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## Beneficiation potential of a low-grade coal from the Emalahleni (Witbank) coalfield

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**Abstract:** The challenge of coal depletion has, among other resolutions, forced countries such as South Africa which depend heavily on coal-generated electricity to consider low-grade coal to meet their energy requirements. The Emalahleni Coalfield has an abundance of low-grade coal in-situ and in discards obtained from the No. 4 seam. This research thus seeks to give a technical assessment of the beneficiation potential of such coal for use in power stations linked to the coalfield. To that end, gravimetric and flotation beneficiation techniques were used, and their demineralisation capacities were assessed using physicochemical and petrographic analysis techniques. The results obtained showed that demineralisation of the coal was possible; with 29.1 and 33.6% ash obtained for an ~50% mass yield from gravimetric and flotation beneficiation techniques, respectively, against a thermal ash content requirement of 25–34% for coal-generated electricity.

**Keywords:** low-grade coal, beneficiation, gravimetric separation, flotation, physicochemical analysis, petrographic analysis

### 1. Introduction

Coal continues to be an important energy resource despite attempts to switch to other cleaner and renewable sources. In the global context, coal reserves remain sufficiently abundant to last the current century compared to natural gas and oil which are expected to be exhausted in the next 50-60 years (Chary et al., 2015). Coal presently powers the South African economy and that of most developing countries and will continue to dominate the energy sector in the coming decades (Department of Energy, 2019). This is due to its local availability, the magnitude of power infrastructure investment into coal-based technologies, stability in the price compared to oil, and shale gas (World Coal Association, 2015).

Malumbazo (2016) submits that of the 336 Mt annual output of mined coal in South Africa, 93.2 Mt is consumed in thermal power generation (Eskom), 42.9 Mt in synthetic fuels production (Sasol Synfuels), 25.0 Mt in smaller local markets, 78.7 Mt in exports, and 74.8 Mt is discarded because of low-grade. Snyman et al. (2003) suggest that such discarded coal currently exceeds 1000 Mt in abundance. It is expected that the usable good-grade coal reserves will be exhausted within 100 years at the anticipated consumption rate. Deposits of acceptable grade are available in Springbok Flats Coalfields in association with uranium deposits which render their beneficiation and utilisation formidable (Cairncross, 2001; Jeffrey, 2005). The beneficiation of such to provide both safe coals for burning and uranium for reactors requires concerted research and development work considering the importance of the latter in future energy scenarios.

Considering the increasing energy demand, it is inevitable that the consumption of low-grade coal will increase. The importance of coal in electricity and synthetic fuel production is not limited to the

current generation but will perpetuate into the upcoming hydrogen economy which is also expected to utilise coal to produce hydrogen. This is evidence of the enduring need for coal in the global energy economy (Mohr and Evans, 2009; Miller, 2017). Accordingly, the beneficiation of low-grade coal becomes a viable option to meet both present and future energy needs. Besides use in processing in-situ coal and discards from the Emalahleni Coalfield, successful technology development will also improve the viability of mining operations for low-grade coal deposits such as those which exist in the Free State Coalfields and the Molteno-Indwe Seams.

To meet feed specifications for local coal-fired thermal power stations that use pulverised- fuel (*PF*) technology, demineralisation of such coal is necessary before utilisation. The fundamentals of power generation using *PF* technology are well explained by Rackley (2010). By design, only one power station in operation, Lethabo, is capable of firing low-grade coal. Lethabo has an installed capacity of 3708 MW which comprises about 8% of Eskom's generating capacity and contributes 7.34% of the total feed to the national grid after adding the contribution of independent power producers (IPPs) (Jeffrey, 2005). However, despite the grade of coal acceptable at Lethabo being lower than that at other power stations, it remains relatively higher than some of the mined low-grade coal hence 74.8 Mt continue to be discarded per annum.

To render such coal usable, highly capable technologies such as inorganic (chemical) leaching are available for the demineralisation of low-grade coal. Singh et al. (2020) employed an alkali-acid treatment of low-grade Indian coal which led to a reduction in ash content from 35.33 to 0.65% (by weight); a powerful exposition of the potential that the technology holds. However, a review by Dhawan and Sharma (2019) indicates that although most chemical leaching protocols developed are capable of 80-90% demineralisation, they are reagent intensive thus further work is required for techno-economic and environmental validation.

An alternative to chemical beneficiation is physical processing using flotation, oil agglomeration, magnetic and gravimetric separation, among other techniques. These can be combined with an upfront waste rejection of coarse material using X-ray transmission (*XRT*) sorting technology before downstream processing by the above-mentioned techniques (Galvin and Iveson, 2013). The primary advantage of this approach is the disposal of coarse reject before comminution which can potentially result in huge cost savings, both CAPEX and OPEX. Flotation and oil agglomeration, better known as physicochemical processes, are surface chemistry-based and traditionally have been recognised as the practical methods of cleaning fine coal. Magnetic and gravimetric separation techniques, however, are purely physical processes based on the magnetic properties and specific gravity of the coal constituents, respectively. Flotation and gravimetric separation are the most mature technologies in this group and enjoy the extensive industrial application in coal processing (Bahrami et al., 2018). However, they show lower demineralisation capability compared to chemical methods (Meshram et al., 2012).

Conventionally, a heavy liquid test (washability/sink-float test) is performed on coal to assess the suitability of dense medium separation, *DMS* (and other gravimetric methods), and to determine the economic separating density. Gravimetric separation using hydraulic dense medium cyclone (*DMC*) equipment is most common in South Africa. The density of the suspension is adjusted in between the densities of coal and the associated mineral matter so that the light coal particles float while the heavy mineral matter particles sink. To achieve an efficient separation, an enhanced gravity field is required, which can be achieved using small diameter cyclones (~15-20 cm) and/or by high feed pressures (>690 kPa) (Meshram et al., 2015). Despite its efficiency for relatively coarse coal, it has limited capability in fine coal cleaning. The gravimetric beneficiation of coal usually requires feed sizes larger than 0.5 mm.

To simulate the possible performance of *DMC* equipment from washability test data, mathematical models that predict partitioning behaviour in the separation vessel can be used. The partition curve obtained for the *DMC* can be used to determine the amount of misplaced material in the different product categories from the process. The S-shaped character of the curve is its key feature. In this fashion, it is analogical to other probability distribution functions, thus the curve can be perceived as a statistical description of the *DMS* process, describing the probability with which a particle of given density reports to the sink product. A classical approach to determine partitioning is the Rosin-Rammler model but this has since been replaced by several better models in recent years. One such alternative, the modified Whitten model, has been applauded by various authors owing to its accuracy in predicting

partitioning behaviour of gravimetric separation equipment (Scott and Napier-Munn, 1992; Wills and Finch, 2016). Eqs. 1 and 2 show the respective models:

$$\text{Rosin Rammler} \quad PN_i = 100 - 100 \exp \left[ -\ln 2 \left( \frac{\rho_i}{\rho_{50}} \right)^m \right] \quad (1)$$

$$\text{Modified Whitten} \quad PN_i = \frac{1}{1 + \exp \left( \frac{\ln 3 (\rho_{50} - \rho_i)}{E_p} \right)} \quad (2)$$

where  $PN_i$  and  $\rho_i$  are the respective  $i$ th partition number and the corresponding sink-float fraction density respectively,  $\rho_{50}$  is the cut-point density,  $m$  is the steepness of the curve and  $E_p$  is the Ecart probability (probability of separation). High values of  $m$  indicate more efficient separations as does low  $E_p$  values.

Flotation is an established hydraulic beneficiation technique in processing -500  $\mu\text{m}$  sized coal. In South Africa, it has only found use in the beneficiation of coal fines but is yet to be applied at an industrial scale to beneficiate low-grade coal. Flotation practice, however, is not uncommon; it is the chief means applied in the processing of local platinum group metal (PGM) ores. Besides, flotation has been applied to low-grade coal within Southern Africa in Moatize, Mozambique thus significantly lessening the burden in future technology transfer, among other advantages (Castro and de Brum, 2017). The ash and sulfur-bearing minerals found in coal are primarily hydrophilic and are often rejected to the tailings in flotation. However, the efficiency of the process depends on the hydrophobicity of coal particles. The key to the flotation process, among other factors, is an understanding of how particles interact with gas bubbles in the pulp (Xing et al., 2017). Coal flotation is achieved by the preferential attachment of gas bubbles to coal particles (macerals) based on their surface hydrophobicity and the rejection of the gangue (mineral matter) due to its surface hydrophilicity - even a small portion of coal in the gangue would be a cause of concern (Ozgen et al., 2009). The underlying principle applied to realise separation is the difference in density between the flotation medium and the air bubbles to which the coal particles and collector droplets attach. The resulting agglomerate is of lower density than the medium in which they are immersed hence it rises to the surface where the clean coal is then recovered through an overflow launder.

While studies have been conducted on the processing of coal from the Emalahleni Coalfield of South Africa, they have been primarily focused on the coal of marketable grade and its fines (Opperman et al., 2002; Swanepoel, 2012), but very little work is published with regards to low-grade coal. This study thus offers coalfield-specific novel insight on how to unlock the value in the large volumes of low-grade coal that are available. This was achieved through undertaking a comprehensive technical assessment of the beneficiation potential of low-grade coal from the Emalahleni (Witbank) Coalfield using froth flotation and sink-float testing. The coal demineralised using both technologies was assessed to determine if it met local steam coal requirements for firing in thermal power plants using *PF* technology. An in-depth evaluation of the significance of each characterisation method was attempted.

## 2. Materials and methods

### 2.1. Raw materials and characterisation procedures

Low-grade coal of size -31.5 mm was received from Ingwe Colliery located in the Emalahleni Coalfield. The first experimental step taken was the analysis of the overall physicochemical composition, density, and petrographic properties of the coal. Physicochemical properties were determined by proximate, gross calorific value (GCV), and total sulfur analysis of the coal. Proximate analysis was done through the study of weight change during thermal decomposition of coal using an SDT Q600 V20.9 Build 20 thermo-gravimetric analyzer (MTA) which also provided a concurrent measurement of true differential heat flow (DSC). In preparation for the analysis, the coal samples were crushed to a nominal size of 95% passing 212  $\mu\text{m}$ . The analysis was conducted in continuous mode on 10 mg samples following an automated 44-min program whose key steps are shown in Table 1. This analysis (proximate) was also done for all the feed size classes selected for beneficiation.

GCV was analyzed on a DRYCAL modular calorimeter following (South African National Standards (SANS) 1928, 2009). Total sulfur was analyzed according to (American Society for Testing and Materials (ASTM) D4239-18e1, 2018). Petrographic imaging and analysis of the maceral and mineral composition

based on (SANS 7404-3, 2016) were conducted on a Zeiss Axiolmager M2M reflected light polarising microscope.

Table 1. Micro-thermogravimetric procedure for proximate analysis

Step	Parameter	Procedure
1	Inherent moisture	Ramp 20°C/min to 110°C, isothermal for 4 min, in N <sub>2</sub> gas 45 cm <sup>3</sup> /min
2	Volatile matter	Ramp 80°C/min to 950°C, isothermal for 15 min, in N <sub>2</sub> gas 45 cm <sup>3</sup> /min
3	Ash	Isothermal for 25 min, in O <sub>2</sub> gas 80 cm <sup>3</sup> /min

## 2.2. Beneficiation methodologies

The gravimetric separation was conducted through sink-float testing on the size fractions -4500+1800 µm and -9500+4500 µm obtained by size reduction using a jaw crusher followed by the screening of the coal using a Macsalab ES-200 220 V electrical sieve shaker. Density baths, in the range 1.5-1.8 SG, with aqueous solutions of sodium polytungstate (SPT-2) were used in ascending order to perform the sink-float test. The sink material from a preceding bath was washed and dried before being transferred into the succeeding bath, while the float was washed, air-dried, and prepared for analytical testing. The feed size for flotation was obtained by comminution of a representative composite sample of the coal (-31500+1000 µm) using a laboratory rod mill to produce a targeted- 300 µm size fraction, the coarsest size recommended for maximum coal recovery (Sokolovic and Miskovic, 2018). For flotation, Denver D12 batch froth flotation equipment was used, maintaining an impeller speed of 1100 rpm and an air bubbling rate of 60 mm<sup>3</sup>/sec. The tests were conducted at variable diesel collector dosages (7; 14; 21 g/kg coal) and a constant frothing agent volume (0.125 cm<sup>3</sup> Senfroth). Manual collection of coal float was done at reasonably set time intervals (1, 3, and 9 min), considering system controllability and loaded froth discharge volumes. The float and tailings slurries from each run were dewatered using an MIT laboratory filter press and air-dried in preparation for analytical testing. To evaluate beneficiation progress, the same battery of analytical tests conducted on the feed coal was applied to products from both techniques.

## 3. Results and discussion

### 3.1. Process work

The results from gravimetric beneficiation indicated that there was no significant variation in yield and grade for products from demineralisation of the two size fractions investigated. The results from the analysis of the size class -9500+4500 µm are reported henceforth. The economic density range for the separation was identified to be between 1.65-1.7 SG for both fractions. At 1.6 SG, the float yield was 23.08% and this had improved to 41.91% at the next density fraction, 1.7 SG. This change also corresponded to the respective decrease in coal grade from 22.19 to 26.88% ash, indicating a decrease in demineralisation capability. Since sink-float testing is better considered to be investigative rather than process work, some basic modeling was conducted to determine performance using gravity equipment. The approach indicated that the coal, based on its high near-gravity material content (>30), a feature common with Gondwana coals such as those in the Emalahleni Coalfield, would be best beneficiated using a dense medium cyclone, DMC. Such coals generally have an  $E_p$  of 0.05 (Fourie et al., 1980; Bhattacharya et al., 2016). The use of the Rosin-Rammler and Whitten equations on the sink-float data showed that the latter produced a better partition model for the coal.

In flotation, the near-optimum conditions, within the experimental set-up, were identified to be a diesel collector dosage of 14 g/kg Coal and a residence time of 1 min that corresponded to a float yield of 51.16% at which the coal had been demineralized to 33.61% ash. This mass yield and grade, support process feasibility from a production standpoint. Beyond the identified dosage, the response of the system to increase in diesel collector dosage was marginal and past the selected residence time, the grade of the float yield decreased significantly to beyond the targeted consumer (Eskom) specifications of 25-34% ash. An analytical study of beneficiation progress is given in Sections 3.2 and 3.3.

### 3.2. Physicochemical assessment of beneficiation

#### 3.2.1. Primary chemical analysis

The primary market for thermal coal from the Emalahleni Coalfield is Eskom which generally requires coal of grade 25-34% ash, total sulfur 0-2%, and calorific value 21-24 MJ/kg. The few power stations capable of consuming low-grade coal accept coal of ash content 37.8% and a CV of 16 MJ/kg. Thus, in this section, a comparison of feed coal and beneficiation products will be done against these target specifications. Also, discussed are other physicochemical parameters leading to a better understanding of the coal. Proximate analysis is the first basis for coal characterisation and prediction of its potential areas of utilization. The calorific value, on the other hand, refers to the energy or heat content of the coal, thus it is a vital parameter for coal-fired power stations that need to effectively predict the heat energy input. Understanding the sulfur content helps to determine if it is necessary to consider its removal during coal beneficiation and also finds importance in predicting sulfur-based emissions such as SO<sub>2</sub>, H<sub>2</sub>S, and acid mine water. Thus, total sulfur is a significant parameter in the assessment of the low-grade coal as strict penalties are applied in the market for high-sulfur coals (Wagner et al., 2018). Table 2 shows proximate, total sulfur, and calorific value analysis results for the low-grade coal. Flotation feed coal is of similar chemical properties to the as-received composite, but gravity separation feed coal is different due to its preparation procedure described in Section 2.2.

Table 2. Chemical properties of feed coal to flotation and gravimetric separation

Parameter	Inherent Moisture (wt %)	Volatile Matter (wt %)	Fixed Carbon (wt %)	Ash Content (wt %)	Total Sulfur (wt %)	Calorific Value (MJ/kg)
Overall Feed (Flotation)	2.96	18.94	25.21	52.86	0.449	14.04
Gravity (-9500+4500 μm)	2.94	15.8	38.78	42.45	-	15.10

The feed coal results confirm that the coal is of low-grade and of inferior physicochemical parameters compared to the coal required for steam generation in most of the *PF* boilers in use at Eskom. Therefore, a beneficiation step is necessary to avoid reduced power plant boiler efficiency and subsequent load loss and an increase in the ash removal burden (Eskom, 2019). From Table 2, it can be deduced that significant changes in ash and subsequently the calorific value will have the most impact on the grade of the product coal. The total sulfur content of the coal is only 0.449% thus is already within range and subsequently is not a target specification for the beneficiation processes. Besides, the average sulfur content of South African coals has been reported to be generally quite low according to Hancox and Gotz (2014) thus often is not worth considering when processing for thermal power generation.

The demineralisation potential of the beneficiation technologies is thus the focus of the investigation. The study of the ash content and calorific value is also of commercial benefit since they are the most common parameters upon which coal is traded. Table 3 gives the product (Prod.) yields and the results of chemical analysis obtained from gravity separation and the best-performing set of conditions in flotation. Fig. 1, which follows, gives a comparison of the two approaches to coal beneficiation in terms of mass yield of product, ash content, and calorific value.

The results exhibit the capability of both techniques to produce coal with ash, volatile matter, and calorific value specifications which conform to the target specifications of Eskom. Both beneficiation techniques show the highest product recovery at the first recovery positions, 1.6 SG and  $T=1$  min, which gradually decreases as the experiment progresses. Fig. 1 shows that although gravity separation has achieved greater demineralization its mass yield to product is less than that of the flotation, regardless of its slightly higher calorific value. This indicates that there is a chance for performance optimization in flotation which can simply be through a reduction in residence time, resulting in a product yield of comparable chemical properties. A residence time of  $T=1$  min is close to optimum for the production of thermal coal to meet the South African market's need (Eskom). At this position, an ~50% yield of a grade of 33.6% Ash was obtained. This product fits the Lethabo specification (37.8% ash) but barely fits the general Eskom specification (25-34% ash) (Steyn and Minnitt, 2010; Eskom, 2020). Thus, the blending of the coal would be necessary for the latter application. For a 50% yield, gravimetric beneficiation

modelling work indicated that the DMC product of grade 29.1% ash can be produced at 1.7 SG, which is the upper limit of the economic separation density range (1.6-1.7 SG). Thus, coal beneficiated through gravity methods easily fits the firing conditions for both categories of Eskom firing units. The tailings from both processes, however, have considerably less value post beneficiation (<10 MJ/kg CV) thus no re-flotation is necessary. Argiz et al. (2017) proposed that coal products whose calorific value is now within the above-mentioned range can still find use in the manufacture of Portland cement and brickmaking based on the properties of the gangue component.

Table 3. Results of mass yields and chemical analysis for gravimetric separation and flotation

Technique ( $\mu\text{m}$ )	Recovery Position	Prod. Yield (wt%)	Cumulative Prod. Yield (wt%)	Inherent Moisture (wt%)	Volatile Matter (wt%)	Fixed Carbon (wt%)	Ash (wt%)	Calorific Value (MJ/kg)
<i>Gravity</i> -9500+4500	1.6 SG	23.08	23.08	3.13	18.90	51.48	26.49	22.11
	1.7 SG	18.83	41.91	3.28	17.60	50.98	28.14	19.70
	1.8 SG	18.51	60.42	2.84	15.70	42.22	39.24	16.62
	Tailings	39.58	100	1.79	13.72	21.17	63.32	8.03
<i>Flotation</i> -300	1 min	51.16	51.16	1.29	18.86	46.25	33.61	20.14
	3 min	14.08	65.24	1.85	17.19	38.86	42.10	18.58
	9 min	5.25	70.49	0.66	16.08	29.65	53.61	-
	Tailings	29.51	100	0.89	12.94	12.39	73.79	9.19

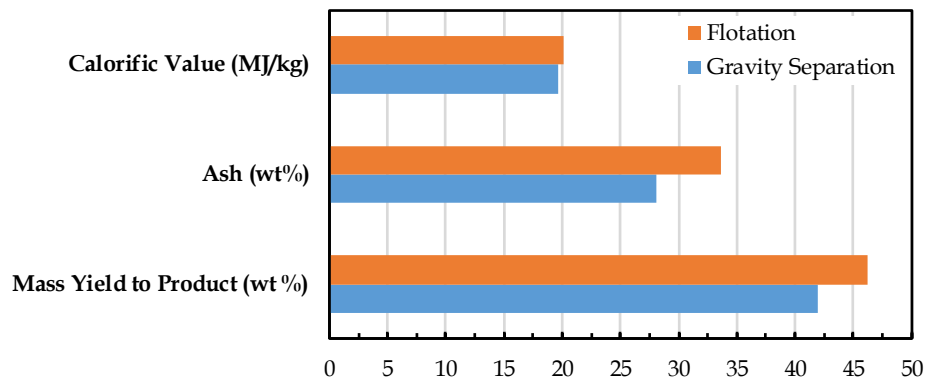


Fig. 1. Comparison of gravity separation to flotation performance

### 3.2.2. Heat flow analysis

The beneficiation processes can also be monitored through analysis of the heat flow which finds comparative use between enthalpy changes of the feed and those of the process products (Wagner et al., 2018). Fig. 2 shows the heat flow profile during thermal decomposition; the primary trend observed between 0-950°C ( $R_1$ ) represents the successive regions of low and high-temperature carbonization and the secondary trend at 950°C ( $R_2$ ) with distinctive sharp negative peaks representing combustion.

Fig. 2 shows that with beneficiation, there is a change in the enthalpy profiles of the coal. In the carbonization region denoted by  $R_1$ , positive heat flow is primarily observed which indicates a series of endothermic reactions undergone by the mineral groups constituting the coal. The profiles of the feed and flotation product are closely related and exhibit greater endothermic behavior compared to gravimetric beneficiation. This observation corresponds to the proximate analysis results which determined that more demineralisation occurred in the latter beneficiation process.  $R_2$  represents a series of sharp negative peaks related to exothermic reactions that are concomitant with oxidative combustion of the coal. It can be observed that the sharpest peak is that of the gravity separation product while those from the feed and the flotation product are less sharp and continue to be closely related. This relationship further affirms the results of the proximate analysis which determined the following order of abundance for organics/combustibles; gravity separation product > flotation product > feed.

Identification of the actual compounds responsible for the enthalpy changes observed will assist in developing a quantitative approach study of the phenomenon.

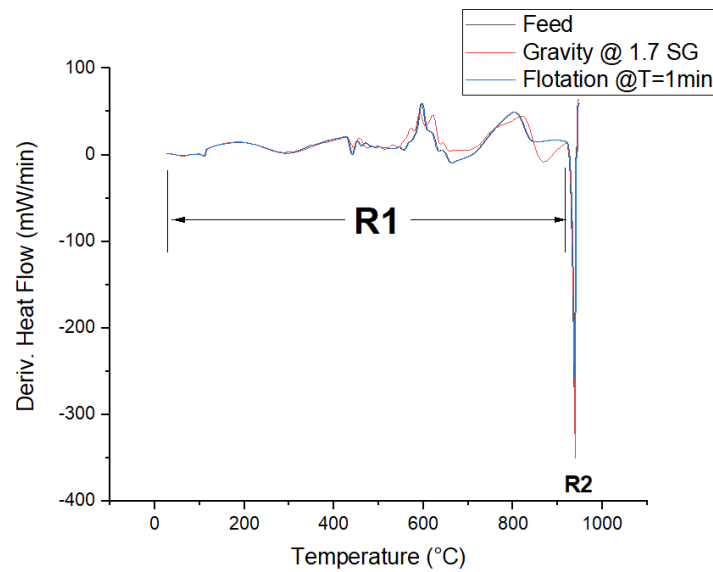


Fig. 2. Heat flow profiles of feed and beneficiation products

### 3.3. Petrographic assessment of beneficiation

Analysis by petrography provides valuable insight into the characteristics of the coal and yields near-accurate inferences about technological performance (Wagner et al., 2018). Fig. 3 shows petrographic photographs of some of the different macerals and minerals present in the coal. The petrographic photographs indicate that processing of the low-grade coal will be rather formidable due to the different maceral-mineral group association types which need to be factored into the demineralization scheme. According to coal type, Gondwana coals such as those present in Southern Africa tend to be high in inertinite, followed by vitrinite content, and lastly liptinite in order of abundance (Falcon and Ham, 1988). Semifusinite and inertodetrinite, which Fig. 3 indicates are abundant in the coal, are subgroups of the inertinite maceral group. Inertinite macerals are characterized by high carbon and low hydrogen and oxygen content, with a high degree of aromatization relative to the other maceral groups. Based on their change in structure and form, relative to other macerals when subjected to heat, inertinite macerals are considered non-reactive (Wagner et al., 2018). In other words, the combustion of an inertinite-rich coal charge happens at a slower rate compared to one abundant in either of the other macerals. From an observation of the association of pyrite,  $\text{FeS}_2$  with the maceral in Fig. 3D, it can be deduced that targeting its liberation will imply grinding the coal to  $< 25 \mu\text{m}$  which is sufficiently low for its intended application in electricity generation. It is also not feasible considering the energy impact and the overall abundance of sulfur in the coal which is 0.449%. Besides, the *PF* technology used to burn the fuel requires a coarser size fraction,  $< 75 \mu\text{m}$ . To coal processing specialists, the detailed information provided by petrographic analysis is useful in the selection and determination of the parameters that the beneficiation process must tolerate for effective operation. The photographs show the complexity in association between the macerals and gangue which in turn determines the choice of grinding parameters required to liberate the coal for a targeted recovery. Quantitative data, which helps to determine the relative abundances of the macerals and minerals present, suggests the theoretical limit to recovery and the general technological performance expected of the coal.

The 2D waterfall graphs, Figs. 4 and 5 provide maceral and mineral composition data for gravity separation and flotation across the whole range to allow for beneficiation progress assessment. The specific gravity of the feed coal is 2.08 SG and that of the respective tailings is  $> 2.61 \text{ SG}$ . From the plots in Fig. 4, it can be observed that beneficiation is possible through gravity separation but with different measures of success for each maceral and mineral group. Inertinite and quartz are the most abundant maceral and mineral groups in the feed, with quantities of 48.8 vol% and 29.5 vol%, respectively. Thus, their response to the separation processes has the highest impact on the beneficiation outcome. Between

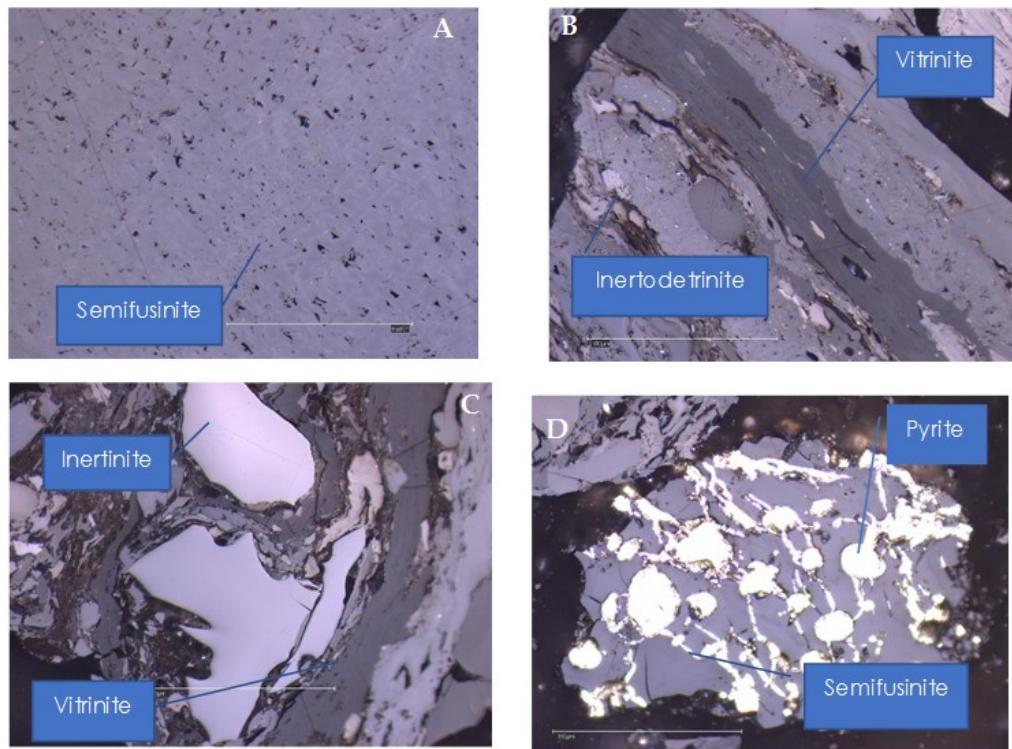


Fig. 3. Petrographic photographs of feed coal [500X, Oil Immersion, Scale Bar 100  $\mu\text{m}$ ]; (A) Clean semifusinite, (B) Clean layers of vitrinite and inertodetrinite, (C) Vitrinite and inertinite with epigenetic clay and quartz, (D) semifusinite with epigenetic pyrite

1.7-1.8 SG, gravity separation is still capable of inertinite recovery (81.4-76.4 vol%), but beneficiation extension is less viable because of reduced quartz rejection (6.5-12.1 vol%) resulting in reduced float grade and subsequently, increased process inefficiency. Based on abundance, the recovery of vitrinite and liptinite macerals and the rejection of the other mineral groups have a lesser impact compared to that of inertinite and quartz, respectively.

Fig. 5 shows flotation progress plots, which have some features closely related to the gravity separation plots in Fig. 4. The recovery of inertinite and vitrinite peaks at the cut-point  $T=1$  min (70.1 and 5.9 vol%, respectively) which concurs with the maximal rejection of quartz (14.2 vol%) and the other mineral groups. Inertinite recovery decreases between 1-3 min (70.1-61.1 vol%) but process perpetuation is less viable due to the complementary decrease in the mineral rejection capability as observed by the spike in mineral groups abundance on the graph. To extend the cut-point to  $T=3$  min, a techno-economic evaluation of the impact of introducing quartz depressant and to a lesser extent clay depressant, on the process economy will be required.

In terms of combustibility, more study of the enthalpy changes related to the minerals present is required but the performance of coals from both processes will be mainly influenced by inertinite, the most abundant maceral. For a constant mineral composition, the coal will have a slower combustion rate compared to those more abundant in either vitrinite or liptinite. Further study of the microlithotypes, epigenetic and syngenetic interactions in the coal will be required to determine the behavior of individual coal particles and the impact of comminution (Wagner et al., 2018).

### 3.4. Proposed flowsheet

From this beneficiation potential study, it has been established that the two separation techniques investigated are capable of beneficiating the coal. However, considering the size variability of the as-received low-grade coal and association effects, which is typical of such resources, gravity separation and flotation methods work best together than in isolation. Fig. 7 shows a proposed flowsheet, based on the investigation procedure applied in this study, which can guide the processing of low-grade coal for power stations.



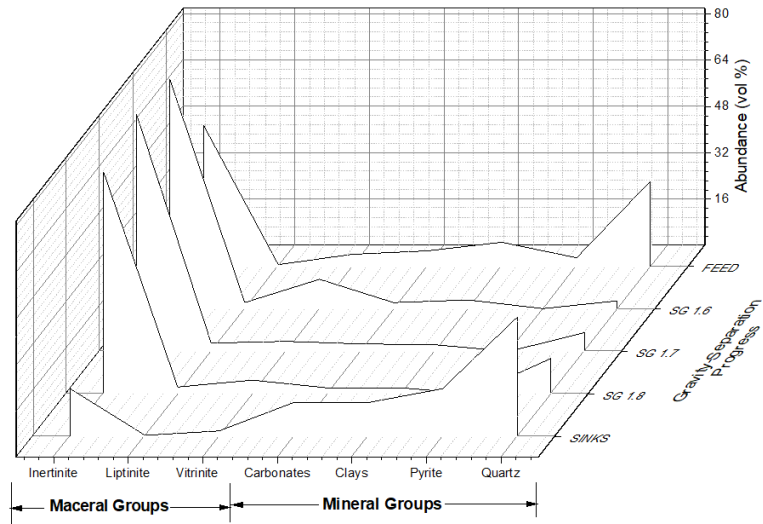


Fig. 4. Petrographic assessment of gravity separation progress

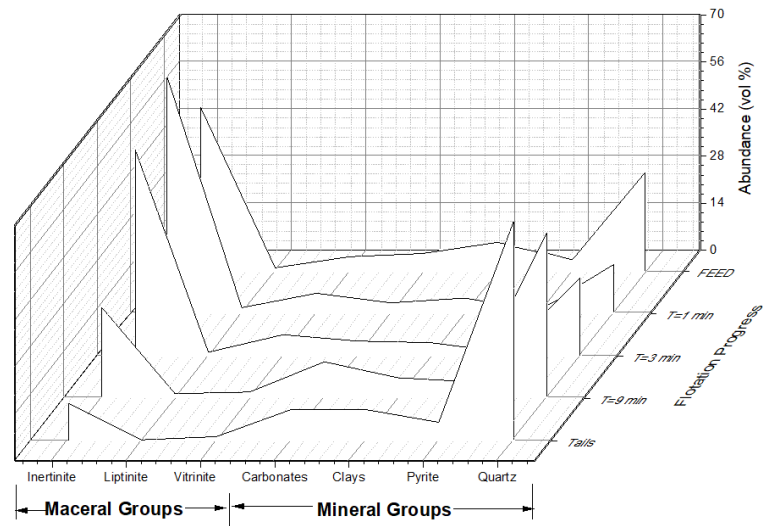


Fig. 5. Petrographic assessment of flotation progress

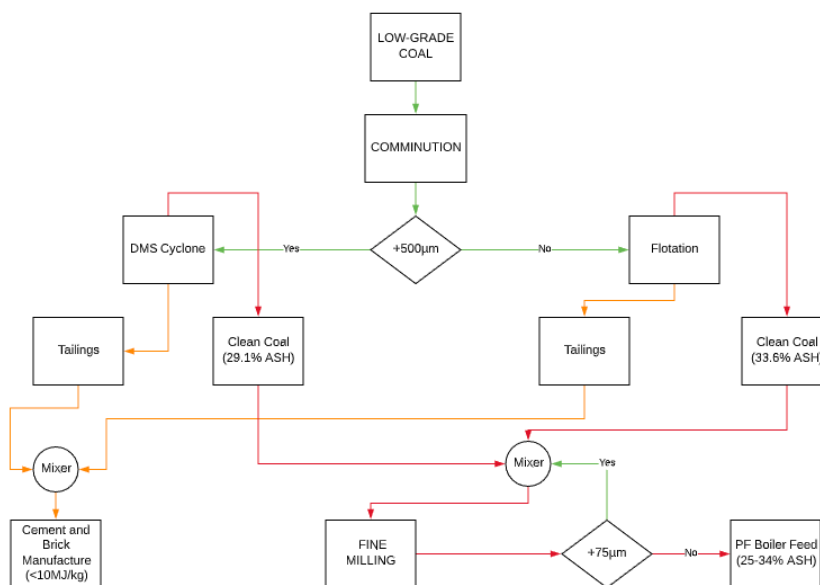


Fig. 6. Proposed flowsheet to process the low-grade coal

#### 4. Conclusions

The technical assessment of the beneficiation potential of low-grade coal, using froth flotation and sink-float testing, undertaken in this study revealed important insights. A process designed for the beneficiation of low-grade coal from the Emalahleni Coalfield must focus on the demineralization of quartz and the recovery of inertinite macerals. While sulfur removal is often a major challenge, that is not the case for this low-grade coal, and that reduces the variables to control in the beneficiation of the coal. Gravity separation, specifically using dense medium cyclone equipment exhibits the greatest capability to upgrade coarse fractions of the coal. The investigative data from sink-float analysis and subsequent modeling work determined that at a near-optimum cut-point of 1.7 SG, a ~50% yield of slow-burning, inertinite-rich (81.9 vol%) coal with an ash content of 29.1% which conforms to general grade specification, 25-34% ash, for the South African thermal coal market (Eskom) can be achieved. Froth flotation, on the other hand, was useful for fine coal sizes and the research indicated its potential to improve clean coal recovery, albeit with further optimization work and study of the reagent regime required. In  $T=1$  min, the technique also produced a ~50% yield of inertinite-rich (70.1 vol%) coal of grade 33.6% Ash which easily meets Lethabo specifications but barely meets the general Eskom ash specifications, hence requires blending for this application. This study has shown that information from physicochemical analysis best serves to complement that from petrographic analysis as the latter provides better data from which target process specifications are defined and the beneficiation response is measured.

The research also revealed alternative channels to improve coal recovery, energy footprint, and environmental impact concomitant with the investigated processing options. To lower the energy impact of comminution and reduce the volumes in downstream processing by gravity separation and flotation, among other applicable techniques, the potential for *XRT* sorting must be considered.

Future work would look at alternative dry fluidization methods for beneficiation which avoid the effluent burden from the wet processes investigated and when ultra-fine sizes are needed to liberate the macerals from inorganic associations.

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#### References

- AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) D4239-18e1., 2018. *Standard test method for sulfur in the analysis sample of coal and coke using high-temperature tube furnace combustion*. ASTM International.
- ARGIZ, C., SANJUAN, M.A., and MENENDEZ, E., 2017. *Coal bottom ash for Portland cement production*. Adv. Mater. Sci. Eng. 6068286.
- BHATTACHARYA, S., MAHESHWARI, A., PANDA, M., 2016. *Coal cleaning operations: The question of near gravity material*. Trans. Indian Inst. Met., 69, 157-172.
- BAHRAMI, A., GHORBANI, Y., MIRMOHAMMADI, M., SHEYKHI, B., KAZEMI, F., 2018. *The beneficiation of tailing of coal preparation plant by heavy-medium cyclone*. Int. J. Coal Sci. Technol., 5(3), 374-384.
- CAIRNCROSS, B., 2001. *An overview of the Permian (Karoo) coal deposits of Southern Africa*. J. Afr. Earth. Sci. 33, 529-562.
- CASTRO, A., DE BRUM, I.A.S., 2017. *Fine particles flotation of the Moatize coal/Mozambique*. AIP Conference Proceedings 1902(1), 020014.
- CHARY, G.H.V.C., GUPTA, A., DASTIDAR, M.G., 2015. *Oil agglomeration of coal fines in continuous mode of operation*. Part. Sci. Technol., 33, 17-22.
- DEPARTMENT OF ENERGY., 2019. *Energy Sources: Coal | Department: Energy | Republic of South Africa [www document]*. [http://www.energy.gov.za/files/coal\\_frame.html](http://www.energy.gov.za/files/coal_frame.html) (accessed 4.15.19)
- DHAWAN, H., SHARMA, D.K., 2019. *Advances in the chemical leaching (inorgano-leaching), bioleaching and desulphurisation of coals*. Int. J. Coal Sci. Technol., 6(2), 169-183.

- ESKOM., 2019. *Fact Sheets-4. Supply of water and coal [www document]*.  
[http://financiarresults.co.za/2012/eskom\\_ar2012/fact-sheets/004.php](http://financiarresults.co.za/2012/eskom_ar2012/fact-sheets/004.php) (accessed 4.26.19).
- ESKOM., 2020. Eskom heritage website. [www document].  
<http://www.eskom.co.za/sites/heritage/Pages/default.aspx> (accessed 6.22.20)
- FALCON, R., HAM, A. 1988. *The characteristics of South African coals*. J. South Afr. Inst. Min. Metall., 88, 145–161.
- FOURIE, P., VAN DER WALT, P., FALCON, L. 1980. *The beneficiation of fine coal by dense-medium cyclone*. J. South Afr. Inst. Min. Metall., 80, 357–361.
- GALVIN, K.P., IVESON, S.M., 2013. *Chapter 10 - Cleaning of coarse and small coal*, in Osborne (Ed.) *The coal handbook: Towards cleaner production*. Woodhead Publishing, pp. 263–300.
- JEFFREY L.S., 2005. *Characterization of the coal resources of South Africa*. J. South Afr. Inst. Min. Metall., 105, 95–102.
- MALUMBAZO, N., 2016. *Type, distribution and use of coal in South Africa*. Presentation: 35<sup>th</sup> International Geological Conference GIFT Workshop, Capetown. [https://static2.egu.eu/media/filer\\_public/ab/bf/abfffe4a-ec58-44a6-aac7b9527aae0782/9\\_-\\_malumbazo.pdf](https://static2.egu.eu/media/filer_public/ab/bf/abfffe4a-ec58-44a6-aac7b9527aae0782/9_-_malumbazo.pdf) (accessed 4.26.19).
- MESHARAM, P., SINHA, M.K., SAHU, S., PANDEY, B., 2012. *Chemical beneficiation of low-grade coal-A review*. 16<sup>th</sup> International Conference on Non-Ferrous Metals, 1–13.
- MESHARAM, P., PUROHIT, B.K., SINHA, M.K., SAHU, S.K., PANDEY, B.D., 2015. *Demineralization of low-grade coal-A review*. Renewable Sustainable Energy Rev., 41, 745–761.
- MILLER, B.G., 2017. *4-Introduction to coal utilization technologies*, in Miller, B.G. (Ed.), *Clean coal engineering technology* (2<sup>nd</sup> Edition). Butterworth-Heinemann, pp.147–229.
- MOHR, S.H., EVANS, G.M., 2009. *Forecasting coal production until 2100*. Fuel., 88(11), 2059–2067.
- OPPERMAN, D., NEBBE, S., POWER, D., 2002. *Flotation at Goedehoop Colliery*. J. South Afr. Inst. Min. Metall., 102, 405–409.
- OZGEN, S., TURKSOY, V.O., SABAH, E., ORUC, F., 2009. *Process development studies on recovery of clean coal from ultra-fine hard coal tailings using enhanced gravity separator*. Can. J. Chem. Eng., 87(5), 715–725.
- RACKLEY, S. A., 2010. *Chapter 3 - Power generation fundamentals*, in S. A. Rackley (Eds.), *Carbon capture and storage* (1<sup>st</sup> Edition) (pp 29-64) Butterworth-Heinemann.
- SCOTT, I., NAPIER-MUNN, T., 1992. *A dense medium cyclone model based on the pivot phenomenon*. Trans. Inst. Min. Metall., Sect. C. 101, C61–C76.
- SINGH, J.P., KUMAR, S., MOHAPATRA, S.K., 2020. *Chemical treatment of low-grade coal using Taguchi Approach*. Part. Sci. Technol. 38(1), 73–80.
- SOKOLOVIC, J., MISKOVIC, S., 2018. *The effect of particle size on coal flotation kinetics: A review*. Physicochem. Probl. Miner. Process., 54(4), 1172–1190.
- SOUTH AFRICAN NATIONAL STANDARDS (SANS) 1928., 2009. *Solid mineral fuels-determination of gross calorific value by the bomb calorific method, and calculation of net calorific value*. (ISO 1928:2009).
- SOUTH AFRICAN NATIONAL STANDARDS (SANS) 7404-3., 2016. *Methods for the petrographic analysis of coals- Part 3: Method of determining maceral group composition*. (ISO 7404-3:2009).
- SNYMAN, C.P., BOTHA, W.J., 1993. *Coal in South Africa. Geology and development in Southern Africa*. J. Afr. Earth. Sci., 16(1), 171–180.
- STEYN, M., MINNITT, R., 2010. *Thermal coal products in South Africa*. J. South Afr. Inst. Min. Metall., 110, 593–599
- SWANEPOEL, C., 2012. *Fine coal processing developments in Anglo American Thermal Coal South Africa in Klima, M.S., Arnold, B.J., Bethell, P.J. (Eds.) Challenges in Fine Coal Processing, Dewatering, and Disposal*, (pp. 95–121). Society for Mining, Metallurgy, and Exploration (SME).
- WAGNER, J., MALUMBAZO, N., FALCON, R.M.S., 2018. *Applied organic petrography, in Southern African coals and carbons: Definitions and applications of organic petrology* (1<sup>st</sup> Edition) (pp. 58–79). Struik Nature.
- WORLD COAL ASSOCIATION., 2015. *Coal market and pricing*. [www document].  
<https://www.worldcoal.org/coal/coal-market-pricing>
- WILLS, B.A., FINCH, J.A., 2016. *Chapter 11 –Dense medium separation (DMS)*, in B. A. Wills, J. A. Finch (Eds.), *Wills' mineral processing technology* (8<sup>th</sup> Edition) (pp. 245–264). Butterworth-Heinemann.
- XING, Y., GUI, X., PAN, L., PINCHASIK, B.-E., CAO, Y., LIU, J., KAPPL, M., BUTT, H.J., 2017. *Recent experimental advances for understanding bubble-particle attachment in flotation*. Adv. Colloid Interface Sci., 246, 105–132.