut-points cannot be achieved. In industry improvements have been made using the spiral and TBS concentrator in-series, but the total recoveries as those achieved with Fine DSM cyclones have not been obtained. The concern is with the medium recovery circuit in the case of fine dense medium cyclone application. In addition, the inclusion of more fine material results in a negative medium and viscosity effect during separation. In the case of typical low grade export production, depending on the raw feed quality, spiral separation would be sufficient. Another aspect of wet fine coal processing is that fines dewatering remains less efficient resulting in an increased heat loss. Dry screening with a net heat value gain in the case of low grade product production should be sought after; here dry screening has a definite application.

2.3.2.7 Ultra-fine coal beneficiation

Coal Froth Flotation

It was only recently (post 1995) that coal flotation to produce thermal export quality coal was considered amenable in South Africa. This was mainly due to the increase in thermal coal export prices and developments in adequate technology. Froth flotation with South African ultra-fine lower rank coal is considered to be more difficult than high ranking coals from the northern hemisphere.

Developments of froth flotation cells, which design combined the high intensity mixing of the mechanical cell with the quiescent nature of column cells allowed for the achievement of economic recoveries. These cells included the Multi-cell (Figure 35) developed by Anglo-American and the subsequent improvement design called the Dual Cell. The Multi-cell entailed pumping of the primary cell tailings to the
secondary cell, with little to no froth dynamics in the secondary cell. Note that in the secondary cell no reagent addition and mixing is incorporated. The Dual-cell allows for the gravitational flow of the primary cell tailings from the primary cell to the secondary cell. Recirculation pumps in both the primary and secondary cells allow for mixing and additional upgrade potential.

![Multicell Schematic Diagram](Opperman et al. 2002)

2.3.2.8 Treatment of Ultra-fines in Slimes Compartments

Agglomeration of ultra-fines from redundant waste slimes compartments in co-disposal facilities is creating interest throughout the industry. The process with and without a suitable binder is energy intensive (above 1 MW for a 50 tph plant). Allowing for a stable process with minimal fines generation, pre-drying is required which could increase the total energy required even more to above 3 MW for a 50 tph plant, as in this instance thermal drying would be required. The agglomeration of slimes compartments could allow for additional low grade export in some instances, although only briquetting for domestic utilisation has been considered at present.
The Briquetting plant installed at Mafube Colliery has encountered the following difficulties (Swanepoel, 2012):

- High percentage fines creation post the briquetting machine – green strength.
- Impact of the weather has been significant on briquette curing strength and time taken to cure.
- Inconsistent briquette strength.

In essence the cause of the challenges referred to can be summarised as follows:

- Inadequate & homogeneous binder mixing.
- Briquette machine speed setting to ensure efficient pocket filling.
- Transfer points and stacker luffing contributing to the fines creation.

### 2.3.2.9 Chemical Cleaning of coal

Although chemical cleaning could prove efficient in organic sulphur removal and related trace elements, there is no industrial application of chemical coal cleaning currently in operation. Chemical cleaning is deemed to be too expensive and
operationally dangerous in industry. Figure 38 provides an example of a chemical coal cleaning circuit.

![Chemical cleaning plant diagram](image)

**Figure 37: Illustration of chemical cleaning plant using high temperature chemical cleaning (Leonard and Hardinge, 1991)**

2.3.2.10 Microbial Cleaning of Coal

Brivastava (1984) researched a combined physical/chemical/microbial process for removal of sulphur from coal. It was demonstrated that micro-organisms are capable of specifically cleaving carbon-sulphur bonds and removing substantial amounts of organic sulphur from coal. However, lengthy treatment times were required. Due to the lengthy treatment times and the unpredictability of micro-organism performance it is envisaged that industrial application of this cleaning mechanism is low.
2.3.2.11 Retreatment of Discard Dumps

There are a number of projects underway to retreat the existing coal discard dumps in the Witbank Area. There are however a number of factors to take into consideration prior the undertaking:

- Weathering of the existing coal, this could present fissuring of the vitrinite and a degree of devolatilisation.
- Raw discards are even more heterogeneous than ROM coal and hence quality and yield fluctuations would be significant. Process control and blending should be allowed for this factor.
- The new discards from the discard retreat plant could be of significantly poorer quality with extremely high sulphur contents. This would entail large amounts of acid water generation. Subsequent water treatment processes could be required.
- Due to the poor state of liberation of the raw discards, crushing might not achieve adequate liberation for subsequent beneficiaion.
- Dewatering of the arising slimes material and new discards would be required to curb some of the water acidification challenges.

2.3.2.12 Dewatering of Coal Technologies

Coal drying is of both theoretical and economic importance. Considering that thermal coal products is sold on an As-Received Basis (NAR and GAR), drying of coal is carried out to increase its calorific value and facilitate its transport (Pikon and Mujumdar, 1996). There are considerable challenges in handling wet coal. Especially in cold seasons in the Northern hemisphere, the coal could freeze and make handling extremely difficult.

The most common methods of drying:

- For medium sized coal (typically -50+0.5 mm) is a coarse coal centrifuge. Free moistures of below 6% can be achieved.
• For fine coal fine-coal-centrifuges (basket type) and screen-bowl centrifuges are used. In the United States decanters are used, which could in future be employed in South Africa. Dewatering screens in series with fine coal centrifuges have proven popular in industry. Low moistures of below 12 % free moisture can be achieved.

• For ultra-fine coal the most popular method in industry currently is plate and frame pressure filters, where free moistures in the order of 18 % can be achieved. Much research is currently underway to find innovative methods for ultra-fine coal drying. One such method is Nano-drying, where nano-drying media and mechanical moisture screening is used to reduce moisture levels. Free moisture levels of below 4 % have been achieved with this technology.

2.3.2.13 Acid generation from coal discard facilities

Acid generation from coal discard facilities can be affected by the quality of the discards, especially the sulphur and calcium oxide content. The production of low grade export coal could entail a higher yield, but a counter decrease in the quality of the coal (increased pyrite and hence sulphur content), depending on the inherent washability characteristics of the coal. As a result the mechanism of acid generation from coal discard facilities is important to quantify the overall impact on the environment.

Besides the application of QEMSEM evaluation techniques for process optimisation, there is an application to pyrite liberation evaluations and the possibility of acid mine drainage. The mineral pyrite upon oxidation results in considerable acid formation. Petruk (2000) highlighted that all sulphide minerals in coals through oxidation would result in acidic water generation. The mechanism of acid generation is given in Figure 38.
2.4 Trace Elements in Coal

In general, inorganic elements in coal in concentrations less than 100 mg/kg or 100 parts per million (ppm) are considered as trace elements.

The concentrations of most of the trace elements in coal are lower than the average concentration of the trace elements in the earth’s crust, although there are exceptions. Previous work done by Cairncross (1990) on the Witbank Coalfield No. 2 Seam coals and Wagner et al., (2005) on Highveld and Waterberg coals respectively gave a good indication of the likely concentrations of the trace elements in South African coals. What is significant in these South African coals is that *in situ* they have higher ash and hence higher mineral contents on average than similar deposits in the Northern hemisphere. Despite this South African and other Permian coals of the southern hemisphere also contain lower concentrations of sulphides, halogens, and trace elements compared to the northern hemisphere Carboniferous coals.

There are different cleaning mechanisms that can be used to reduce the concentration of trace elements in the thermal coal product. This was illustrated by Akers and Raleigh (1998), Capes *et al.* (1996) and Finkelman and Stanton (1978).
Akers (1998) found that the factors affecting trace element reduction during cleaning are the degree of liberation of the trace-element-bearing mineral matter; the relative intensity of cleaning; the way in which the trace element was found (its partitioning) in the coal (mode of occurrence), and the method of cleaning.

Figure 39: Trace element reduction compared to ash and forms of sulphur reduction (Akers 1998).

Based on Figure 39, Akers et al., (1998) and Capes et al., (1990) indicated that the removal of the sulphur components would entail an associated removal of some of HAP’s originated trace elements.

Davidson (1998) indicated that much of the trace element content can be removed, and that careful design of conventional coal cleaning circuits should allow some optimisation of this additional benefit. Akers and Raleigh (1998), however, commented that if during cleaning, a trace element is removed in the exact proportion to the reduction in ash content, and then its concentration in the combustion fly ash will be unchanged. Conversely, if an element is not efficiently removed relative to ash reduction, then it will be present in the organic concentrated
product. In the US, the trace element cleaning potential in Pittsburgh coals are shown in Figure 40.

Figure 40: Trace element cleaning potential coal beneficiation for Pittsburgh coals (Davidson, 1998).

2.5 Coal Utilisation

Gupta (2007) highlighted that the characterisation of such a complex material as coal necessitates more than one analytical technique to accurately predict its behaviour during conversion processes such as combustion, gasification, coking, and liquefaction. In this thesis, various techniques including mineralogical, petrographic, chemical analysis, mathematical and statistical techniques are employed to develop the characterisation model to enhance validation of the parameters relevant to the prediction of combustion and gasification performance.
The coal utilisation performance is more dependent on the specific component minerals and macerals than the bulk qualities of the coal products to be utilised. Juniper (1995) indicated the distribution of costs involved in the operation of a power station. It can be seen that the coal preparation plant only contributes 5% to the total operating expenditure, see Table 10 (a).

**Table 10 (a): Distribution of power station costs (after Juniper, 1995).**

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Handling Plant</td>
<td>5%</td>
</tr>
<tr>
<td>Pulverizing Plant</td>
<td>30%</td>
</tr>
<tr>
<td>Boiler (excluding pulverize)</td>
<td>9%</td>
</tr>
<tr>
<td>Electrostatic Precipitators (ESP)</td>
<td>4%</td>
</tr>
<tr>
<td>Flue Gas Desulphurization (FGD)</td>
<td>9%</td>
</tr>
<tr>
<td>Ash Handling Plant</td>
<td>5%</td>
</tr>
<tr>
<td>Other Non-coal Plant</td>
<td>38%</td>
</tr>
</tbody>
</table>

Even though the cost contribution of the coal preparation plant is small, the net effect its efficiency has on subsequent utilisation is economically and environmentally significant. Figure 41 illustrates the potential impact on subsequent utilisation of a lower quality coal (high ash content), typically not upgraded through beneficiation.
It is important to look at the process of sulphur and Hazardous Air Pollutant (HAP) trace element emission reduction through chemical means and understand that the additional costs will be significant. In the combustion chamber of a power plant, pulverized fuel is burned producing heat and residual gases (Figure 42).

**Figure 41:** Influence of lower quality coal on total coal utilisation chain (Juniper 1995).

**Figure 42:** Schematic of mineral transformation during combustion and gas-solid partitioning of trace elements (Thorwardth 2007).
The different trace elements do have different rates of vaporisation in the combustion chamber, while according to (Thorwardth 2007) the volatilisation of trace elements is in the first phase synonymous with vaporisation, shown in Chapter 1.

According to Thorwardth (2007), some of the low volatile trace elements do not vapourise during the combustion process and are directly bound to mineral particles. Elements with higher degrees of volatility are more likely to be released to the gas phase and might even evaporate completely. Element specific attributes like vapour pressure and boiling point are decisive for the volatilisation of trace elements. Furthermore, the heating rate, the temperature profile in the boiler and the residence time of the fuel particles in different temperature areas are of importance (Thorwardth, 2007). Important for the volatilisation of trace elements are the maximum temperature and thermal conductivity of the fuel particle.

SOx and HAP emissions may be reduced by wet flue gas desulphurisation, but this process is costly. Through the use of coal beneficication scrubbing costs can be reduced, without which could increase the costs of using wet flue gas desulphurisation, and in the process reduce HAP’s and unwanted ash forming constituents.

![Figure 43: Wet FGD Scrubber Module, from Gupta (2007).](image-url)
<table>
<thead>
<tr>
<th>Acids or glass formers (add bulk to the deposit)</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Titanium dioxide</td>
<td>TiO₂</td>
</tr>
<tr>
<td><strong>Base or fluxing agents (act as bonding agents)</strong></td>
<td></td>
</tr>
<tr>
<td>Iron oxide</td>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>CaO</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>MgO</td>
</tr>
<tr>
<td>Potassium oxide</td>
<td>K₂O</td>
</tr>
<tr>
<td>Sodium oxide</td>
<td>Na₂O</td>
</tr>
</tbody>
</table>

**Figure 44**: *Metal Oxides in the ash acting as bulk to ash deposits and unwanted bonding/fluxing agents (after Gupta 2007).*

The non-mineral inorganic components contribute significantly to the formation of ash constituents (Figure 44) during the combustion of low-rank coals (Ward 2002).

According to Gupta (2007), the mineral matter in coal is very significant to many different coal utilisation processes. A range of mineral-related factors is also involved in coal combustion including abrasion, erosion, corrosion, fouling and slag development.

### 2.6 Steam Coal Trade Economics

Export quality coal from South Africa is exported mainly through the Richard’s Bay Coal Terminal (RBCT). The export demand for low quality coal lies mainly within Eastern Asia currently, more specifically India and China. Comparatively high steam coal export prices can be obtained for low quality export coal which enhances the financial feasibility of low thermal coal exports to a great extent. There are, however, increasing concerns about the feasibility of lower quality thermal coal exports and their broader implications. These concerns are related to the environmental impact of low quality thermal coal exports and the threat to the security of domestic thermal coal supply within South Africa.

From a financial perspective, the higher saleable volumes (due to the increased yield) that could be derived from low grade export production could deliver higher profit margins.
Table 10 (b) summarises the coal quality specifications as listed by RBCT.

**Table 10 (b): RBCT Thermal Export Coal product grade specifications (Schemikau (2010)).**

| Specifications | RB1 Specifications | | | RB2 Specifications | | | RB3 Specifications |
|----------------|--------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Calorific Value Basis | 6,000 kcal/kg NCV adb | | | 6,000 kcal/kg NCV adb | | | 5,500 kcal/kg NCV adb |
| Calorific Value | Min 5,850 kcal/kg NCV adb | | | Min 5,850 kcal/kg NCV adb | | | Min 5,300 kcal/kg NCV adb |
| Total Moisture | (arb) 12.0% max | | | (arb) 12.0% max | | | (arb) 14.0% max |
| Volatile Matter | (arb) 22.0% min | | | (arb) 25.0% min | | | (arb) 20.0% min |
| Ash | (arb) 15.0% max | | | (arb) 15.0% max | | | (arb) 23.0% max |
| Sulphur | (arb) 1.0% max | | | (arb) 1.0% max | | | (arb) 1.0% max |
| HGI | 45 – 70 | | | 45 – 70 | | | 45 – 70 |
| Nominal Topsize | 50 mm | | | 50 mm | | | 50 mm |
| IDT | Min 1,250 degrees Celsius in a reducing atmosphere | | | Min 1,250 degrees Celsius in a reducing atmosphere | | | Min 1,150 degrees Celsius in a reducing atmosphere |
| Calcium Oxide in Ash | (db) 12.0% max | | | (db) 12.0% max | | | |

The economics of coal supply and demand can be described by the analysis of the supply and demand curve in Figure 45. A positive shift in the demand curve would result in an increased price (demand curve D3), whereas a negative shift in the demand curve results in a ‘lower’ price (from demand curve D2). The negative shift
in demand is the scenario that occurred in the second half of 2012. With the economic slowdown, a drop in demand caused a drop in the thermal coal export price. As a result the net US$ per ton that could be achieved producing a lower grade export product was greatly affected, as explained in Figure 45.

![Figure 45: Thermal coal supply and demand curve. D = Demand Curve Scenario, S = Supply Curve Scenario, P = Price Scenario](image)

When producing a lower grade export product a CV adjustment ($/GJ) is made to the product. The result is that the CV adjustment penalty incurs too high a margin reduction to make it financially feasible. Another significant risk with low grade export production is the transport of a higher ash product. A lower grade product entails a higher ash content, and therefore a lower energy value per ton railed scenario. Given the performance constraints with rail capacity in South Africa, this could be a significantly negative factor.
The costs of abatement can be described for example as the costs of stack gas scrubbers and other pollution control devices as well as any foregone output that results from abatement. These costs are a reflection of the benefits in the above pollution model (Dahl 2007). In Figure 46, the amount abated for scenario one (coal producer) from the left hand axis and the amount abated for scenario two (coal combustion power generation company) from the right hand axis are illustrated. The horizontal axis represents the hypothetical amount that the law requires to be abated.

Increased ash generation and Risk of Pollution (HAP Emissions) would require an increase in abatement costs for the power generation company to fall within legislative limits and increase marginal cost. However, the marginal cost for the coal producer would increase in the event that lower quality products are produced, which result in larger discard dump footprints and a consequent increase in associated water pollution or spontaneous combustion.
2.7 Mining Life Cycle Assessments

Coal mining from mine to utilisation involves quite an intricate cycle. From an environmental perspective multiple sources of pollution could occur into the receiving environment, air and water being the worse affected. Figure 47 illustrates the complete life cycle and the reduction in carbon emissions should coal beneficiation precede utilisation.

![Figure 47: Coal LCA System, adapted from National Renewable Energy Laboratory – Report on Life Cycle Assessment of Coal Fired Power Generation Plants (NREL 2009).](image)

The coal mining viewpoint is that the environment is affected through spontaneous combustion, dust and AMD from mining activities and discards facilities.

From a coal utilisation aspect, the environment is affected through emissions of gas and particulates and the generation of ash dumps.

In the case of higher grade coal utilisation, lower pollution could be achieved in the power generation industry, but more pollution could be incurred during mining. In addition a total potential value loss of potential energy recovery could occur. This is covered in more detail in Sections 10 and 11.
In the case of a lower grade coal utilisation, smaller dump footprints and associated water pollution would be achieved and more of the mined energy utilised. There is, however, in this instance more air pollution on the power generation side through increased emissions (and FGD costs) and ash handling and potential thermal efficiency loss.

Due to coal being an energy production source, the ranking of the coal-based performance is directly determined by overall thermal efficiency of energy generation. These two contrasting scenarios need to be properly validated relative to this effect, and will be addressed in the thesis by focus on coal preparation and its future role.