ESTIMATING LIBERATION IN COALS

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ABSTRACT

The potential usefulness of liberation estimates is discussed and the issues arising from the presence of inherent ash in coal components are considered. The concepts of native ash and native coal and the appropriate corrections to ash assays are introduced prior to presenting a technique for estimating the degree of liberation of both components from the results of washability analyses. If the washability data relates to a separation, the liberation in the products can also be estimated. For generality, the analysis is based on imperfect separations in the first instance and it therefore incorporates a selectivity correction, but this feature suitably ceases to be effective when perfect separations are achieved.

The analysis is presented and illustrated by reference to a typical set of feed washability data, and it is shown that the liberation of native ash is higher than that estimated from the uncorrected ash assays. A range of washability data relating to gravity separations is then analysed and it is shown that a correlation exists between liberation and the yield of free native coal achieved. The variation in liberation with particle size and across the products of separations is then investigated in detail for one separation and it is shown that the liberation is greater at finer particle sizes and varies in accordance with product quality. The size data available from a range of separations is then reviewed and the performance at sizes greater than 250 μm also correlates with the yield of free native coal within the size fractions. Finally, liberation estimates derived from spiral test data are compared with those based on washability analyses and it is concluded that test based estimates are only valid with low grade materials.

Keywords
Coal, liberation, washability.

INTRODUCTION

The structure and liberation characteristics of coals have always been recognized as crucial to the success of both washing treatment and eventual use. The development of a comprehensive system of gravimetric fractionation followed by ashing and chemical analysis has been an essential prerequisite to the design of effective treatment processes and has been mirrored in the procedures adopted in the treatment of iron ores.

The washability data are most frequently presented in the form of plots which reflect the densiometric and analytical structure of the sample, and these provide the coal preparation engineer or metallurgist with a visual appreciation of the properties of the coal and a means for assessing possible separations. However, when a number of separation products and size fractions are involved, the total amount of information that is generated can become formidable and considerable experience is required in order to assimilate and interpret the results. In particular, when assessing the amount of physical processing likely to be needed, it would be of considerable assistance if it were possible to characterise samples of coal according to their degree of liberation.[1] This facility, which the present work is designed to provide, should also be very helpful when presenting comparative data to non-specialist audiences. There will obviously be circumstances when the reduction of a complex structural relationship to a single number will be inappropriate, but the availability of a liberation estimate may still be helpful in interpreting or comparing full analyses.

The main issue to be dealt with in considering liberation in coals is the mutual dissemination of the coal and mineral matter phases. Although this characteristic occurs in many mineral ores, the degree of dissemination is often less pronounced and in those cases it is possible to treat the components as separate entities.[1] In discussing liberation in coals, it will be necessary to draw a distinction between the chemical analyses and the physical entities: in this work the chemical analyses will be referred to as coal and ash and the physical entities as native coal and native ash, the latter terms denoting that inherent ash in the coal and inherent coal in the ash are included in the quantities under consideration. For the purpose of studying liberation, it would be preferable if the analysis of the coal was performed on the basis of quantifying the physical phases present rather than burning the samples and grouping all non-combustible components as ash. In consequence, liberation considerations are isolated to some extent from the original physical structure in current washability testing and coal preparation procedures.

The nature of the problem and the end objective are best illustrated by an example as shown in Fig.1. The top diagram shows the specific gravity fractions determined by a washability analysis (see Table 1), plotted with percent mass on the horizontal axis and native ash and coal contents on the vertical axis. The specific gravities increase from left to right, with the lowest specific gravity fraction being almost entirely composed of native coal (99.1%) and the highest specific gravity fraction being almost entirely composed of native ash (97.1%). The basis for the calculations will be explained in detail later in the paper, but it is clear that the bulk of the native coal is contained in the three left hand fractions (specific gravity < = 1.5) and much of the native ash in the three right hand fractions (specific gravity > 2.0). The fractions between specific gravities of 1.5 and 2.0 contain relatively small amounts of material but significant levels of native ash.

In the formal sense, the only liberated material present is that reporting to the two extreme specific gravity fractions and all other fractions contain locked coal and ash in varying proportions. A separation operating to this definition would need to have a cut point at an specific gravity of 1.3 and a good deal of relatively low ash coal would be rejected, so in practice a higher cut point is usually employed. This makes it possible to adopt a modified definition of liberation that is convenient to calculate and corresponds more closely with typical separation objectives.

The lower diagram in Fig.1 illustrates the liberation structure for this sample calculated by use of the techniques described in this paper. Even a superficial comparison of the relative areas in the upper and lower diagrams suggests that the lower diagram could be approximated by assigning the three left hand fractions in the upper diagram to liberated coal and the three right hand fractions to liberated ash and then making some minor transfers between the central fractions so as to provide the locked components. The overall assessment provides a realistic estimate of the liberation and the purpose of the remainder of this paper is to explain the basic assumptions and illustrate how they are applied.

The basic principles of both the theory and the computations have been described previously[1,2] but only in relation to materials containing discrete and homogenous components. Also, the original analysis dealt with imperfect separations rather than high quality sink-float separations. A coal example was in fact quoted[1] in the original work, but the inherent ash contents of the coal and mineral matter were ignored.

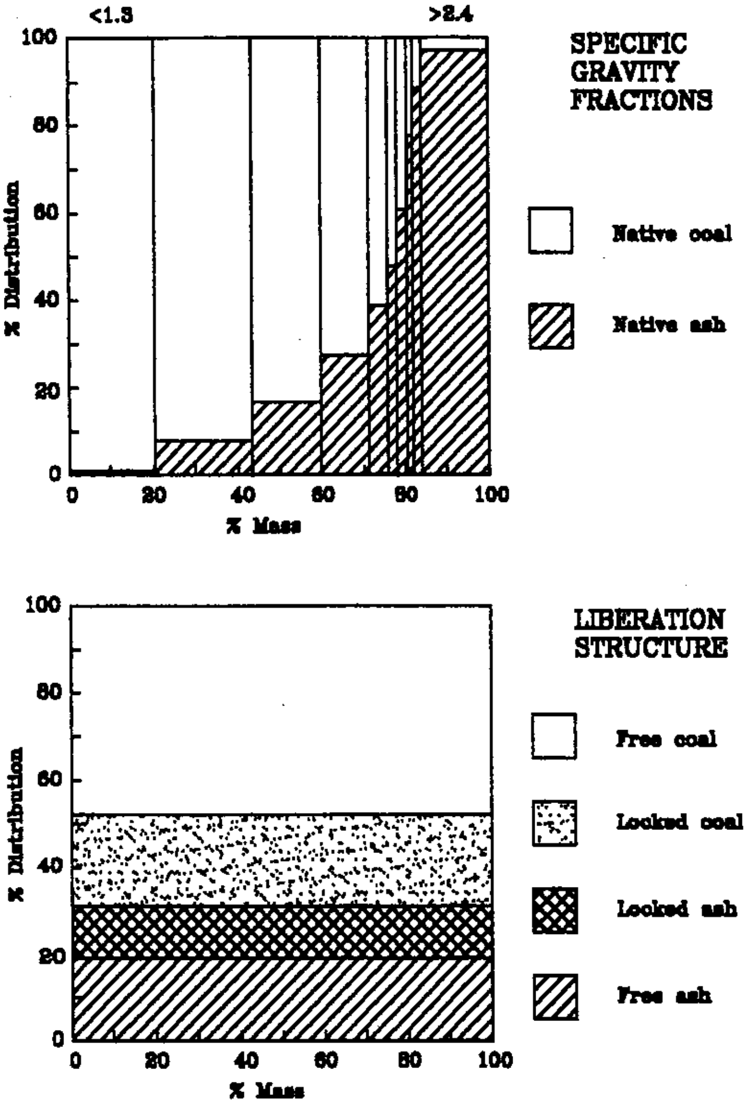


Fig.1 Structure of a coal sample.

In the next section, the relationships between the assayed quantities and the native components are established prior to examining how the liberation of a coal sample is estimated from the washability analysis. A restricted set of data is then used to demonstrate the procedures and then thirty-five sets of data are then examined to determine if the anticipated relationship between liberation and separation performance exists. Following this, the computational basis is expanded to illustrate how liberation varies with particle size and product quality, and the available size based data is then analysed to verify the link with separation performance. Washability data is not always available, and in any case the composition of individual coal samples drawn from a bulk supply can often diverge from the analysis recorded for the bulk sample, so the final portion of the paper examines the issue of obtaining liberation estimates directly from test results when the assay of the locked material is not known.

THEORETICAL BASIS

The relationship between native components and assays

The ash analyses performed on samples provide the total ash content, but in the context of liberation this is of secondary importance to the content of native ash (and native coal) in the sample. To proceed from total ash analyses to the contents of native ash and native coal requires a knowledge of the both the inherent ash content of the native coal and the inherent coal content of the native ash. These parameters can be estimated from the washability plot by determining the interception points of the extrapolated cumulative floats and cumulative sinks curves on the ash axis.

If a sample of total mass M has amounts m_a and m_c of native ash and native coal present, then

$$m_a + m_c = M \tag{1}$$

If the fractional ash assays of the native ash and native coal are i and j ($i \approx 1$ and $j \approx 0$) and the ash assay of the sample as a whole is a, then

Total ash in sample $= aM$

Ash associated with native coal $= jm_c$

Ash in native ash $= aM - jm_c$

Mass of native ash $m_a = \dfrac{aM - jm_c}{i}$

Substituting for m_c from equation 1 and rearranging gives the assay of the sample in terms of native ash as

$$\frac{m_a}{M} = \frac{a - j}{i - j} \tag{2}$$

and the content of native coal in the sample as

$$\frac{m_c}{M} = 1 - \frac{a - j}{i - j} = \frac{i - a}{i - j} \tag{3}$$

These relationships will be employed later in modifying the basic liberation equations.

Liberation in coal samples

The object of the analysis is to determine how much free native ash and free native coal are present in a sample that has been separated into a number of gravity fractions. It will be desirable to be able to apply the findings both to high quality washability analyses and to results obtained from less efficient separations, so the analysis will initially be based on the assumption that there will be some misplacement of components. The impact of this on ideal separations will be discussed later when the necessary equations have been developed.

Considering the cumulative sinks, let x, y, and z represent the units of locked native ash, locked native coal, and free native coal respectively in the cumulated sinks fraction, which represents a mass fraction C of the feed and has a total ash assay c. If the liberation function L is defined to represent the proportion of the total native ash in the sample that has reported to the cumulative sinks in free form, then L is given by

$$L = \frac{Cc - x}{f} \tag{4}$$

where c and f will be taken for now to denote the *native* ash assays of the sinks and feed respectively. If the locked material has an native ash assay of c', then

$$c' = \frac{x}{x + y} \tag{5}$$

By re-arranging equation 5 the amount of locked native coal can be estimated as

$$y = x(\frac{1}{c'} - 1)$$

Also, the free native coal is equal to the difference between the total native coal and the locked amount i.e.

$$z = C(1 - c) - y$$

and on combining these expressions the free native coal is

$$z = C(1 - c) - x(\frac{1}{c'} - 1) \tag{6}$$

The native ash assay extralopated at zero cumulative sinks (c_o) now requires further consideration. This assay is the complement of the *inherent coal content* and in a perfect separation this limiting case represents the composition of fully liberated native ash. In a less precise separation, this assay also reflects the selectivity of the operation or the extent to which free native coal has reported incorrectly. In a washability analysis, the selectivity of the operation is normally perfect at lump sizes and remains high even for fines provided centrifuges are employed where needed, so the dominating contribution comes from the inherent ash content of the mineral matter. Most other types of separation will usually require a selectivity correction and it will be assumed that this is necessary for the purpose of the analysis.

In any even moderately selective process the very first particles of native ash recovered should be liberated rather than locked, so any residual coal content at the zero cumulative sinks point must by definition represent free material. The value of c_o may therefore be defined as

$$c_o = \frac{Cc - x}{Cc - x + z}$$

and on re-arranging the amount of free native coal may be represented as

$$z = (Cc - x)(\frac{1}{c_o} - 1) \tag{7}$$

If z is eliminated between equations 6 and 7 the locked native ash x may be expressed as

$$x = \frac{Cc'(c_o - c)}{(c_o - c')} \qquad (8)$$

If x is now substituted back into equation 4, then on simplifying and re-arranging, the liberation function is given as

$$L = \frac{C(c - c')}{f(1 - c'/c_o)} \qquad (9)$$

The native ash content of the locked material was introduced in equation 5 without discussion, but it is now appropriate to consider this quantity in more detail. If it is assumed that locked material is present in all the specific gravity fractions (which does not contradict the earlier assumption that there is none at the zero mass take point) the ash contents will clearly vary in the same sense as the specific gravity. In a perfect separation *all* the material in the intermediate fractions is locked, though c ' will vary between fractions in accordance with the mean specific gravity. However, even in non-ideal separations most of the locked material should report in the intermediate fractions and when dealing with washability data it is possible to quantify the ash content. If we assume that the intermediate specific gravity range from say 1.5 up to 2.0 will encompass the locked material, then the assay of this material may be determined as

$$c' = \frac{\Sigma \text{ mass x assay}}{\Sigma \text{ mass}} \qquad (10)$$

In order to avoid the introduction of additional symbols, it has been assumed to this point that the analyses represent the content of native ash. In practice they will be total ash assays and it will be necessary to convert them to the native format by use of equation 2. Converting the assays in equation 9 gives L_a as

$$L_a = \frac{C(c - c')(c_o - j)}{(f - j)(c_o - c')} \qquad (11)$$

Following a similar line of argument for the coal component, with C now denoting the cumulative floats, yields the liberation function for the coal as

$$L_c = \frac{C(c' - c)(i - c_o)}{(i - f)(c' - c_o)} \qquad (12)$$

The liberation function L_a is an estimate of how much of the total native ash present has been recovered in liberated form in the cumulative sinks. To determine the *total* liberation, it is merely necessary to determine the value of L_a when all the free material has been recovered. It will be helpful to consider for a moment the form of the function as defined in equation 4, which equates it to the total native ash in the cumulative sinks less the locked amount. If the symbols R_T and R_L are adopted to represent the recoveries of total and locked native ash, equation 4 can be re-written as

$$L = R_T - R_L \qquad (13)$$

Clearly, at the start of the separation $C = 1$ and R_T and R_L are zero, hence $L = 0$. When $C = 1$, R_T and R_L are equal to unity and again $L = 0$. At intermediate values of C, R_T will rise faster than R_L and L will attain a positive value, so the liberation function rises from zero to a maximum and diminishes again to zero. As will now be shown, the maximum value of L_a represents the liberation of the total sample.

To locate the maximum in the function, it is merely necessary to differentiate equation 13 and equate to zero

$$\frac{dL}{dC} = \frac{dR_T}{dC} - \frac{dR_L}{dC} = 0 \qquad (14)$$

and at this point the recovery rates of total and locked native ash are the same: i.e. all liberated material has been recovered.

The procedure to determine the degree of liberation is therefore to carry out a separation that provides a number of incremental products, to analyse the products for ash and then to calculate the liberation function for the cumulative products. By plotting or numerical curve fitting, the degree of liberation is then estimated by determining the value of the maximum in the liberation function. The maxima in the liberation functions for ash and coal will in general not yield the same liberation values: the only exception is when the inherent ash assays are not known and have to be assumed equal to zero for the coal and 100% for the non-combustibles respectively, and the ash content of the locked material is also unknown and is assumed equal to the feed level. This special set of circumstances only arises when estimating liberations from test results in the absence of washability data and the implications will be considered in more detail in the final portion of the paper.

APPLICATIONS

Calculating the liberation function

Standard procedures are followed in calculating the cumulative ash content (c) and mass fraction (C) for the floats and sinks. For full precision, these quantities are graphed against each other and the initial assay (c_0) determined by extrapolation to zero mass. If the standard washability graphs have been prepared, this step can be performed on the cumulative floats and sinks curves. For convenience, the assay of the lowest gravity fraction can be employed instead with a small reduction in accuracy. The cumulative liberation functions for the native ash and the native coal are then calculated from equations 11 and 12 and plotted against the cumulative sinks and floats, and the respective degrees of liberation determined as the maxima in the liberation functions. Alternatively, the maxima can often be determined with acceptable precision by inspecting the tabulated values of the functions.

A worked example is provided in Table 1 and Figures 1-3, based on the assumption that the locked material reports to the specific gravity range between 1.5 and 2.0. The upper diagram in Fig.1 shows the information available from the original washability data and the lower diagram shows the further information provided by the liberation analysis. The washability data and the liberation analysis is given in Table 1, with the ash analysis based on the cumulative sinks in the upper part and the coal analysis based on the cumulative floats in the lower part. On inspecting the values of the liberation functions for both native components, it is clear that the two components exhibit different degrees of liberation, with 61.3% of the native ash liberated and 69.3% of the native coal.

A standard washability plot for the sample is shown in Fig.2 and the graphical determination of the liberation of the native coal has been illustrated in Fig.3. The inherent ash in the mineral matter was determined from the graph to be 90.4% and the inherent ash in the coal 1.9%. The maximum value of 69.3% recorded in the plot and in Table 1 for the liberation function represents the liberation of the native coal in the sample. If the standard ash assays had been employed directly in equation 12 (see Table 1) the liberation estimate would have been 66.3%. This relatively small divergence from the more accurate value could vary over a wider range with different levels of inherent ash and coal in the components of the coal. (It will be shown later in the paper that the effect of failing to include the inherent ash in the calculations is to reduce the liberation estimates by absolute amounts ranging from 5% to 8%.)

Table 1 Washability data for total feed solids

Relative	Individual fractions					Cumulative sinks			Libn.	Function
Density	Mass	Assay	Native	%Distribution		Mass	Assay	Native	Ash	Native
Fractions	(%)	%Ash	%Ash	Ash	Native	%	%Ash	%Ash	%	%
S2.4	15.88	86.54	95.64	46.73	48.86	15.88	86.54	95.64	45.48	47.59
F2.4 S2.2	2.18	79.25	87.40	5.87	6.13	18.06	85.66	94.64	50.85	53.22
F2.2 S2.0	1.56	69.97	76.92	3.71	3.86	19.62	84.41	93.23	53.91	56.42
F2.0 S1.8	2.48	55.36	60.41	4.67	4.82	22.10	81.15	89.55	56.80	59.45
F1.8 S1.7	2.11	44.25	47.85	3.17	3.25	24.21	77.94	85.92	57.98	60.69
F1.7 S1.6	4.68	36.21	38.77	5.76	5.84	28.89	71.18	78.28	58.56	61.29
F1.6 S1.5	11.43	26.50	27.80	10.30	10.22	40.32	58.51	63.97	53.91	56.42
F1.5 S1.4	16.31	17.25	17.34	9.57	9.10	56.63	46.63	50.54	39.07	40.89
F1.4 S1.5	22.93	9.71	8.82	7.57	6.51	79.56	35.99	38.52	8.78	9.19
F1.3	20.44	3.80	2.15	2.64	1.41	100.00	29.41	31.08	0.00	0.00
Feed	100.00	29.41	31.08	100.00	100.00	-	-	-	-	-

Inherent ash in native coal = 1.90   Locked %Ash = 33.96
Inherent ash in native ash = 90.40   Locked native = 36.23
%Ash at zero sinks = 90.40
%Native ash at zero sinks = 100.00

Relative	Individual fractions					Cumulative floats			Libn.	Function
Density	Mass	Assay	Native	%Distribution		Mass	Assay	Native	Coal	Native
Fractions	(%)	%Coal	%Coal	Coal	Native	%	%Coal	%Coal	%	%
F1.3	20.44	96.20	97.85	27.86	29.02	20.44	96.20	97.85	26.72	27.90
F1.4 S1.5	22.93	90.29	91.18	29.33	30.34	43.37	93.08	94.32	50.83	53.07
F1.5 S1.4	16.31	82.75	82.66	19.12	19.56	59.68	90.25	91.13	62.64	65.40
F1.6 S1.5	11.43	73.50	72.20	11.90	11.98	71.11	87.56	88.09	66.34	69.26
F1.7 S1.6	4.68	63.79	61.23	4.23	4.16	75.79	86.09	86.43	65.88	68.79
F1.8 S1.7	2.11	55.75	52.15	1.67	1.60	77.90	85.27	85.50	64.94	67.81
F2.0 S1.8	2.48	44.64	39.59	1.57	1.42	80.38	84.02	84.09	62.64	65.40
F2.2 S2.0	1.56	30.03	23.08	0.66	0.52	81.94	82.99	82.93	60.21	62.86
F2.4 S2.2	2.18	20.75	12.60	0.64	0.40	84.12	81.38	81.10	55.93	58.39
S2.4	15.88	13.46	4.36	3.03	1.01	100.00	70.59	68.92	0.00	0.00
Feed	100.00	70.59	68.92	100.00	100.00	-	-	-	-	-

Inherent coal in native ash = 9.60   Locked %Coal = 66.04
Inherent coal in native coal = 98.10   Locked native = 63.77
%Coal at zero floats = 98.10
%Native coal at zero floats = 100.00

It was assumed for the purpose of the analysis that a selectivity correction c_0 was required: if the definition of c_0 is examined in relation to equation 9, it is clear that as the separation tends towards perfection, c_0 tends to unity and at the limit it ceases to influence the value of the liberation function. The introduction of this parameter has therefore not produced any bias in the assessments of washability data, but does in principle permit the analysis of data derived from less selective separations.

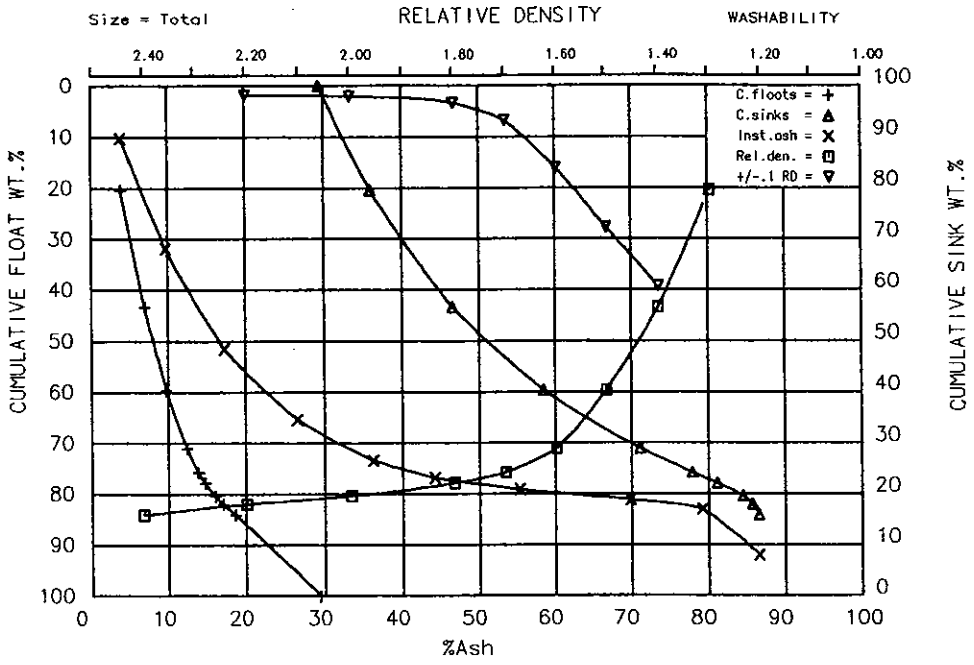


Fig.2 Washability analysis for feed to an LD4 spiral test.

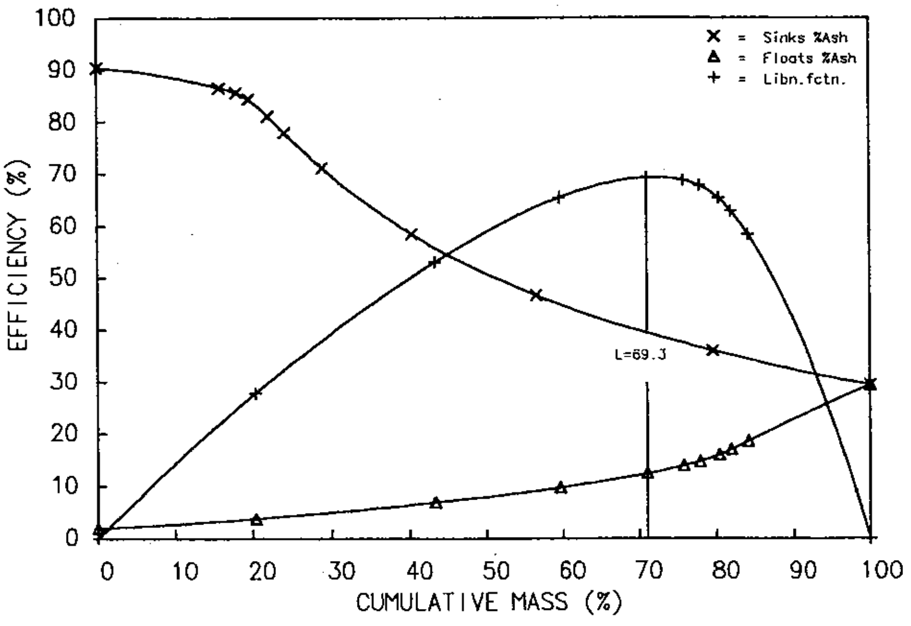


Fig.3 Liberation plot for the washability analysis shown in Fig.2.

Liberation by size

One of the main aims of comminution is to enhance the liberation of the material and the basic improvement created at finer sizes is often artificially enhanced by further breakage of material already liberated at coarser sizes. A trend to increased liberation at progressively finer sizes is to be anticipated, possibly obscured at very fine sizes by the difficulties in achieving adequate separation even with centrifuging. The data shown in the previous example related to the total solids in a feed sample, but the same techniques can be applied both to individual size fractions and to the products from separations to examine how liberation varies with particle size. If there are a number of products and size fractions this becomes computation intensive and the optimum approach is to devise a computer program to perform the task and display the results (see appendix). The procedures in carrying out the calculations remain unchanged, but in dealing with an individual size fraction within the products from a separation, parameters such as the assay of the locked material and the inherent ash content are based entirely on the data for that size fraction. By way of illustration, a full set of washability data for a spiral test has been analysed in the manner just described and the liberation data is summarised in Table 2. The column headed R.D. value provides the specific gravity at which the maximum in the liberation function was recorded: as noted earlier, at this point all liberated material has been grouped with the cumulative product. This value also demonstrates the extent to which the ideal liberation definition (requiring an R.D. value of 1.3) has been altered. The following three columns display the composition of the cumulative product and the residue and the final column shows the liberation.

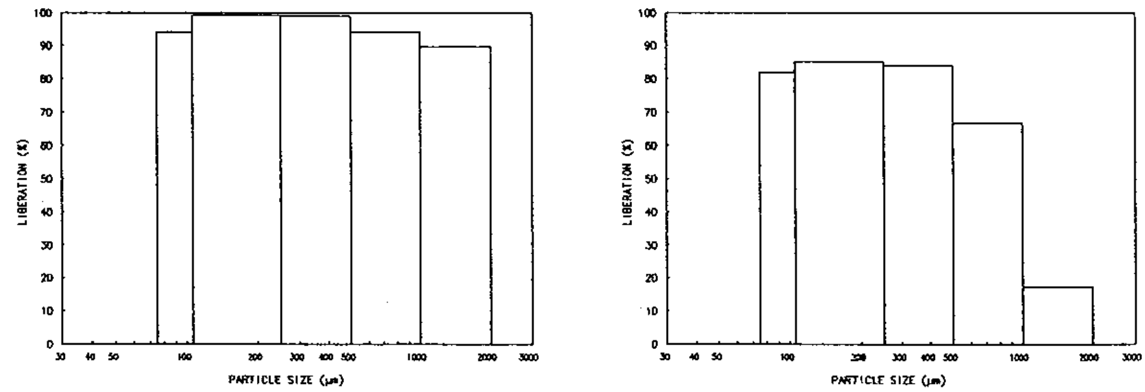
Table 2 Liberation by size (LD4 spiral test)

Product	Size	Inherent ash		Feed	Locked	R.D.	SG<R.D.		SG>R.D.	Coal
	Limit	Refuse	Coal	Assay	Assay	Val.	Yield	Assay	Assay	Libn
	µm	%Ash	%Ash	%Ash	%Ash	(-)	(%)	%Ash	%Ash	%
Coal	1000	85.03	1.70	12.22	23.02	1.589	98.78	6.11	38.85	89.67
	500	75.00	1.20	11.34	22.68	1.597	99.33	5.11	42.10	94.17
	250	75.00	1.20	12.16	23.62	1.602	99.32	4.60	47.76	98.95
	106	71.49	1.10	14.02	19.49	1.542	96.82	4.13	44.89	99.06
	75	71.41	1.00	18.03	21.13	1.601	91.52	5.42	63.10	94.20
	Total	71.14	1.18	12.73	16.95	1.478	96.31	4.38	31.95	91.96
Middling	1000	76.25	1.50	12.22	16.29	1.423	23.11	6.80	53.58	17.31
	500	71.23	1.20	11.34	38.49	1.671	72.56	9.12	54.37	66.82
	250	69.75	1.10	12.16	34.90	1.632	85.11	6.90	54.87	84.04
	106	72.11	1.05	14.02	33.33	1.628	81.35	5.65	63.10	85.34
	75	72.12	1.05	18.03	30.54	1.642	73.21	5.40	68.05	81.99
	Total	72.53	1.09	12.73	35.51	1.642	80.91	6.63	59.10	81.10
Refuse	1000	76.10	1.90	12.22	73.37	2.231	9.91	56.00	75.57	2.80
	500	73.70	1.85	11.34	71.43	2.500	45.22	65.55	76.62	4.40
	250	77.03	1.25	12.16	66.51	2.231	10.90	36.40	71.50	5.88
	106	79.63	1.25	14.02	57.85	2.054	15.30	11.90	72.37	14.84
	75	75.58	1.25	18.03	49.54	1.872	21.75	7.50	73.90	24.46
	Total	77.26	1.26	12.73	64.11	2.222	13.14	27.33	72.40	9.06
Feed	1000	79.06	1.70	12.22	34.97	1.615	90.42	6.33	67.83	90.09
	500	77.99	1.20	11.34	34.45	1.610	90.26	5.32	67.10	91.10
	250	76.73	1.19	12.16	32.42	1.602	88.19	4.88	66.50	90.97
	106	76.87	1.10	14.02	32.60	1.624	85.25	4.59	68.56	91.39
	75	74.30	1.01	18.03	27.98	1.613	80.28	5.46	69.18	87.32
	Total	76.84	1.17	12.73	32.93	1.610	87.58	4.96	67.53	91.04

The liberations have been plotted against size to a logarithmic scale in Fig.4 and it can be seen that the liberation generally increases with diminishing particle size, with very high levels being recorded at fine sizes in the coal product. The middlings show lower liberations with a rapid fall off at coarser sizes and the refuse has very little liberated coal present. The overall liberation in the feed was estimated at 91%, which is considerably higher than the first example (Table 1, Fig.3). The washability curves for the total feed solids are shown in Fig.5 and on examining the shapes of the curves and the locations of the plateaux according to the categories proposed by Whitmore[2] and comparing them with the curves in Fig.2, the first coal would be rather more difficult to wash than the second. The liberation estimates are therefore in accord with the classifications of the coals.

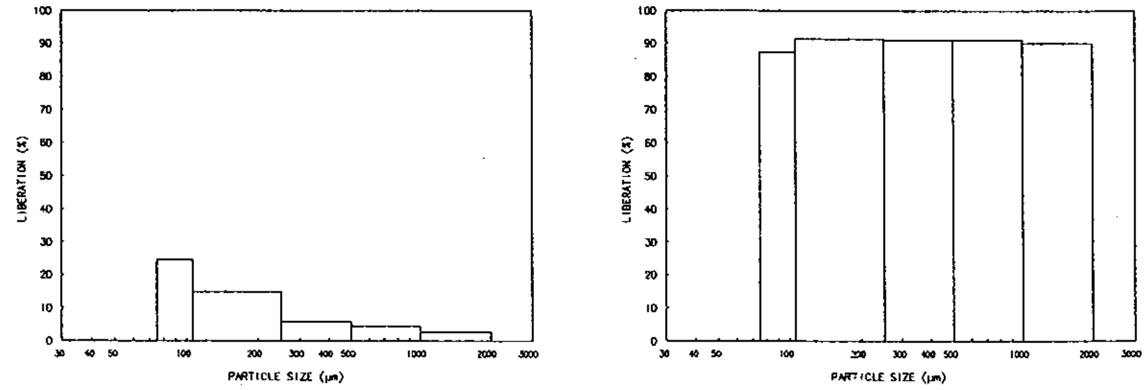
The effect of liberation on separation behaviour

It was pointed out in the introduction that the main application for liberation estimates would be in characterising coal samples according to their likely response to treatment: in particular, there should be a definite correlation between the recovery of the native components in the products from a separation and the degree of liberation existing in the feed to the separation.



(a) Product.

(b) Middlings.



(c) Refuse.

(d) Feed.

Fig.4 Liberation in feed and products for an LD4 spiral test.

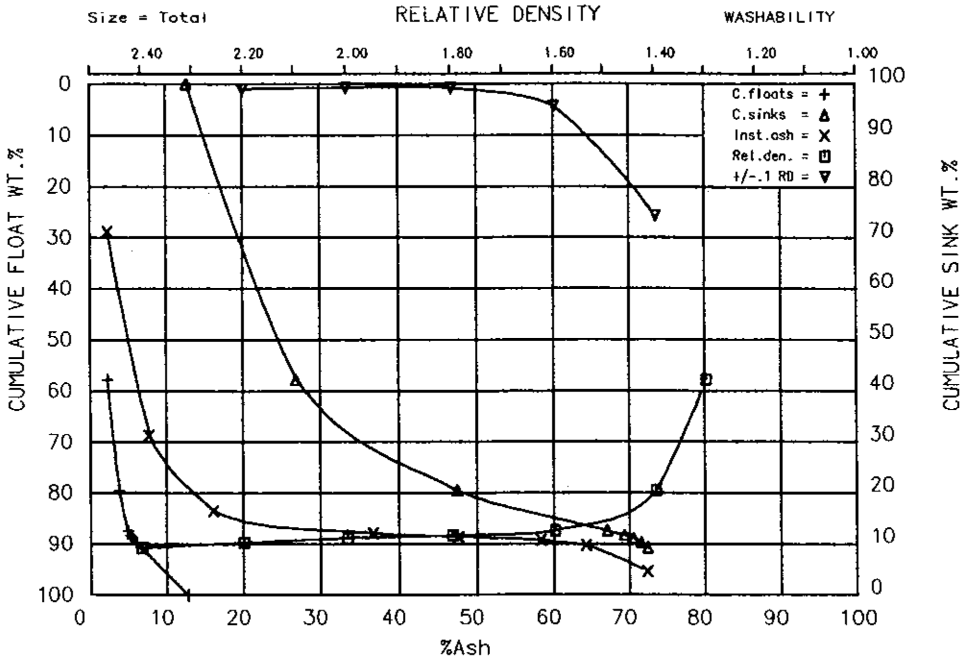


Fig.5 Feed washability for LD4 spiral test.

In order to investigate this effect, company records spanning fifteen years of coal testing were reviewed and all reliable test records that included full washability analyses were analysed. The search yielded thirty-five sets of data covering three types of gravity separator (Table 3), of which twelve included size by size data (Table 4). The data were analysed by use of the techniques already described and it was assumed that the locked material reported to the specific gravity range from 1.5 up to 2.0. In a few cases the analysis terminated at a specific gravity of 1.8 and this was of necessity adopted as the upper limit.

Total sample liberations

The coal liberations were estimated both in native form and in standard form neglecting the inherent ash contents (Table 3). The data have been identified by type of separator and the feed characteristics have been grouped in the left hand portion of the table. The single point labelled S/F relates to an experimental sink/float separation employing media which yielded a lower quality of separation than usual. The liberation calculations are presented in the central portion of the table and the performance achieved in the tests is summarised in the three right hand columns. The yield (mass recovery to coal product) and ash analysis are shown together with the calculated mass yield of free native coal. In order to determine the latter quantity, it is necessary to correct the total coal yield by assuming that any ash content in excess of the inherent level is due to the presence of locked material and to deduct this amount from the total. If the fractional mass yield to coal product is denoted by C and it has an ash content c which exceeds the inherent ash content j of the coal, then the mass m of locked coal present in the product may be defined in terms of the relationship

$$(C - m).j + m.c' = C.c \tag{15}$$

and the yield of free native coal Y_c which is equal to $C - m$ may be derived as

$$Y_c = \frac{C(c' - c)}{(c' - j)} \tag{16}$$

The example considered earlier showed that omitting the inherent ash from the calculations reduced the estimated coal liberation by 3%. This effect has been investigated in more detail by plotting the two forms of liberation estimate against each other in Fig.6 with the ash liberations on the vertical axis and the native ash liberations on the horizontal axis. The overall effect is somewhat greater than was found previously, the absolute reduction in the liberation estimate varying from a maximum of 8% at 60% liberation to a low of 5% at 100% liberation. A solid line based on full equality has been included together with the dashed line corresponding to the result of a linear regression analysis and it can be seen that there is a high degree of correlation between the two sets of data ($R^2=0.97$) with minimal scatter but some bias present. The existence of a bias is not necessarily a major concern if it is consistent, as it should be in the case of a series of comparative tests on samples of the same coal type. The scatter introduced by neglecting the inherent ash and coal in the simplified approach is limited in the data sets examined here: however, it could increase if a wider range of inherent ash values was encountered and it will in general be safer to employ the more accurate approach.

The influence on separations of an improvement in the liberation should be to increase the yield of free native coal achieved in the coal product. The results shown in Table 3 have been investigated by plotting the estimated yield of free native coal in the product against the liberation of native coal in the feed (Fig.7). A strong trend towards greater yields is evident as the liberation increases, the effect having been roughly quantified by carrying out a linear regression analysis plotted as a dashed line on the figure. There is considerable scatter about the trend line ($R^2=0.77$) but this is a superficial analysis that has been included purely for illustrative purposes. There are several different coal spirals involved and other strong influences such as feed rate that affect the separation behavior on spirals have been excluded. The dominant influence exerted by the feed rate has already been established in a much larger survey reported recently.[4] The experimental sink/float separation was included to verify that the analysis is valid for alternative separation techniques.

Liberations within size fractions

The size by size data were processed in the same manner as the total solids and the results are reported in a similar format in Table 4. The effect of omitting the inherent ash from the calculations has been illustrated in Fig.8 and the results are similar to those for the total solids, but with the scatter increasing as the particle size diminishes.

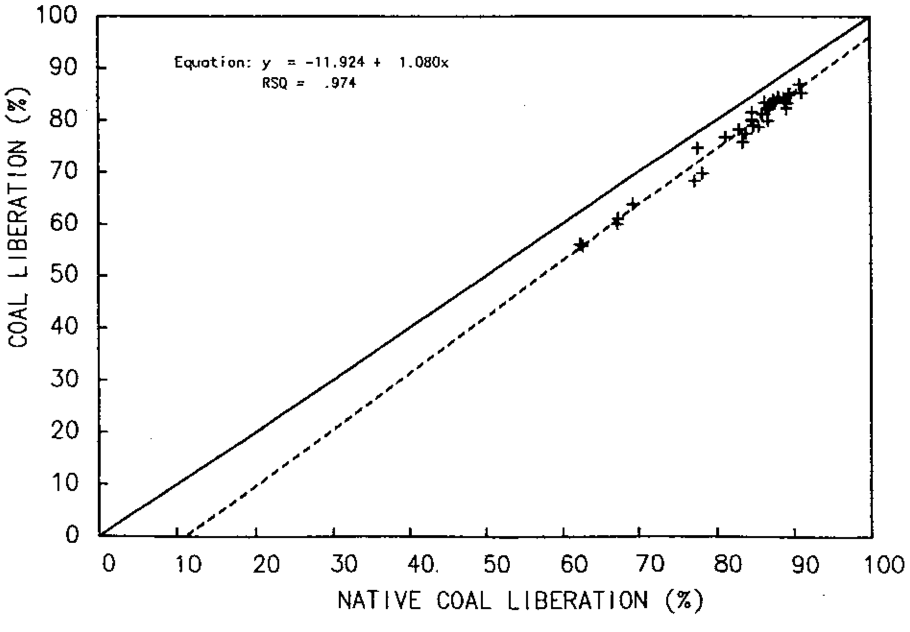


Fig.6 Coal liberations for total samples compared with native coal liberations.

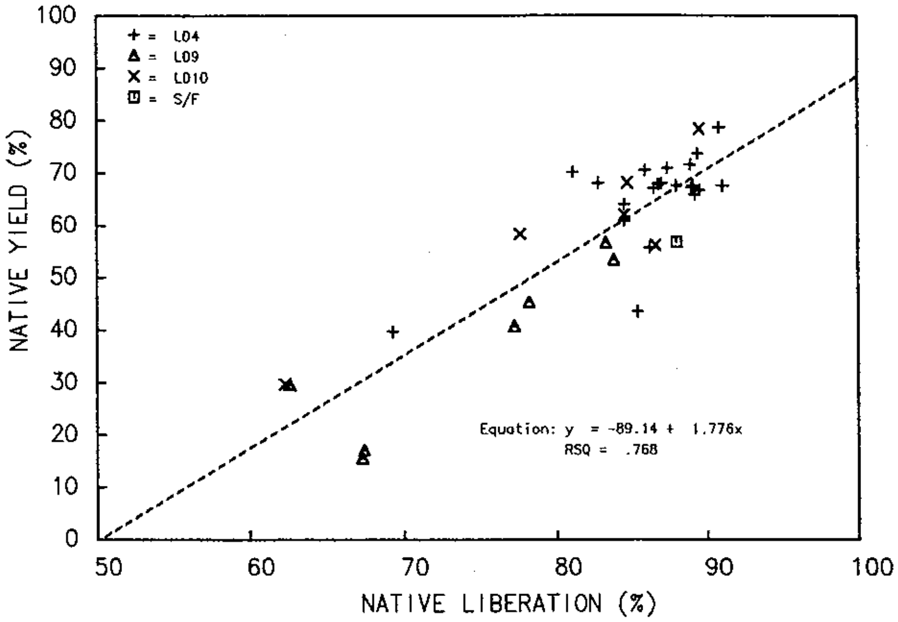


Fig.7 The effect of liberation on the yield of native coal achieved in spiral tests.

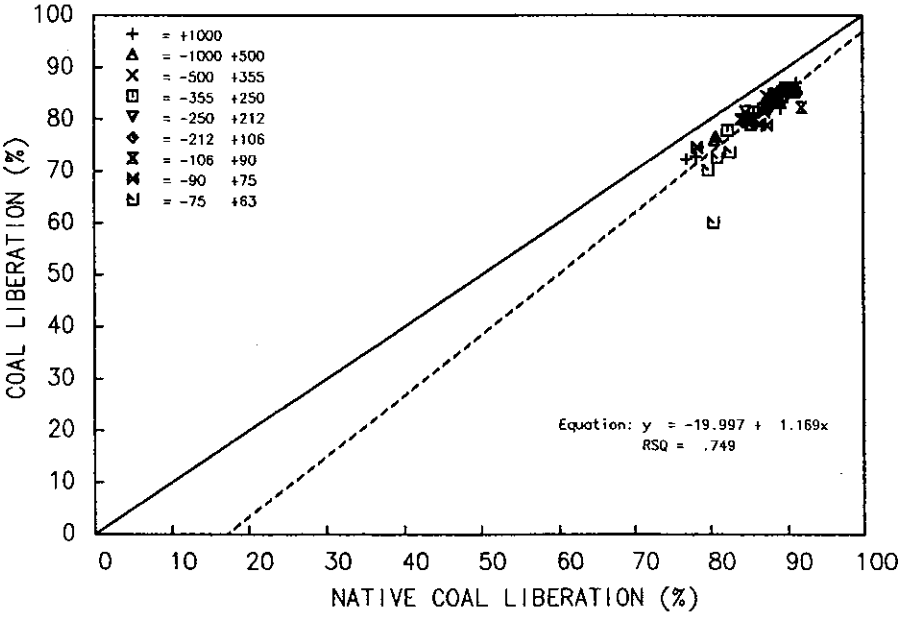


Fig.8 Coal liberations for size fractions compared with native coal liberations.

The correlation between liberation and yield of native coal has been investigated in Fig.9, and at coarser sizes a trend to increasing yields at higher liberations is evident. At 250 μm the trend has virtually disappeared and at particle sizes below 250 μm there is no clear trend and considerable scatter is present. This is due to the poor selectivity displayed by spiral separators as the inertia of the particles diminishes with decreasing particle size and fluid forces overwhelm the gravity effect.

Liberations from test data

On occasion, feed washability analyses are not available for test samples and liberation estimates must then be derived from the test results. If the tests are carried out on gravity separators, the principles employed are the same as in the washability analyses, but the selectivity is reduced and liberation assessments must incorporate an appropriate correction. A related problem is that the inherent ash levels are not known and the selectivity correction term c_o therefore includes the effects of both inherent ash and imperfect separation performance. A final and major difficulty is that the grade of the locked material is unknown: this problem was dealt with in mineral applications by assuming that the locked material would have the same assay as the feed and good correlations were obtained with both release analyses and the results of a multi-stage gravity separation on a coal sample[1]. From a practical point of view, it is also important to note that the friable nature of most coals leads to rapid degradation when fines are recirculated in test rigs and this can also have a substantial effect on the quality of the separation.

In view of these considerations, the accuracy of liberation estimates derived from gravity tests will be greatly diminished relative to those based on washability studies and it is clearly important to establish the extent to which this occurs. In order to eliminate errors due to choice of computational technique, the liberations for the total samples have been estimated both from the washability data and the test results assuming that locked material is at feed grade and employing uncorrected assays (Table 5). When the two sets of estimates are plotted against each other (Fig.10), a correlation is found ($R^2=0.60$) but considerable bias and scatter are present, the deviations reflecting the difference in precision between gravimetric analysis and spiral separations.

Table 3 Coal liberation estimates for total samples

Spiral	Feed	Inherent ash		Locked		Floats		Sinks	%Liberation		Coal prdt.		Native
type	%Ash	Coal	Refuse	%Ash	RD	Yield	%Ash	%Ash	Native	Coal	Yield	%Ash	Yield
LD9	20.4	3.5	92.2	33.1	1.623	82.0	8.7	73.5	83.3	75.8	72.2	9.9	56.7
LD9	21.5	2.3	85.2	40.5	1.666	78.7	9.2	66.9	83.8	77.4	73.6	12.8	53.4
LD9	31.7	2.3	85.1	42.4	1.669	69.8	13.4	73.9	78.2	69.8	65.9	14.8	45.4
LD9	34.4	2.3	85.2	43.1	1.684	66.1	13.9	74.4	77.2	68.3	58.8	14.8	40.8
LD9	42.1	2.7	90.6	41.7	1.699	56.5	17.8	73.5	62.6	55.8	61.3	22.8	29.6
LD9	53.1	1.6	94.0	38.6	1.701	42.6	12.7	83.2	67.4	61.0	40.0	22.8	17.1
LD9	56.8	1.6	94.0	36.2	1.669	38.1	11.6	84.7	67.3	60.0	40.0	22.8	15.5
LD10	9.0	1.2	79.4	32.1	1.621	95.0	5.9	67.8	89.5	85.2	93.8	6.3	78.4
LD10	16.2	2.1	81.8	40.7	1.645	82.2	7.9	54.1	84.7	78.9	92.8	12.3	68.1
LD10	18.8	1.0	93.1	31.8	1.612	85.1	9.2	73.5	77.6	74.6	87.3	11.2	58.4
LD10	21.1	0.9	93.2	36.0	1.688	81.3	7.5	80.1	84.5	81.5	81.1	9.2	62.0
LD10	27.1	1.9	87.1	40.4	1.706	71.4	7.5	76.1	86.6	79.8	70.2	9.5	56.2
LD10	43.2	1.5	90.5	40.1	1.678	52.6	15.8	73.6	62.3	56.1	57.8	20.2	29.7
LD4	8.7	0.7	82.4	33.5	1.609	95.6	6.8	48.6	86.2	83.4	67.0	6.3	55.7
LD4	9.1	0.9	78.4	22.3	1.590	93.9	5.7	60.0	81.1	76.7	95.5	6.5	70.1
LD4	10.1	0.8	77.8	23.9	1.600	92.9	5.8	66.4	82.8	78.2	94.1	7.2	68.1
LD4	10.9	1.1	81.1	37.5	1.638	91.8	5.9	67.4	90.8	86.9	93.9	7.0	78.7
LD4	11.6	2.5	80.1	42.6	1.606	95.6	9.7	53.0	88.9	83.5	89.0	10.3	71.6
LD4	11.9	1.1	80.9	31.2	1.616	89.6	5.2	69.9	89.5	84.8	78.2	5.5	66.7
LD4	12.4	0.8	78.7	29.3	1.601	89.9	6.1	68.6	85.9	81.2	90.7	7.1	70.5
LD4	12.7	1.2	76.8	32.9	1.610	87.6	5.0	67.5	91.0	85.2	77.9	5.4	67.5
LD4	12.8	1.1	83.1	37.4	1.647	89.6	6.4	68.5	89.4	85.2	93.0	8.7	73.7
LD4	13.4	0.7	80.1	30.5	1.600	88.5	6.0	69.9	86.5	82.0	88.9	8.0	67.1
LD4	13.5	2.1	83.4	43.7	1.639	93.3	10.4	56.1	86.8	82.1	87.0	11.3	67.8
LD4	14.5	1.4	89.4	35.1	1.623	87.7	6.6	70.8	87.0	83.2	90.9	9.8	68.0
LD4	15.9	1.3	89.5	39.0	1.697	86.7	7.1	73.6	88.0	84.4	91.9	11.2	67.6
LD4	16.3	1.2	89.7	39.2	1.631	85.3	7.0	70.7	87.4	83.9	87.8	8.6	70.9
LD4	16.8	1.1	88.4	29.9	1.601	82.9	5.9	70.0	84.5	80.1	80.9	7.2	64.0
LD4	16.9	2.0	89.8	37.3	1.656	84.5	6.4	74.0	89.0	84.2	89.3	10.7	67.2
LD4	17.5	1.7	79.4	38.3	1.652	82.2	6.7	67.5	89.1	82.2	77.9	6.5	67.6
LD4	18.7	1.2	81.6	40.2	1.644	82.6	7.3	72.9	89.2	83.2	85.8	10.3	65.8
LD4	19.4	2.5	89.0	46.4	1.702	86.1	11.8	66.8	84.5	79.8	78.6	12.5	60.8
LD4	23.0	0.8	81.9	35.5	1.652	76.8	7.5	74.2	85.4	78.7	52.1	6.6	43.5
LD4	29.4	1.9	90.4	34.0	1.610	71.7	12.6	72.0	69.3	63.8	65.5	14.5	39.7
S/F	9.1	1.3	81.8	36.3	1.633	96.2	7.4	52.3	88.0	84.2	67.0	6.6	56.8

It was earlier demonstrated that the influence on separations of an improvement in the liberation is to increase the yield of free native coal in the coal product. A similar effect is visible for the test based estimates when the estimated yield of free coal is plotted against the liberation in the feed (Fig.11), but the overall trend is weak ($R^2=0.40$) due to a couple of anomalous results for the LD9 spiral which relate to tests conducted at very high feed ash contents (>50%). This aspect will be discussed in more detail, but if the effects of differing spirals and high feed assays are eliminated by restricting the analysis to the LD4 spiral, the correlation improves considerably with the R^2 value rising to 0.83. These results indicate that the use of the feed assay as an measure of the grade of the locked material provides a self-consistent set of data for low to medium feed assays but generates erratic results with high feed assays.

Table 4 Coal liberation estimates for size fractions

Spiral	Size	Feed	Inherent ash		Locked	Rel.	Floats		Sinks	%Liberation		Coal prdt.		Native
type	(μm)	%Ash	Coal	Refuse	%Ash	Dens.	Yield	%Ash	%Ash	Native	Coal	Yield	%Ash	Yield
LD10	1000	7.7	1.4	81.2	31.7	1.603	97.3	6.2	61.8	88.9	84.9	98.5	6.7	81.2
	500	8.7	1.2	79.4	32.5	1.618	95.3	5.8	67.1	89.8	85.7	95.2	6.0	80.4
	250	10.5	1.0	78.5	32.9	1.621	92.1	5.5	68.6	90.2	85.8	85.0	5.6	72.6
	106	15.1	0.9	79.8	31.3	1.637	85.4	5.3	72.3	88.9	83.4	79.2	6.3	65.1
LD10	355	13.9	1.0	91.0	37.2	1.682	89.5	7.0	73.3	87.3	84.5	90.2	7.5	73.9
	212	20.2	0.8	92.1	36.7	1.696	82.1	7.6	78.2	84.6	81.6	79.6	8.1	63.6
	75	35.2	0.9	94.8	34.0	1.685	65.3	8.8	84.8	78.3	74.6	66.1	14.8	38.3
LD4	1000	8.2	1.2	84.1	20.3	1.577	95.2	6.1	48.0	76.9	72.3	98.1	7.0	68.3
	500	8.4	0.9	77.6	21.6	1.585	94.6	5.7	55.5	80.5	76.0	96.7	6.4	71.0
	250	9.7	0.8	78.6	23.4	1.598	93.3	5.7	65.0	82.2	77.9	94.2	6.6	69.9
	75	12.5	0.7	77.2	26.7	1.600	89.1	5.7	68.4	85.2	80.2	91.1	8.7	63.1
LD4	1000	10.7	1.1	80.2	36.6	1.621	92.0	5.7	68.0	91.2	87.0	94.6	6.9	79.2
	500	10.6	1.0	89.6	21.3	1.470	86.6	4.4	50.4	80.7	76.7	94.1	6.6	68.2
	250	11.5	1.1	84.0	37.5	1.641	91.2	6.2	66.5	89.7	86.1	93.2	7.4	76.9
	75	18.8	1.4	85.5	37.0	1.666	82.7	8.1	70.1	84.7	79.6	90.4	14.2	58.0
LD4	1000	10.8	1.3	81.6	23.1	1.596	93.5	7.0	64.6	78.1	72.8	95.3	7.8	67.0
	500	12.0	0.8	79.6	28.6	1.600	90.7	6.3	67.8	84.8	80.4	92.2	7.1	71.5
	250	12.9	0.7	78.2	29.9	1.603	89.0	5.9	69.3	86.9	82.1	89.1	7.0	69.7
	75	15.4	0.6	81.8	32.6	1.604	85.6	5.8	72.3	87.5	83.1	85.0	10.0	60.0
LD4	1000	12.2	1.7	79.1	35.0	1.615	90.4	6.3	67.8	90.1	84.4	89.5	6.5	76.5
	500	11.3	1.2	78.0	34.4	1.610	90.3	5.3	67.1	91.1	86.1	86.0	5.4	75.2
	250	12.2	1.2	76.7	32.4	1.602	88.2	4.9	66.5	91.0	85.3	77.0	4.9	67.9
	106	14.0	1.1	76.9	32.6	1.624	85.3	4.6	68.6	91.4	85.2	72.0	5.4	62.1
	75	18.0	1.0	74.3	28.0	1.613	80.3	5.5	69.2	87.3	78.8	70.9	10.3	46.5
LD4	1000	13.5	1.5	81.3	35.4	1.638	89.4	7.0	68.8	88.1	82.9	85.9	7.0	71.8
	500	10.7	1.1	76.0	30.6	1.604	91.2	5.5	65.1	89.0	83.8	85.5	5.4	73.0
	250	11.3	1.2	80.6	30.0	1.621	90.6	5.2	69.2	89.2	84.3	78.1	5.1	67.5
	106	13.0	1.1	82.9	32.8	1.640	88.2	4.9	73.8	90.8	86.2	72.6	5.7	62.0
	75	16.3	1.2	84.2	28.4	1.685	84.0	5.3	73.4	87.0	81.4	72.3	8.9	51.7
LD4	1000	15.6	1.6	88.9	39.9	1.627	86.2	6.6	71.4	89.1	85.1	88.6	7.9	74.0
	500	15.2	1.1	89.0	38.2	1.615	86.5	6.8	69.1	87.3	83.9	89.5	8.2	72.3
	250	18.0	1.1	83.1	40.1	1.644	83.1	7.1	71.5	88.4	83.3	85.1	9.2	67.3
	75	27.8	1.3	84.5	42.4	1.735	72.9	9.2	77.8	86.4	79.1	78.3	17.8	46.8
LD4	1000	17.5	1.7	79.4	38.3	1.652	82.2	6.7	67.5	89.1	82.2	77.9	6.5	67.6
	500	11.7	1.2	88.1	38.5	1.637	91.4	6.4	68.4	89.5	86.3	93.6	7.7	77.4
	250	14.6	1.2	89.3	36.4	1.666	87.3	6.3	72.0	88.1	84.6	94.4	11.2	67.7
	90	22.8	1.6	90.3	37.5	1.753	78.6	8.0	77.4	84.9	80.2	84.7	14.8	53.4
	63	38.4	8.5	91.6	62.6	1.536	66.7	20.6	74.1	80.9	72.6	70.5	31.9	40.1
LD4	500	12.5	1.3	87.6	38.4	1.657	90.4	6.5	68.4	89.3	85.8	92.4	7.9	75.8
	250	13.2	1.0	88.6	34.9	1.651	88.6	5.8	70.3	88.2	84.9	89.6	7.4	72.7
	90	15.7	1.7	90.6	31.7	1.601	85.0	5.8	72.4	87.3	82.5	91.7	12.2	59.5
	63	34.7	18.7	91.4	50.1	1.428	73.7	23.4	66.2	80.4	60.1	83.7	29.8	54.2
LD4	500	13.2	1.5	88.1	35.8	1.627	89.4	6.6	69.1	88.1	84.0	92.0	8.2	74.2
	250	14.5	1.6	89.7	36.6	1.659	87.2	5.9	72.4	89.4	85.4	93.8	10.7	69.4
	90	31.5	4.0	90.4	39.9	1.547	63.4	4.4	78.4	91.9	82.3	68.3	15.1	47.2
	63	38.4	5.5	92.2	48.3	1.538	60.9	12.3	79.0	82.6	73.7	61.5	28.5	28.5
LD4	500	15.1	2.0	84.8	31.0	1.604	85.9	6.8	66.0	85.2	79.0	86.4	7.3	70.5
	250	15.6	1.1	88.0	30.5	1.611	84.6	5.7	70.2	85.6	81.5	82.7	6.2	68.3
	90	19.0	0.9	89.7	28.6	1.609	79.6	5.3	72.5	84.0	80.0	74.9	7.8	56.2
	63	27.2	4.1	91.4	31.9	1.548	70.4	8.7	71.1	79.7	70.2	77.3	17.6	39.7

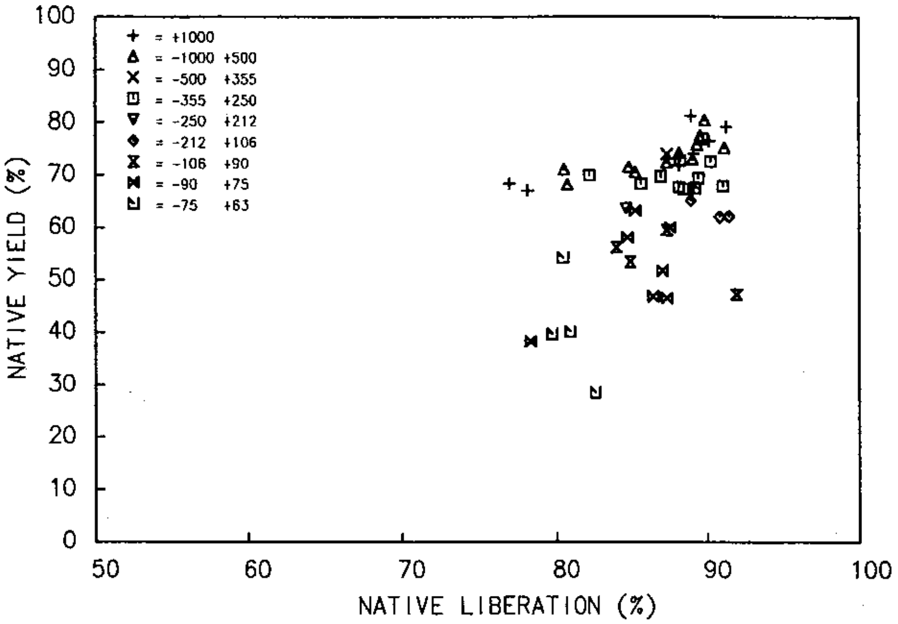


Fig.9 The effect of liberation on the yield of native coal in various size fractions achieved in spiral tests.

Table 5 Coal liberation estimates, locked at feed assay

Spiral	Feed	Inherent ash		Liberations		Coal product		Free
Type	Assay	Coal	Refuse	Wash.	Test	Yield	Assay	Coal
(-)	%Ash	%Ash	%Ash	%	%	%	%Ash	Yield
LD9	20.4	3.5	92.2	60.8	52.1	72.2	9.9	37.2
LD9	21.5	2.3	85.2	61.0	42.5	73.6	12.8	29.8
LD9	31.7	2.3	85.1	60.2	61.8	65.9	14.8	35.1
LD9	34.4	2.3	85.2	60.9	65.1	58.8	14.8	33.5
LD9	42.1	2.7	90.6	56.2	60.5	61.3	22.8	28.1
LD9	53.1	1.6	94.0	70.3	72.3	40.0	22.8	22.8
LD9	56.8	1.6	94.0	72.0	73.9	40.0	22.8	23.9
LD10	9.0	1.2	79.4	47.3	39.3	93.8	6.3	28.1
LD10	16.2	2.1	81.8	59.0	34.8	92.8	12.3	22.3
LD10	18.8	1.0	93.1	56.0	47.1	87.3	11.2	35.3
LD10	21.1	0.9	93.2	68.7	61.1	81.1	9.2	45.7
LD10	27.2	1.9	87.1	71.8	72.1	70.2	9.5	45.6
LD10	43.2	1.5	90.5	58.8	67.6	57.8	20.2	30.8
LD4	8.7	0.7	82.4	40.6	27.9	67.0	6.3	18.5
LD4	9.1	0.9	78.4	51.2	39.2	95.5	6.5	27.3
LD4	10.1	0.8	77.8	54.8	39.0	94.1	7.2	27.0
LD4	10.9	1.1	81.1	60.8	45.6	93.9	7.0	33.6
LD4	11.6	2.5	80.1	45.7	20.2	89.0	10.3	10.0
LD4	11.9	1.1	80.9	61.4	54.2	78.2	5.5	42.1
LD4	12.4	0.8	78.7	57.8	48.9	90.7	7.1	38.8
LD4	12.7	1.2	76.8	63.9	56.2	77.9	5.4	44.8
LD4	12.8	1.1	83.1	62.6	42.2	93.0	8.7	29.8
LD4	13.4	0.7	80.1	60.4	45.7	88.9	8.0	35.8
LD4	13.5	2.1	83.4	49.3	25.5	87.0	11.3	14.2
LD4	14.5	1.4	89.4	61.5	42.7	90.9	9.8	29.5
LD4	15.9	1.3	89.5	63.6	40.7	91.9	11.2	27.2
LD4	16.3	1.2	89.7	64.9	53.9	87.8	8.6	41.5
LD4	16.8	1.1	88.4	66.8	61.2	80.9	7.2	46.2
LD4	16.9	2.0	89.8	66.5	46.1	89.3	10.7	32.8
LD4	17.5	1.7	79.4	63.3	65.1	77.9	6.5	49.0
LD4	18.7	1.2	81.6	66.7	51.8	85.8	10.3	38.5
LD4	19.4	2.5	89.0	55.9	41.2	78.6	12.5	28.0
LD4	23.0	0.8	81.9	68.3	69.9	52.1	6.6	37.1
LD4	29.4	1.9	90.4	58.2	57.6	65.5	14.5	33.2
S/F	9.1	1.3	81.8	39.1	27.6	67.0	6.6	18.4

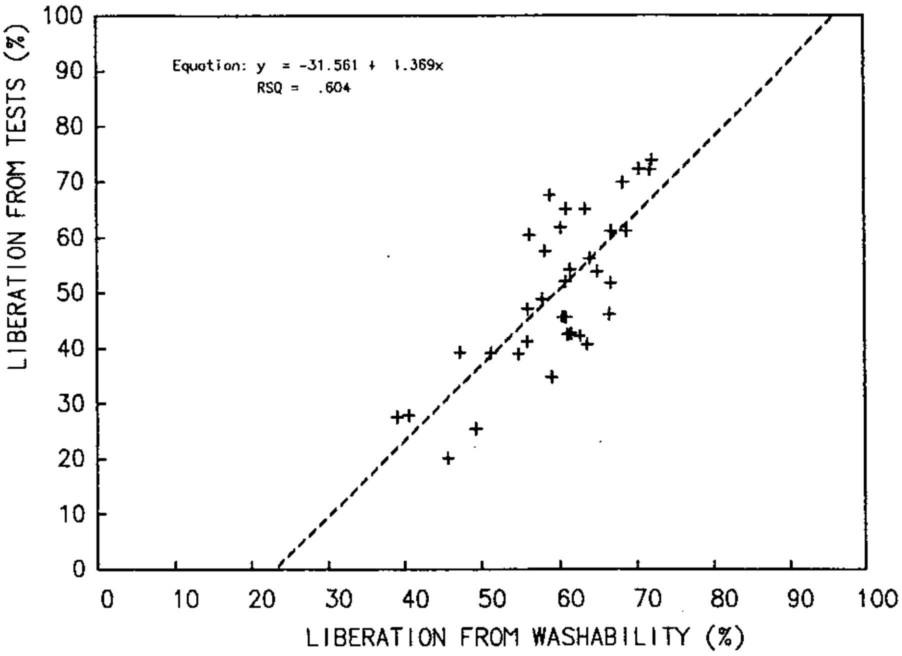


Fig.10 Liberations based on test data compared with those based on washability data.

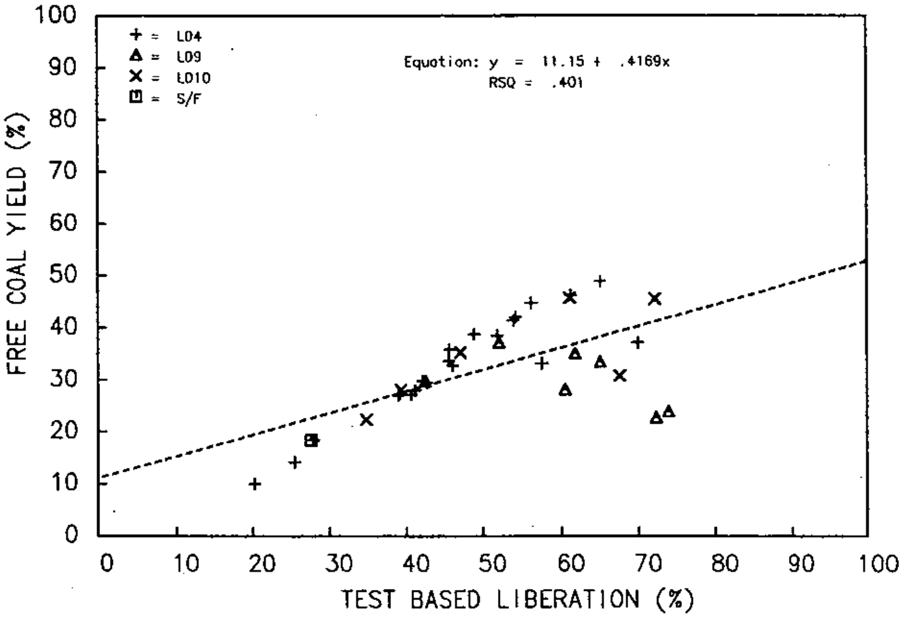


Fig.11 The effect of liberation on the yield of coal achieved in spiral tests.

As a definitive check on the validity of the test based approach, the results were compared with the coal liberation estimates shown in Table 3 (i.e. neglecting the inherent ash but using the measured assay for the locked material). A good correlation was not expected, but in fact no satisfactory relationship could be established between the two sets of estimates. The basis of the two approaches was then checked by plotting the assays of the locked material against those of the feed (Fig.12) and it is clear that there is no effective correlation ($R^2 = 0.133$). It is possible that the use of a fixed specific gravity interval to characterise the locked material was not appropriate for all the washability based calculations, but the main reason why the two approaches yield incompatible results must be the assumption that the locked material in the test samples is at feed grade.

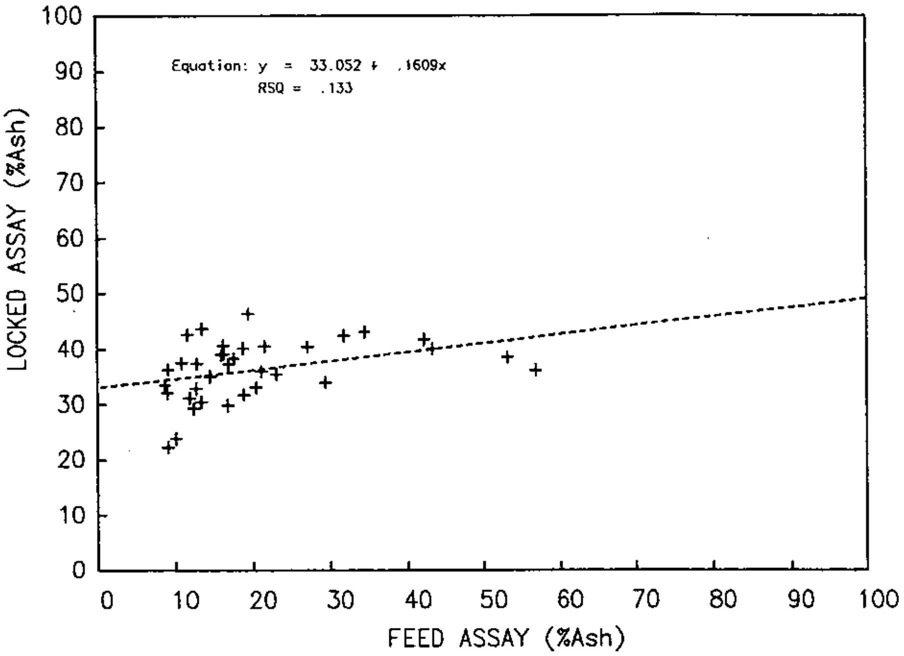


Fig.12 Locked assay versus feed assay.

This finding contradicts the excellent agreement found between the liberation estimates derived from test data and those obtained by use of other techniques in mineral applications[1], but on reviewing these earlier examples it was found that most of them related to low grade feeds.

If equation 9 is examined, when c' is put equal to f and c_0 is relatively large compared with f, then the liberation function simplifies to the form

$$L = R - C \qquad (17)$$

where R denotes the cumulative recovery of the component of interest and C the cumulative mass recovery. Even in the event that c' is significantly different from f, if both values are small and c_0 remains large compared with f, the recovery term should dominate and the error introduced would then be small. This would explain the success achieved in the earlier work with the test based approach and would also account for the failure at higher feed grades.

It is clear that the use of test data to estimate liberations in the absence of information regarding the grade of the locked material will only be valid with low grade feeds or where comparative studies are being undertaken on the same bulk material. In the latter case, liberations will be ranked in the correct order despite absolute errors introduced by employing an incorrect grade for the locked material. A cautionary feature of the test based approach that has been identified is that even where the assumption that the locked material is at feed grade fails, the comparisons can produce apparently well-correlated sets of data. A recent study of the effect of feed rate on the performance of coal spirals[4] illustrates this effect because surprisingly high significances for the liberation variable were found and it was incorporated into the predictive equations. The findings from the present work do not invalidate the equations developed as part of the study, but the liberation variable should be regarded as a useful predictive component rather than a true measure of liberation.

Generally speaking, in order to obtain accurate liberation estimates it will be necessary to determine the grade of the locked material by some form of direct analysis. This may be by use of imprecise separation techniques applied in a repetitive manner or by performing full washability-type analyses. When dealing with coal data it will be advisable to employ the most accurate form of data analysis by including the inherent ash assays and dealing with the native components.

SUMMARY

The methods of interpretation presented in this paper are designed to provide estimates of the degree of liberation from the results of incremental separations of varying precision. The recommended approach provides practical estimates that are relevant to typical separation conditions and, in the case of washability analyses, modifies the formal definition of liberation to increase otherwise artificially low estimates. The procedures take account of the partial dissemination of the phases in coals and can be applied to separations exhibiting a range of selectivities. The selectivity correction introduced to compensate for imperfect separation does not prejudice the interpretation of washability analyses because the effect diminishes as the quality of the separation improves. If the inherent ash and coal contents are excluded from the calculations, the liberation estimates for the total samples contain a bias towards lower values but with minimal additional scatter. When considering individual size fractions, the same effect is identifiable at coarser sizes but the scatter became excessive at sizes finer than 250 μm.

By applying the techniques described, it has been shown that the variations in liberation that occur across a range of separation products and particle sizes generally agree with the anticipated behaviour, with the coal liberation increasing at finer particle sizes and diminishing from coal product through middlings to the refuse product. Studies based on a wider range of data have also shown that the total yield of free native coal obtained from spiral tests is related to the degree of liberation in the feed and a similar relationship was demonstrated in the coarser size fractions when individual size fractions were considered. This highlighted an important application for liberation estimates derived from sample data as an indicator of the performance to be anticipated from subsequent physical processing of the coal.

Finally, the liberation estimates obtained from washability data were compared with those obtained from separation tests where it was assumed that the ash content of the locked material was identical to that in the feed. It was found that the test based approach is only valid with low grade feeds under certain specified conditions, though it is capable of providing biased but comparable liberation estimates for higher grade samples provided the locked material exhibits a similar grade. In all other circumstances the more precise approach based on determining the grade of the locked material should be adopted.

In conclusion, the main justification for making use of liberation estimates is that they condense an otherwise formidable volume of information into a single measure and this can be very helpful in a number of ways, for example in developing process requirements, in comparative studies of alternative physical processing schemes, and in summarising technical studies for presentation to non-technical audiences. Some additional computational effort is required the first time the procedures are used, but this can be economically applied in the form of additional software code or spreadsheet modifications that need only be carried out once.

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SYMBOLS

C	Mass fraction of solids reporting to the cumulative sinks
c	Ash assay of cumulative sinks (fractional)
c_o	Ash assay in cumulative sinks at zero cumulative mass (fractional)
c'	Ash assay in locked material (fractional)
f	Ash assay in feed (fractional)
i	Inherent ash content of native ash (fractional)
j	Inherent ash content of native coal (fractional)
L	Liberation function (defined in text)
L_a	Liberation function for ash
L_c	Liberation function for coal
m_a	Mass of native ash in total solids mass M (g)
m_c	Mass of native coal in total solids mass M (g)
M	Mass of total solids (g)
R_L	Recovery of locked native ash to cumulative sinks (fractional)
R_T	Recovery of total native ash to cumulative sinks (fractional)
x	Units of locked native ash in cumulative sinks
y	Units of locked native coal in cumulative sinks
z	Units of free native coal units in cumulative sinks

APPENDIX

The processing and storage of the test data and washability analyses referred to in this paper were carried out using release 7.2 of the GRAVTEST software package developed at Mineral Technologies. In response to requests from some coal producers, the washability module from GRAVTEST has been supplied free of charge under the title of COALWASH. It has curve fitting and interrogative capabilities built in to facilitate reading out data for ideal separations and in the latest release it also provides estimates of the degree of liberation existing in washability samples. Potential users should contact the marketing department at Mineral Technologies.