paper 7A

The Future of Thermal Coal Flotation

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ABSTRACT

The drive toward greater resource utilisation, and increased yields, has placed the issue of thermal coal flotation in focus of the industry. Historically, the opportunities for the flotation of non-coking coal have been limited based on the net energy gain achieved by the beneficiation and dewatering technologies available at the time. Recent advances in coal liberation, flotation and dewatering have created an opportunity to increase resource yield by the addition of a clean, fine coal component whilst maintaining or potentially increasing the energy content of the final product.

Increased focus on plant efficiencies, and the sustainability of operations in general, has identified opportunities once deemed uneconomic or inherently not viable as plausible improvement options. Cost pressures are heightening the need to maximise energy recovery from existing operations. The industry as a whole is now realising that the most economical source of adding more value is via the recovery of the fine coal currently being lost to tailings. Such losses have in the past been largely due to inefficient plant designs and/or unsuitable flowsheets that are not capable of providing for optimisation of the resource.

This paper investigates the industry trend towards thermal coal flotation and the drivers and technology responsible for this shift. The techniques used to exploit this opportunity will be investigated in detail and case studies will be presented.

THERMAL COAL PROCESSING

History of Thermal Coal Processing

Thermal coal beneficiation is generally governed by 3 sets of major parameters:

- coal washability
- particle size distribution
- marketing specification.

Thermal coal is generally washed to an energy target (or ash value, which is directly related), and this can be affected by changes in the above parameters throughout a mine's life. The aim of thermal coal beneficiation is to maintain as large a particle size as possible in the beneficiation phase, whilst achieving adequate liberation and optimal yield. This has typically been achieved historically with dense medium processes including drums, baths and cyclones or in an earlier generation of plants, via jigs alone. Fine material (nominally -1 mm) is typically processed through water-based gravity separation devices predominantly spirals, teetered bed separators (TBS), or more recently, reflux classifiers (RC). Material -0.1 mm is typically discarded to tailings due to low energy contribution to the final product and cost of processing.

The mine operator has certain controls at his disposal to optimise output whilst meeting the required product quality. These are:

- density cut-point (D_{50}) control
- blending
- bypass of seam types or particle size fractions directly to product or waste.

Due to the unit process efficiencies available at the time, moisture content has generally precluded the introduction of the flotation process from being viable due to a net product energy loss created by the addition of the concentrates with higher clay and moisture contents, as evident in a typical Hunter Valley thermal coal. Technology advances have allowed yield and resource optimisation to improve over the years. These have included improvements in both processing and dewatering via the avenues of process control, plant stability, maintenance programs and new wear materials.

Historically Accepted Losses

The traditional thermal coal flowsheet typically routes desliming cyclone overflow directly to the tailings circuit. No attempted recovery is undertaken and the material is simply thickened and then pumped to a site tailings storage facility. A typical size distribution in the Hunter Valley can contain 5–10% of ROM material in this stream. This material routinely contains a high amount of clay but also contains recoverable and saleable coal values. The viability of this stream can no longer be ignored and must be considered for recovery in new and existing operations.

MOISTURE IMPACTS

The level of total moisture contained within a thermal coal is critical to how much energy within the coal is available for customers to generate useable energy. Any energy used to dewater the coal becomes essentially wasted and does not contribute to kWh generation. The presence of fines in a thermal coal product also plays a crucial role in the overall total moisture holding capacity and this is primarily a function of surface area.

To optimise the effect of particle surface area, "bottom size analysis" (Osborne et al, 2014) investigates via detailed simulation, the optimum bottom size for a particular resource to maximise saleable product volumes and quality resulting in maximum revenue. This simulation estimates the impact of fine particle surface moisture on the saleable product quality. The simulation shown below (Figure 1) illustrates the interaction between increasing product volumes and increased product total moisture as the bottom size decreases. A critical input to this process is the use of Non-Centrifugal Moisture (NCM) testing (Firth et al, 1998).

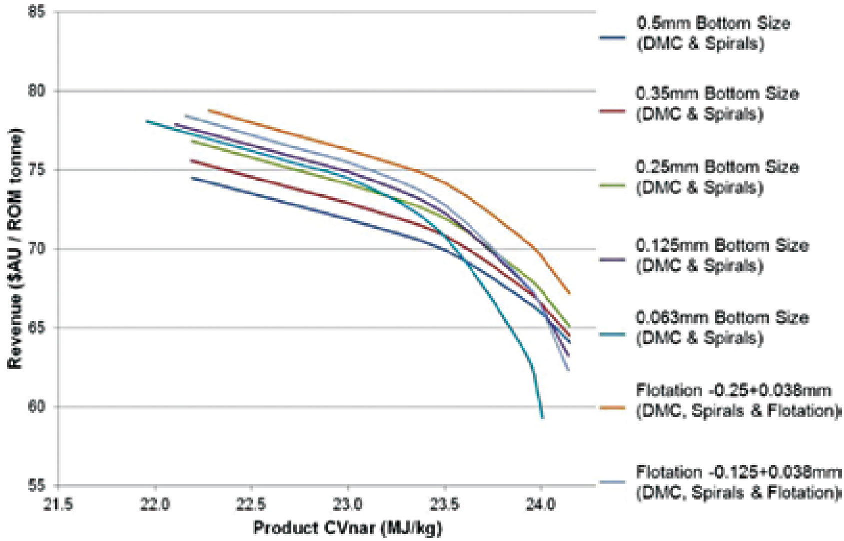

Figure 1 Example Bottom Size Analysis Results (Osborne et al, 2014)

ADVANCES IN FLOTATION TECHNOLOGY – CURRENT INDUSTRY BEST PRACTICE

Pneumatic Flotation

In order to achieve low product ash levels in flotation, pneumatic style flotation technologies are generally employed. Technologies including the Jameson Cell, Micro Cell and Pneuflot exhibit features that target low concentrate ashes. The fundamentals of pneumatic flotation are well explained by the operation of the Jameson Cell (Evans, Atkinson and Jameson, 1993). It involves feed slurry being pumped through a restriction to create a high pressure jet which then enters a cylindrical contact chamber where particle contact occurs. The jet of liquid first shears and then entrains air from the atmosphere. Removal of air into the jet causes a vacuum to be generated inside the contact chamber. When a hydraulic seal is formed at the bottom of the chamber, the vacuum causes a column of slurry to be drawn up inside the chamber. The jet of slurry plunges onto the liquid surface and the high kinetic energy of the jet will then disseminate the entrained air into very fine bubbles. In this zone, the high intensity of the system creates a very favourable environment for the bubbles and particles to collide and attach. The air bubbles, coal and mineral particles move continuously down the chamber before exiting into the tank. The particle laden bubbles then float to the top to form the froth whilst the hydrophilic rock and mineral particles remain in the pulp phase to be removed as tailings. To ensure consistent operation, tailings recycle can be employed. This dampens feed fluctuations to the cell allowing the downcomer to operate at a constant feed pressure and flowrate.

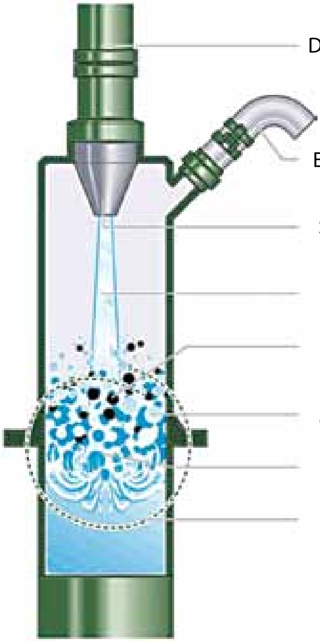

Figure 2 Jameson Cell Downcomer (Courtesy XT)

This technology employs rapid kinetics so the flotation vessel volumes tend to be very much smaller than that for mechanical and column cells of equivalent capacity leading to economic advantages.

Froth Washing

A flotation technology that has froth washing capabilities has advantages over those that do not. Froth washing is one of the most effective methods employed to reduce entrainment thereby enabling concentrates with the lowest ash (and highest energy) value to be produced. The amount of wash-water used is therefore an important process variable, i.e., the system must be able to be operated over the desired flow-rate range for a flotation cell of a particular size. This must be based on the designed concentrate tonnage range and solids content of the concentrate.

In practice, the wash-water addition is dependent on the process operation and in particular factors such as the structure and stability of the froth and the required ash value target. This in turn is influenced by factors such as particle size and hydrophobicity of the particles recovered in the froth. A stable froth allows froth washing to be effective in producing a clean concentrate without having a detrimental effect on combustibles recovery.

Bubble Size

Bubble size is one of the most important factors in any flotation system as it has a strong influence over flotation kinetics. Fine bubbles increase the flotation kinetics across all particle sizes (Diaz-Penafiel and Dobby 1994, Ahmed and Jameson 1985), and not just recovery of fine particles as has often been hypothesised. In coal flotation, fine bubbles also improve separation as they intensify the difference in the kinetics of the coal from non-coal particles, allowing concentrates with lower ash value to be produced without loss in yield.

Carrying Capacity

Bubble size dictates the carrying capacity of a flotation machine. Finer bubbles increase the carrying capacity (often measured as the mass flow rate (t/h) of concentrate per m^2 of surface area of the flotation machine) as there is more bubble surface area per volume of air added for particles to attach. Essentially, this means that if two different types of flotation machine are used to float the same coal using the same amount of air, the one generating air bubbles (measured as a distribution) that are half the mean-size of the other machine will have four times the bubble surface area available for flotation. This is therefore a very important consideration, especially for coal feeds offering very high potential yields. The more bubble surface area that is available from the machine, the lower will be the cross-sectional area required and fewer cells will be required to recover all the coal.

The air bubbles generated by the Jameson Cell are in the range of 0.3 to 0.7 mm (Sauter mean diameter, D32) (Evans, Atkinson and Jameson, 1993). Figure 3 compares the bubble size of a range of industrial mechanical and columns cells (Nesset, Finch and Gomez, 2007) to that of the Jameson Cell (Osborne et al, 2013). All results collated in Figure 3 were determined by the same bubble size measurement technique as developed by McGill University and described by Chen, Gomez and Finch (2001) and Gomez and Finch (2007).

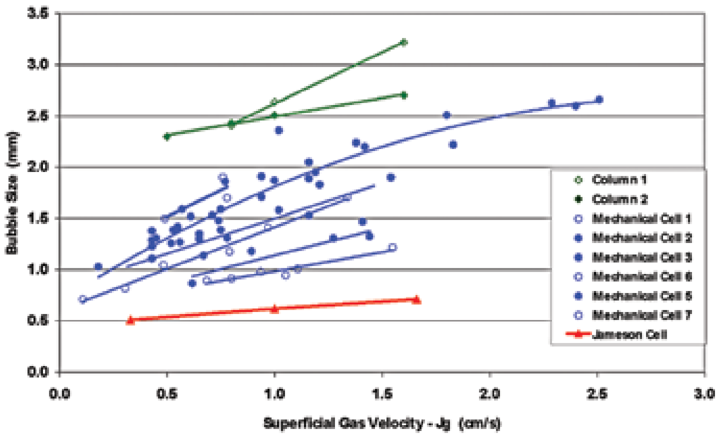

Figure 3 Bubble Size Measurement (Osborne et al, 2013)

PILOT PLANT PERFORMANCE ON A HUNTER VALLEY THERMAL COAL TAILINGS STREAM

A range of different thermal coal types have been tested in a two stage pilot scale Jameson Cell flotation circuit.

These have had qualities ranging from a 30% ash (ad) tailings sample from easily treated coal seams to very high >60% ash (ad) coal seams containing difficult fine clays.

Table 1 Pilot Plant Coal Quality Results by Seam

Seam	Feed Ash % (ad)	Concentrate Ash % (ad)
A	30–35	7–8
B	35–45	8–12
C	>60%	15–16

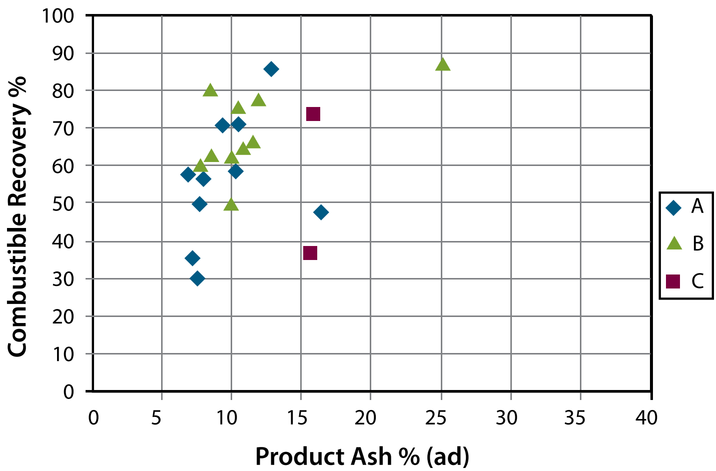

Figure 4 Pilot Plant Results

It can be seen that the Jameson Cell flotation circuit was able to achieve a low ash concentrate of 7–12% (ad) (Figure 4) at up to 70–80% combustible recovery for some feed types with the lower clay content, and 15–17% (ad) ash for coal seams with much higher clay content.

The fine mineral matter and clay in the coal concentrate reduces filtration rate and increases product moisture, by removing more of these particles improved product moisture is achieved. The plant is configured in a rougher-scavenger flowsheet where the tailings from the rougher (primary cell) feeds to the scavenger (secondary cell).The cleaning effect can be seen by the colour of the two product streams (concentrate which is high in vitrinite and tailings which is predominantly kaolinite clay) from the Jameson Cell circuit, shown in Figure 5.

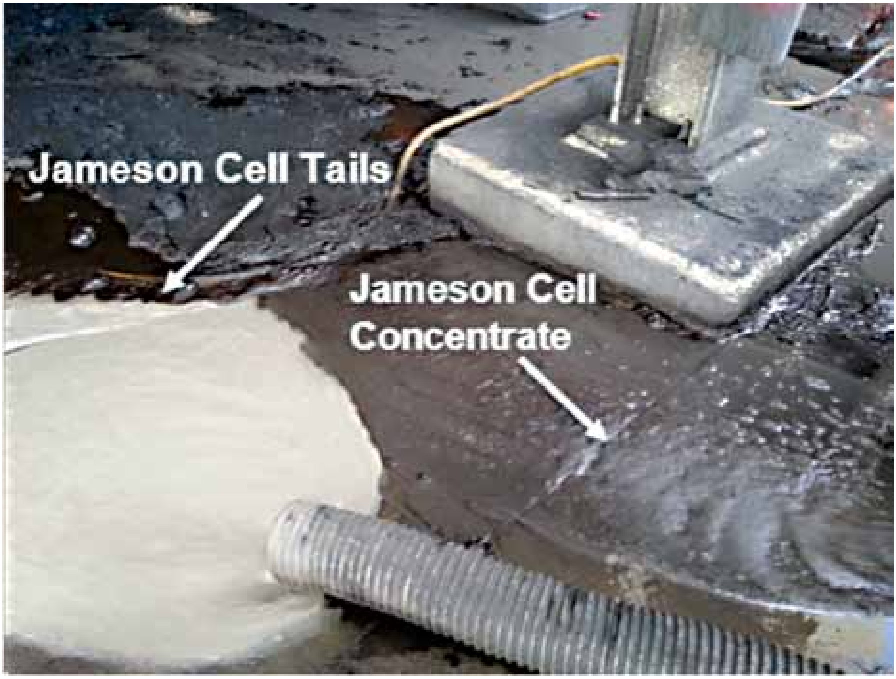

Figure 5 Concentrate and Tailings Streams from Pilot Plant Testwork

DEWATERING TECHNOLOGY

Dewatering options available for fine coal are listed in Table 2. Recent advances in "by zero" fines dewatering has enabled total moistures of flotation product to be reduced to a target whereby it can become viable, from an energy balance perspective, to include flotation concentrates into the final thermal coal product at a greater number of mine sites.

Table 2 Equipment Used for Dewatering Coal (adapted from Bickert's chapter in Osborne 2013)

Equipment	Size	Throughput (dry solids)	Product Moisture (% w/w)	Feed Preparation	Application
High frequency screen	0.6–2.4 x 3 m	10–100 t/h	15–25	Cyclone underflow	Fine coal
Screen scroll centrifuge	0.5–1.5 m dia	45–100 t/h	11–18	Cyclone underflow	Fine coal
Horizontal vacuum belt filter	75–150 m^2	50–130 t/h	20–30	Flocculation	Ultrafine coal
Screen bowl centrifuge	1.1 m dia x 3.3 m long	20–60 t/h	16–27	Thickening	Ultrafine coal
Centribaric centrifuge	1.1 m dia x 3.3 m long	15–20 t/h	15–20	Thickening	Coal slimes
Disc filter	120–200 m^2	50–150 t/h	20–32	Thickening / flocculation	Ultrafine coal
Hyperbaric disc filter	70–200 m^2	30–150 t/h	17–25	Thickening / flocculation	Ultrafine coal
Paste thickening	25 m dia x 6–12 m high	100 t/h	45–55	Flocculation	Coal tailings
Solid bowl centrifuge	1.1 m dia	20–60 t/h	30–45	Thickening	Coal tailings
Belt press filter	3–3.5 m wide	10–20 t/h	25–45	Thickening / flocculation	Coal tailings
Filter press	200–800 m^2	15–30 t/h	14–32	Thickening	Ultrafine coal and tailings

ECONOMICS

The economic argument for pursuing fines recovery is compelling. Technology advances allowing ultrafine product to be included in final product streams without penalising product quality is supported by the simplistic revenue scenario below.

Raw plant feed containing 10% passing 0.1 mm.

Yield of 50%.

For a thermal coal operation of 16 Mt/y ROM = 1.6 Mt/y of raw feed currently sent to waste.

Assuming a nominal 50% yield equates to 0.8 Mt/y of potential saleable product.

At a Newcastle benchmark price of US$86/product tonne **= US$69M revenue loss per annum** (not accounting for freight, port, tonnage adjustments, etc).

Including conservative capital and operating costs produces a very attractive investment opportunity.

Table 3 Economic Evaluation of Brownfields Flotation Installation

Capex $	Opex $/feed t	Rate t/h	Direct Costs $/t	Tax rate %	Discount Rate %	NPV $	IRR %	Pay back yrs
50M	15	230	30	30%	10%	78M	51	2.5

FUTURE DIRECTION – REDUCING PRODUCT ASH AND MOISTURE

The challenge of cost-effectively recovering a saleable fines component from tailings has been with us for many years and periodically an apparent solution emerges. XT has been operating a pilot-plant as described earlier and this plant incorporates the combination of fine grinding and Jameson Cell flotation technology for the preparation of coal-water slurry fuel (CWSF). The inclusion of a fine grinding stage enables slurries to be prepared whereby the non-value components are liberated from the carbon material thereby facilitating recovery of a highly concentrated ultrafine, low ash coal product.

Figure 6 1.0 t/h Coal Tailings Treatment Pilot-plant

This combination has already been proven capable of achieving very good combustible recoveries (material dependent, but normally over 90%) for coal from the raw tailings stream. The milling step reduces particles down to a p80 of 0.015 mm enabling enhanced flotation recovery by increased liberation and the formation of fresh surfaces on the ultra-fine coal particles. Further enhancement of the addition of improved ultrafine dewatering of the flotation concentrate using a membrane filter press or equivalent and a "fit-for-purpose" mixing system has resulted in the preparation of highly stable slurries with solids concentrations over 60% (w/w). This fuel has been specifically prepared for use in direct coal injection engines (DICE) to replace diesel fuel.

Other coal-water slurries with a slightly coarser particle size distribution (p80 of 0.075 mm) can be prepared in a similar way to create a coal-water slurry fuel (CWSF) at over 70% solids that can be used for direct firing to boilers as a potential replacement for heavy fuel oil (HFO).

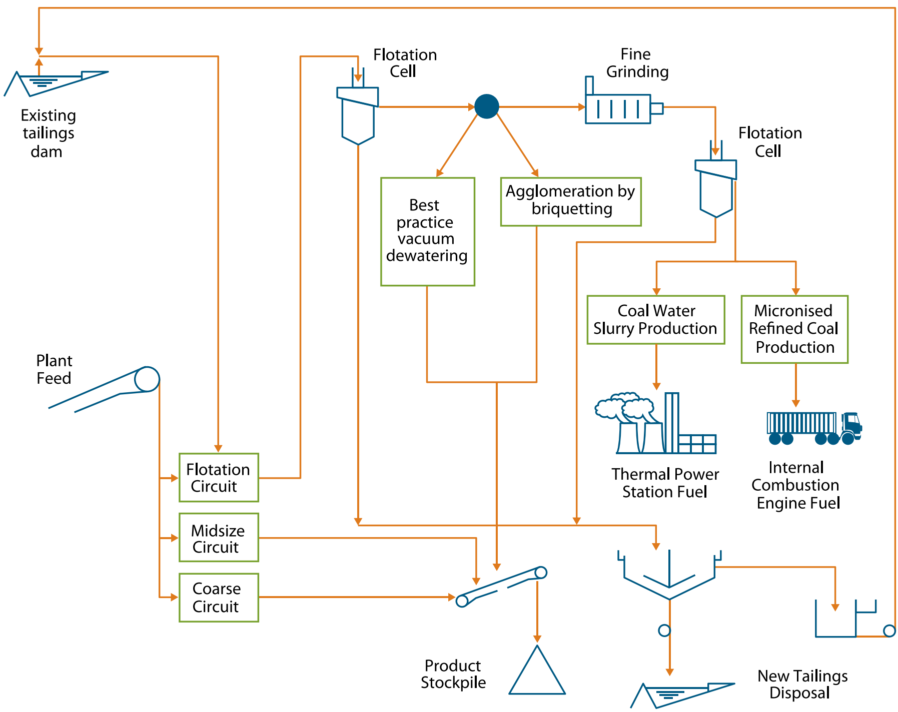

Figure 7 Alternative Fines Treatment of Thermal Coals Flowsheet

Figure 7 shows the flowsheet for these alternatives with the inclusion of the Jameson Cell and fine grinding for the purposes described earlier. Adding the milling step will be optional for CWSF but essential for micronised refined coal (MRC). Various filter options, also described earlier will need to be evaluated to achieve the required solid-liquid outcome for each coal source and each product component. Alternatively, a briquetted product that can be included in the normal product stream is another way of dealing with increasing fines related problems in coal product handling and transportation.

The integrated plant design has the functionality of the dual product offering, i.e., coal briquettes that can be added to the conventional product and/or coal-water slurry fuel (CWSF) for either heavy fuel oil replacement of more novel applications such as the MRC and DICE combination The concept of CWSF supply chains is being promoted to industry whereby slurry fuels employ existing heavy fuel oil infrastructure to transport and store the fuel at the customer facility.

COAL SUPPLY CHAIN CONSIDERATIONS

The current Coal Supply Chain (CSC) is hampered by an inability to dewater and transport fine coal. As a result, significant loss of coal value to tailings occurs also often leading to a significant loss of yield, which in turn impacts the coal mining price/tonne, adding further cost due to the need for tailings handling. The irony is that it is often necessary to exclude fines from product coal in order to transport it to the power station because of reduced revenue due to moisture, dust or sticky coal handling issues, etc. However, on arrival at the user's power plant a significant amount of money is then spent grinding it down to the conventional specification of ~70% minus 0.075mm.

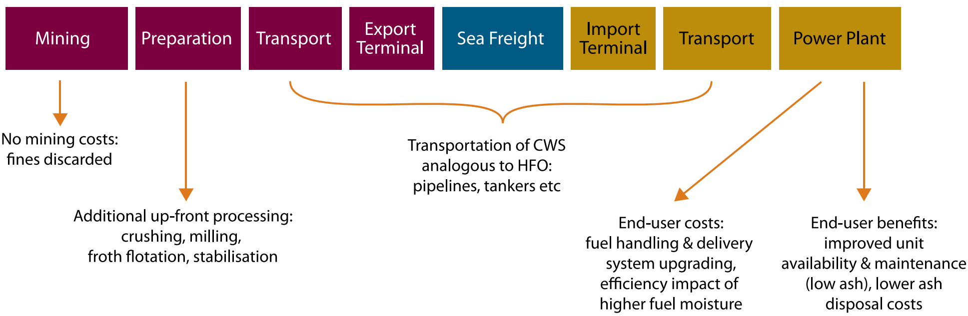

Figure 8 Coal Water Slurry Fuel Supply Chain (Osborne, 2013)

An innovative way to address this is to recover and use all the fines via coal-water slurry thereby recovering potential lost coal creating higher yield and lower cost/tonne. This could then be handled and transported as liquid fuel, avoiding the ever increasing problems associated with sticky, wet or dusting solids. There would then be less tailings material to dispose of, further lowering cost especially if the residual tailings can be paste-thickened and further dewatered so as to be disposable with coarse plant and mine waste.

No further grinding would be required at the power station, significantly lowering their cost and despite thermal efficiency being reduced, this would be offset to a large extent by cost reductions on coal that otherwise would not have been sold. Figure 8 shows a simplistic example of the chain. Some very simplistic cost-in-use analysis was conducted for this model which suggested a very definite benefit of about 1.0 to 1.5 c/kWh saving, would be generated for the user once the power plant boiler had been converted to accept CWSF to replace about 30% or more of the pulverised coal capacity (Osborne, 2013).

SUMMARY

This paper has provided insight as to the potential offered from thermal coal flotation. Waste in coal operations has for many years been "justified" by the impact that the added moisture has on the net value of the coal products. This may not be tolerated indefinitely because of increased awareness of sustainability issues and environmental impacts of adopting lowest cost disposal practices. With the concomitant emergence of better flotation technologies and improved solid-liquid separation equipment, arguments against recovery of wasted coal can be constructively challenged.

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