On-Line Coal Slurry Analysis for Flotation Control*

C. J. Clarkson¹, D. T. Hornsby¹ and D. J. Walker²

ABSTRACT

An on-stream coal slurry analyser for both ash and % solids has been developed co-operatively by the Julius Kruttschnitt Mineral Research Centre and the Utah Development Company Limited. An industrial prototype of this unit has been operating successfully at the Peak Downs coal preparation plant since April 1984, and has been used for automatic control of a bank of coarse flotation since January 1985.

This paper will include a brief description of the ASHSCAN coal slurry analyser together with details of its accuracy. An analysis of the limitations of present manual control will precede a discussion of computer control of flotation utilizing the ASHSCAN signals to control cell level and reagent addition. The aim of the control is to use the ash and % solids assays from the feed, concentrate and tailings streams to maintain the concentrate ash at specification ash while maximizing recovery.

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This paper was presented at 78th Mineral Beneficiation Conference, the Research Society of Resources Processing Japan, on June 16-17, 1987, in Tokyo. The presentation was realized by the introduction of Mr. K. W. Bateman, manager of Coal Preparation and Coal Technology, Utah Development Company Limited, Brisbane, Queensland, Australia. There are Mr. Bateman's introductory words regarding the paper as follows;

The attached paper was presented at the Coal Preparation 86 Conference at Lexington, Kentucky by Dr. D. T. Hornsby.

K. W. Bateman was responsible for the establishment of the Utah Research and Development Laboratory in 1979 and is responsible for the overall direction of the laboratory programme. The programme includes a significant effort into the evaluation and development of on-stream analysis techniques for coal slurries and the application of such techniques to the control of coal flotation circuits.

The ASHSCAN coal slurry analyser was developed co-operatively by the Julius Kruttschnitt Mineral Research Centre and Utah Development Company Limited. During the period of development a major input was provided by Dr. C. J. Clarkson and more recently by Dr. D. T. Hornsby. The first prototype analyser was installed at Peak Downs Mine under the supervision of D. J. Walker. Process control strategies were developed and the analyser and control system tested for many months on one loop of the coal flotation circuit. The success was such to give the significant increased coal yield with automatic control over the standard manual flotation control.

It is planned to install such automatic control to the complete Peak Downs coal flotation circuit.

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INTRODUCTION

An industrial prototype of an ASHSCAN coal slurry gauge has been in operation at Peak Downs preparation plant since April 1984. This gauge evolved from the initial unit developed by the Julius Kruttschnitt Mineral Research Centre (1) under a research grant by the Utah Development Company Limited, and has successfully operated for over 5000 hours.

During this time, it has sequentially analysed the feed, concentrate and tailings streams of a bank of 5×8.3 cu.m. Wemco cells for % ash and % solids. Since the beginning of 1985, this flotation bank has operated for extended periods under computer control by applying the gauge output to various control algorithms. Experience to date suggests that a 10% relative improvement in flotation yield can be achieved under computer control while maintaining a more consistent concentrate % ash and % solids.

DESCRIPTION OF PLANT

The flowsheet for the Peak Downs preparation plant is shown in Figure 1. It is a conventional dense medium cyclone/froth flotation plant with the 1/2.mm×0 coal being cyclone deslimed at approximately 70 µm. The overflow and underflow are floated separately in single stage banks of nominally five minutes residence time. The concentrates are flocculated and recombined to feed the disc filters directly without pre-thickening.

Fig. 1 Peak Downs preparation plant flowsheet. Nameplate feed tonnage 1540 tph.
A notable feature of this plant is that because of the high rank (20% volatiles) and friable nature of the coal, the fines represent a significant proportion of the feed (25%) as well as being very rich in vitrinite. Thus efficient operation of the fines circuit is essential to achieve reasonable overall plant recovery and quality. The automatic control is being evaluated on one of four coarse loops of 5 x 8.3 cu.m. Wemco “hogtrough” cells.

DESCRIPTION OF ASHSCAN COAL SLURRY GAUGE

Principles

The theory and design of the original gauge have been described in some detail by Lyman and Chesher (1). A simultaneous measurement of the transmission of $^{137}$Cs (662 keV) and $^{241}$Am (60 keV) gamma radiation is made through fixed path lengths of slurry. The $^{137}$Cs transmission depends solely on the slurry specific gravity while the $^{241}$Am transmission is a function of both the slurry specific gravity and coal ash content. Figure 2 illustrates the layout of the measuring section with the sources and detectors being located so as to minimize cross talk. An alternative source, $^{153}$Gd is presently being trialled and will be discussed later.

Due to the relatively small difference in density between coal and water, entrainment of air within the measuring section has to be eliminated. After preliminary de-aeration in Sala sumps, the slurry is pressurized via a piston pump to approximately 1800 kpa prior to measurement so that any residual air bubbles are collapsed to an insignificant volume, if not fully dissolved. The back pressure is achieved by passing the slurry through approximately 50 m of 12 mm I.D. ABS pipe to ensure no blockages and minimize wear (the ABS is manufactured as an inexpensive, readily replaceable coil).

Physical Layout

Figure 3 shows the overall schematic for the present prototype ASHSCAN unit. Sample

Fig. 2 Layout of gauge measuring section showing location of sources and detectors. All dimensions shown in mm.
by-lines of feed, concentrate and tails each pass approximately 100 lpm to a separate Sala sump with a fourth unit on standby. All four Salas either discharge directly to waste or to a common manifold which in turn feeds the piston pump and gauge section. A relief valve is inserted at the end of the measuring section in case of blockage of the let-down hose (this has not yet occurred). A vezin sampler under computer control is placed on the outlet to ensure accurate calibration sub-sampling.

The whole system is fitted with level, flow and pressure sensors under computer surveillance so that the streams may be cycled through the gauge, together with water, in a predetermined sequence. If a particular stream is unhealthy for any reason (such as plant feed off or sample line blockage), the rig will automatically cycle to the next healthy stream and log an alarm. In the event of a high pressure pump or measurement section failure, the rig will immediately convert to water and shut down in an orderly sequence.

Wear materials such as polyurethane, ceramic, ABS and ni-hard have been extensively tested and utilized in critical wear areas. Major maintenance items now include:

- Piston pump—scheduled overhaul with standby unit. Plungers and valves are replaced after 400 hours operation.
- Letdown hose—ABS letdown coil requires changing after 500 hours operation.
- Salas, valves, etc.—reconditioned every 12 months.

Electrical Layout

Figure 4 illustrates the signal path and logic flow of the % ash and % solids data. The primary NaI (T1) scintillation detectors and associated photomultiplier tubes are housed in sealed, water cooled units. The raw signals are passed through interim pre-amplifiers to multi-channel analysers capable of resolving the spectra into 1024 channels. Two stage gain control involving both the PM
tube and pre-amplifier ensures 24 hour count stability within 0.7% (Table II). Both detectors and MCAs are of the same type as used in the Coalscan coarse coal analysers.

An HP9915 ("counter") microcomputer enters the count rates from appropriate windows of the MCAs, and after a selected counting period (20 to 100 seconds), calculates the % solids and % ash for the particular stream according to predetermined calibration equations. A second HP9915 ("controller") microcomputer controls all the rig functions such as stream monitoring and selection, and communicates the assay data to an HP86 ("supervisory") computer in the preparation plant office. Here the data is displayed, trended, stored and used to control the flotation bank via the appropriate algorithm.

All computers and communication electronics (Opto 22) operate on battery backup to avoid "brown-outs", power surges, and to allow automatic start-up after power failures. The electronics on the rig are located within a sealed cabinet cooled by a solid state heat exchange unit.

Calibration

A concise calibration algorithm has been developed from a theoretical analysis of the gauge assuming thin beam geometry and using order of magnitude analysis to simplify some of the equations (2). A single linear equation describes the ash-solids-photon intensity relationship for each $\gamma$ photon energy over the full range of ash and % solids encountered for flotation feed, concentrate and tailings streams (see Figure 5).

$$\Delta \ln C_s/(S.C.) = a_1 + b_1 A$$  \hspace{1cm} (1) \\
$$\Delta \ln A_m/(S.C.) = a_2 + b_2 A$$  \hspace{1cm} (2)

where $A$=ash fraction, wgt/wgt \\
$S$=solids fraction, wgt/wgt \\
$\Delta \ln C_s, \Delta \ln A_m$=difference between the natural logarithm of the transmitted counts/second for slurry and water for the Cs and Am beams respectively.

$C$=a "correction factor" which is a function of $S$, $A$ and density of coal, $\rho_c$, and ash, $\rho_a$.

$$=1 + S(1-1/\rho_c-(1/\rho_a-1/\rho_c)A)$$  \hspace{1cm} (3)
Fig. 5 Calibration curves for “Ecal” series showing good linear fit for both the Cs and Am counts. The curves are valid for concentrates, feed and tails.

\[ a_1, b_1 = \text{empirically determined calibration constants.} \]

From theory (2), it can be shown that \( a_1 \) and \( a_2 \) are functions of the slurry path length, \( I \), and the physical properties of the carbonaceous material and water (mass attenuation coefficients \( \mu_c \) and \( \mu_w \), and densities \( \rho_c \) and \( \rho_w \) respectively). The parameters, \( b_1 \) and \( b_2 \), depend on the above properties plus those of the ash material, \( \mu_a \) and \( \rho_a \).

An algebraic solution can be derived from equations (1), (2) and (3):

\[
A = \left( a_2 \lnCs - a_1 \ln Am \right) / \left( b_1 \ln Am - b_2 \ln Cs \right) \quad (4)
\]

\[
S = \left\{ \frac{1}{2} \left[ 1 + \frac{4 \ln Am (1 - m_1 - m_2 A)}{(a_2 + b_2 A)^{1/2} - 1} \right] (1 - m_1 - m_2 A) \right\}^{1/2} \quad (5)
\]

where \( m_1 = 1/\rho_c \) and \( m_2 = 1/\rho_a - 1/\rho_c \).

This then allows very rapid calculation of % ash and % solids from the raw signals without resorting to iterative techniques.

For a given coal measure, experience has indicated that \( \rho_w, \rho_c, \rho_a \) and \( \mu_w, \mu_c \) are essentially constant. Thus once the values for \( m_1, m_2, a_1, a_2 \) and \( b_1 \) are empirically derived, they may be held constant. Only \( b_2 \) varies according to ash composition.

Accuracy

Six factors predominantly affect the accuracy:

(i) % Solids. With increasing % solids, there is an increasing amount of material to attenuate the beam and so a better measurement of ash is achieved. This becomes a problem with tailings where the % solids is often 3% or less and very little solids is available to be measured in a fixed

\[ \text{Table I. } \gamma\text{-attenuation coefficients and relevant ratios for elements of interest at different} \]

\[ \text{source strengths} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>( \mu_C ) (6)*</th>
<th>( \mu_{Si} ) (14)</th>
<th>Si/C</th>
<th>( \mu_{Fe} ) (26)</th>
<th>Fe/Si</th>
<th>( \mu_{Ba} ) (56)</th>
<th>Ba/Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd (44 KeV)</td>
<td>.200</td>
<td>.584</td>
<td>2.92</td>
<td>2.90</td>
<td>4.96</td>
<td>21.7</td>
<td>37.2</td>
</tr>
<tr>
<td>Am (60 KeV)</td>
<td>.176</td>
<td>.318</td>
<td>1.81</td>
<td>1.18</td>
<td>3.71</td>
<td>8.69</td>
<td>27.3</td>
</tr>
<tr>
<td>Gd (100 KeV)</td>
<td>.151</td>
<td>.184</td>
<td>1.22</td>
<td>.370</td>
<td>2.01</td>
<td>2.16</td>
<td>11.7</td>
</tr>
<tr>
<td>Co (122 KeV)</td>
<td>.144</td>
<td>.167</td>
<td>1.16</td>
<td>.293</td>
<td>1.75</td>
<td>1.54</td>
<td>9.2</td>
</tr>
<tr>
<td>Cs (660 KeV)</td>
<td>.078</td>
<td>.078</td>
<td>1.00</td>
<td>.074</td>
<td>.95</td>
<td>.077</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* Atomic Number, N in brackets
volume of slurry.

(ii) Ash Composition. From the previous section, the calibration can be seen to depend upon $\mu_a$ (the attenuation coefficient of the ash component). This may vary significantly with atomic number, N (see Table I) and so affect the calibration, especially for low energy beams. The measurement essentially regards the ash as Al and Si (N=13, 14) and the coal as C (N=6). Therefore variable amounts of Fe (N=26) and especially Barium (N=56) can significantly affect $\mu_a$ and hence the calibration.

(iii) Counting Statistics. The process of radioactive decay which provides the initial radiation beam is a totally random event. Therefore a high total count (say $10^6$-$10^7$) is necessary before statistical errors due to this factor alone are rendered insignificant (say <0.5% RMS relative error). This can be achieved by either large source intensities or long counting times.

(iv) Electronic Drift. Changes in countrate can be affected by instability in the pulse counting circuitry. This error is reduced by referring all counts to a periodic water count. This technique, combined with the excellent stability of the MCA system chosen, has meant that error due to electronic drift is minor.

(v) Temperature Variation. Referencing the countrate against periodic water counts also reduces the influence of density changes in the medium induced by temperature fluctuations. In addition it can be shown (2) that because the linear coefficient of expansion of the ABS measuring tube ($10^{-4}/^\circ C$) is similar to the volume coefficient of water ($10^{-4}/^\circ C$ at 11°C) this effect is of relative inconsequence.

(vi) Analytical Errors. There will be sampling and analytical errors associated with the primary vezin sampler on the gauge outlet, sample preparation, and ashing errors.

Table II shows the reproducibility of the gauge on concentrate and tailings samples in closed circuit which should reflect errors in (iii) and (iv). Error due to (iii), (iv) and (v) from long term tests on water (2) is equivalent to less than 0.5% relative RMS error in ash. Table III shows RMS errors from two separate calibration runs. The RMS relative errors illustrate that ash composition variation, especially due to BaO, is the most significant source of error.

**Barium Correction.** Figure 6 shows the relative ash error for each sample from the “Kcal”

| Table II. Reproducibility tests showing countrates and calculated % ash and % solids for water, concentrate and tailings. (N= no. of 100 sec. counting cycles) |
|-----------------|---|---|---|
|                | Am | Cs | % ASH | % SOLIDS |
| WATER (N=1571, open circuit) | 36093 | 23365 | 8.43 | 22.86 |
| Mean            | 36093 | 23365 | 8.43 | 22.86 |
| S. Error (Abs)  | 19  | 16  | .05  | .07   |
| S. Error (Rel), % | .05 | .07 | 1.9  | .8    |
| CONC (N=4, closed circuit) | 25060 | 20408 | 44.73 | 8.02 |
| Mean            | 25060 | 20408 | 44.73 | 8.02 |
| S. Error (Abs)  | 37  | 15  | .24  | .18   |
| S. Error (Rel), % | .15 | .07 | 1.9  | .8    |
| TAILS (N=5, closed circuit) | 27720 | 21134 | 44.73 | 8.02 |
| Mean            | 27720 | 21134 | 44.73 | 8.02 |
| S. Error (Abs)  | 44  | 15  | .25  | .10   |
| S. Error (Rel), % | .16 | .07 | 0.6  | 1.2   |

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Table III. Results of calibration tests for both a typical low Barium series, “Ecal”, and a high Barium series, “Kcal”. Up to 60 samples constitute each calibration run.

<table>
<thead>
<tr>
<th></th>
<th>RMS ERROR</th>
<th>ASH COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% ASH</td>
<td>% SOLIDS</td>
</tr>
<tr>
<td></td>
<td>Abs Rel</td>
<td>Abs Rel</td>
</tr>
<tr>
<td>“Ecal”—low Barium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc</td>
<td>0.2  2.8</td>
<td>0.5  0.8</td>
</tr>
<tr>
<td>Feed</td>
<td>1.5  7.1</td>
<td>0.6  3.3</td>
</tr>
<tr>
<td>Tails</td>
<td>4.4  9.2</td>
<td>0.5  5.2</td>
</tr>
<tr>
<td>Average</td>
<td>2.7  6.9</td>
<td>0.5  3.6</td>
</tr>
<tr>
<td>“Kcal”—high and erratic Barium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc</td>
<td>0.9  7.8</td>
<td>0.4  2.0</td>
</tr>
<tr>
<td>Feed</td>
<td>9.4  32.8</td>
<td>1.5  11.2</td>
</tr>
<tr>
<td>Tails</td>
<td>16.1 22.7</td>
<td>1.1  16.1</td>
</tr>
<tr>
<td>Average</td>
<td>11.0 24.0</td>
<td>1.1  11.5</td>
</tr>
<tr>
<td>“Kcal”—corrected for BaO content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conc</td>
<td>0.7  6.2</td>
<td>0.2  1.7</td>
</tr>
<tr>
<td>Feed</td>
<td>2.1  6.9</td>
<td>0.5  4.6</td>
</tr>
<tr>
<td>Tails</td>
<td>5.6  7.6</td>
<td>0.3  6.1</td>
</tr>
<tr>
<td>Average</td>
<td>3.5  6.9</td>
<td>0.4  4.6</td>
</tr>
</tbody>
</table>

Fig. 6 Relative ash error (compared to 0% BaO in ash) versus BaO content for “Kcal” calibration series.

calibration series versus BaO content in the ash. Whilst not normally regarded as a significant component in coal ash, Ba appears to be a localized but important component in some Bewen Basin measures.

Three avenues have been pursued to minimize the error due to variation in Ba levels.

(i) Measuring the Ba fluorescence peak (32 keV) induced in the slurry. Due to the isotropic nature of the fluorescence combined with its high reabsorbance in the slurry, this proved to be an impractical approach because of the dominant influence of % solids and % ash variations.
(ii) On-line compensation using a third $\gamma$ photon energy. A dual energy $^{153}$Gd source is being trialled in place of the Am source. Due to the different effect of atomic number on attenuation of the primary 100 keV Gd photon peak and the associated 41–48 keV Europium K X-ray peak, separate equations, similar to (2), can be derived for each peak. The three unknowns (ash, solids, % BaO in ash) may be determined from Cs 662 keV, Gd 100 keV and Eu 41–48 keV peaks. To date this approach has shown promise but with present countrates and geometry, statistical noise is too great to allow an immediate on-line correction.

(iii) Autocalibration. Even without on-line compensation for Barium, acceptable results have been obtained in practice by the development of an “autocalibration” algorithm. A shift composite sample is accumulated by collecting a single increment each time a particular stream (usually tailings) is analysed during that shift. Comparison of the laboratory ash with the gauge composite data may then be used to adjust the calibration constants (usually $b_2$) to compensate for long term changes in ash composition. This technique has proven quite suitable for process control, and yields shift composite RMS accuracies of about 0.2% ash for concentrates and 5% ash for tailings.

**DESCRIPTION OF FLOTATION CONTROL HARDWARE**

Figure 7 illustrates the flotation control electronics operated from the HP86 computer in the preparation plant office. Interfacing with field equipment is via an Opto 22 system and inputs include:

1) ash and % solids for all three streams from ASHSCAN;
2) tph signals from feed and filter cake;
3) cell level;
4) reagent addition; and
5) filter level.

Control variables operated from the HP86 include:—

**Cell Level** (via PI control of a dart valve in the tailings box). The cell level input signal to the remote controller can be the signal from either a bubble tube/DP cell transmitter or the MCI $^1$ “Pulp Height-Froth Depth Monitor”.

(a) The bubble tube signal is subject to variations in pulp relative density, which in turn can be affected by both the feed % solids and ash, and probably most importantly, the “free” frother in the system and aeration rate. The latter two affect the degree of bubble hangup in the cell.

(b) The MCI “Pulp Height-Froth Depth Monitor” consists of a number of probes of different length immersed in the cell which, activated by an AC source, discriminate between pulp, froth and air on the basis of conductivity. The signals from the various probes are integrated and two 4–20 mA outputs are generated to yield a “pulp height” and a “froth depth” signal. This pulp height signal, unlike the DP cell measurement, gives an absolute measurement of level which isn’t influenced by variations in feed solids and the degree of bubble hangup.

In conjunction with this signal, the froth depth and DP cell signals (pulp and froth density for a given pulp height) are presently being utilized to develop an on-line measure of reagent status.

**Reagent Addition** (frother and collector) with Clarkson reagent feeders. These were chosen because

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$^1$ MCI—Mineral Control Instrumentation Pty Ltd, Unley, South Australia.
they are reliable, readily adjustable with a remote 4–20 mA signal, and relatively independent of viscosity effects associated with reagent temperature or contamination.

**MANUAL FLOTATION CONTROL**

Present manual control is fairly standard. Diesel at 0.7 kg/tonne is added as collector to the flotation sump prior to classifying to allow two minutes conditioning. Frother (polyglycol) is added at 120 gm/tonne to the flotation feed box. The pulp level is controlled by a pneumatic PI controller which receives a signal from a bubble tube in the third cell and drives a dart valve to regulate release of tailings from the bank.

The basic objective is to maximize yield subject to producing a product at specification ash. Level is the primary adjustment, and the operator has an ash assay of combined flotation tails (6 banks) every two hours. Reagent addition rates are adjusted on a longer term based on testwork and shift composite assays.
Manual Control—illustrates typical position response to variable feed conditions.
Constraints and Problems

There are a variety of constraints restricting the operator from gaining the maximum performance. However, the major problem is that the operator is expected to control a dynamic, variable process virtually by visible impressions alone. Figure 8a, based on ASHSCAN data, illustrates the highly variable nature of the process at times. Two hourly composites of filter cake and tailings for all six banks provide insufficient assistance to the operator during such difficult operating conditions. Specific causes of loss of efficiency include:

a) Variability of feed. The plant is fed a blend of up to four coal types, the proportions of which may vary from hour to hour. Based on ASHSCAN data over a six month period, feed ash may vary from 15% to 40%, feed % solids from 10% to nearly 30%, and surface hydrophobicity from superficially oxidized box-cut coal to easily floating, deep-mined high rank vitrinite. The feed sizing (hence feed % solids) is exacerbated by the degree of rehandle during stockpiling. There is no conditioning/surge capacity prior to the flotation banks apart from the desliming cyclone pump sumps. Figure 8a shows distinct feed % solids peaks associated with the use of dozers on stockpiles.

b) Lack of distinct criteria for good flotation. In the absence of regular short term assays (such as from ASHSCAN), the operator has to rely on "experience" and qualitative criteria such as "colour of tailings". Figure 8b illustrates the variable influence on both concentrates and tailings ash as a result of adjustments to level in the absence of any real information as to how the cell was operating other than appearance.

c) Plant restraints. Each plant has its own unique operating restraints. The Peak Downs plant is confronted with two of particular importance to efficient flotation.

(i) The concentrate is fed directly to the filters without surge capacitance so that any restrictions in filtration rate, depending on coal type, size distribution and concentrate % solids, may necessitate a restriction to flotation recovery.

(ii) If the module that feeds the flotation bank is isolated, then that flotation bank operates on a bleed from the other modules. Flotation feed is then only about 8% solids, which when floating coarse coal, produces a thin froth which makes cell level control extremely difficult.

AUTOMATIC CONTROL - ASHSCAN BASED

Significant advantages in flotation performance can be realized by utilizing the continuous output of assays on all three streams from ASHSCAN (5-10 minute cycle) and implementing simple automatic control algorithms based on level and reagent.

a) Product ash can be controlled to a specific tolerance on a short term basis. Product ash specification is 9.3% and control to within 0.5% ash is usually possible, depending on source of coal. The actual target ash can be determined by balancing incremental ash of slimes and coarse flotation and the coarse dense medium circuit to achieve optimum overall yield (3).

b) The recovery may be maximized by suitable use of level and reagent, subject to the twin constraints of product ash and filter capacity.

c) The qualitative aspects of manual control can largely be eliminated since the system at all times can immediately make an appropriate response to any feed or process changes, based on continual assays.

d) Present reagent addition is determined by long term performance. With the variable nature of
the feed, there are clearly times when present reagent dosages are excessive. By adjusting reagent dosages to instantaneous feed conditions, reagent usage can be optimized, resulting in significant operating savings.

Control Algorithm

Figure 9 is a schematic of the present flotation control algorithm which at present incorporates three tiers of control. This system has been developed on the basis of past flotation testwork and plant experience, and will no doubt continue to evolve as further experience leads to improved optimization.

The basic objective is to maximize the recovery subject to a given concentrate ash specification. To achieve this objective, three broad loops operate;—

Cell Level. The most significant variable affecting flotation performance for a given feed is pulp level in the cell. Variations in this parameter primarily determine the cut-off point between concentrate to product and tailings to waste. If we treat the flotation process as two phases—a clean coal froth (say 7.8% ash and 35% solids) floating on a pulp, then depending on where the level is set, varying mixtures of the two will be recovered.

In practice, this idealized two phase model will be affected by:—

a) no distinct transition point out a gradual change from “dry” well drained concentrate at top, through closely agglomerated, coal-rich bubbles at the interface, to less heavily laden coal-depleted pulp deeper in the cell;

b) total concentrate is recovered from five cells, so depending on relative cell levels, the cutpoints from each cell may be expected to vary. The pulp from cell 1 may be loosely equated to feed (say 25% ash, 11% solids) whereas cell 5 may be equated to tailings (say 70% ash, 4% solids)
Fig. 10  Relationship between concentrate % ash and % solids for varying cell level during fairly steady feed conditions.

with intermediate pulp from cells 2 to 4;

c) due to the large physical dimensions of the cells, effective cutpoints for areas near the outer edge of the cell will be deeper than for areas near the middle from which the froth has to travel considerable horizontal distances and suffer excessive drainage; and

d) dynamic variations due to paddle splashing, etc, will cause cross contamination.

Figure 10 illustrates the relationship between concentrate % solids and % ash for average feed of 25% ash and 11% solids. The line of best fit clearly shows that the pulp which is recovered with the concentrate has been beneficiated (13.5% ash and 15% solids) compared to the feed.

However, the overall effect of variation in pulp level on flotation performance remains the same. When the level is too low, insufficient froth is recovered resulting in low product and tailings ashes at reduced recovery. At too high a cell level, excess pulp is included in the concentrate. Thus high concentrate ash above specification due to inclusion of entrained gangue, and low % solids (say 20%) is fed to the filters. This in turn reduces filter performance and may ultimately exceed the filter capacity.

The optimum is somewhere in between, so the primary loop controls the concentrate ash via cell level, subject to filter capacity (level) not being exceeded. In practice however, limits to concentrate solids are also imposed (e.g. irrespective of concentrate ash, if the froth % solids is above 33% and hence pure froth with no pulp, no further significant reduction in concentrate ash can be achieved by lowering the cell level).

Reagent Addition. The effect of frother is to promote bubble formation and hence mass flow of coal-laden froth into the launder as concentrate. The non-polar collector can have two effects. Firstly it enhances the hydrophobicity of the coal component, and so initially enhances the flotation of the coal. However, excess free collector will associate with the frother and so suppress its frothing capability. Figure 11 illustrates the basis of reagent addition.
Collector. In theory this should be added in proportion to the surface area of the feed. In practice, feed % solids is used in the absence of particle size and mass flow data. (See line 1A in Figure 11). However, the attachment of diesel to the coal is itself a first order reaction akin to the particle/bubble attachment model. Therefore as % solids reduces to zero, the probability of collector/solids attachment reduces accordingly, and so a finite amount of collector is necessary at 0% solids. Thus curve 1A becomes curve 1B in practice.

Frother. Since flotation is fed by a fixed speed pump, to a first approximation, the volume of pulp is fixed and so a constant amount of frother is required to sustain a suitable froth (line 2A, Figure 11). However, in practice line 2B is required with increasing % solids due to both the suppressing action of free diesel on the frother and the loss of frother to concentrate as the recoverable solids is increased.

The project is presently testing the above reagent model and tuning the above curves.

Due to varying requirements for collector for different feed types, a second reagent loop is being implemented. If flotation is operating at the appropriate setpoint and tailings ash or combustibles recovery is still low, then it is quite possible that superficially oxidized coal is present which is known to require substantially increased diesel dosages. In this instance base collector addition will be increased, but again reduced as soon as tailings ash is acceptable (>70% ash).

In addition, both the bubble tube/DP cell and the MCI conductivity probe are being used concurrently, providing information on absolute pulp height, froth depth and pulp and froth density. Present research is aimed at utilizing this information in conjunction with the ASHSCAN signals to provide means of assuring the correct reagent addition.

Plant Transients. The above two loops have been found suitable for maintaining control in the intermediate to long term in response to feed changes. However, at times a more immediate response has been found necessary to maintain control during rapid plant transients such as sudden stopping.
No control for transitions was implemented at this stage.

A novel control strategy (Figure 15) integrates automatic control, thereby ensuring consistent concentration, solids and % ash.

Figure 15

On-line Coal Slurry Analysis for Flotation Control
of plant feed. Possible feed forward control responses include:

a) If plant feed off, immediately stop reagent addition, especially frother to avoid excessive frothing.

b) Adjust cell level according to feed solids or feed tph to anticipate changes in bubble tube response.

A reduction in feed solids means reduced pulp relative density and hence for the same setpoint, the cell level will rise and flood the launders. However, use of the MCI probe tends to reduce this effect.

Comparative Results

Figure 8a shows typical variation under local control. Figure 12a shows typical flotation response under computer control using various elements of the preceding control algorithms. It can clearly be seen that even with variations in feed, the concentrate ash and % solids can be maintained at a steady setpoint. Figure 12b shows how steady operation is maintained by embodying elements of the transient control responses with short periods of “feed off”.

However, the underlying justification for installing a process control system must be to gain extra recovery at the same product specification.

A comparative evaluation of a total of 43 shifts under automatic control were compared with 58 shifts under manual control either immediately before or after. This evaluation quantifies the benefits attributable solely to controlling a single bank. The benefits attributable to overall balancing of a number of parallel banks are not included. Thus the figures quoted may be expected to be conservative compared to the overall benefits that should reasonably accrue from a full plant installation.

Table IV summarises the results achieved during these shifts. Selection of all automatic control shifts attempted during the year were included for statistical completeness subject to the following conditions:

(i) the shift was operated with less than approximately 20% plant downtime;

(ii) no calibration changes were undertaken during the period in question (this would render calculation of meaningful comparative statistics difficult);

(iii) manual shifts were chosen as the eight hour period of useful data nearest to the automatic period, and not greater than 24 operational hours from the auto period. This minimizes the influence of changes in mine planning. Often software or hardware changes were undertaken prior to or just after an auto shift so immediate continuity of data was not possible; and

(iv) all tailings data was corrected according to the corresponding laboratory ash on the cumulative ASHSCAN shift sample. This compensated for changes in calibration, primarily due to ash composition. However, with the large number of shifts evaluated, no relative difference in yield improvements were achieved with either raw gauge data or corrected data. Hence gauge calib-

| Table IV. Total shift averages comparing manual and automatic control for 1985 |
|----------------|----------------|----------------|----------------|----------------|
|               | Total Tonnes  | FEED           | CONC           | TAILS          | YIELD          | COMBUSTIBLES |
|               |               | Ash | Sol | Ash | Sol | Ash | Sol |             | RECOVERY       |
| MANUAL—Average| 710,000       | 25.2| 14.8| 9.2 | 29.1| 52.4| 5.1 | 62.8         | 76.3           |
| —St. Dev.     |              | 4.6 | 3.8 | 1.7 | 5.2 | 13.3| 3.1 | 14.5         | 16.2           |
| AUTO —Average | 450,000       | 26.5| 15.1| 9.9 | 28.1| 62.9| 4.5 | 68.8         | 84.2           |
| —St. Dev.     |              | 4.7 | 3.7 | 1.2 | 3.0 | 9.5 | 3.4 | 8.8          | 7.5            |
| DIFFERENCE    | +1.3          | +0.3| +0.7| -1.0| +10.5| -0.6| +6.0| +7.9         |                |

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ration has no influence on the cost/benefit analysis.

Table IV shows an average increase of 6% yield from 62.8% to 68.8%, corresponding to an increase in tailings ash from 52.4% under manual control to 62.9% under automatic control. Plant shift data show overall plant tailings ash of 57.3% over the same period, although shift data are calculated on a different basis (tonnage averaged, whereas gauge data are yield adjusted as well which produces a lower figure).

To compensate for the difference in average feed ash between manual and automatic, combustibles recovery is a more useful guide, indicating an increase from 76.3% to 84.2% or a 7.9% increase (10.4% relative increase). Applied to full plant recovery where 25% of the feed goes to the fines circuit, the above gains mean an increase of approximately 2% over present product tonnage.

Statistical variations from shift to shift may affect the above data, but it should be noted that the standard deviation of the combustibles recovery reduced from 16.2% for the shifts under local control to 7.5% for the shifts under automatic control. This reflects the more consistent operation under computer control. In addition, the potential development of the control system is far from realized, and so further gains in recovery may be expected.

**FULL PLANT INSTALLATION**

Figure 13 is a schematic of a proposed full plant ASHSCAN installation for both slimes banks and all four coarse banks. It incorporates four separate gauge units, each one dedicated to analysing a specific stream from each bank in sequence (i.e. slimes concentrate, coarse concentrate, feed and tails). It is considered necessary to control each bank from their own separate assays for the following reasons:—

a) level has proven to be such a sensitive parameter (e.g. 3 mm can be a significant change) it would be extremely difficult to achieve optimum performance in all loops based on ash data from one;

b) various loops or partial loops may be out of service at any one time, causing variations in feed between banks;

c) with two slimes banks and four coarse banks feeding three filters, concentrate requirements for each bank may at times vary according to their respective filters; and

d) substantial variations occur in primary feed distribution.

By cycling all the slimes and coarse concentrate streams through separate gauges and all the feed and tails through third and fourth gauges, flushing between sequential streams may be minimized and calibration tuned for a narrow range of slurry properties. This should allow cycle times of approximately two minutes (4 × 30 seconds) for concentrate and 5–7 minutes (8 × 30–50 seconds) for food and tails. This is sufficient to control a process with a residence time of 5–10 minutes.

The siting of the gauges at a lower level than the existing prototype will allow steeply sloping sample lines for all streams, thus minimizing the chance of blockages.

Experience to date and preliminary calculations for such a system based on the preceding recovery gains suggest payback periods are of the order of months and so implementation of on-stream analysis and process control in flotation would appear to be economically feasible.

**CONCLUSIONS**

The extended testing of the ASHSCAN coal slurry analyser over 5000 hours in the Peak Downs preparation plant has proven it to be both sufficiently reliable and accurate to be effective for process control. Initial developments of computer based flotation control have shown distinct improvements in control resulting in a more consistent product, both in ash and % solids, and improvements in relative combustibles recovery of approximately 10%.

There still remains considerable further potential in development of automatic flotation control.
The views expressed are those of the authors and not necessarily those of Utah Development Company Ltd.

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