Premium coal fuels with advanced coal beneficiation

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Abstract

Research and pilot plant trials over the last 5 years have shown that a range of premium quality coal fuels, with ash contents as low as 1%, can be produced economically from a wide range of coals (including coal tailings). This capability can improve both the economic and environmental performance of coal through increased grade recovery, recovery of saleable coal from existing tailings emplacements, and new higher value products such as a fuel oil replacement in boilers, enhanced coking blends, and for higher efficiency power generation using the direct injection carbon engine (DICE). While a conventional coal preparation plant can be used to produce suitable ultra-low ash coal for these fuels, changes to both the philosophy of coal preparation and operating strategy are needed for achieving the best results. Further improvements are possible via the application of the latest milling and dewatering technologies. These fuels also require a rethink of the supply logistics. The paper discusses findings from both laboratory and pilot scale trials in Australia, in the context of new export products for DICE and boiler fuels.

Key words: ultra-low ash coal, coal grain analysis, coal slurry fuel, advanced beneficiation, DICE, high efficiency engine

INTRODUCTION

Producing very low ash coal products has for many years been a challenge for coal treatment specialists and researchers. Much of the early work in the 1970s and 1980s used chemical cleaning processes involving leaching with acidic or caustic solutions, most of which proved uneconomic when scaled up to commercial application. The most successful of these include the AMAX 2-stage leach process developed with US-DOE funds in the mid-1980s[1] and the Australian UCC process[2].

The use of physical cleaning to ultra-low ash levels, using more conventional coal processing technologies, has proven more challenging. Old school thinking typically regards ash contents below 2-3%, as both technically and economically unviable. This is due to several factors/misnomers:

- The so-called "inherent ash" content of coal is usually regarded as the lowest ash possible
- Lower ash contents require finer grinding to increase liberation which is costly and produces a product for which there are few markets
- Flotation of ultra-fine coal can be problematic, and requires high reagent consumption

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[1] Berggren, M. H., Chemical coal cleaning and cost refinement for coal-water slurry manufacture. Report DOE/MC/20700-T1, February 1985.

[2] http://www.yancoal.com.au/page/key-assets/technology/UCC

- Fine coal products are inevitably high moisture (> 35%) which means costly dewatering and/or drying to produce saleable products
- Ultra low ash coal products are uneconomic to produce

All of these factors are incorrect, or at best very misleading, as recent research/pilot plant tests have shown.

Fine coal cleaning is generally regarded as being the treatment of coal sized below 0.5mm (500µm) but the challenges have tended to descend further down the size distribution to 0.1mm (100µm) and lower. Most recently, with the widespread use of micro-flotation using the Jameson and Microcell technologies, the elusive size fraction is now <0.05mm (50µm) and this is probably where the current research and development focus lies. Such a size range usually means that coal particles are extensively liberated from the mineral content and are recoverable, providing that the concentrate can be recovered and dewatered to a commercially acceptable level.

Not surprisingly, much of the research and development that has occurred in ultra-fine coal cleaning has taken place for higher value products, often metallurgical, and almost all techniques for both cleaning and dewatering have undergone some form of improvement or development during the past decade in this context. These improvements have been in all areas - optimised design, improved materials of construction and improved wear resistance[3], process control and monitoring, integrated automation and sampling/analysis.

This paper describes recent work carried out at laboratory and pilot scale in Australia, that has successfully produced coal concentrates with <2% ash content from a wide range of coals and tailings, using a combination of fine grinding and froth flotation. The potential to achieve even lower ash levels is also discussed. The main objective of this work has been to produce a stable, coal-slurry fuel (i.e. micronised refined coal or MRC) for use in DICE, an application which demands the lowest possible ash content in the slurry fuel (preferrably <1%) and very fine particle size distribution (typically d_{80} of 20-40µm). This is much finer than the conventional coal water slurry fuel (CWSF) for boilers or gasifiers.

CHEMICALLY CLEANED COAL

Ultra-clean coal can be produced by chemically cleaning coal, and a 2- and 3-stage caustic leach process has been successfully demonstrated in Australia by UCC Energy Pty Ltd. A significant feature of the process is that the coal needs only to be coarsely milled (typically to -2mm) to provide sufficient contacting: all other processes for producing ultra-low ash coals require a higher degree of milling. The main process consumables are sulphuric acid, and lime; caustic soda is regenerated in the process. The waste materials are environmentally benign (gypsum and calcium alumina silicates) and the final ultra-clean coal product has 0.5-0.7% ash (with less than 0.2% possible for some coals). UCC Energy Pty Ltd (a wholly owned subsidiary Yancoal Australia Pty Ltd) owns and has operated a pilot plant at Cessnock in the Hunter Valley, New South Wales. The nominal 350kg/h facility (see Figure 1) was commissioned in 2002[4]. The main focus has been in the production of low ash coal fuels for gas turbines and DICE, as well as for electrode carbon and other high value applications – several using briquettes.

[3] Osborne, D. G.; 2012. Milestones in Fine Coal Development, *Challenges in Fine Coal Processing, Dewatering and Disposal*, editors M.S. Klima, B. J. Arnold and P.J. Bethell, SME, TN816.C375 2012, pp3-32

[4] http://www.uccenergy.com.au/the-process/

Fig 1 Ultra-Clean Coal pilot-plant, Cessnock, NSW (courtesy UCC Energy Pty Ltd)

Fuel from this plant has been used for longer duration tests in an adapted diesel engine (*ie* DICE) at the CSIRO, and scale up of the process is now under consideration by Yancoal and partners.

PHYSICAL CLEANING

Although chemical cleaning has been proven to produce very low ash coal products for the highest value applications (e.g. electrode carbon and MRC for DICE – especially smaller engines), the process is more costly than physical cleaning, is less tolerant of coal rank, and requires a coarser lower ash feed coal for optimum results. Physical cleaning is therefore preferred for the production of coals with ash contents <2% from a variety of coals and tailings, and is the focus of the present paper.

Liberation – removing the "inherent ash" constraint

Efficient analysis of the occurrence of mineral matter within the feed coal is key to economically producing premium coal products by physical cleaning. CSIRO in Australia has developed an optical reflected light microscopy system for assessing coal petrography samples. This system collects and creates mosaic images so that quantitative information can be obtained on individual coal/mineral grains. Size and compositional information (the amount of vitrinite, inertinite, liptinite and mineral type) is obtained for each particle, and this information can then also be used to estimate the density and ash value of each particle (both macerals and minerals) and that of the sample.

Although coal grain analysis (CGA) is generally conducted on a small representative sub-sample of -1 mm material, the technique has also been successfully used to characterise particles up to 4 mm in size (a size which perhaps report to a middlings circuit), and for samples which have been micronised to give particle size of less than 20 µm (e.g. for producing ultra-low ash concentrate by flotation).

For the ultra-fine material, CGA is particularly useful to assess the degree of liberation and therefore assist in optimising the beneficiation process to produce the lowest possible ash products (for uses such as DICE, or even direct carbon fuel cells[5]).

5 O'Brien G., Firth B., Adair B. The Application of the Coal Grain Analysis Method to Coal Liberation Studies, 2011, *International Journal of Coal Preparation and Utilization 31*: pp 96–111

For advanced beneficiation, CGA enables liberation to be assessed and the expected yield at different target ash levels to be estimated. As the CGA information also provides detail on the intrinsic and entrained minerals in a sample, it benchmarks the lowest ash value which could be obtained if all entrained minerals are removed from the sample at that top-size.

An example of its application in the production of MRC for DICE is given in Figure 2 below. The characterised CGA images shown illustrate the extent of liberation for raw tailings (-250µm) and the corresponding micronised concentrate with a d_{80} of 15µm. The results show that milling has enhanced significantly the particle liberation, and has produced essentially single component grains. This indicates that it is physically possible to reduce the intrinsic mineral being carried over to the product. This implies that an appropriate circuit of grinding and flotation operations should be capable of producing a very low ash product concentrate. In this case sufficient liberation has occurred to enable a product coal with less than 1% ash to be obtained, provided entrainment within the froth can be eliminated. Although it is anticipated that the fineness of the entrained mineral particles will make separation more difficult, there are a number of process optimisations available to achieve this (e.g. use of reagents which enhance the hydrophobicity of the coal and hence allow more aggressive application of wash water to be used, optimisation of the pull between flotation stages). Both have been shown to be effective in practice at the pilot scale.

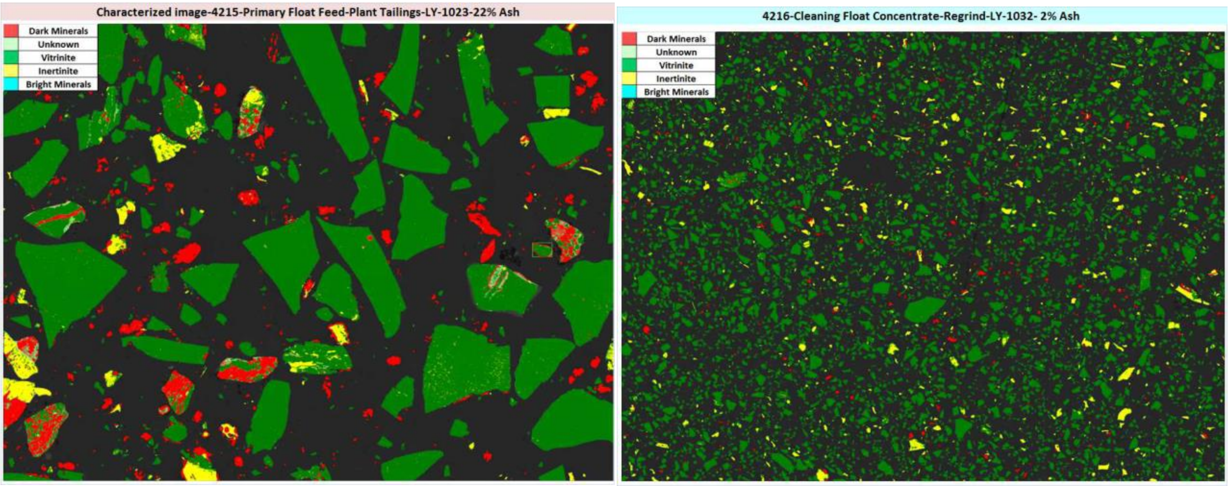

Fig 2 Characterised images for raw coal tailings feed and final concentrate (courtesy QCAT-CSIRO)

The results obtained from several CGA studies with a pilot plant, and other minerals tracking studies by the CSIRO with 9 Australian bituminous coals/tailings, have provided a valuable insight into the separation and recovery performance of the current beneficiation work, by tracking the selective recovery of individual grain types. In particular, this has enabled optimising the milling and flotation steps for processing raw tailings samples.

Overall, CGA has proved a valuable method for applying research in a commercial environment.

Milling/flotation process approach

In order to achieve lower ash levels, a liberation step needs to be introduced by fine grinding. Typically fine grinding for coal water slurry fuels is by ball mills; for example, ball mills are commonly used in China where over 30Mt of slurry fuel is currently produced annually with ash levels below 4%. However, to enable even lower ash contents and maximum liberation (and with a reduced energy consumption), the present work has used bead mills (IsaMills) for both laboratory and pilot scale tests.

Using this mill, a 3 tonne/day pilot-plant, see Figure 3, owned and operated by Glencore Technology (formerly Xstrata) has been used for proving the feasibility of producing ultra-low ash coal from freshly generated raw coal tailings. The plant is sited at Bulga mine, a large thermal coal operation in the Hunter Valley. The pilot plant comprises two Jameson flotation cells, a small IsaMill and a membrane filter press, which can be configured to simulate a number of circuit designs.

Fig. 3 The 3 t/day coal tailings treatment pilot-plant (Courtesy Glencore)

A range of different coal feed types have been tested with raw coal ash contents ranging from ~ 30% feed ash (ad) from easily treated coal seams, to much higher ash coal seams containing difficult-to-separate colloidal clays. The plant is usually configured in a rougher-scavenger circuit where the tailings from the rougher (primary cell) feeds to the scavenger (secondary cell).

The cleaning efficiency of this circuit is clearly shown by the difference in colour of the two product streams in Figure 4 below; the black concentrate is high in vitrinite and the white tailings stream is predominantly kaolinite clay.

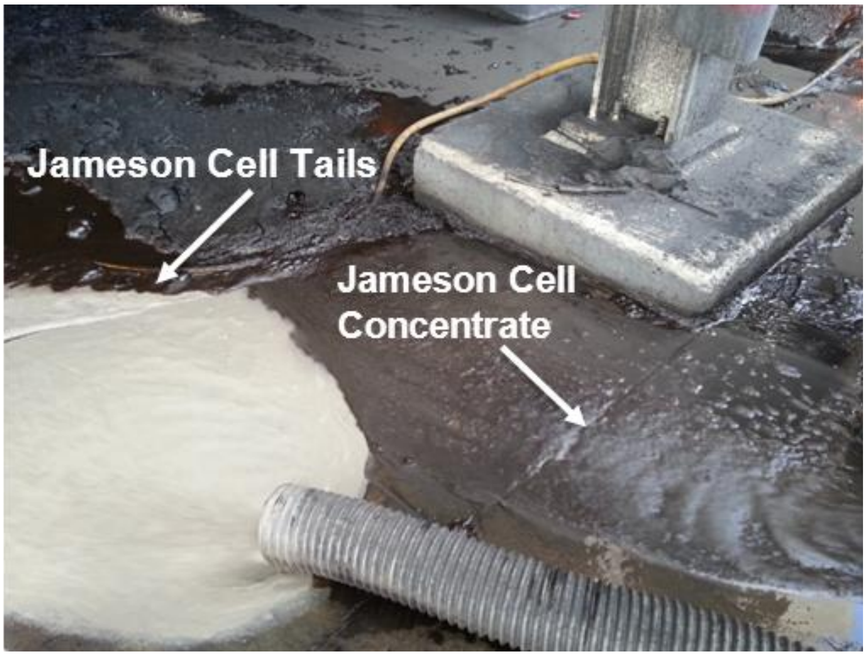

Fig. 4 Concentrate and tailings streams from pilot plant test-work (courtesy Glencore)

A secondary effect of cleaning is a marked improvement in dewatering: Fine mineral matter and clay in a coal concentrate significantly reduces filtration rate and increases product moisture. By removing much of this material, a significant reduction in product moisture can be achieved – essential for metallurgical and briquette products.

Cost effective and efficient dewatering is thus essential to producing premium coal products, for treating both the concentrate and barren tailings streams. Dewatering options available are listed in Table 1. Recent advances in "by zero" fines dewatering has enabled total moistures of flotation product to be reduced to a target whereby it has become commercially viable to include flotation concentrates into the final thermal coal product at a greater number of mine sites. Tailings dewatering still has some challenges, but high-G solid-bowl centrifuges offer promise for on-line dewatering.

Table 1 Equipment Used for Dewatering Coal (adapted from Table 13-1, *The coal handbook*[6])

Equipment	Footprint size	Throughput (t/h dry solids)	Product moisture (% w/w)	Feed preparation	Application
High frequency screen	0.6-2.4 x 3m	10-100 t/h	15-25	cyclone underflow	fine coal
Screen scroll centrifuge	0.5-1.5m dia.	45-100 t/h	11-18	cyclone underflow	fine coal
Horizontal vacuum belt filter	75-150m^2	50-130 t/h	20-30	flocculation	ultrafine coal
Screen bowl centrifuge	1.1m dia. x 3.3 m long	20-60 t/h	16-27	thickening	ultrafine coal
Solid bowl centrifuge	1.1 m dia. x 3.3 m long	15-20 t/h	15-20	thickening	ultrafine coal slimes

[6] Bickert, G. 2013. Solid-separation Technologies for Coal, Chapter 13, The coal handbook; Volume 1; Woodhead Publishing Series in Energy, pp 422 – 444, edited by D. G. Osborne, 2013

Equipment	Footprint size	Throughput (t/h dry solids)	Product moisture (% w/w)	Feed preparation	Application
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	barren tailings
Solid bowl centrifuge	1.1 m dia	20-60 t/h	30-45	thickening	barren tailings
Belt press filter	3-3.5 m wide	10-20 t/h	25-45	thickening /flocculation	barren tailings
Filter press	200-800 m^2	15-30 t/h	14-32	thickening	ultrafine coal & barren tailings

The economic argument for pursuing fines recovery in this application is now very compelling. Technology advances, particularly in dewatering, allow ultrafine product to be included in final product streams without penalising product quality (or introducing handling difficulties) as shown by the simplistic revenue scenario below.

Based on the following assumptions:

- Raw plant feed containing 10% passing 0.1 mm
- Thermal coal operation of 16 Mt/y ROM (1.6 Mt/y of raw feed currently sent to waste)
- Assuming a nominal 50% yield which equates to 0.8 Mt/y of potential saleable product
- At a benchmark price of US$85/product tonne (equivalent to US$69M revenue loss per annum, excluding freight, port, tonnage adjustments, etc.)

Including conservative capital and operating costs produces a reasonably attractive investment opportunity as given in Table 2 below.

Table 2 Economic evaluation of brownfields flotation installation

Capex $M	Operating $/t feed	Coal rate t/h	Direct costs $/t	Tax rate %	Discount rate %	NPV $M	IRR %	Payback years
50	15	230	30	30%	10%	78	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. Glencore Technology has been operating the pilot plant described above for over 4 years, and this plant incorporates the combination of ultra-fine grinding by an Isamill and Jameson Cell flotation technology[7]. The inclusion of a fine grinding stage enables slurries to be prepared whereby mineral components are almost completely liberated from the carbonaceous material, thereby facilitating recovery of a highly concentrated ultrafine, low ash coal product, with ash levels well below traditional inherent ash limits – even from tailings.

This combination has already been proven capable of achieving very good combustible recoveries (material dependent, but normally over 90%) for coal derived from the raw tailings stream. The milling step produces a feed with a d_{80} of 15-30µm, enabling enhanced flotation recovery by a combination of increased liberation and the formation of fresh surfaces on the ultra-fine coal particles. This also reduces reagent consumption to levels significantly below traditional fine coal flotation.

Further enhancement by the addition of improved ultrafine dewatering of the flotation concentrate using a membrane filter press, or equivalent, and appropriate mixing system has resulted in the preparation of ultra-low ash, highly stable slurries with solids concentrations over 60% (w/w). This product should be very suitable for DICE, a potential large new market for a range of power generation markets:

- To replace fuel oil and natural gas,
- To provide highly efficient, highly flexible and modular coal-based power to backup increased renewables (giving an extremely low CO_2 and secure electricity system), and
- For incremental, low CO_2, coal-based generation capacity[8].

In the shorter term, slurries with a slightly coarser particle size distribution (typically with a d_{80} of 75µm) can be prepared in a similar way to create conventional coal-water slurry fuels, at over 70% solids, for direct firing into boilers as a replacement for heavy fuel oil (HFO) and for gasifiers.

Figure 5 below shows a nominal flowsheet based around an Isamill for micronising, and the Jameson Cell for separation. Adding the milling step can be optional for boiler grade product, but is essential for producing MRC for DICE. Various dewatering options, as described earlier, need to be carefully evaluated to achieve the desired solid-liquid outcome for each coal source/product combination. Alternatively, a briquetted product can be included in the normal product stream, thus avoiding slurry or fines related problems in product handling and transportation.

The integrated plant design thus 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 for heavy fuel oil replacement for boilers, or for more innovative, value added applications such as DICE.

To facilitate logistics, and to enable early adoption of the technology, the concept of coal water slurry 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's facility. The use of these systems was been extensively demonstrated in Japan in the 1990s, and more recently in China.

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[7] Mercuri, F., Osborne, D.G. and Young, M; 2014. The Future of Thermal Coal Flotation. Australian Coal Preparation Society conference 2014, Gold Coast, Qld.

[8] Wibberley, L.J. DICE – The best option for coal? Publication on the DICEnet web-site www.dice-net.org http://www.dice-net.org/images/pdf/Media/Papers

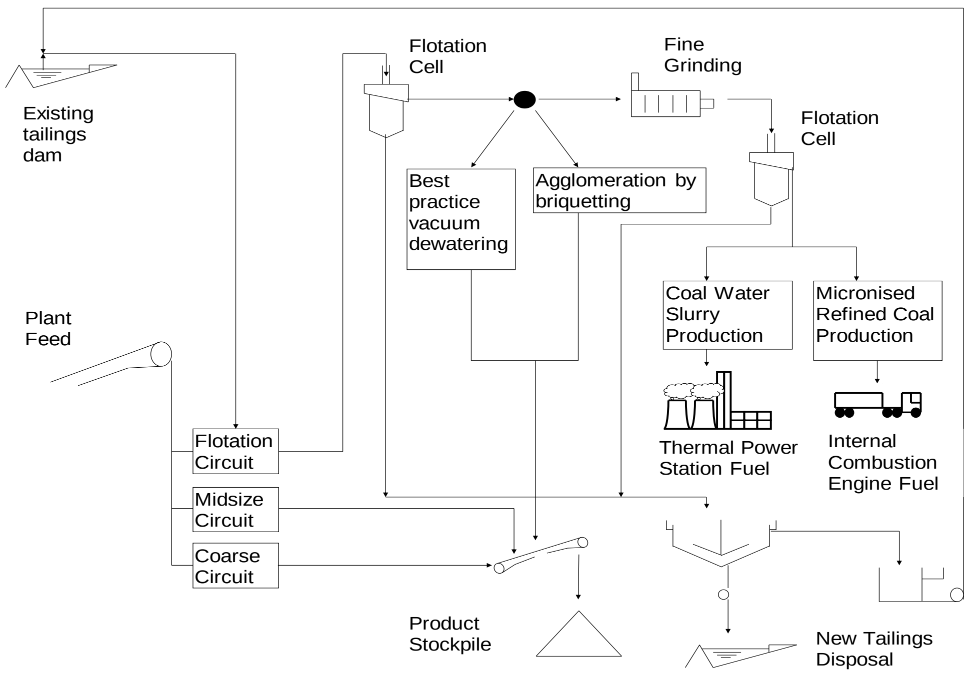

Fig. 5 Alternative fines treatment for thermal coals

Conclusions

For more than two decades the appeal of so-called "deep cleaning" of coal via liberation and subsequent beneficiation has been recognised in terms of the significant downstream improvements that would result - maximised resource recovery, minimised transport and handling costs, numerous end-user process improvements, reduced maintenance and wear, lower environmental impacts and sustainable improvements.

While the capability of ultrafine particle separation has matured via progressive improvements in froth flotation, the capability of dewatering the concentrate has continued to be the major barrier until recently. The emergence of larger capacity membrane filter presses, hyperbaric dewatering via decanter centrifuges or large disc filters now offer commercial solutions.

Binderless briquetting has also progressed to machines with capacities of up to ~40t/h for fine coal applications, and providing an alternative product for conventional transportation infrastructure.

The manufacture of stable coal-water slurries with over 65% solids content, and MRC slurries with over 60% solids content, have also reached commercial adoption; such products can also be produced from tailings.

With these technical barriers now overcome, the scene is set for these new applications to progress to become the new generation of clean coal technologies for a wide range of applications, with key economic drivers being a much higher fuel cycle efficiency (i.e. lower carbon intensity), highest grade recovery, and lowest solid waste disposal.

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