THE PREDICTED COKE STRENGTH AFTER REACTION VALUES OF BRITISH COLUMBIA COALS, WITH COMPARISONS TO INTERNATIONAL COALS

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KEYWORDS: Coal quality, coke strength after reaction (CSR), coke reactivity index (CRI), ash chemistry; base-acid ratio (BAR), pulverized coal injection (PCI), blending.

INTRODUCTION

This paper provides background to the coke strength after reaction (CSR) test and gives perspective regarding changes in the coking coal market. It provides a summary of some of the predicted relationships between the ash chemistry of coal, and coke properties of British Columbia coals.

A brief overview of the ash chemistry of British Columbia coking coals is presented. The data are used to comment upon the potential coke strength after reaction (CSR) of these coals based on their ash chemistry. Finally comparisons are made with coals from other parts of Canada, U.S.A and Australia.

BACKGROUND

Coke making is a major production step in the steel making process. The blast furnace operator must be able to assess the performance of the coke in the furnace in order to run the furnace efficiently. Blast furnaces are operated on a continuous basis with every effort made to reduce variations in the operating conditions. They are only shut-down for expensive relining or because of unforeseen circumstances. It is therefore almost impossible to measure the actual performance of coke in a furnace and the operator must depend on predictions of its performance.

A variety of tests have been developed to predict the performance of coke in blast furnaces. Historically attempts were made to predict the cold strength of coke (stability factor, SF) by measuring various petrographic and rheological properties of the parent coal. Fluidity, dilatation and FSI (free swelling index) are all useful pointers to the strength of coke that can be made from a parent coal. Unfortunately they do not cover all aspects of the quality control required in modern blast furnaces.

More recently, pilot coke ovens have been used to produce samples of coke that can be used for quality tests. The tests, such as stability factor, measure the resistance of the coke to breakage and abrasion, both problems in the top of the blast furnace where the sintered iron ore and coke are loaded into the furnace. As it sinks lower into the furnace it heats up, dissolving and reducing the iron ore by the solution loss reaction (Boudouard reaction) which in part provides carbon monoxide to reduce the iron. This reaction consumes coke which at the same time is still required to support the iron ore and maintain a permeable pathway for the gases. Finally the coke descends to the raceway area of the blast furnace where it is totally consumed leaving an unvolatilized ash residue.

As blast furnace operation techniques evolved to make the process more efficient, so also have the techniques used to predict coke performance in blast furnaces. A recognition of the importance of evaluating the performance of coke in the mid-region of the furnace led to the development of a number of hot-coke evaluation tests (Ishakawa, 1983). The most accepted of these measure the coke strength after reaction (CSR) and coke reactivity index (CRI). The CSR test involves measuring the resistance of coke to breakage after it has been reacted in a carbon dioxide atmosphere at a temperature of 1100°C. The CRI test measures the loss of weight after this reaction. The acceptance of the CSR test recognizes the fact that coke performance must be evaluated in all parts of the blast furnace, not just the top, colder regions.

Coke is an expensive component in the steel-making process. It is made in coke ovens that most companies would like to see last as long as possible while they decide which new technology to invest in as a replacement. For both reasons there is incentive to reduce the amount of coke used to produce a ton of hot metal.

In the short term, pulverized coal injection (PCI) is the easiest way of replacing some of the coke used in the blast furnace. This technology provides heat and carbon monoxide but does not help maintain gas permeability in the furnace. This means that the remaining coke must be even stronger if it is going to support the same weight of iron ore. With increased use of PCI, coals with improved hot coke strengths will be required for continued efficient and consistent performance in the furnace. The CSR test will become an even more important measure of coke performance.

Figure 5-1-1 (from Chardon and Barry, 1991) illustrates the projected requirements of coke and PCI in European blast furnaces.

Steel producers are increasingly relying on the CSR values of coal to assess their value, which means that it is now important to know what properties in the parent coal influence the CSR value of coke. Fresh-coal physical properties that influence CSR are rheology, rank, ash content and major oxide chemistry of the ash. Oxidation "damages" the rheological properties of the coal and will result in lower CSR values. It should not be forgotten that the dynamics of the coke making process also influence CSR.

For CSR to be a useful screening test for coals, values of CSR obtained on coke from small test pilot coke ovens must be similar to results obtained on the same coal when it is
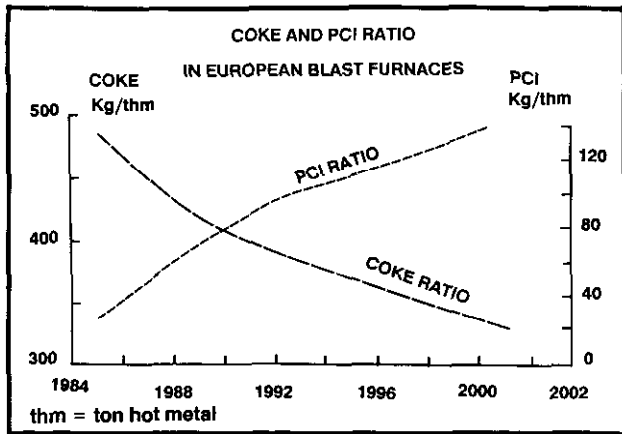
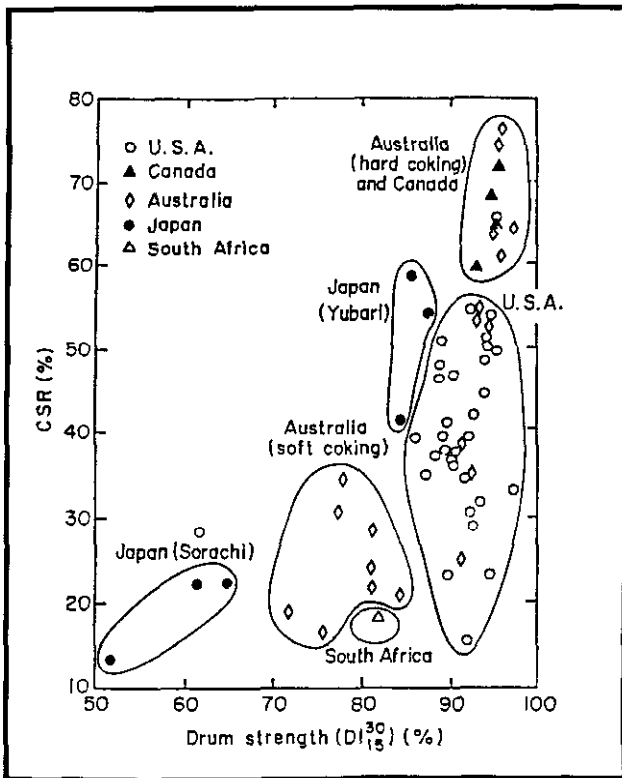Figure 5-1-1. Plot of projected coke and PCI used in European blast furnaces.

Figure 5-1-2. Plot of CSR versus JIS drum strength, adapted from Figure 5-1-1, Pearson (1989) data from Ishakawa (1983).

coked in an industrial coke oven battery. The experience of steel companies confirms that the CSR values obtained on coke from a pilot oven are in fact similar to values obtained on the same mixture of coal coked under similar conditions in an industrial coke battery.

The original comparison of CSR to other coke properties (Ishikawa, 1983) compared CSR to Japanese Industrial Standard (JIS) drum strength (D 30/15; Figure 5-1-2). This latter property is a measure of the resistance of cold coke to breakage and is similar to the ASTM stability factor test. Pearson (1980, Figure 14) illustrates that the ASTM and JIS

tests behave similarly with reference to petrography and rank. It is obvious from Figure 5-1-2 that CSR does not correlate with cold coke tests. One way of interpreting the diagram is to draw a line from the origin through the point providing the maximum slope so that all points are either on or below the line. If one assumes that under ideal conditions all points should plot on the line then there is some factor which is variably degrading CSR values but which has either no effect or constant effect on the cold coke strength. Canadian and Australian hard coking coals have the least degraded CSR values.

This is to some extent an intuitive and not a scientific argument, but it leads to two important conclusions. Firstly, CSR and cold strength values do not necessarily correlate. The blast furnace operator who wants good stability factors and good CSR values will have to perform both tests or have separate procedures available for predicting both values. Secondly, one must look for a coal parameter, one generally not used to predict cold coke properties, to help in predicting CSR values.

TABLE 5-1-1
EQUATIONS RELATING CSR TO COAL PROPERTIES

A: PRICE ET AL

$CSR = 56.9 + 0.08268x(c+d) - 6.86 \cdot (MBI)^2 + 11.47x\bar{R}_{max}$
     based on 33 Western Canadian Coals (Price et al., 1988)
                                    (Equation A)

$CSR = 52.7 + .0882x(c+d) - 6.73x(MBI)^2 + 14.6x\bar{R}_{max}$
     based on 33 Western Canadian and 22 Appalachian coals
                    (Price et al., 1988)

     RELATIONSHIP OF FLUIDITY TO DILITATION
$Log(fluidity) = .994 + 0.0635x(c+d) - 0.00012x(c+d)^2$
          (Price and Gransden, 1987)
     This Equation can be approximated by
          $Log(fluidity) = 0.3891x(c+d)^{0.5894}$
          or
          $(c+d) = 4.97x(Log(fluidity))^{1.695}$

B: BHP AUSTRALIA
$CSR = 133.8 - 15.56xBAR - 3.1xVM + 8.5xlog(fluidity) - 0.22xInerts$
                                    (Equation B)
                    (Pearson, 1989)

C: KOBE STEEL
$CSR = 70.9 x \bar{R}_{max}\% + 7.8 x Log(fluidity) - 89 x BAR - 32$
                                    (Equation C)
                    (Goscinski et al., 1985)

     ABBREVIATIONS
c+d =   total dilatation
MBI =   modified basicity index

MBI = $100xashx(Na_2O + K_2O + CaO + MgO + Fe_2O_3)$
          ─────────────────────────────────────
          $(100 - VM)x(SiO_2 + Al_2O_3)$

$\bar{R}_{max}$ =   Mean maximum reflectance
VM =   per cent volatile matter
ash =   per cent ash
fluidity = maximum fluidity
          in drum dial divisions per minuite (ddpm)
Log =   logarithm to base 10
Inerts = total inert material in sample

CSR PREDICTION

A number authors have investigated the possibility of using coal properties to predict CSR values of coke. Goscinski *et al.* (1985) provide a good summary of some equations that have been developed. Pearson (1989) provides an equation used by BHP Australia. Price *et al.* (1988), have developed an equation for predicting CSR of British Columbia and Appalachian coals using rheology, base-acid ratio and rank. Equations developed by Price *et al.*, BHP and Kobe Steel are outlined in Table 5-1-1.

All three equations introduce ash chemistry as an important variable for predicting CSR. In all probability, ash chemistry is the extra variable that confuses the correlation between cold coke properties and CSR.

The Price Equation (Equation A, Table 5-1-1) uses a modified form of base-acid ratio (modified basicity index; MBI). The rheology term is a measure of total dilatation (c+d, Table 5-1-1), measured using a Ruhr dilatometer. It can be converted to an equivalent value of maximum fluidity measured with a Geisler plastometer using a relationship provided by Price and Gransden (1987). Rank is represented in the equation by the mean maximum reflectance of the coal ($\overline{R}_{max}$).

BHP Australia uses an equation described by Pearson (1989; Equation B, Table 5-1-1), that has some important differences from Equation A. It has terms for base-acid ratio, volatile matter, fluidity and total inerts.

Goscinski *et al.* (1985) provide an equation (Equation C, Table 5-1-1) used by Kobe Steel which is similar to that of BHP but has no term for the amount of inert material in the sample and therefore cannot respond to changes in ash content.

A computer program has been written to calculate CSR values using Equations A, B and C. Equation A was modified to allow for input of either fluidity or dilatation. The program allows for the consideration of the uncertainties attached to each of the input variables (ash per cent, base-acid ratio, volatile matter, $\overline{R}_{max}$ and maximum fluidity). A specific value of each variable is picked from a gaussian distribution of possibilities defined by a mean and standard deviation for the variable. A number of predictions of CSR using one of the equations scatter about a mean CSR with a standard deviation that is a result of the combined effect of the uncertainties of the input variables. This process illustrates the sensitivity of CSR to fluctuations in the values of variables such as base-acid ratio, fluidity,$\overline{R}_{max}$ and ash per cent.

British Columbia product coking coals are characterized by moderate ash levels, low fluidity and low base-acid ratios. A hypothetical British Columbian coking coal is represented by the following properties: ash, 9.5 per cent; $\overline{R}_{max}$, 1.35 per cent; fluidity, 50 drum dial divisions per minute and base-acid ratio, 0.10. Table 5-1-2 indicates the sensitivity of CSR to these variables, as predicted by the three equations. At the starting values the three equations agree well with Equation A predicting the lowest values. This equation is also more sensitive to ash chemistry and less sensitive to rank and fluidity than the other two equations. Figure 5-1-3 illustrates the sensitivity of CSR to

changes in base-acid ratio as predicted by the three equations. A CSR value of 57.5 is usually considered to be an acceptable minimum (Price and Gransden, 1987) and this value is indicated in Figure 5-1-3.

The process of varying a single property while keeping the others fixed is not totally justified because the variables are not independent, but it does give an intuitive feeling of how the variables effect CSR over a limited range.

All three equations only apply to medium and low-volatile bituminous coals. The CSR is generally at a maximum in the range high-volatile bituminous to low-volatile bituminous and decreases either side of this rank window

These coal quality parameters have uncertainties attached to them that derive from measurement errors and also tea variations from shipment to shipment. If the uncertainties are: ash, 9.5 ± 0.5 per cent; fluidity, 50 ± 10 ddpm; $\overline{R}_{max}$, 1.35 ± 0.05 per cent; and base-acid, ratio 0.10 ± 0.03, then the coal is predicted to make coke with CSR values of 64 ± 6.0 (Equation A) 64 ± 6.5 (Equation B), or 68 ± 4.3 (Equation C) at one standard deviation. These ranges in CSR values are acceptable when the mean value is high but could cause problems at lower CSR values.

Price *et al.* (1988), plot actual CSR values against CSR values predicted using Equation A. Data scatter about the best fit line. This scatter is caused by measurement errors in

TABLE 5-1-2
CSR PREDICTIONS USING EQUATIONS FROM TABLE 5-1-1

STARTING COAL

Ash %	9.5
VM %	23.9
Organic Inerts %	30
Max Fluidity ddpm	50.
R_{max}	1.35
BAR	0.10

BAR

Equation	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
A	70.5	67.6	63.8	59.3	53.8	47.1	40.5	32.6
B	64.8	64.5	64.1	63.8	63.5	63.1	62.9	62.6
C	71.6	69.9	68.1	66.3	64.5	62.7	61.0	59.2

R_{max}

Equation	1.15	1.25	1.35	1.45	1.55	1.65
A	60.6	62.3	63.8	65.4	66.9	68.1
B	53.9	59.0	64.1	69.3	74.4	79.5
C	53.9	61.0	68.1	75.2	82.2	89.3

MAX FLUIDIDTY

Equation	5	10	50	100	500	1000
A	60.7	62.3	63.8	65.4	66.9	68.1
B	55.6	58.2	64.1	66.7	72.6	75.2
C	60.3	62.6	68.1	70.4	75.9	78.2

Equations A, B and C from Table 5-1-1
BAR = base-acid ratio
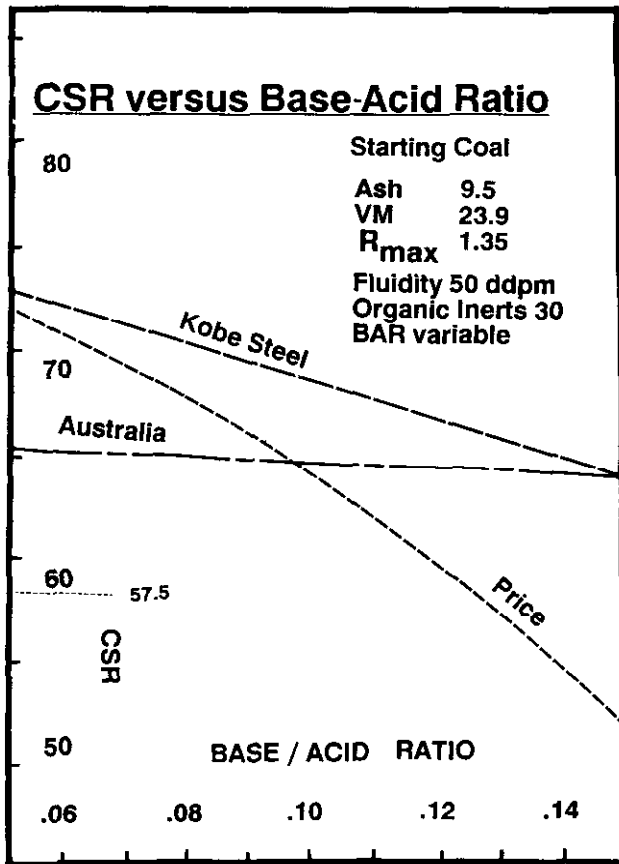
Figure 5-1-3. Plot of CSR versus base-acid ratio illustrating equations in Table 5-1-1.

Figure 5-1-4. Tertiary diagram illustrating coal ash chemistry for British Columbia coals.

actual CSR and by the inability of equation A to precisely predict CSR. The one standard deviation error about the line for the data is approximately ±4.0 CSR units, which is similar to the calculated uncertainty of the predicted CSR values. Within the range of base-acid ratios represented by the samples, the equations can predict CSR well without the introduction of other important variables such as moisture and variations in the coke making process.

ASH CHEMISTRY OF BRITISH COLUMBIA COALS

The major formations in British Columbia that contain reserves of coking coal are the Upper Jurassic to Lower Cretaceous Mist Mountain Formation and the Cretaceous Gates and Gething formations. Possible resources of coking coal exist in the Jurassic Minnes Group and Cretaceous Currier, Comox and Red Rose formations. There is very little coking coal in Tertiary rocks.

Data in this paper illustrate that ash chemistry is probably the most important parameter affecting the CSR of British Columbia coking coals, but coal rank is also important. The rank of coal in the Mist Mountain Formation generally varies from low or medium-volatile bituminous at the base of the formation to high-volatile bituminous at the top. The range in rank in the Gates and Gething formations is similar.
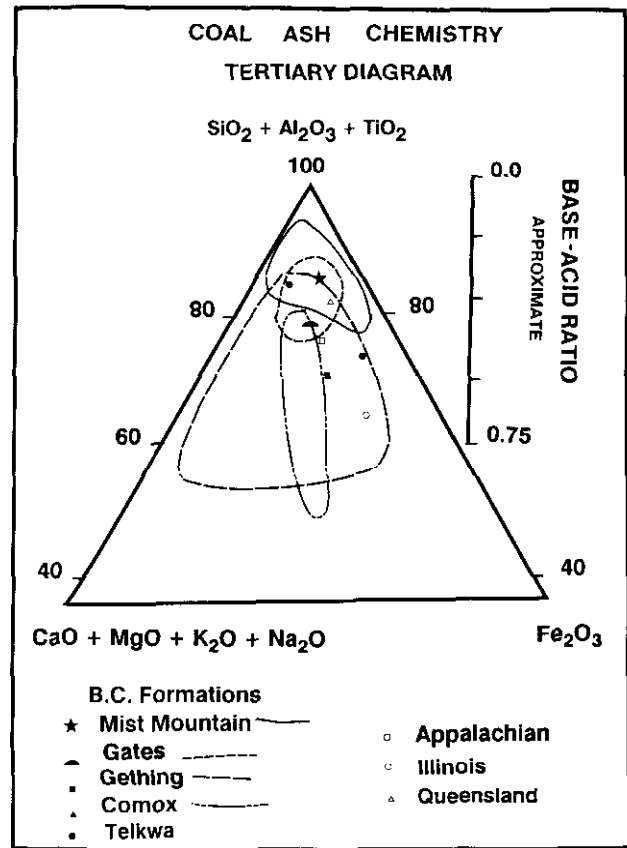
Coal in the Currier Formation varies from low volatile to anthracite. Coal in the Comox Formation is high-volatile bituminous whereas coal in the Red Rose Formation varies from high-volatile bituminous to semi-anthracite. Coal in these formations is generally not coking.

The ranges of base-acid ratio for most of these formations are illustrated in Figure 5-1-4, which is adapted from Figure 3.7 of Matheson (1986). Most coals from formations in British Columbia have base-acid ratios less than 0.3, although some values for the Gething and Comox formations are higher. Data from Pearson (1981) provide average base-acid ratios for the three major coking coal formations of 0.13 for the Mist Mountain Formation, 0.18 for the Gates Formation, and 0.33 for the Gething Formation (Figure 5-1-4 and Table 5-1-3).

In the Mist Mountain Formation it appears that the base-acid ratio increases up section. Data in Table 5-1-3 which are from the lower half of the formation indicate a weak trend towards higher base-acid ratios up section; average values range from 0.057 at the bottom of the section to 0.21 at the top.

Base-acid ratios from the upper coal-bearing section at Telkwa (Red Rose Formation) vary from 0.13 at the base of the coal section to 0.33 at the top (Table 5-1-3). A single analysis for the lower coal-bearing section provided a value of 0.05, indicating that the lower section might have coking

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Jura-Cretaceous Coking Coal Formations

Formation	Base-acid ratio	% S.D	Count
Mist Mountain	0.128	56	8
Gates	0.179	28	11
Gething	0.326	56	7

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Mist Mt	53.3	30.9	1.5	6.2	2.8	0.8	0.15	1.05
Gates	54.5	22.6	1.7	7.0	4.3	1.26	0.75	0.77
Gething	47.2	22.4	1.2	13.4	4.9	1.4	1.1	0.96

Data from Pearson (1981)

Formation	Base-acid ratio	% S.D	Count
Red Rose Formation Upper Coal-bearing section at Telkwa			
Top	0.327	49	4
	0.16	69	24
Base	0.13	25	10

Mist Mountain Formation Lower Section

top	0.213	89	8
	0.07	14	4
	0.094	35	8
	0.09		3
	0.077	60	5
	0.075	45	20
Base	0.057	28	4

Data from assesment reports
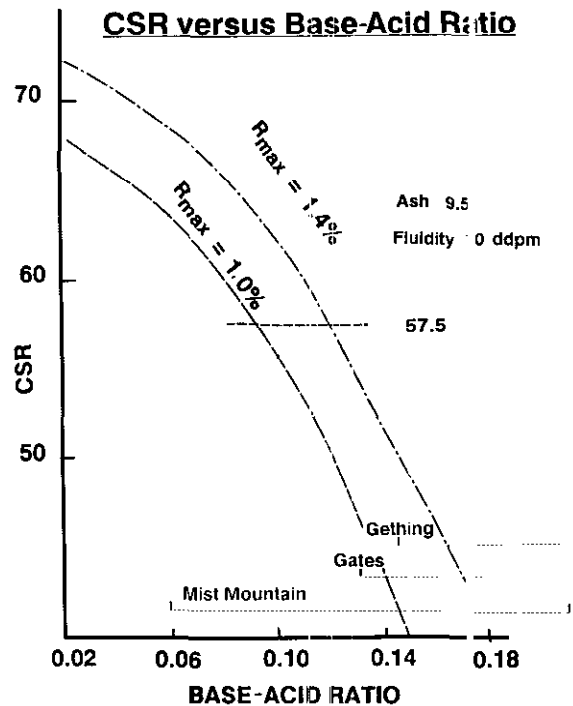*S.D. = standard deviation*

Figure 5-1-5. Plot of CSR versus base-acid ratio as predicted by Equation A for a coal with 9.5 per cent ash and a fluidity of 10 ddpm.
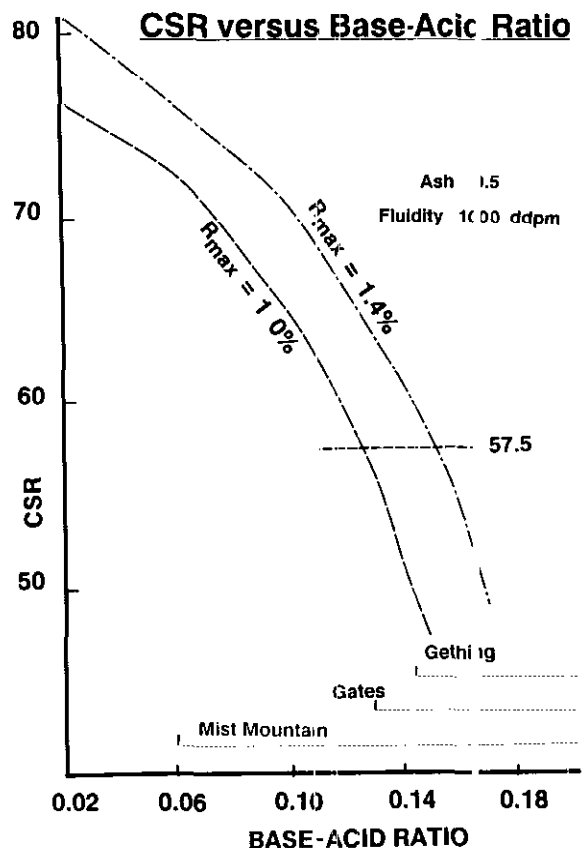
Figure 5-1-6. Plot of CSR versus base-acid ratio as predicted by Equation A for a coal with 9.5 per cent ash and a fluidity of 1000 ddpm.

coal potential in areas where the rank is medium-volatile bituminous or higher.

Most of the coal in the Currier Formation is non-agglomerating because of the high rank. Some coal in the Comox Formation is reported to have good fluidity (Bickford and Kenyon, 1988), but the rank of high-volatile bituminous and moderately high base-acid ratios probably means that the coal will make a weak coke with low CSR values.

Coal in most of the Tertiary coal basins is not coking. One exception is the Seaton coal basin near Smithers which has base-acid ratios averaging 0.16.

PREDICTED CSR VALUES OF BRITISH COLUMBIA COKING COALS

The low base-acid ratios of coal from the Mist Mountain, Gates and Gething formations ensure that, despite low fluidity, cokes from British Columbia coking coals will generally have good CSR values.

Equation A is used to predict ranges of CSR values for possible British Columbian coking coals with 9.5 per cent ash. Figures 5-1-5 and 5-1-6 illustrate the relationship of base-acid ratio to CSR for different values of $\bar{R}_{max}$ when the

fluidity is kept constant at 10 ddpm (Figure 5-1-5) and 1 000 ddpm (Figure 5-1-6). The ranges of base-acid ratio for the Mist Mountain, Gates and Gething formations are indicated on the figures. The CSR value of 57.5, which is an acceptable minimum value for coke (Price and Gransden, 1987), is also plotted on the figures. It is apparent that if the base-acid ratio is greater than 0.20 then the coals must be cleaned to an ash much lower that 9.5 per cent to obtain an acceptable CSR value.

The sample to sample variability of base-acid ratios is considerable (Table 5-1-3) and standard deviations are usually greater than 30 per cent. Figure 5-1-7 illustrates how a standard deviation of 30 per cent in base-acid ratio affects the scatter of possible CSR values. What appear to be insignificant changes in low to very low base-acid ratios from one coal batch to the next can cause major changes in CSR.

It is important to recognize which mineral phase in the coal is responsible for causing most of the variation in CSR values. Blast furnace operators require consistent coke quality. Anything that the mine operator can do to ensure this will make the coal more saleable.

The effect that variations in the concentration of an individual mineral phase have on the base-acid ratio of an ash depends on three things;

- the amount of the mineral already in the coal;
- the percentage of the mineral that remains in the ash as oxides after ashing;
- the base-acid ratio of the mineral.

For example, all the quartz in the coal will remain in the ash as SiO_2 and it has a base-acid ratio of 0.0 but because there is usually a lot of SiO_2 in the ash, removal or addition of small amounts of quartz will not have much effect on the base-acid ratio of the ash.
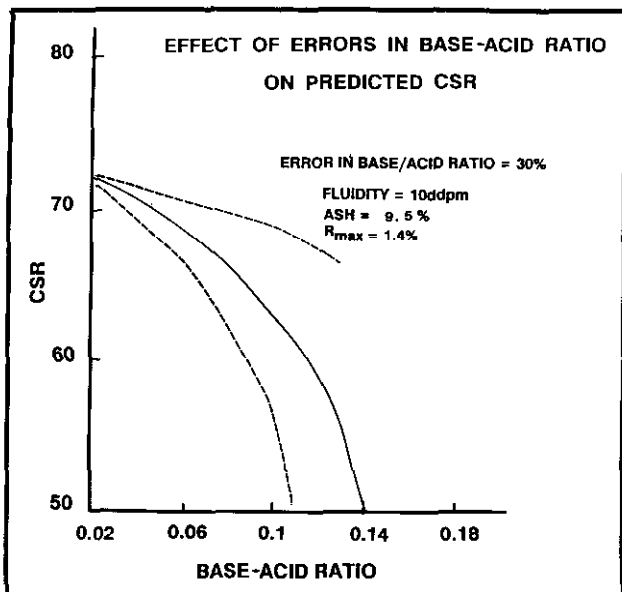
On the other hand pyrite in the coal will contribute all its iron (46.5 weight %) to the ash as Fe_2O_3 and this will have a base-acid ratio of infinity. If the iron content in the ash is not high then small changes in the pyrite concentration of the coal will cause large changes in the base-acid ratio of the ash. The situation is similar for carbonates; for example the calcium in calcite (40 weight %) will remain in the ash as CaO and it has a base-acid ratio of infinity.

Table 5-1-4 illustrates the effect of addition of small amounts of pyrite or carbonate on CSR. For a typical cleaned southeast British Columbia coal with 0.5 per cent sulphur (1.0% or less visible pyrite) a 0.2 per cent increase in pyrite will result in a 12 per cent increase in base-acid ratio and a decrease in CSR of 3 points. Similarly a 0.1 per cent increase in calcite in the coal will result in a 6.0 per cent change in base-acid ratio. Obviously apparently insignificant changes in the pyrite or calcite content of the raw coal can result in surprisingly large changes in CSR.

Minerals such as illite fall midway between quartz and pyrite in terms of their effect on the base-acid ratio of the ash. About 90 weight per cent of the illite remains in the ash

TABLE 5-1-4
EFFECT OF SOME MINERAL ADDITIONS TO COAL ON THE BASE-ACID RATIO OF THE ASH AND ON THE CALCULATED CSR VALUE

STARTING COAL

Ash	=	10 %
BAR(Base-acid ratio)	=	0.10 %
Sulhpur	=	0.5 %
R_{max}	=	1.4 %
Fluidity	=	10 ddpm

EFFECT OF ADDITION OF PYRITE
Pyrite = 46.5 % Fe and 53.5 % Sulphur

Add 0.19 % pyrite to sample
Sulphur of sample increases by 0.1 %
Iron concentration of the sample increases by 0.087 %
This reports to the ash as a 1.24 % increase in Fe_2O_3
BAR to change from 0.10 to 0.112
This causes CSR to decrease from 61.2 to 58.3

If pyrite increases by 0.93 % then sulphur increases 0.5 %
BAR changes from 0.10 to 0.167
This causes CSR to decrease from 61.2 to 41.4

EFFECT OF ADDITION OF CALCITE
Calcite is 56.0 % CaO 44.0 % CO_2

Add 0.1 % calcite to sample
This provides 0.056 % CaO to the coal or 0.56 % to the ash
BAR increases from 0.10 to 0.105
This causes CSR to decrease from 61.2 to 59.8

Addition of 0.5 % calcite to sample
BAR increases to 0.125
This causes CSR to decrease from 61.2 to 55.0

Figure 5-1-7. Plot of the effect of 30 per cent plus or minus errors in base-acid ratio on predicted CSR.

as oxides, but it has a base-acid ratio of about 0.2 which is not markedly different from the composite base-acid ratio of many ashes. Therefore generally small fluctuations in the concentration of illite will not cause major changes in the ratio of the ash.

Correlation analysis of ash oxide data from the lowermost seam in the Mist Mountain Formation indicates that much of the variability of base-acid ratios is related to changes in iron oxide concentrations. The best base-acid ratio versus oxide correlation is for Fe_2O_3 (Table 5-1-5). The iron oxide is negatively correlated with sulphur. Obviously not all of the iron is in the coal as pyrite.

The sulphur content of samples from this seam averages 0.43 and most of it is organic. It appears that as the organic sulphur content increases the iron content decreases. The iron oxide is correlated with calcium and magnesium oxides, indicating either a carbonate or mixed-layer clay

TABLE 5-1-5
CORRELATION MATRIX FOR BASE-ACID RATIOS AND OXIDE DATA

MIST MOUNTAIN FORMATION BASE SEAM (19)

	Fe₂O₃	CaO	MgO	Na₂O	K₂O	S
BAR	.954	.942	.819	.032	-.45	-.524
Fe₂O₃		.850	.700	-.041	-.56	-.35
CaO			.830	-.120	-.53	-.56
MgO				-.170	-.38	-.47
NaO					.31	-.07
K₂O						-.19

GATES FORMATION (11)

	Fe₂O₃	CaO	MgO	Na₂O	K₂O	S
BAR	.842	.865	.845	.489	-.180	ND
Fe₂O₃		.497	.697	.179	-.089	ND
CaO			.661	.657	-.332	ND
MgO				.227	.046	ND
Na₂O					-.735	ND

GETHING FORMATION (7)

	Fe₂O₃	CaO	MgO	Na₂O	K₂O	S
BAR	.635	.445	.720	.108	-.362	ND
Fe₂O₃		-.408	-.05	-.595	.064	ND
CaO			.906	.819	-.500	ND
MgO				.575	-.324	ND
NaO					-.639	ND

RED ROSE FORMATION AT TELKWA (66)

	Fe₂O₃	CaO	MgO	Na₂O	K₂O	S
BAR	.802	.366	.4030	-.003	-.058	.681
Fe₂O₃		-.24	-.038	-.004	.2390	.930
CaO			.6290	-.072	-.555	-.33
MgO				.0050	-.213	-.19
Na₂O					.2260	-.02
K₂O						.282

BAR = Base-acid ratio
$$BAR = (Fe_2O_3 + CaO + MgO + K_2O + Na_2O) / (SiO_2 + Al_2O_3 + TiO_2)$$
Numbers in parentheses after formation names = data count

origin. Normative calculations indicate that variations in base-acid ratio are probably related to changes in the ow concentration of iron carbonate and possibly pyrite.

Base-acid ratios for the Gates Formation Table 5-1-5 correlate with iron, calcium and magnesium oxides. Variations in the base-acid ratios are probably caused by variations in the amount of calcite and to a lesser extent clays Base-acid ratios for the Gething Formation correlate best with magnesium oxide, possibly indicating a chlorite/clay influence on variability in ratios. Iron oxide has a negative correlation to calcium oxide in the Gething Formation Pearson (1981) did not report sulphur data for these formations although sulphur contents of washed Gates coals are typically less than 0.5 per cent.

Correlation analysis of base-acid ratio and oxide data for coal from the upper coal-bearing section in the Telkwa basin (Table 5-1-5) indicates that variations in base-acid ratios correlate with changes in iron and sulphur concentrations. Changes in the pyrite content must be influencing the variability in base-acid ratios. Normative calculations indicate that most of the iron is present as pyrite with minor amounts present in clays and carbonates.

Iron oxide seems to be one of the most important base oxides responsible for variations in base-acid ratio. Three possible mineral hosts for the iron are pyrite mixed-layer clays and carbonates. It is obviously important to know the mineral form of the iron. Low-temperature ashing of the coal and x-ray diffraction analysis of the residue mineral matter may be a way of identifying changes in the iron carbonate or pyrite content. Using this information it might be possible to influence the base-acid ratio and CSR values by changing the way the coal is mined or washed.

Some coal-washing plants now have on-line radioactive ash monitors that can also detect variations in iron content. Data from these instruments could be used to provide real-time estimates of the CSR values of the coal as it is washed.

A plot of iron versus sulphur in the total coal can help indicate if the iron is mostly in pyrite and can also indicate if there is excess sulphur or excess iron after accounting for pyrite in the coal. If all the iron and sulphur are in the coal as pyrite then the plot should produce a straight line with a slope of 0.871. If iron is in excess then carbonate or clay hosts are probable, and if sulphur is in excess then a pyrite host is probable. Iron in pyrite is probably most responsible for fluctuations in base-acid ratios. Iron versus sulphur data for the Mist Mountain and Red Rose formations are plotted in Figure 5-1-8. Coals from both formations have excess sulphur although the Red Rose (Telkwa) coals have the most.

Actual CSR values of clean coals are generally not published for obvious reasons, but there are sufficient data in the literature to make some estimates. Ash chemistry and rank data for many production coals are available in Price and Gransden (1987). Base-acid ratios for coals from the mines in southeast British Columbia range from 0.06 to 0.11 with Byron Creek higher at 0.285. Values for mines in the northeast range from 0.10 to 0.22. Values for metallurgical coals from Alberta range from 0.127 to 0.22.

IRON VERSUS SULPHUR
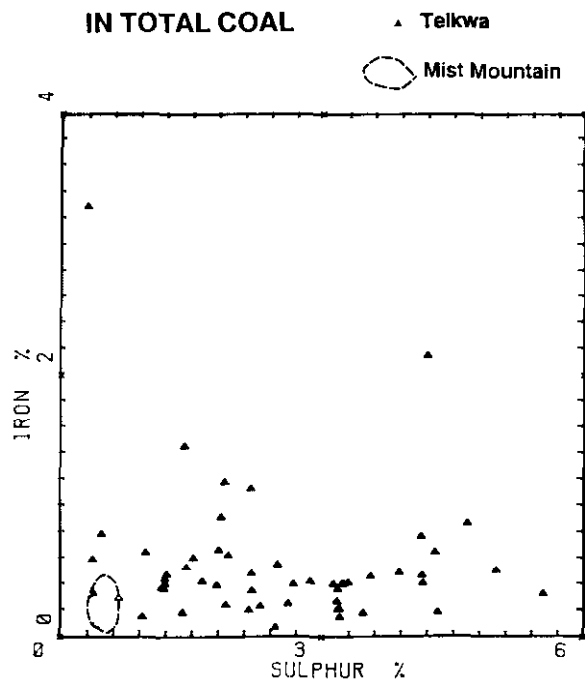
IN TOTAL COAL

▲ Telkwa

◯ Mist Mountain

Figure 5-1-8. Plot of iron versus sulphur in Telkwa and
Mist Mountain coal.

COMPARISON OF BRITISH COLUMBIA COALS TO OTHER CANADIAN AND INTERNATIONAL COALS

Most Upper Jurassic to Cretaceous coals of British Columbia formed in an environment with very little marine influence. Mineral matter in coal is therefore rich in kaolinite and quartz and has low base-acid ratios. In contrast, most of the bituminous coals in eastern North America formed in paralic environments. The marine influence caused moderate to high pyrite and illite contents, ensuring higher concentrations of iron, potassium and sodium in the ash compared to western Canadian coals.

Base-acid ratios for the Carboniferous coking coals from eastern Canada and eastern U.S.A. are reported in Table 5-1-6. Base-acid ratios of Nova Scotia coals are high, averaging 1.05 (average of 24 analyses reported by Cape Breton Development Corporation in Faurschou *et al.*, 1982) because of high iron oxide contents. The base-acid ratios of eleven Carboniferous coals from Illinois average 0.49±0.11 and seven coking coals from the Appalachian region average 0.23±0.05 (Abernethy *et al.*, 1969).

Eleven coking coals from Queensland, Australia have base-acid ratios averaging 0.21±0.014 (Queensland Coal Board, 1975). This is somewhat higher than base-acid ratios for the Mist Mountain and Gates formations in British Columbia. It appears that some Australian Permian coals are similar to British Columbian coals but that they may contain slightly higher concentrations of iron.

In general eastern Canadian and eastern U.S.A. bituminous coals have high to very high fluidities and wash to a

Location	Base-acid ratio	% S.D.	Count
Nova Scotia	1.05	90	24
Appalachian	0.23	22	7
Illinios	0.49	22	11
Queensland	0.21	69	11

APPALACHIAN COKING COALS (7)

	Fe_2O_3	CaO	MgO	Na_2O	K_2O	S
BAR	.773	.687	.805	.102	-.214	.45
Fe_2O_3		.226	.354	-.144	-.081	.735
CaO			.68	-.103	-.731	.081
MgO				.405	-.141	.051
Na_2O					.503	-.306
K_2O						-.178

AVERAGE OXIDE ANALYSIS (7)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	S
47.2	28.8	10.0	3.23	1.44	0.73	1.97	0.79

QUEENSLAND COKING COALS (11)

	Fe_2O_3	CaO	MgO	Na_2O	K_2O	S
BAR	.167	.931	.753	.113	-.06	.143
Fe_2O_3		-.19	.099	.525	.185	.064
CaO			.673	-.134	-.173	.139
MgO				.400	-.236	-.175
Na_2O					.21	-.353
K_2O						-.180

AVERAGE OXIDE ANALYSIS (11)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	S
50.0	30.2	7.71	5.78	.76	0.5	0.68	0.58

% S.D. = per cent standard deviation
BAR = Base-acid ratio
Note: S is sulphur content in coal sample; oxides are per cent values in ash.

lower ash than western Canadian coals. The improved fluidities are not sufficient to overcome the detrimental effects of high base-acid ratios which will usually ensure that these coals produce cokes with lower CSR values than British Columbia coals.

Equation A was developed using British Columbia and Appalachian coals, which generally do not have base-acid ratios greater than 0.30. The equation cannot be used to predict meaningful CSR values for Nova Scotia coals.

Correlation analysis of the ash oxide data from Appalachian coals (Table 5-1-6) indicates that base-acid
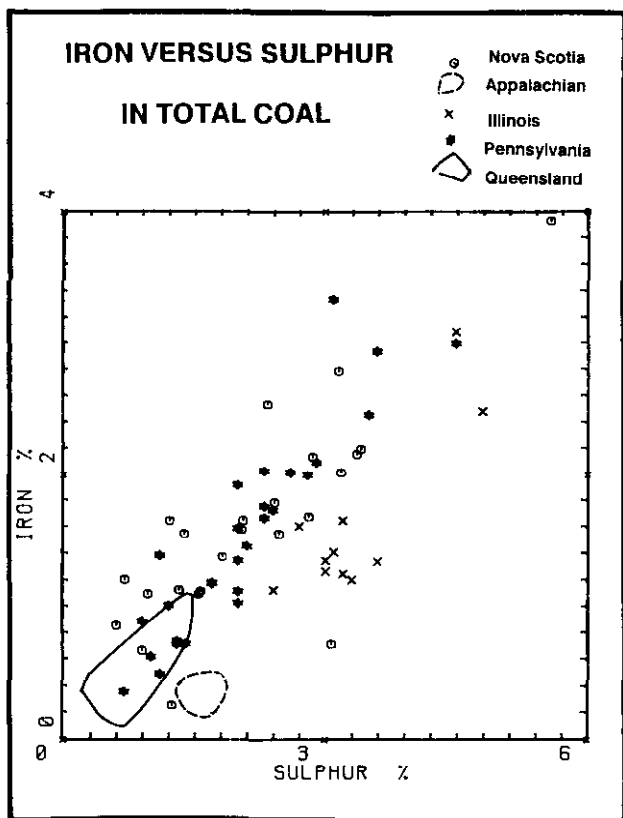
Figure 5-1-9. Plot of iron versus sulphur in some
Canadian and international coals.

ratio correlates with iron, calcium and magnesium oxides and that iron oxide correlates with sulphur. Apparently most of the iron is in pyrite and the calcium and magnesium is in clays. In contrast to British Columbia coals calcium oxide correlates with base-acid ratios for the Queensland coals, possibly indicating a carbonate influence on base-acid ratio.

A plot of iron oxide versus sulphur concentrations (Figure 5-1-9) for Pennsylvania and Nova Scotia coals produces linear trends with data plotting near the pyrite line. Data from Illinois and Appalachian coals plot to the right of the pyrite line and indicate excess sulphur.

Base-acid ratios of eastern Canadian and eastern U.S.A. coals are high mainly because of varying amounts of pyrite and possibly iron carbonates. The coals do wash to a low ash and this provides flexibility for blending with British Columbia coals to reduce base-acid ratios.

BLENDING FOR IMPROVED CSR

Recent work investigated the effect on CSR values of coke of adding specific minerals to the parent coal samples (Price et al., 1992). The addition of minerals such as calcite, pyrite and quartz changed the base-acid ratios of the doped coal sample and produced a change in the CSR values of the resultant coke. The CSR values were changed generally in amounts predicted by changes in the base-acid ratios and Equation A. This suggests that CSR values of coal blends can be estimated using the calculated blended base-acid

ratio as long as there is not a wide disparity of rank or rheology.

Equation A predicts that CSR decreases nonlinearly as base-acid ratio increases (Figure 5-1-3). This means that there will be a better than additive improvemen in CSR i° a high base-acid ratio coal is blended with a low base-acid ratio coal. Table 5-1-2 can be used to provide an example. If two coals A (57% of blend) and B (43% of blend) with BAR/CSR values of 0.06/70.5(A) and 0.20/32.5(B) (line 1, Table 5-1-2) are mixed, then the resulting BAR/CSR values are 0.12/59.3. This is an 82 per cent improvement in the CSR value of coal B and the blend has an acceptable CSR value. There is adequate flexibility to produce blends with good CSR values for the range of base-acid ratios of British Columbia coals.

The study by Price et al. (1992) also indicated that the mineral used to produce a change in CSR also had an effect on the CSR value independent of its effect on base-acid ratio. Thus if the base-acid ratio was changed a constant per cent by addition of the appropriate amount of apatite, gypsum, calcite or lime, the decrease in CSR value depended on the mineral (least for apatite most for lime). Similar results were observed for iron. Siderite addition had less effect than pyrite addition which had les effect than adding iron oxide.

This has interesting implications when considering the effect of weathering on CSR. For a property so dependent on ash chemistry one might expect it to be resistant to weathering, which mainly affects coal, not mineral matter. This is not the case, and an answer might be that weathering changes the form of some of the base oxides. For example, pyrite weathers to iron sulphate and in this way increases the detrimental effect of the ash on CSR without actually changing the base-acid ratio.

DISCUSSION

Coke strength after reaction is an important measure of coke quality, especially at a time when the ratio coke(kilogram)/ton hot metal is being decreased by the use of pulverized coal injection (PCI).

A sensitivity analysis using an empirical equation that predicts CSR values provides for a better understanding of the relative importance of ash content, base-acid ratio, rank and fluidity in influencing the resultant CSR. The base-acid ratio of the coal is one of the most important coal properties effecting the CSR of the resultant coke.

Correlation analysis of ash oxide data can indicate which oxides are responsible for variations in base-acid ratio. It then becomes important to identify the mineral host for these oxides. This can be achieved using correlation analysis, iron-sulphur plots, normative calculations or low-temperature ashing combined with x-ray diffraction. Often variations in base-acid ratio are correlated with variations in iron oxide concentration, probably present as pyrite or an iron carbonate. This information may lead to ways of selecting or washing run-of-mine coal for improved CSR.

On-line ash analyzers in coal wash-plants may be able to measure changes in iron content. From these data it might be possible to predict fluctuations in the CSR values of the clean coal before it reaches the customer.

Estimated values of CSR for coal from the major coal-bearing formations in British Columbia are good to excellent. Producers of British Columbian coking coals are fortunate: they generally have base-acid ratios which are lower than the competitor coals in the rest of Canada and in U.S.A. This is an important advantage that should help improve the marketability of British Columbia coals.

Data suggest that for coals with low to moderate base-acid ratios there is a better than additive advantage to blending for improved CSR.

There is a mineralogical influence on CSR which may help explain why CSR is sensitive to weathering while also being strongly dependent on ash chemistry.

CONCLUSIONS

- It is possible to predict CSR values using Equation A and these values compare favourably with measured values.
- For a limited range of bituminous coking coals base-acid ratio is one of the most important factors controlling CSR.
- British Columbia coals generally have good to excellent CSR values.
- It may be possible to predict the CSR of a coal blend using the calculated composite base-acid ratio.
- Because CSR decreases non-linearly with increasing base-acid ratio there is a better than additive advantage to blending for improved CSR.

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