In Situ Fracture Porosity and Specific Gravity of Highly Sheared Coals from Southeast British Columbia (82G/7)

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INTRODUCTION

Converting *insitu* volumes to tonnages available for processing is an important step in coal reserve calculation and in reconciling tonnages predicted to exist *insitu* with those that arrive at the wash plant. An important first step in the process is to assign a density or specific gravity (SG) to the *insitu* volume. Coal companies use a number of empirical equations, which provide SG values based on air-dried ash contents, to convert *insitu* volumes into *insitu* tonnages. Unfortunately many of these equations predict SG values as measured in the laboratory and not that of the *insitu* material. The problem is further compounded when coal seams are effected by folding or shearing, which are suspected of increasing the fracture porosity of the coal and decreasing its effective *insitu* specific gravity (ISG). Papers by Smith (1989) and Ryan (1991) use a more theoretical approach. The paper by Ryan (1991) generated an equation, that in contrast to some equations, predicts SG using the amount of mineral matter, coal, free moisture and void space making up the solid. This equation can therefore respond to changes in a wider range of coal properties than empirical equations and can predict ISG values effected by increased shearing within coal seams.

The process of reconciliation involves the careful consideration of many mining factors that influence the amount of coal delivered to the wash plant. These factors, such as, out-of-seam dilution (OSD), coal loss and breaker rejects, are difficult to quantify accurately. Often reconciliation is achieved by picking values for these factors that are within acceptable ranges and fit with the general perception of the mining operation. Thus, if less coal is reporting to the plant than is predicted by the *insitu* volumes in the pit, coal loss or breaker rejects can be increased to account for the difference. However, when the mining parameters appear to be outside the range accepted by mining experience, one has to question the accuracy of *insitu* tonnage calculations, which means questioning the volume determination, assigned ash content, or SG values used to convert *insitu* volumes to tonnages.

This paper uses the Ryan equation, and a data set of ash *versus* SG measurements for coal from a mine in southeast British Columbia, to derive an ash *versus* SG relationship. The equation provides a good fit to the data and allows terms for SG ash-free coal, SG mineral-matter-free, moisture and void porosity to be derived. This allows the SG used in the reconciliation calculation to be checked for credibility. The data set includes measurements of ash and SG on an air-dried basis using 60 mesh (0.25 millimetre) sized fragments. The SG measured in this way is not a true specific gravity because the coal grains contain some void porosity that is not penetrated by the liquid (kerosene) used in the SG measurement. The SG measured is therefore referred to as an apparent specific gravity (ASG). However in that these micro fractures are too small to be penetrated by ground water, ASG is a good starting point for calculations of ISG and there is no need to attempt to determine the SG of the coal solid minus all porosity. The validity of this assumption was checked by analyzing the ASG of 60 and 200 mesh samples. The petrography of some samples was measured to see if varying percentages of inert macerals produced measurable changes in SG.

It is difficult to measure *insitu* specific gravity (ISG), but there are some approaches that may help derive approximate values of ISG. Useful data can be extracted from washability data and from comparison of air-dried and as-received moisture contents of samples.

A "reconciliation" excel spread sheet is constructed to compare the effects of a number of parameters on the tonnage and the ash content of the coal delivered to the plant. Though the maths involved in this exercise is not complex, care has to be taken over a number of points, in particular, in converting tonnages to different water bases, and in recognizing when percentages are referring to volumes or weights.

SPECIFIC GRAVITY DATA

Proximate and SG analyses were performed on 28 air-dried raw coal samples from the mine (Table 1). The ASG (apparent SG on air-dried samples) was measured using the ASTM D167 test on 60 mesh coal (0.25 milli-

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TABLE 1
MINE 1 RAW SG DATA

Sample	as-received M %	Air-dried M %	VM %	Ash %	FC %	SG (60)	SG (200)
1	3.4	0.5	20.0	16.6	62.9	1.42	
3	5.8	0.4	24.0	10.3	66.4	1.38	
5	3.9	0.4	21.7	15.2	62.7	1.4	
7	2.0	0.4	21.1	13.4	65.1	1.38	1.38
9	1.9	0.4	14.4	56.4	28.8	1.84	1.82
11	2.9	0.4	20.9	15.2	63.5	1.41	
13	2.3	0.3	21.3	14.0	64.5	1.38	
15	2.8	0.4	20.7	12.9	66.1	1.37	
17	3.8	0.3	22.0	23.8	53.9	1.46	1.44
19	1.8	0.3	19.6	38.3	41.9	1.64	1.55
21	2.0	0.5	15.1	61.9	22.6	2.02	
23	3.8	0.3	20.1	33.2	46.4	1.6	
25	3.3	0.4	20.7	10.2	68.8	1.4	
27	2.9	0.5	22.6	28.0	48.9	1.54	1.51
29	5.3	0.4	23.5	21.2	54.9	1.45	
31	2.2	0.4	19.7	37.2	48.8	1.63	
33	3.8	0.3	23.3	24.4	52.0	1.46	
35	2.4	0.3	19.1	38.6	42.0	1.64	
37	3.1	0.4	21.7	11.3	66.6	1.38	
39	4.7	0.5	20.2	19.5	59.8	1.45	
41	5.7	0.4	20.2	17.8	61.6	1.44	
43	4.3	0.5	20.2	21.1	68.4	1.46	
45	4.8	0.4	20.2	21.1	68.4	1.46	
45a	2.2	0.3	20.0	38.0	41.7	1.63	
47	1.6	0.3	16.8	58.3	24.6	1.92	
49	1.7	0.3	16.1	61.6	22.0	1.98	
51	3.3	0.2	20.8	30.7	48.2	1.54	1.52
53	3.9	0.4	22.8	20.6	56.2	1.44	

M=moisture 200 and 60 refer to mesh size

TABLE 2
MINE 1 AND 2 SG DATA FROM WASHED SAMPLES

Sample	Fraction	Weight %	Air-dried M %	VM %	Ash %	FC %	SG (60)
6	1.4 float	49.5	0.3	22.4	7.0	70.2	1.36
6	1.4-1.6	27.3	0.4	21.4	18.6	59.7	1.44
6	1.6-1.8	12.0	0.5	18.8	38.0	42.7	1.64
6	1.8 sink	11.3	0.6	14.6	64.5	20.4	2.02
16	1.4 float	54.6	1.1	24.0	6.7	68.2	1.34
16	1.4-1.6	29.5	0.9	21.4	15.8	61.9	1.42
16	1.6-1.8	6.7	0.8	18.5	37.4	43.3	1.64
16	1.8 sink	9.2	0.6	14.8	63.5	21.1	2.01
26	1.4 float	40.3	0.5	26.5	9.4	63.7	1.33
26	1.4-1.6	43.4	0.7	21.4	21.1	56.9	1.47
26	1.6-1.8	14.3	0.5	19.3	35.6	44.7	1.66
26	1.8 sink	1.9	0.6	16.2	51.4	31.8	1.92
36	1.4 float	49.3	0.7	24.3	6.5	68.5	1.35
36	1.4-1.6	28.3	0.7	21.3	19.1	59.0	1.45
36	1.6-1.8	8.9	0.5	19.4	37.9	42.2	1.67
36	1.8 sink	13.5	0.4	15.3	72.4	11.9	2.24
44a	1.4 float	19.0	0.4	26.3	8.3	65.0	1.33
44a	1.4-1.6	18.8	0.9	22.9	19.8	56.4	1.48
44a	1.6-1.8	16.3	1.5	20.4	36.6	41.5	1.66
44a	1.8 sink	45.9	1.2	15.7	65.2	17.9	2.09
A	1.4 float	59.7	0.4	22.7	7.5	69.4	1.33
A	1.4 1.5	27.2	0.4	20.3	23.7	55.6	1.48
A	1.5 1.6	7.1	0.3	20.1	27.1	52.5	1.52
A	1.6 1.7	3.1	0.3	19.7	37.1	42.9	1.61
A	1.7 1.8	0.7	0.3	18.6	45.4	35.7	1.73
A	1.8 sink	2.1	0.4	16.0	68.7	14.9	2.13

metre) and in addition the ASG values of 6 samples were measured using the ASTM test on 200 mesh coal (0.075 millimetre). Washability tests were performed on 5 samples and the ASG measured on a number of air-dried washability increments to provide an additional 20 samples (Table 2). A single bulk sample from another mine, (Mine 2) with similar rank but different petrography from the first mine, was collected. Six washability increments of this sample were analyzed (Table 2). Specific gravity data from a previous study on the Telkwa deposit (Ryan, 1991) were also used.

A number of different equations were fitted to the mine data set. It was found that an equation of the form Y=1/(A-B*ash) fitted the data very well with an R^2 value of about 0.99 indicating that an equation of this form provides a very good representation of the data. The Ryan equation also has the form ASG=1/(A-B*ash) and in this case constants represent real terms:

A=1/DC where DC is the ASG of ash-free coal (air-dried basis);

B=wtlos*(DMM-DC)/(DMM*DC) where DMM is the ASG of mineral matter adb (air-dried basis);

wtlos is the ratio of mass of mineral matter divided by mass of ash;

The constant B does not provide unique solutions for either DMM or wtlos though if one is assumed the other can be calculated.

The Ryan equation was fitted to the data sets and values of A, B and DC derived (Table 3, Figure 1). It is apparent that there is very little difference in the clean coal ASG values predicted for raw 60 mesh (0.25 millimetre) samples and the raw 200 mesh (0.075 millimetre) samples and both predict clean coal ASG values of about 1.28. The 200 mesh ASG data do however, predict a lower ASG for mineral matter and the reason for this is not clear. In

TABLE 3
CONSTANTS DERIVED BY CURVE FITTING TO THE SG DATA SETS FROM MINE 1, MINE 2 AND TELKWA

constants		Mine 1 data			Mine 2	Telkwa
	SG60 all	SG60 raw	SG60 wash	SG200 raw	SG60 wash	SG60 raw
A	0.778	0.778	0.776	0.784	0.786	0.763
B	-0.0045	-0.0044	-0.0046	-0.0040	-0.0046	-0.0046
DC	1.285	1.285	1.288	1.276	1.273	1.311

ASG=1/(A-B*ash)

A=1/DC B = wtlos*(DMM-DC)/(DMM*DC)

DC = ASG of ash-free coal (air-dried basis)

DMM = ASG of mineral matter (air-dried basis)

wtlos = ratio weight mineral matter / weight ash

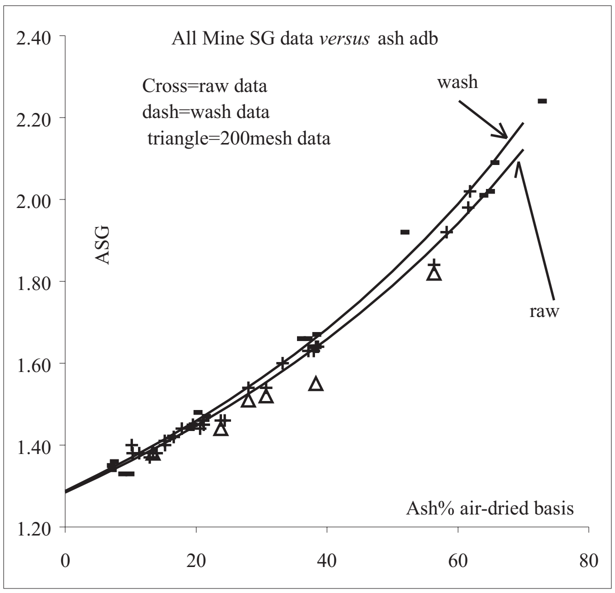

Figure 1. Plot of Raw ASG data *versus* ash % adb, Mine 1; triangles represent 200 mesh data the rest is 60 mesh data with the dashes being washed and the crosses being raw data.

general it appears that crushing the coal to a finer size has not destroyed any of the micro porosity in the coal, which if destroyed would cause an increase ASG for the smaller sized ash-free coal. Therefore, the 60 mesh analyses provide a reliable measurement of ASG on an air-dried basis and any gas filled microporosity must exist on a scale finer than the 60 to 200 mesh size.

Sometimes it is difficult to collect samples with a wide range of ash concentrations required to establish good ash *versus* SG curves. Incremental samples of different specific gravities (washability increments) overcome this problem but may not be representative because of variations in petrography or ash chemistry of the samples. A number of mine samples were separated into a number of SG increments and the ASG of each increment sample determined. The data define a similar ash *versus* ASG relationship as the raw data (Table 3, Figure 1) indicating that reasonable ash *versus* SG relationships can be established from a limited number of samples subdivided into a number of SG splits.

Having established that washed incremental samples provide reliable ASG data, the Ryan equation was fitted to the raw and wash data sets from the mine and the smaller 200 mesh data set (Figure 1). The values of A and B were derived and the clean coal ASG values calculated (Table 3). The clean coal ASG values for the mine coal (1.285) and for coal from the second mine (1.27) are similar and both somewhat lower than the Telkwa data suite (1.31; Ryan, 1991). Coal from the second mine has similar petrography and rank to the first mine samples indicating that there are no marked differences between the ASG values of coals of similar rank and petrography from the two mines.

The wtlos factor and DMM have to be picked based on the most likely paired values as they can not be determined independently. It appears that wtlos varies from 1.09 to 1.15 and DMM from 2.66 to 2.74 (Table 4). Higher wtlos factors are associated with mineral matter enriched in carbonates and this will also increase the value of DMM. The wash data has higher values because the carbonate material is concentrating in the higher SG wash increments.

TABLE 4
REFLECTANCE AND PETROGRAPHY OF MINE 1 AND MINE 2 SAMPLES

	Rmmax%	liptinite	telinite	telocollinite	desmocollinite	detrovitrinite	total reactives	semifusinite	fusinite	macrinite	inertodetrinite	total inerts	mineral matter	ash
17	1.1	3.3	3.7	21.7	22.3	5.7	56.7	11.0	1.0	8.7	7.3	28.0	15.3	23.3
39	1.2	2.3	8.3	12.7	26.0	0.7	50.0	19.0	0.3	14.3	6.7	40.3	9.7	15.5
44a 1.4f		2.7	5.0	34.7	25.7	0.3	68.3	13.3	0.3	7.0	7.3	28.0	3.7	6.2
44a 1.4-1.6		2.7	4.7	13.7	30.3	4.7	56.0	17.7	0.3	7.7	11.0	36.7	7.3	12.0
44a 1.6-1.8		1.0	2.3	5.0	23.0	14.7	46.0	8.0	0.0	5.7	10.7	24.3	29.7	40.1
A	1.3	1.3	8.7	14.0	24.7	2.7	51.3	17.3	0.3	16.0	13.7	47.3	1.3	2.3

TABLE 5
VALID VALUES OF WTLOS AND DMM FOR RAW, WASH AND 200 MESH

B=(DMM-DC)/(DMM*DC)*wtlos DC=1/A				ASG=1/(A+B*ash)	
	Mine 1 raw	Mine 1 wash	mine 1 all data	Telkwa	Mine 1SG200
A	0.77849	0.77629	0.77629	0.7629	0.78361
B	-0.00439	-0.00456	-0.00449	-0.00457	-0.00403
DC	1.285	1.288	1.288	1.311	1.276
wtlos	DMM raw	DMM wash	DMM all	DMM Telkwa	DMM SG200
1.08	2.69	2.82	2.77	2.94	2.44
1.09	**2.66**	2.79	2.74	2.91	2.42
1.1	2.64	2.76	2.72	2.88	2.40
1.11	2.61	2.74	2.69	2.85	2.38
1.12	2.59	2.71	**2.66**	2.82	2.36
1.13	2.56	2.68	2.64	2.79	2.34
1.14	2.54	**2.66**	2.61	2.76	2.33
1.15	2.52	2.63	2.59	**2.74**	2.31
1.16	2.50	2.61	2.57	2.71	2.29

wtlos = wt mineral matter/wt ash
DC = SG ash-free coal DMM = SG dry mineral matter

PETROGRAPHY AND RANK OF SAMPLES

The mean maximum reflectance (Rmmax%) of two samples from the mine (1.11% and 1.12%) and one from the second mine (1.13%) are similar (Table 5). Data were obtained using the procedure of Kilby (1988), which allows the shape of the optical indicatrix to be obtained. The two samples are biaxial positive and the sample from the other mine is biaxial negative. The Telkwa data have Rmmax values that average 0.95% and range from 0.9% to 0.98%.

The petrography of five mine samples and one from the other mine were estimated using 300 point counts. The petrography of the six samples are similar, all containing moderate organic inert contents. Three samples were SG splits of a single sample and these revealed interesting changes in maceral composition as the SG increases. Reactives are concentrated in the low SG fractions mainly as vitrinite A or telinite and telocollinite. Semifusinite is concentrated in the intermediate SG increments and in high SG increments, desmocollinite intermixed with ash predominates. These trends in petrography are similar to those seen by Bustin (1982).

EFFECT OF MACERAL COMPOSITION ON COAL SPECIFIC GRAVITY

The SG of individual pure macerals varies as rank increases. The SG of vitrinite is about 1.4 to 1.5 at lignite rank and decreases to the range 1.25 to 1.35 for medium and low-volatile bituminous ranks, before increasing to over 1.6 in anthracite (Taylor *et al.,* 1998). The SG varies because of devolatilization and changes in the chemical structure and amount and type of micro porosity. The SG of fusinite is high, probably greater than 1.5 in most coals, though it may increase with rank as the original organic texture is destroyed. The SG of semifusinite will be in between that of vitrinite and fusinite and will depend on the amount of fusinization or increase in reflectance experienced.

The ASG of clean coal will be a minimum at medium-volatile bituminous rank (Taylor *et al.,* 1998). The higher ASG at zero ash (1.31) for the Telkwa data compared to the mine (1.285) is probably caused by the lower rank of these coals (Rmmax about 0.95%). The difference in clean coal ASG values may also reflect higher micro porosity in the more deformed coals in southeast British Columbia.

At any rank, SG will vary based on the relative amounts of inert and reactive macerals in the coal. Maroto-Valor *et al.* (1998) demineralized a medium volatile (Rmmax=1.14%) coal and separated enriched maceral fragments (0.075 millimetres) into various SG splits. It is possible to use their data to estimate the ASG values of the pure maceral types vitrinite, semifusinite and fusinite. The best fit with the washability ASG increments was achieved by assigning ASG values of 1.265 to vitrinite, 1.33 to semifusinite and 2.2 to fusinite. Based on these values the predicted DC value for the coal is 1.36. This value is higher than that calculated for the mine data (1.285) and may reflect slightly higher rank or lower micro porosity.

Bustin (1982) studied the washing characteristics and petrography of sheared and non sheared coals sized less than 12.5 mm. It is possible to use his data to estimate the difference in SG between the reactive and non reactive macerals. Composite SG values were calculated for each SG washability split by assigning SG values to three components (mineral matter, reactive and non reactive macerals). The assigned SG values were adjusted until the predicted SG value for each sample fell within the SG bracket for that split (Figure 2). The calculated SG of mineral matter is in the range 2.55 to 2.4, that of reactives is in the range 1.19 to 1.22 and inerts in the range 1.3 to 1.38. It also appears that compared to unsheared samples, mineral matter and reactives have lower SG values and inerts higher SG values in sheared samples. Possibly shearing has mineralized inert macerals, increasing their SG and introduced some additional micro porosity into the reactive macerals, thus reducing their effective SG. The lower SG values calculated from the Bustin (1982) data compared to those calculated using the Maroto-Valer *et al.* (1998) may reflect the difference in size of the two sample sets and increased porosity in the coarser Bustin samples.

The procedure described above does not provide unique solutions for the SG of reactive and inert macerals and mineral matter, but it does provide a rough estimate of

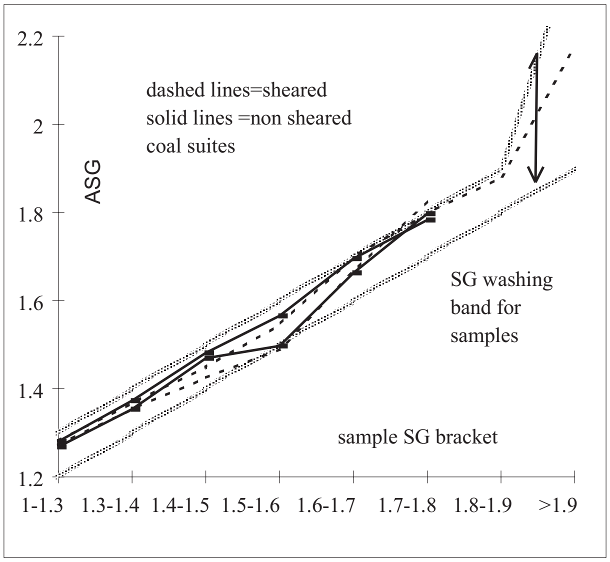

Figure 2. Plot of calculated ASG values for each SG washability increment versus SG increment; data from Bustin (1982).

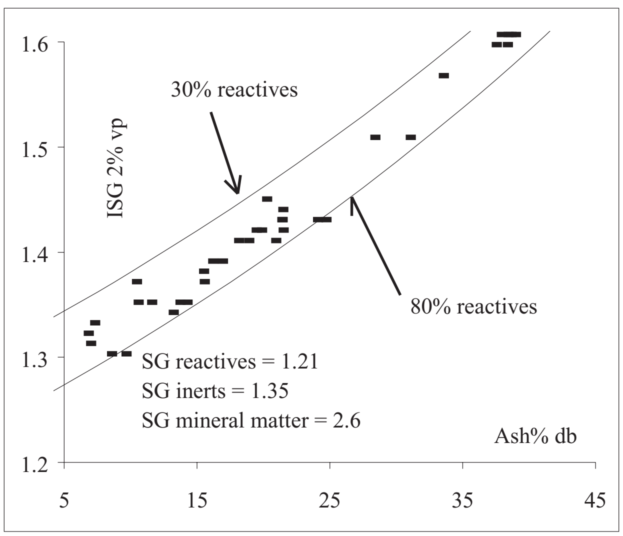

Figure 3.Plot of ISG (2% vp) *versus* ash % dry-basis (db) (Mine 1 data) illustrating possible effects of varying the reactives/inerts ratio in samples.

the difference in SG values between reactives and inerts of about 0.5 to 0.1 for the Bustin coal with a rank in the range Rmmax=1.35% to 1.4% and for the Maroto-Valer *et al.* coal with a rank of Rmmax=1.14%. Based on the difference in SG values and the ranges in reactives/inerts ratios found in Mist Mountain Formation coals, it is possible to construct a plot that illustrates the possible SG values for samples with varying reactives/inerts ratios (Figure 3).

The ASG values for the macerals in the Bustin study seem to be low and this is probably because the heavy liquid, used to wash the < 12.5 mm sized air-dried coal particles, does not penetrate air filled fractures in the particles. This means that in an ash *versus* SG plot, a band representing a petrography variation from 30% reactives to 80% reactives on a mineral free basis, appears to be low when compared to the mine data, which was crushed to <0.25 millimetres. However, when the mine data are corrected for 2% air filled fracture porosity, the data scatters within the 30% to 80% envelope (Figure 3), calculated by assigning SG values of 1.21 to reactives, 1.35 to inerts and 2.6 to mineral matter. Apparently a lot of the scatter seen in Figure 1can be explained by changes in the reactives/inert ratio of the samples. Also the increased size of the air-dried Bustin samples may be responsible for an additional 2% porosity not penetrated by the heavy liquids.

The effect of petrography on the SG of five mine samples was checked by posting the values of the reactives/inerts ratios of samples against their plotted position in an ash *versus* SG plot (Figure 4). It is apparent that samples with high reactives/inerts ratios tend to plot below the curve defined by all mine samples.

PRELIMINARY DETERMINATION OF FRACTURE POROSITY IN COAL

It is exceedingly difficult to measure the *insitu* fracture porosity of a coal seam. Ideally if one could cut out a cubic metre of a seam, seal the sides and measure the weight, then this might provide an answer. A more practical approach involves using well calibrated geophysical density logs to provide the *insitu* specific gravity of a coal seam (ISG). By matching core from a seam to the log pattern for the seam, ash concentrations corresponding to geophysical log densities can be determined. The ASG of the coal at the measured ash concentrations can be determined by laboratory measurement or by using the Ryan Equation. It is then possible using Figure 5 and the values of ISG and ASG to determine possible combinations of volume of water, weight of water, and void volume in the coal. Generally the method is difficult to apply because

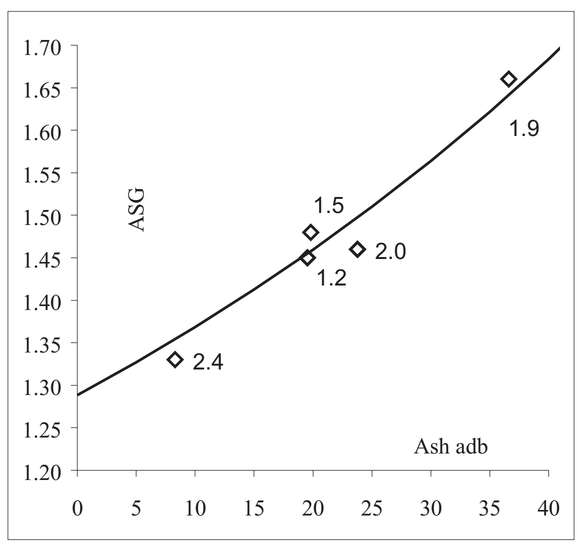

Figure 4. Plot of ash *versus* SG with values of reactives/inerts ratios of samples posted.

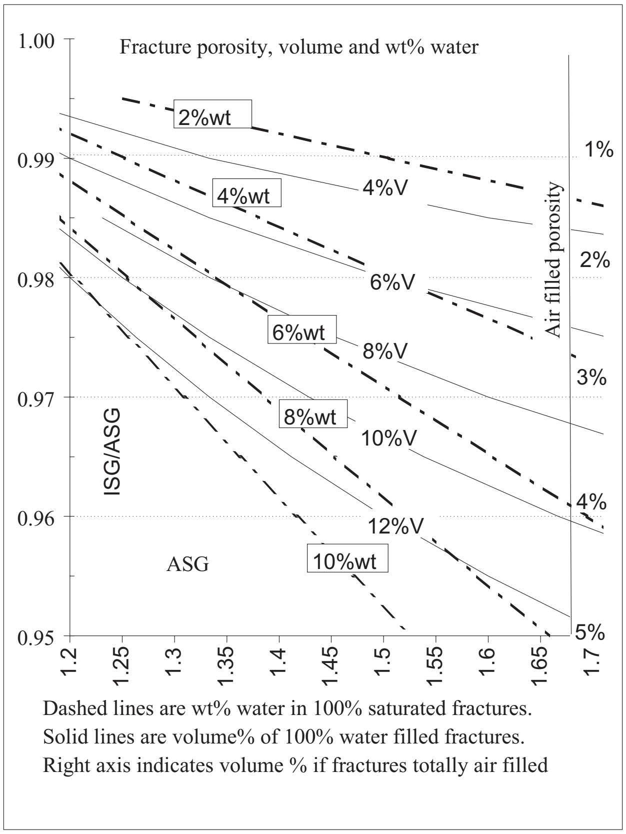

Figure 5. Relationship of SG to void or water filled fracture porosity.

calibration of geophysical logs is not good enough and core recovery of less than 100% introduces uncertainties into the ash determination. The method does however offer the possibility of estimating *insitu* fracture volume at depth. Long spaced density logs can be well calibrated and the density scale linearized. Short spaced density logs are difficult to calibrate and the scale is not linear, however it is possible in some cases to use a combination of long and short spaced logs to determine the density of quite thin coal layers.

Other types of logs can provide relative estimates of fracture porosity. Resistivity of coal seams decreases markedly as the water content increases so that a combination of density logs to identify coal seams and resistivity logs to identify water content can indicate areas in seams of increased fracture porosity. Edwards and Banks (1978) describe a way of using density and resistivity logs to determine volumes of coal, water and wet ash. A resistivity *versus* apparent density plot provides the apparent density of dry ash-free coal and the resistivity of wet mineral matter. These data and data from the resistivity and density logs are used in calculations of water volume. The paper provides data on a 6 metre coal seam, in which the calculated average water volume is 9.5%. The approach is interesting because it does not require core, but it does require an open hole for the resistivity log. Once the volume of water is determined it is easy to use the value to, either calculate ISG based on measured values of ASG, or to calculate the in place tonnage of coal minus free moisture. In general neutron logs are not useful for detecting changes of moisture content in coal seams.

Generally, in the 1980's and 1990's coal geophysical logging concentrated on determining seam thickness and general lithology and not many attempts were made to determine *insitu* seam porosity. However, based upon the recollections of Keith Banks of Roke Logging (personal communication, Banks, 1999) the *insitu* fracture porosity of coals in southeast BC is probably in the range of 4% to 7% and higher at a number of locations. At Sage Creek, coal was carefully cut from an adit and immediately weighed and then weighed after drying. The difference in weights implied an *insitu* porosity of over 20%. In Alberta, near Grande Cache, geophysical logging provided estimates of *insitu* fracture porosity of 15% and in a thrust zone the porosity was estimated to be 32% to 38%. It appears that in deformed coals the *insitu* fracture porosity is increased and can be much greater than 7%.

At depth, increase in fracture porosity in coal generated by shearing may survive because hydrostatic pressure is similar to lithostatic pressure (over pressuring), which is probably a requirement for thrust movement. As the depth of cover decreases and over pressuring disappears the fracture porosity may decrease. This means that in some cases coal volumes calculated at considerable depth may be greater than the volume eventually exposed at surface and that fracture porosity at surface may be less than that which existed at depth. This does not appear to be the case at the mine.

It maybe possible to estimate fracture porosity in laboratory samples using washability and SG data, as illustrated using data in Bustin (1982). The SG for clean coal air-dried basis (adb) with average petrography is about 1.26, which is lower than that predicted by direct measurements for the mine data (1.28). The difference may be explained by the higher rank of the Bustin samples (Rmmax=1.35% to 1.4%) compared to the mine samples (Rmmax=1.12%). The increase in rank moves the Bustin samples closer to the minimum vitrinite SG on the SG *versus* rank relationship described by Taylor *et al.* (1998). Another explanation may be that the mine ASG measurements were made by immersing 60 mesh air-dried samples in kerosene, which penetrates fractures in the air-dried 60 mesh samples more than the heavy liquids, used in washability tests, penetrated the fractures in <12.5 millimetre sized air-dried samples. In fact, by comparing the SG values determined by two approaches it may be possible to calculate the volume of fractures in the washability samples.

The Bustin samples were crushed to minus 12.5 millimetres and immersed in heavy liquids whereas the mine samples were crushed to minus 0.25 millimetres and immersed in kerosene. Based on the difference in estimated SG values for clean coal (1.28 =ASG for the mine and 1.255=ISG for the Bustin samples) this could indicate, if water was removed from the fractures by air drying, an increase in volume of void porosity of 2%, or if the

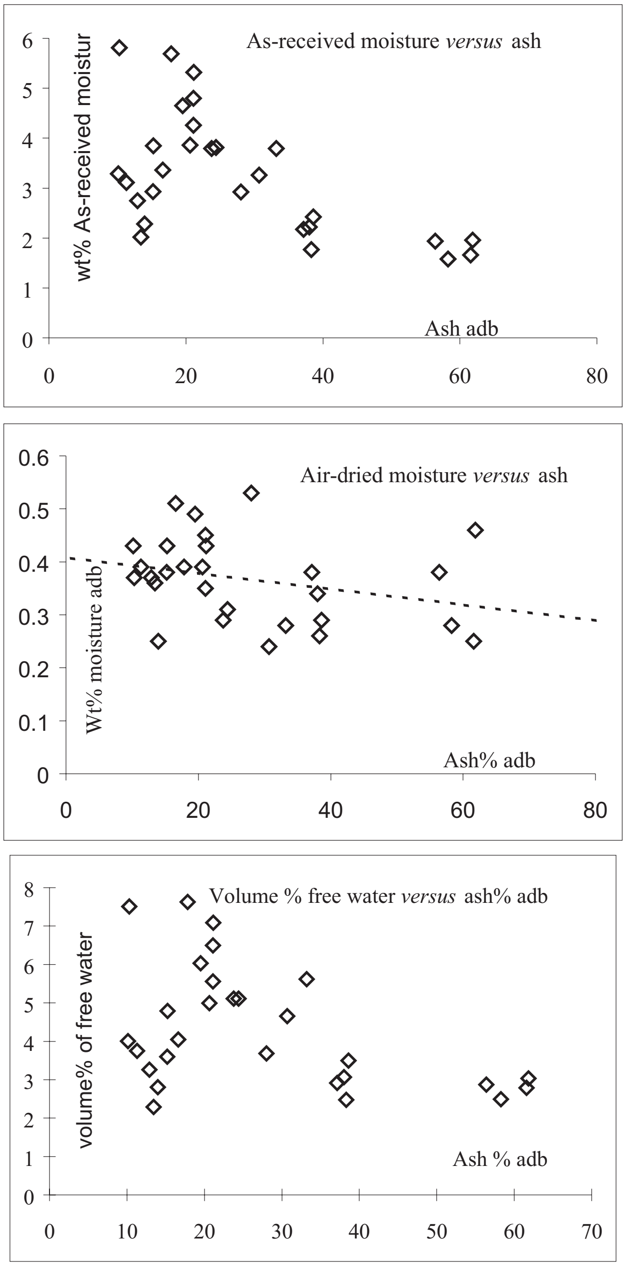

Figure 6. Plots of as-received and air-dried moisture contents *versus* ash contents.

fractures remained filled with water an increase in weight of free water of 7% equivalent to a water filled volume of about 9% (Figure 5). It is apparent that, even if ISG is only slightly less than ASG, this may still indicate quite a large volume of fracture porosity, if it is water filled. In this case, the argument is confused by the rank difference between the Bustin samples to the mine samples.

Washability analyses of samples from the Telkwa property were performed on suites of samples ranging in size from 0.3 millimetres to plus 25 millimetres (Ledda, 1992). As sample size increases the ash content in each SG increment increases, probably in part because preservation of fractures decreases the effective SG of the air-dried samples. The clean coal SG with no fractures is 1.31 (from Ryan, 1991); the SG for 0.3 to 2.0 millimetre material appears to be about 1.26 to 1.28 and for the coarser sized material, it decreases to 1.24 to 1.26. These values were derived by assigning SG values to the coal and mineral matter and attempting to calculate a combined SG that fitted into the SG wash increments. The difference in SG values implies an increase in air filled fracture porosity from zero at SG=1.31 to 5.3% for the coarse sized wash material with an SG of 1.24. This assumes that the differences in SG derive from the fact that the heavy liquids used in the washability analysis do no penetrate air filled fractures in the larger sized air-dried samples and in the smaller sized coal most of the fractures are destroyed. If the fractures remained water filled then the difference in SG would imply a water filled volume of 18%, which appears to be too high.

A volume percent porosity of 5.3% if water filled would be equivalent to 4.3% weight of water. The total water in the coal would therefore be 4.3% plus air-dried moisture for a total of about 5% to 6%. This estimate is similar to estimates of *insitu* water estimates and the average as-received moisture for Telkwa coal (Ryan, 1991). The SG of the mineral matter in the Telkwa coal is estimated to be between 2.4 and 2.5 from the washability data and, as with the coal SG, appears to decrease as the size consist increases. The estimated SG mineral matter from the SG data (Ryan, 1991) is 2.7 this would imply a void porosity of about 9% if air filled.

Using a combination of washability data, sized from 25 or 50 mm to 0.3 mm, and ASG data derived from 0.25 mm sized samples, it is possible to estimate fracture porosity in the coarsest size washed coal based on a number of assumptions. That it is possible to estimate the SG of the wash samples in each SG increment: that variations in the estimated clean coal SG of washed samples are caused by the varying ability of the heavy liquids to penetrate fractures in the coal and by the progressive destruction of these fractures in finer sized coal: that the fractures in the coarser sized fragments are devoid of water because the samples were air-dried.

Another method of estimating minimum fracture porosity from laboratory samples involves using the difference between as-received and air-dried moisture contents. If samples are collected from fresh outcrops, in which the coal still contains most of its *insitu* moisture, then the as-received moisture content is higher than the air-dried moisture in part because fracture spaces in the coal still contain free water. Air drying the samples removes this water and therefore the difference between as-received and air-dried moisture contents may be a minimum estimate of the weight of free water in small fractures. The volume occupied by the free water is given by:

Volume = weight percent free water x ASG

The as-received moisture content of samples decreases as the ash content increases. This appears to indicate that the fracture porosity in high ash or rock samples is much less than in low ash samples. However the data is

TABLE 6
RECONCILIATION CALCULATION SPREADSHEET

Enter data in shaded boxes only. Spread sheet calculates ROM, plant and insitu data depending on inputs.

SG CONSTANTS

set for all calculations

wtlos	DC	DMM	adm
1.09	1.285	2.66	0.4

SG EQUATIONS

ASG =1/(A-B*wt%MM)

wt% MM = wtlos*ash/100

SGfw=ASG/(1-wt%fw+wt%fw*ASG)

ISG = SGfw*(1-vp)

A = 0.778 A=1/DC

B = 0.402 B=(DMM-DC)/(DMM*DC)

DEFINITION OF TERMS

ASG = SG at adm, no fractures no free water

MM = mineral matter wtlos = MM / ash

SGfw = SG corrected for free water (fw) no void porosity

ISG = SG of coal with free water and air filled fractures (vp)

DC = SG of zero ash coal at adm

DMM = SG of mineral matter at adm

OSD = out-of-seam dilution

adm = air-dried moisture

adb = air-dried basis

bcm = bank cubic metres

lcm = loose cubic metres

Ash db = Ash adb /(100-adm)

Volume% water=wt% water x SGfw

Ash ROMm = Ash adb/(100-adm)* (100-ROMm)

constants to convert tonnes from different water bases

wt ratio adb/ROM and adb/insitu = insitu to plant 0.954 0.944

plant to insitu 0.954 0.944

in seam loss % of insitu volume with same free	OSD at adm volume% of total insitu volume	OSD ash at adm	total insitu moisture WT%	free moisture wt% not quite the same as total insitu -	air filled void porosity Volume%	ROM moisture wt%	swell factor as bulk porosity calc using ROM coal+rock adb	truck capacity (lcm)	reject ash at breaker adb	Breaker reject wt% of ROM tonnes at ROM moist	
20	8	65	6	5.62	0	5	10	110	65.7	9.5	**insitu**
20	8	65	6	5.62	0	5	10	110	65.7	9.5	**plant**

		from insitu to plant	from plant to insitu		DESCRIPTION
Insitu fracture vol		**8.44**	**8.44**		**percent volume occupied by free water+void porosity**
INSITU		100000.0	100000.0		insitu coal volume bcm with free water and void porosity
		30.00	30.00		insitu ash adb
		1.546	1.546		ASG of insitu coal at adm no free water no void porosity
		1.500	1.500		SGfw = SG of insitu coal with free moisture no void porosity
		1.500	1.500		ISG = SG of insitu volume with free water and void porosity
		8435.42	8435.42		weight of free water equivalent to volume of free water
		150029.90	150029.90		insitu coal tonnes with free moisture
		141594.48	**141594.48**		**insitu coal tonnes at adb**
		28318.90	28318.90		in seam tonnes mining losses at adb
		91564.58	**91564.58**		**bcm insitu coal adb (no void porosity or free water)**
		20000.00	20000.00		bcm loss of in seam volume
		18312.92	**18312.92**		**volume of coal lost at adb**
RUN OF MINE		2.028	2.028		SG OSD rock at adb
		8000.00	**8000.00**		**volume of OSD at adb added as is to insitu volume**
		16220.55	**16220.55**		**tonnes OSD rock at adb**
		129496.1	**129496.1**		**ROM tonnes coal+rock at adb**
		135766.5	135766.5		ROM tonnes coal+rock at ROM moist
		34.38	34.38		ROM ash adb
		1.594	1.594		SG ROM coal and rock all at adb
		81251.7	81251.7		volume of coal+rock at ROM moisture no void porosity
TRUCKS		90279.6	90279.6		lcm=bcm ROM coal+rock adb corrected for swell factor
		14811	14811		Number of trucks
		110.0	110.0		truck capacity
		6.1	6.1		truck load lcm
BREAKE		**12302.13**	**12302.13**		**breaker reject tonnes at adb**
		2.040	2.040		ASG of breaker reject at adb
		6029.67	**6029.67**		**breaker reject volume at adb**
PLANT		**117194.0**	**117194.0**		**plant delivered tonnes at adb moisture**
		75222.0	**75222.0**		**plant delivered volume at adb**
		122868.7	122868.7		**plant delivered tonnes at ROM**
		31.10	31.10		**plant delivered ash adb**

NOTES FOR TABLE 6

	check reconciliation	
	tonnages adb	volumes adb
insitu	141594	91565
minus lost	28319	18313
plus dilution	16221	8000
minus rejects	12302	6030
equals plant	117194	75222
check	117194	75222

bcm = bank cubic metres ie volume as measured in bank before consideration of swell factor caused by mining and breakage.
bcm contains the fracture volume calculated on the first line of the spread sheet
lcm=insitu air-dried volume with a swell factor added to account for additional breakage during mining.
when swell factor =fracture volume then lcm=bcm with dilution
Solid is assumed to be coal+mineral matter+adm.
Non coal space is occupied by volume of free water plus volume of void porosity
void porosity = fracture or pore space not filled with water (fas filled) it does not include microporosity, which is factored into ASG.

Water is weight percent and porosity is volume percent.
To calculate total non coal space one must convert water wt% to V% in some calculations
It is assumed that adb moisture is an inherent component of coal and ASG. It does not add to coal volume
It does not effect non coal volume which is composed of free moisture and void porosity
The insitu volume available for mining is fixed by the value entered on line 1.
The volume% of non coal space (i.e free water volume+void porosity) depends on values of wt% insitu water and volume% void porosity entered in the appropriate boxes at the top of the sheet. The actual percent total non coal space is calculated in the spread sheet

The basic SG equation for a mixture of coal+mineral matter is ASG=1/(1/DC-(DMM-DC)/(DMM*DC)*MM)
DC=SG pure coal at adm DMM=SG rock at adm MM= wt of mineral matter at adm
MM is converted to ash using wt ash=wt MM x wtlos where wtlos=wt MM / wt ash

The basic SG equation must be adjusted for free water (fw) and void porosity (pv)
SG=Mass /Vol (M/V). After adding water as wt fw% new wt is Mw and Mw=M / (1-fw) Mw-M=M x fw/(1-fw)
Note that fw is not a volume % but Mw is set to 100gm then fw is equivalent cc
SGfw=M/(1-fw%) / (V+M*fw/(1-mf)) but V=M/SG
SGfw=1/((1-fw)/SG+fw) or SGfw=SG/(1-fw+fw x SG)

To handle void porosity
SG=M/V new volume Vn has void porosity Vp Vn=V/(1-vp) ISG=M/Vn=M/(V/(1-vp)) ISG=SGfw x (1-vp)

To convert wt% water to volume% water
SGfw=Mw/Vw mass of water =Mw x fw% is equivalent to cc water therefore volume% water =fw% x Mw / Vw =fw x SGfw

Dilution: Because dilution is added on an ai-dried basis to coal that is at insitu moisture when the volume of dilution material is recalculated to an insitu or ROM water basis its volume relative to that of coal increases
this means that it no longer is in the volume% given as the OSD% and the volume of ROM coal+rock at ROM moisture will not equal insitu volume -loss% + OSD%

ROM volumes: the usefulness of ROM volumes is limited because in reality there is always added porosity or swell generated when the coal is mined and moved. The concept is useful for estimating the size of truck loads.
The most important thing is to compare insitu volumes to tonnes adb delivered to the plant

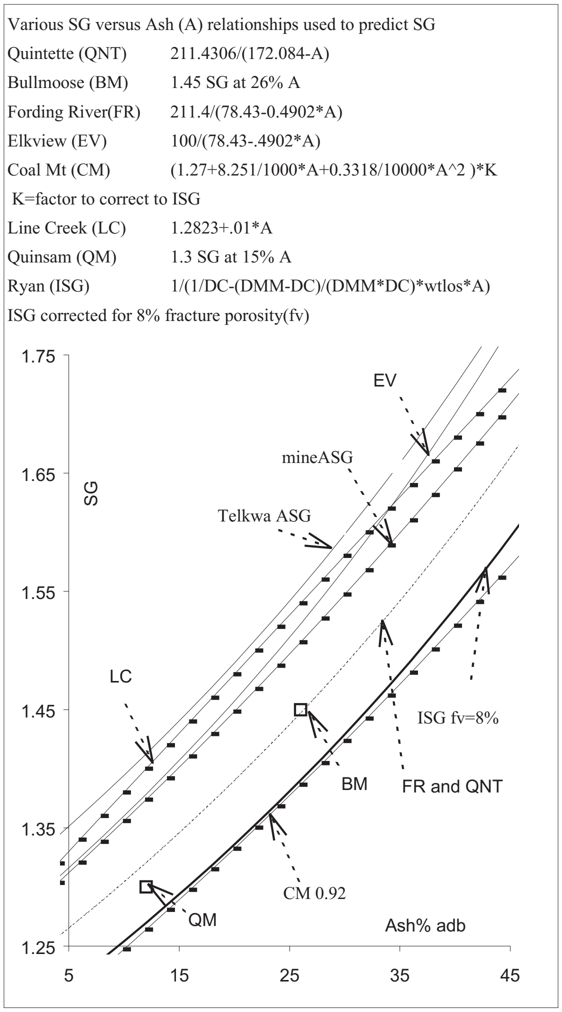

Figure7. Various SG *versus* ash equations used by BC coal mines

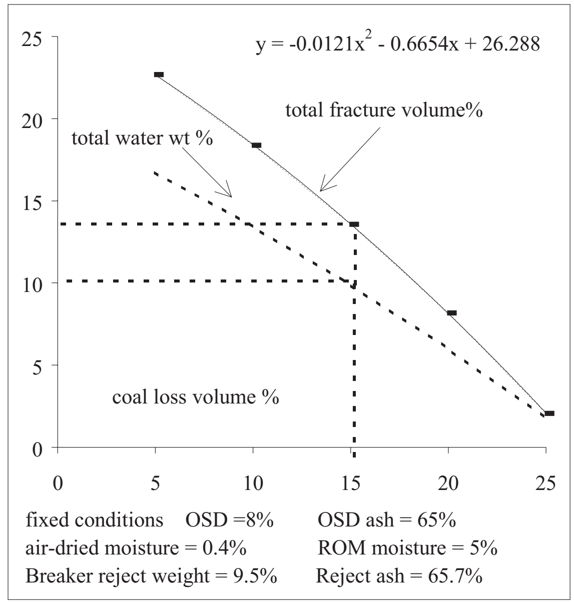

Figure 8. Plot of coal loss *versus* total fracture volume and total weight water.

somewhat deceptive because the effect of a decrease in weight of water is partially offset by an increase in ASG as the ash content of the samples increases. Therefore, a smaller weight percent water can account for the same volume as calculated in low ash samples. The mine as-received moisture data show a moderate trend towards lower values at higher ash contents whereas the air-dried moisture content is almost independent of ash content (Figure 6). By subtracting the as-received moisture from the air-dried moisture and converting the weight percent free water to a volume percent based on using the ASG of the sample, it is possible to estimate the fracture porosity of the samples and illustrate how it changes with increasing ash (Figure 6). At low ash values the porosity is variable ranging from 2% to a high of 8%. At high ash contents the variability seems to decrease and the average volume is about 3%.

RECONCILIATION

Coal reserves are measured in the ground as a volume but the coal is sold as washed tonnes. It is therefore necessary to be able to convert *insitu* volumes into *insitu* tonnes on an air-dried basis and to track these tonnes as they are mined, transported, crushed and washed. Once the *insitu* tonnage on an air-dried basis has been calculated it is necessary to estimate a number of mining factors such as coal loss, out of seam dilution (OSD) and breaker rejects before estimating tonnage delivered to the plant. Conversely, if plant tonnage is accurately known, then by adding back the breaker rejects and coal loss and removing the OSD from the tonnage or volume delivered to the plant it should be possible to calculate the *insitu* tonnage or volume. The calculated value should match or reconcile with that estimated by the mine plan as long as all the calculations are done at the correct water bases.

A detailed excel reconciliation spread sheet (Table 6) was constructed to illustrate the effects of changing coal and mining related parameters on coal tonnage delivered to the plant. A number of definitions and equations are included in the Table. The spread sheet uses the Ryan equation to calculate the SG values of tonnages under *insitu* or air-dried conditions and adjusts tonnages and volumes based on *insitu*, air-dried and ROM moisture contents. The procedure does not involve elaborate mathematics but does require a good understanding of the mining process.

The value of air-dried moisture used in Table 6 is determined from data in Table 1. The values of wtlos, DC and DMM were determined by curve fitting to the mine

ASG *versus* ash data and deriving the constants A and B for the raw wash and combined data (Table 3). Valid combinations of DMM and wtlos are provided in Table 4.

The reconciliation process starts with estimates of *insitu* volume, ash and ISG. When there is sufficient drilling, estimates of *insitu* volume should be good, assuming that the computer model used is appropriate for the type of geology. These data are used to provide a value of the *insitu* fracture volume either directly by comparing ASG, ISG and ash or indirectly by using the weight of *insitu* water and void porosity to calculate the total fracture porosity. The spread sheet uses estimates of total *insitu* moisture and void porosity to calculate total fracture porosity. *Insitu* tonnage on an air-dried basis is then calculated by using the appropriate SG and *insitu* volume. The key to converting *insitu* volume to *insitu* tonnes adb is to know the fracture volume at depth and whether it is filled with water or air. The ISG used must take into account the fracture volume and the degree to which it is water filled. The weight of coal adb is calculated using:

weight of coal adb = ISG* *insitu* volume - weight of free water

Alternatively the weight of coal adb can be derived from:

weight of coal adb = ASG adb* (1-fv) * *insitu* volume; where fv is the total *insitu* fracture volume. The spread sheet (Table 6) displays the total *insitu* fracture volume and allows for variable filling of the fracture volume with water before performing the calculations.

If it is difficult to reconcile tonnages delivered to the plant with estimates of *insitu* volume, then the temptation is to decrease the available tonnage by decreasing the value of SG used. However, it must be kept in mind that, if the SG value is multiplied by *insitu* volume then the implication is that:

SG=ASG * (1-fv);

This assumes a value of fracture porosity that must be credible and that tonnages are calculated on an air-dried basis.

The SG value is derived from a number of SG *versus* ash relationships (Figure 7). Ash *versus* ASG curves were established for Telkwa and the mine coal by analyzing a number of air-dried samples. Ash *versus* ASG curves for the Line Creek and Elkview mines plot close to the mine data line indicating that these relationships are probably modeling coal on an air-dried basis. Using these SG *versus* ash relationships will tend to cause an over estimation of raw coal reserves by about 5% if the ASG value for adb coal is multiplied by the total *in situ* volume, which includes the total fracture porosity present in *in situ* coal.

The Fording River, Quintette and Bullmoose data sets predict lower ASG values for the same ash than the air-dried mine data (mine ASG Figure 7), and therefore, appear to be adjusted to provide ISG values. Compared to mine adb data, the Fording River and Quintette data are compatible with an air-filled fracture volume of 4% that is ISG=ASG*(1-0.04) (Table 6), or if these values of ISG are multiplied by *in situ* volume the result is an estimate of tonnage at adb assuming a 4% *in situ* fracture porosity. Alternatively, the SG values could be lower because higher rank coals up to medium-bituminous rank have lower SG values at similar ash contents. Coal Mountain Operations predicts an ISG based on an 8% air filled porosity. Quinsam uses a fixed SG of 1.3, which unless the raw ash concentration is very low probably under estimates *in situ* tonnage.

Depending on the mining conditions the coal may be above or below the water table when mined. This means that the coal may be completely or only partially saturated. Measurements of ISG at depth derived from geophysical logs can be used, in conjunction with lab measurements of ASG, to calculate the fracture volume, usually assumed to be completely water filled (Figure 5). By the time mining has exposed the coal, some of the water may have drained or additional water added to the fractures. The change in fracture volume does not matter because the ISG value is multiplied by the *insitu* volume measured at depth.

At Mine 1 attempts to reconcile *insitu* volumes with the tonnages delivered to the wash plant have generally required low SG values, implying high fracture porosities, and high coal loss values. In order to keep the coal loss values within an acceptable range, a fracture porosity of 8% has to be assumed. Based on conversations with Keith Banks, a fracture porosity of 8% is probably a conservative value for the mine considering the amount of shearing in the coal. The empirical curve (CM .92) predicts SG values very close to those predicted by the Ryan equation based on the mine data and 8% air filled fracture porosity. It does not model ISG *versus* ash as well if the fracture volume is water filled except at the ash content of about 25%. This does not matter as long as it is assumed to be providing values of ASG*(1-fv) and not values of actual ISG for the total *insitu* volume.

The spread sheet (Table 6) can model an 8% fracture porosity by setting the total moisture equal to the air-dried moisture and the void porosity to 8%, in which case the spread sheet then makes no deduction for weight of free water from the *in situ* tonnage, which is calculated on an air-dried basis. Alternatively, the *in situ* moisture could be set to 6 weight %, which provides about the same fracture volume if the *in situ* ash content is about 25%, and the spread sheet then subtracts the weight of free water before calculating the *insitu* tonnage on an air-dried basis.

Coal losses can be expressed as a percent of tonnage mined, as an absolute thickness of the hangingwall and/or footwall of the seam, or as a percentage of *insitu* volume. In situations where the coal is highly deformed such as at the mine it is probably better to use a percentage of *insitu* volume, though this tends to under estimate actual loses for thin seams and over estimate them for thicker seams. A 10% loss of volume is equivalent to a 10% loss of tonnage whether the tonnage is calculated on an as-received basis or air-dried basis.

Coal loses should be apparent somewhere in the mine (probably waste rock dumps). If high coal losses are suspected, but the lost coal can not be located, then maybe part of the solution is in increasing the estimate of fracture porosity in the *insitu* coal, especially if there is evidence of severe deformation. Increasing the fracture porosity in the *insitu* coal decreases the tonnage delivered to the plant by decreasing the amount of coal in the ground. A plot of total fracture volume *versus* coal loss (Figure 8) illustrates the relationship between these factors, based on fixing the other mining parameters at realistic constant values. If the *in situ* fracture volume is 5% then the coal loss has to be 22.6% (Figure 8). However, when the *insitu* fracture volume is increased to 15% the coal loss decreases to 13.6%, which is intuitively more reasonable. The total *insitu* moisture is 10% in this example. A large fracture volume could in part result from shearing or underground mining in the area.

Ash is usually determined by analyzing chip samples. In some instances fine coal is lost and the reported ash analyses are high and in other cases erosion of fine coal surrounding the hole can result in additional coal being recovered and the analyzed ash values being low. If the ash concentration assigned to the *insitu* volume is too high then *insitu* tonnage estimate will be high and there will be a tendency to correct this by assuming a coal loss value that is too high. However, this will result in the ash concentration of the coal reporting to the plant being lower than predicted. As an example, using spread sheet (Table 6), if the predicted *insitu* ash content adb is 30% (true value 25%), then in order to explain the tonnage reporting to the plant a coal loss of 17% must be assumed as opposed to a true value 14.5% and the predicted ash content of the coal reporting to the plant is 31.1% as opposed to the actual value 26.3%. The actual over estimation of *insitu* tonnage is about 3%. Obviously, if the predicted coal loss and plant ash values seem high then the error is probably in estimating the *insitu* ash content.

Out-of-seam dilution (OSD) is extraneous rock that is incorporated in the coal as it is mined and is not considered when the *insitu* ash of the coal is calculated. It can be defined as a thickness or as a percent of the *insitu* coal volume. In the spreadsheet (Table 6) it is assumed that the OSD has no free moisture or fracture porosity and is added to the coal as rock on an air-dried basis. Alternatively, it could be assumed that the OSD has the same moisture and fracture porosity as the coal. However, fracture volume appears decrease as ash content increases as indicated by the calculation of fracture volume using as-received moisture (Figure 6). The more conservative assumption, which has the effect of increasing percentage dilution, is to assume that OSD is added on an air-dried basis.

Because the coal in most BC mines is soft, rotary breakers are effective at removing rock fragments, which are mainly introduced as OSD. It is difficult to estimate the relative tonnage or volume of breaker rejects, but generally the percentage of material is low and it has a high ash content. It can be expressed as a percentage of the tonnage or volume presented to the breaker. Usually it is expressed as a tonnage, in which case it will be a percent of ROM tonnage at ROM moisture.

The spreadsheet (Table 6) can be used to check various combinations of parameters to see how they effect reconciling *insitu* volume and ash content with tonnage and ash content of the material delivered to the plant. Generally, predicted plant tonnage is reduced by increasing either fracture volume in the *insitu* coal or coal loss. The effect of OSD and breaker rejects will tend to cancel out especially in the situation at the mine where the coal is very friable. As OSD increases so will breaker rejects if they do cancel out then the ash at the plant will be the same as *insitu* ash. If the ash concentration at the plant is higher than *insitu* ash, then OSD is adding more ash than the breaker is removing. This means that:

the value tonnes OSD x ash is greater than the value tonnes breaker reject x ash.

It should be noted that, if breaker reject ash is low and OSD ash high, then plant ash will be increased, and at the same time, tonnage decreased by the net effect of adding OSD and removing breaker rejects.

CONCLUSIONS

It is possible to derive an SG equation that fits laboratory data and provides the opportunity to vary input parameters such as weight of free water and volume of void porosity. Fracture volume is the volume occupied by the free water and void porosity. Fractures in the coal range in size from those that can be penetrated by kerosene in 60 mesh sized particles to major fractures in the coal face. They do not include the micro fractures that may be gas filled but whose effect is incorporated in the calculation of ASG.

The equation can be used to calculate *insitu* tonnages on an as-received or air-dried basis. By increasing the void porosity the equation can be used to help determine tonnages in stock piles. Using differences in ASG and ISG it is possible to estimate the volume of fractures (fv) in *insitu* coal. This is important because to calculate tonnages on an air-dried basis from *insitu* volume requires the values fv and ASG. If the fracture volume is not considered, then *insitu* tonnages will be over estimated by an amount equal to the volume of the fracture porosity.

Some indications of fracture volume can be gained from washability data, which indicates volumes of about 5%. Another way is to use the difference between as-received and air-dried moisture measurements of fresh samples. Both these methods probably under estimate fracture volume. Geophysical logging has indicated fracture porosities of over 20% is some situations. These high porosities survive at depth because hydrostatic pressure equals lithostatic pressure.

The SG of vitrinite decreases from sub-bituminous coal to medium-volatile coal and then increases as the rank increases to anthracite. The SG of inert macerals is higher than that of vitrinite and is probably proportional to reflectance. This means that at a fixed rank and ash content the SG of coal varies depending on maceral composition. Also ash *versus* SG relationships at constant petrographic composition must be established for each rank of coal.

The process of reconciliation and prediction of tonnes and ash content of coal delivered to a plant does not require complex mathematics but it has to be thought out carefully, otherwise mistakes will be introduced that will mask the use of inappropriate values of some of the mining constants.

The mine coal is highly deformed and at depth may have a high fracture porosity of 10% to 20%. It is the volume at depth with the high fracture porosity that is used to calculate *insitu* tonnes so that the ISG used must be corrected for a fracture porosity, that may appear to be too high based on outcrop observations.

ACKNOWLEDGEMENTS

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