CIM SECOND TECHNICAL CONFERENCE ON WESTERN CANADIAN COALS

Energy, Mines and Resources Canada / Énergie, Mines et Ressources Canada

PAPER NO. 10

CANMET

Canada Centre for Mineral and Energy Technology

Centre canadien de la technologie des minéraux et de l'énergie

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December 1981

ENERGY RESEARCH PROGRAM
ENERGY RESEARCH LABORATORIES
REPORT ERP/ERL 81-83(TR)

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by

J.F. Gransden* and J.T. Price**

ABSTRACT

Four western Canadian coals were cleaned to three ash contents in pilot-scale heavy-media cyclone, water cyclone, and flotation circuits. Two of the coals had an ASTM rank of medium volatile bituminous, one was high volatile bituminous and one was low volatile bituminous. Ash reduction was in the range 2.9 - 4.8% and this was insufficient to affect the free swelling indices of 3 of the 4 coals. Other thermal rheological properties, the Gieseler maximum fluidity and Ruhr dilatation increased as ash was removed from the coals. Petrographic analysis revealed that coal cleaning had enriched vitrinite in the clean coal products of at least two of the coals.

Cokes were made in 460-mm and 310-mm width pilot-scale ovens. Stability factors increased as ash decreased at rates in the range of 1.6 - 4.7 stability points per one percent ash. This was accompanied by higher coke hardness factors, smaller mean size of the cokes, and less coke reactivity to carbon dioxide. The removal of large shale particles appeared responsible for the substantially increased strength of coke made from one coal. Coke microscopy showed that ash reduction did not affect substantially the types of optical anisotropy in the cokes.

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INTRODUCTION

Coal is cleaned before cokemaking to reduce the ash and sulphur content of the coke entering the blast furnace where they decrease productivity. Ash decreases productivity not only because it requires heating and fluxing but also because it reduces coke quality. For example coke strength and abrasion resistance is decreased, reactivity to oxidizing gases is increased and the coke size distribution is widened (1,2).

The magnitude of these effects for western Canadian coal are, in general, unknown. Some results have been published by this laboratory, for a low- and a medium volatile coal using laboratory-cleaned coal. Technical-scale coke oven results were only obtained for the low-volatile coal and showed that reducing the ash content by 45% increased the stability factor by 29 points, and increased the coking pressure from 7.3 to 14.7 kilopascals. Surprisingly the thermal rheological properties of the coal showed no or little change. Considerable improvement in these properties was found however when the medium-volatile coal was cleaned (3).

The present program was carried out to obtain data on how reduction of mineral matter in western Canadian coals by methods that simulate commercial cleaning, affect the thermal rheological properties of the coal its petrographic analysis, carbonization behaviour, and the quality of its coke. The results should be of use in the cleaning of coals, selecting coal ash contents for resource evaluation and predicting coke quality from rheological properties. The economic aspects of coal cleaning are not considered, but it is hoped the information may assist in developing traditional and new markets for Canadian coals.

The project was sponsored jointly by CANMET which paid for the coal cleaning and the Canadian Carbonization Research Association. Coal companies donated their coal and were asked to specify a 'commercial' ash content, or, for coals not in production, what they considered to be a 'commercial' ash content. The coals were cleaned to this ash content and to two other levels of ash selected in conjunction with the company, one below and one above the 'commercial' level.

COAL CLEANING

The coals were cleaned by Birtley Coal and Minerals Testing, Calgary, Alberta. The bulk samples of raw coal were homogenized and a sample taken for sink-float analysis. Washability curves were determined on the 19 x 0.6 mm and 0.6 x 0.21 mm size fractions. The following is a summary of the method of pilot plant washing carried out by Birtley.

Plus 19 mm coal is crushed in a jaw crusher. The 19 x 0.6 mm mesh coal is slurried with a magnetite-water slurry of the required specific gravity and fed to the 356 mm DSM heavy media cyclone. The overflow (clean coal) and underflow (shale) are washed with water sprays to remove the magnetite and collected in barrels.

The 0.6 x 0 mm coal is fed to a 152 mm DSM water-only primary cyclone set for the desired ash content with the aid of an adjustable vortex finder. The overflow is directed to a 0.25 mm rapped sieve bend, the oversize constituting the cleaned product which proceeds to the Eimco disc filter for dewatering. The primary cyclone underflow with make-up water is fed to the secondary 102 mm cyclone the overflow of which is directed back to the feed of the primary cyclone and the underflow of which is the waste product of the circuit.

The underflow from the sieve bend proceeds to the froth flotation circuit. First it passes through a thickening cyclone which removes the undesirable -325 mesh slimes (the overflow which reports to the waste product) and provides a feed of correct density for the froth cells. These are two Birtley-Humboldt Multi-Wobble cells in series. The reagents used are kerosene and methylisobutylcarbinal in the ratio 4 to 1 applied at the feed entry point. The froth is directed to the disc filter along with the clean product from the water-only cyclone circuit while the tails enter the waste product. The filter cake is air-dried at 20°C on a heated pad to less than 12% moisture then combined and thoroughly homogenized with the clean coal from the heavy-media circuit.

The feed, product and waste of each circuit and in addition the sieve bend overflow and underflow, the filter cake and the cyclone overflow and underflow are sampled and the ash content determined.

The four coals, A, B, C and D, were each cleaned to three ash contents. Details of circuit yields and ash content of the circuit clean coal and reject are given in Appendix A.

Table 1 summarizes the ash content and free swelling index of the raw and cleaned coals and the yields of clean coal obtained. As required the differences between the high and low ash products is not excessive i.e., 2.7, 3.6, 6.3 and 4.1% for coals A, B, C and D respectively. The cleaned products from a particular coal had identical free swelling indices except for those from coal D which had indices of 6, 7 and 8 for the high, medium and low ash content products. The ash contents of the cleaned coal and the free swelling indices appearing in Table 1 were determined by Birtley and are in good agreement with those obtained later by CANMET and which are used throughout the remainder of this report.

Table 1 - Ash content, yield and free swelling index of the cleaned coals (Birtley results)

	Raw coal	High ash	Medium ash	Low ash
Coal A				
*ash, %	13.7	8.5	7.3	5.8
yield clean coal, %	-	87.3	73.4	69.7
F.S.I.	7	7	7	7
**specific gravity	-	1.60	1.49	1.40
Coal B				
*ash, %	8.9	6.8	5.1	3.2
yield clean coal, %	-	95.8	88.6	82.2
F.S.I.	8	8½	8½	8½
**specific gravity	-	1.63	1.56	1.25
Coal C				
*ash, %	27.9	9.3	6.6	5.0
yield clean coal, %	-	67.7	62.0	54.9
F.S.I.	7	8½	8½	8½
**specific gravity	-	1.45	1.30	1.22
Coal D				
*ash, %	14.2	10.6	8.4	6.5
yield clean coal, %	-	85.6	69.4	51.4
F.S.I.	4	6	7	8
**specific gravity	-	1.37	1.28	1.22

*air-dried basis

**specific gravity of heavy-media cleaning circuit

COAL PROPERTIES

The rank and proximate analysis of the cleaned coal samples are given in Table 2 and their ultimate and ash analysis in Appendix B. Coals A and B have a ASTM rank of medium volatile bituminous (mvb), Coal C is high volatile A bituminous (hvAb) and Coal D is low volatile bituminous (lvb). The average fixed carbon content of the Coal D samples is 78.4% (dmmf) which is close to the dividing point between lvb and mvb, 78%.

Table 2 - Rank and proximate analysis of cleaned coals

	Coal A			Coal B			Coal C			Coal D		
Ash	High	Med.	Low	High	Med.	Low	High	Med.	Low	High	Med.	Low
ASTM rank	mvb	mvb	mvb	mvb	mvb	mvb	hvAb	hvAb	hvAb	lvb	lvb	lvb
International system	431	431	432	432	433	433	633	634	634	421	432	433
Carbon (dmmgb)	89.1	88.8	88.8	91.7	90.8	90.9	86.8	86.5	86.2	92.0	91.4	90.9
Proximate analysis (db)												
Ash %	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
Volatile matter	24.8	25.1	25.8	22.9	23.5	23.8	30.6	32.2	30.2	19.6	20.4	21.2
Fixed carbon	67.0	67.8	68.9	69.2	70.8	73.1	59.8	61.2	64.7	69.2	70.7	72.0

The thermal rheological properties of the samples are shown in Table 3. The Gieseler maximum fluidity increased as ash was removed from the coals except for the medium and high ash samples of Coal A which had similar fluidities, Fig. 1. The melting range of the coals also increased as ash was removed as did the total dilatation, (c+d), in the Ruhr dilatometer, Fig. 2.

Table 3 - Thermal rheological properties of the cleaned coals

	Coal A			Coal B			Coal C			Coal D		
Ash, %	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
F.S.I.	5	5½	7	7	8	8	8	8½	8½	3½	5	7½
Gieseler Plast												
Start, °C	445	444	441	434	432	430	414	412	409	449	446	441
Fusion temp, °C	-	-	-	448	447	444	428	427	425	466	449	453
Max fluid temp, °C	460	462	461	467	468	466	452	453	452	475	476	473
Final fluid temp, °C	467	472	476	489	491	494	479	479	479	488	493	496
Solid temp, °C	480	480	485	494	498	497	483	483	483	495	500	501
Melting Range, °C	22	28	35	55	59	64	65	67	70	39	47	55
Max F, dd/m	2.6	2.5	4.8	72	101	120	495	655	645	7.5	19	58
Dilatation												
Softening temp, °C	415	417	415	402	402	395	381	377	380	416	412	405
Max cont temp, °C	462	462	457	452	447	447	429	427	430	466	455	443
Max dilat'n temp, °C	-	-	471	473	474	472	458	459	460	-	482	475
Contraction, c, %	24	22	26	25	25	24	32	30	30	15	21	25
Dilatation, d, %	Nil	Nil	-24	-14	9	13	47	53	58	Nil	-3	21
c + d, %	0	0	2	11	34	37	79	83	88	0	18	46

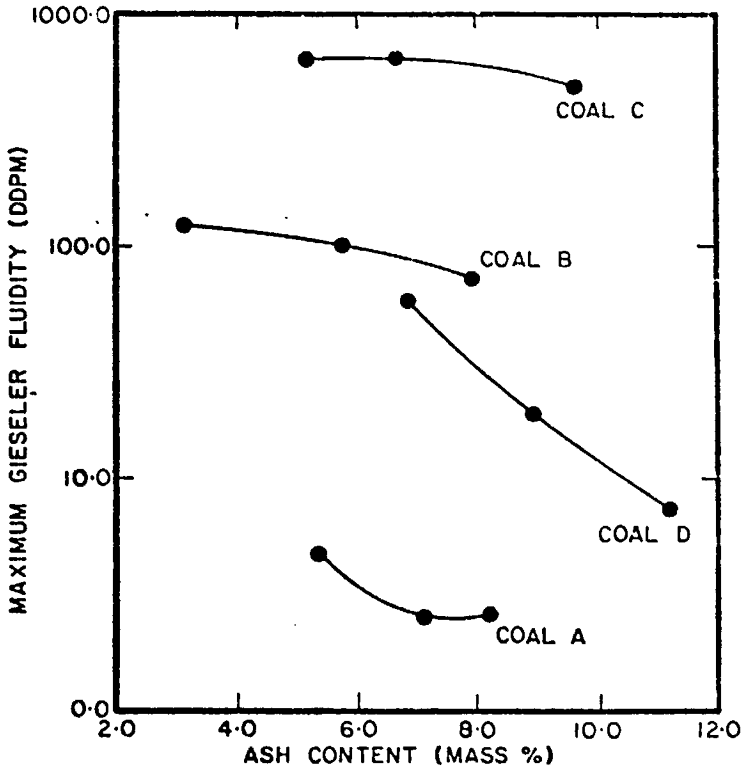

Fig. 1 - Coal maximum fluidities versus ash content

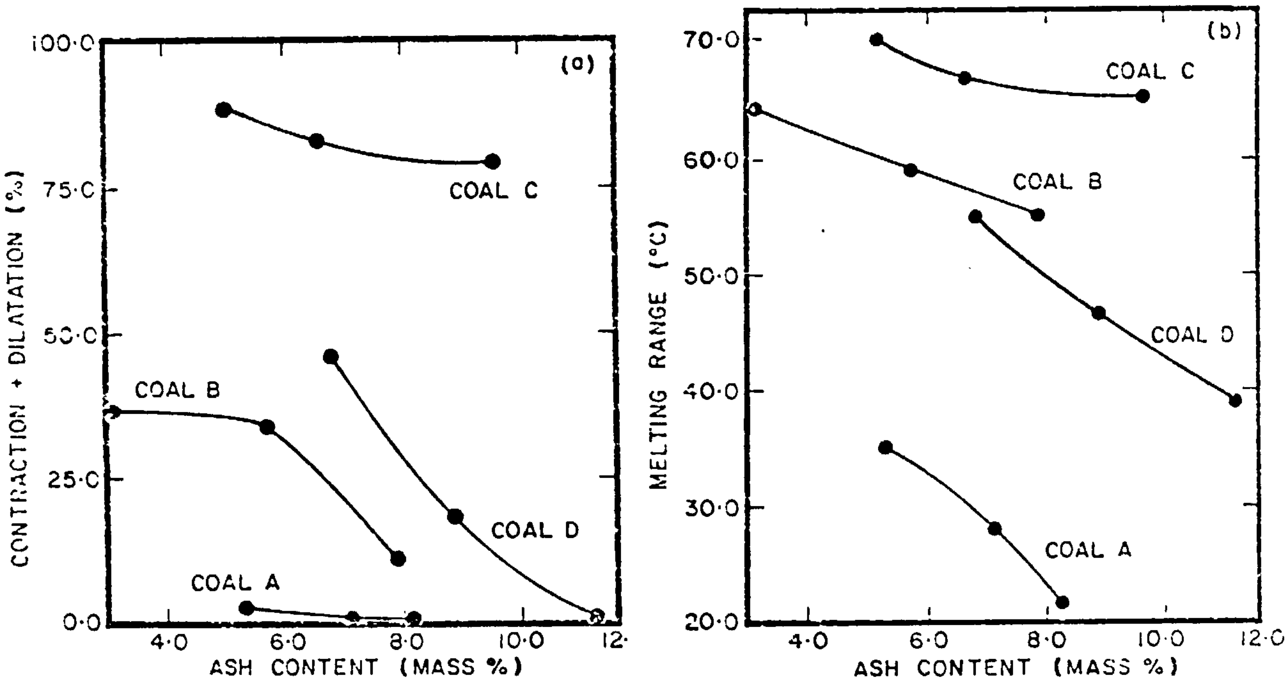

Fig. 2 - (a) Ruhr contraction plus dilatation and (b) melting range versus ash content

PETROGRAPHIC ANALYSIS

Petrographic analysis of the four coals are given in Table 4. Mean maximum reflectance, R_o, a measure of coal rank varies from 0.91% for the high-volatile coal C to 1.36% for the medium-volatile coal D. Coal C has the highest vitrinite content 74.4% and coal D the lowest, 49.0% for the high ash sample. The quantity of reactive components in the coals is also shown and

Table 4 - Petrographic analysis of cleaned coals

	Coal A			Coal B			Coal C			Coal D		
Ash, %	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
R_o, %	1.20	1.20	1.20	1.31	1.32	1.32	0.91	0.91	0.94	1.36	1.36	1.36
Vitrinite %	58.7	64.8	65.1	58.0	60.1	60.6	70.3	74.4	72.4	49.0	57.1	62.5
Exinite %	0.1	0.2	0.2	0.0	0.0	0.0	1.9	2.5	2.6	0.0	0.3	0.0
Semi-fusinite %	19.9	14.9	18.6	25.0	24.6	25.4	14.9	12.9	15.1	33.1	27.2	25.2
Micrinite %	9.4	8.9	6.0	5.0	5.0	4.9	2.2	2.4	2.5	4.9	4.0	6.1
Fusinite %	7.4	7.3	7.2	7.4	7.1	7.3	5.4	4.1	4.6	6.7	5.9	2.4
Mineral matter %	4.5	3.9	2.9	4.5	3.2	1.8	5.3	3.7	2.8	6.3	5.5	3.8
Reactives %	65.4	69.9	71.5	70.5*	72.4*	73.3*	77.2	81.2	80.0	65.5*	71.0*	75.1*
Stability index	49.1	55.2	52.5	56.3	57.9	59.0	41.6	37.8	42.3	53.2	58.7	64.0
Mineral matter free basis												
CANMET												
Vitrinite %	61.5	67.4	67.0	60.8	62.1	61.7	74.3	77.3	74.5	52.3	60.4	65.0
Exinite %	0.1	0.2	0.2	0.0	0.0	0.0	2.0	2.6	2.7	0.0	0.3	0.0
Semi-fusinite %	20.8	15.5	19.2	26.2	25.4	25.9	15.7	13.4	15.5	35.3	28.8	26.2
Micrinite %	9.8	9.3	6.2	5.2	5.2	5.0	2.3	2.5	2.6	5.2	4.2	6.3
Fusinite %	7.8	7.6	7.4	7.8	7.3	7.4	5.7	4.2	4.7	7.2	6.3	2.5
Laboratory A												
Vitrinite %	54.8	57.8	60.2	48.6	57.4	61.1	68.9	69.5	69.4	53.6	57.2	62.6
Exinite %	0.4	0.5	1.5	0.2	0.2	0.0	6.6	6.5	6.4	0.0	0.0	0.0
Semi-fusinite %	26.2	22.6	21.0	31.1	18.2	21.5	15.7	15.1	15.1	24.0	22.7	18.8
Micrinite %	6.5	6.8	6.7	6.7	7.0	7.0	5.3	5.0	4.8	7.6	7.6	5.9
Fusinite %	12.0	12.3	10.6	13.4	17.2	10.4	3.5	3.8	4.2	14.7	12.5	12.5

*based on 50% semi-fusinite reactive

is used to obtain the stability index. CANMET defines reactive components as the percentage vitrinite plus exinite plus one third semi-fusinite unless the total amount of semi-fusinite in the coal is greater than 20% when one half of the semi-fusinite is added to the vitrinite and exinite.

When the results are examined on an mineral matter-free basis it becomes clear that vitrinite has been concentrated in some of the cleaned coal products. Results from CANMET and a second Laboratory, 'A' are shown in Table 4 (see Appendix B for vitrinite reflectance distribution).

Results from both laboratories agree that the vitrinite content of cleaned products from coal D increase progressively as ash is removed so that the lowest ash product has about 10-13% more vitrinite than the highest ash product. Both sets of results show an increase of about 6% vitrinite between the high and low ash products of coal A, but disagree on coal B the CANMET data indicating no vitrinite enrichment, laboratory A an enrichment of 12.5%. Both sets of data show no change in vitrinite content on an mineral matter-free basis for the cleaned products of the high-volatile coal C. In general vitrinite enrichment is usually at the expense of semi-fusinite but sometimes at the expense of fusinite.

COKE PROPERTIES

Coke was made in the Carbolite oven at the Western Research Laboratory in Edmonton and in the Ottawa 310-mm width oven at the Energy Research Laboratories. The Carbolite oven has a width of 460-mm and cokes a coal charge of about 300 kg. It is electrically heated and because the walls are constructed of silicon carbide which has a high thermal conductivity the flue temperature is programmed to start at 875°C and increase at the rate of 15°C/h to 1130°C. The coal is charged with sufficient moisture to give a bulk density of 800 kg/m^3 (dry) in the oven. The gross coking time is normally between 16 and 18 hours. The narrower Ottawa oven cokes a 250 kg coal charge and also has silicon carbide walls heated electrically. The flue temperature is programmed to start at 900°C and increase at 19°C/h to 1070°C. The coal bulk density aimed for is 817 kg/m^3 (dry) and the gross coking time is about 9 hours.

CARBOLITE OVEN

The quality of coke made in this oven improved as ash was removed from the coals. Duplicate tests at each ash level were carried out and the stability factors, hardness factors and mean coke sizes of the cokes produced are shown in Table 5. Complete carbonization results are in Appendix C and the stability factors have been plotted against the ash content of the coal in Fig. 3.

The coke strength, as measured by the stability factor, is remarkably dependent on the ash content of coals A and B. Reducing the ash content of

Table 5 - Coke properties - Carbolite oven

	COAL A					
	% ash in coal					
	8.2		7.1		5.3	
Stability factor	47.6	45.6	53.9	52.5	59.3	57.6
Hardness factor	59.8	60.5	63.1	64.0	68.1	66.8
Mean coke size, mm	58.6	55.9	56.1	56.3	52.8	53.8
Coking pressure, kPa	1.6	2.8	1.2	4.2	3.2	1.5
	COAL B					
	% ash in coal					
	7.9		5.7		3.1	
Stability factor	39.5	39.0	51.6	52.3	63.0	61.4
Hardness factor	67.6	67.4	69.0	68.2	70.7	71.0
Mean coke size, mm	62.5	62.0	58.9	58.4	55.6	54.9
Coking pressure, kPa	12.8	6.5	27.1	19.4	27.8	36.5
	COAL C					
	% ash in coal					
	9.6		6.6		5.1	
Stability factor	39.1	38.7	44.3	46.2	47.9	48.4
Hardness factor	61.4	60.1	64.6	64.6	63.8	64.9
Mean coke size, mm	59.2	59.7	56.9	57.4	57.4	54.9
Coking pressure, kPa	3.3	3.4	2.8	8.2	3.2	4.1
	COAL D					
	% ash in coal					
	11.2		8.9		6.8	
Stability factor	57.7	58.5	61.1	62.3	66.1	64.9
Hardness factor	65.5	66.3	69.3	70.0	71.9	71.3
Mean coke size, mm	66.8	69.9	61.7	64.0	61.2	59.9
Coking pressure, kPa	6.8	4.6	2.0	0.9	2.5	7.4

coal A by 1.1%, from 8.2 to 7.1% ash, increased the stability factor from 46.6 (average) to 53.2. A further reduction of 1.8% increased the factor to 58.5%. For coal B the improvement is larger. The coke strength increased from 39.3 at an ash content of 7.9% to 52% at 5.7% ash and finally 62.2 at 3.1% ash. Coals C and D showed smaller but nevertheless significant increases in coke strength as ash was removed.

The maximum coking pressure developed during carbonization was low for coals A, C and D for all ash contents investigated but increased to high levels as ash was removed from coal B, Table 5.

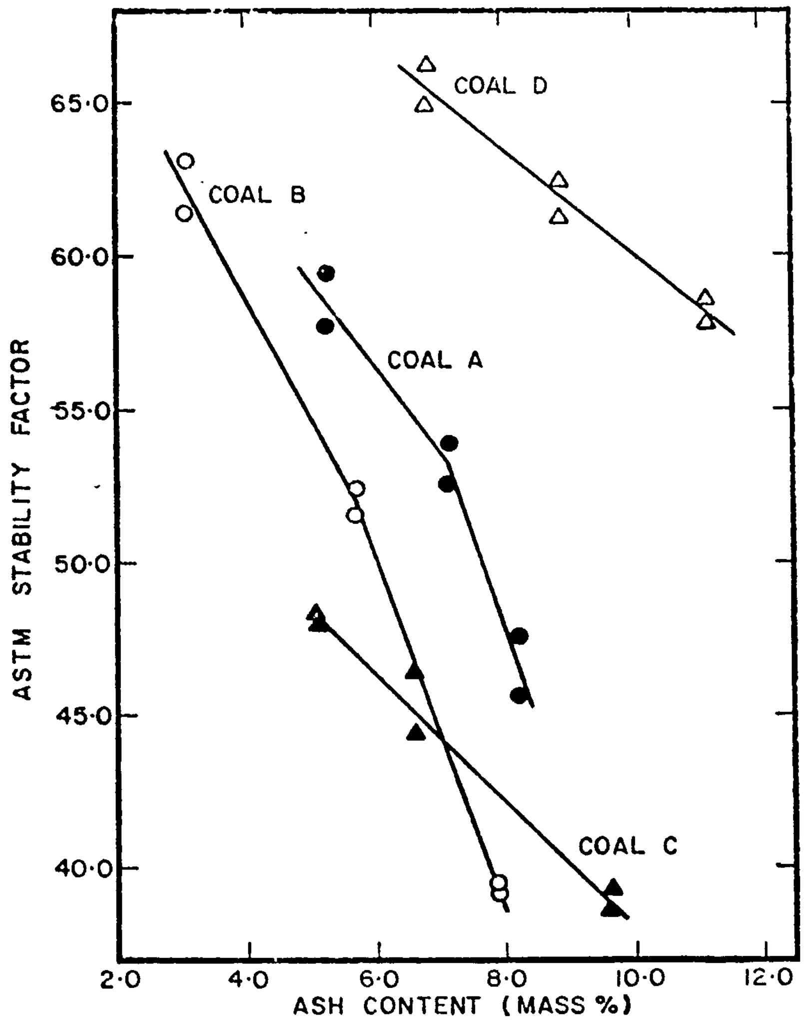

Fig. 3 - ASTM coke stability factor versus ash content of coal - Carbolite oven

OTTAWA 310-mm OVEN

Coal of each ash content was carbonized once in this oven. Blends containing coals A, B, C or D with coals E and/or F were carbonized to determine to what extent the ash content of A, B, C or D affected the coke quality of the blend. Results appear in Appendix C and are summarized in Table 6 and Fig. 4.

The strength of coke made in this oven improved as ash was removed from the four coals but not to the same extent as occurred for coke made in the Carbolite oven. For coal A the differences in the stability factors between the high and low ash products are 11.9 for the Carbolite oven coke but

Table 6 - Coke properties - Ottawa 310-mm oven

	100% A			50% A 37.5% E 12.5% F	
% ash in coal A	8.2	7.1	5.3	8.2	5.3
Stability factor	50.6	50.7	56.2	56.9	58.5
Hardness factor	63.0	61.1	68.9	68.7	69.7
Mean coke size, mm	49.5	48.8	45.7	50.8	49.0
Coking pressure, kPa	4.3	3.6	5.6	4.0	6.5

	100% B			50% B 37.5% E 12.5% F		
% ash in coal B	7.9	5.7	3.1	7.9	5.7	3.1
Stability factor	50.6	54.9	61.3	55.3	57.0	59.0
Hardness factor	71.1	71.5	72.3	69.3	68.0	68.5
Mean coke size, mm	54.4	49.5	45.7	51.1	50.8	50.3
Coking pressure, kPa	13.8	21.0	27.6	22.6	14.1	19.2

	100% C			75% C 25% F		
% ash in coal C	9.6	6.6	5.1	9.6	6.6	5.1
Stability factor	43.1	48.7	46.7	55.4	57.8	57.8
Hardness factor	63.2	66.6	66.3	68.3	69.7	68.5
Mean coke size, mm	50.8	47.2	46.2	52.8	51.3	51.6
Coking pressure, kPa	4.9	6.4	5.9	10.5	14.9	13.4

	100% D			50% D 37.5% E 12.5% F		
% ash in coal D	11.2	8.9	6.8	11.2	8.9	6.8
Stability factor	53.1	59.0	62.5	58.7	61.8	61.0
Hardness factor	67.6	69.4	72.9	69.5	69.5	71.1
Mean coke size, mm	61.0	55.9	52.1	54.9	53.3	51.3
Coking pressure, kPa	3.4	4.3	25.5	8.4	7.4	19.2

only 5.6 for the 310-mm oven coke. Similarly, for coal B the differences are 22.9 and 10.7 and for coal C 9.3 and 3.6. For coal D the differences are much less, 7.4 for the Carbolite oven coke and 9.4 for the 310-mm oven coke.

Maximum coking pressures in this smaller oven were similar to the Carbolite except for coal D with the lowest ash content which produced a higher pressure, 25.5 kilopascals.

The two medium-volatile coals and the low-volatile coal were blended with coal E, an eastern Canadian high-volatile coal, and coal F, a low-volatile coal from the Appalachian coalfields of the United States. Blends contained 37.5% E, 12.5% F and 50% of either coal A, B or D. Coal C, the high-volatile coal was blended with 25% low-volatile coal F.

In general the coke stability factor was higher for the blends containing the least ash but the differences are relatively small. Coal A with 8.2% ash produced a coke with a stability factor of 56.9 which increased to 58.5 when the coal contained 5.3% ash. Coal B produced cokes of 55.3, 57.0 and 59.0 stability at ash contents of 7.9, 5.7 and 3.1% respectively. The values for coal C were 55.4 at 9.6% ash and 57.8 at both 6.6 and 5.1% ash. Coal D with a 11.2% ash content produced a coke with a factor of 58.7 which increased to 61.8 for 8.9% ash but decreased slightly to 61.0 for the 6.8% ash sample.

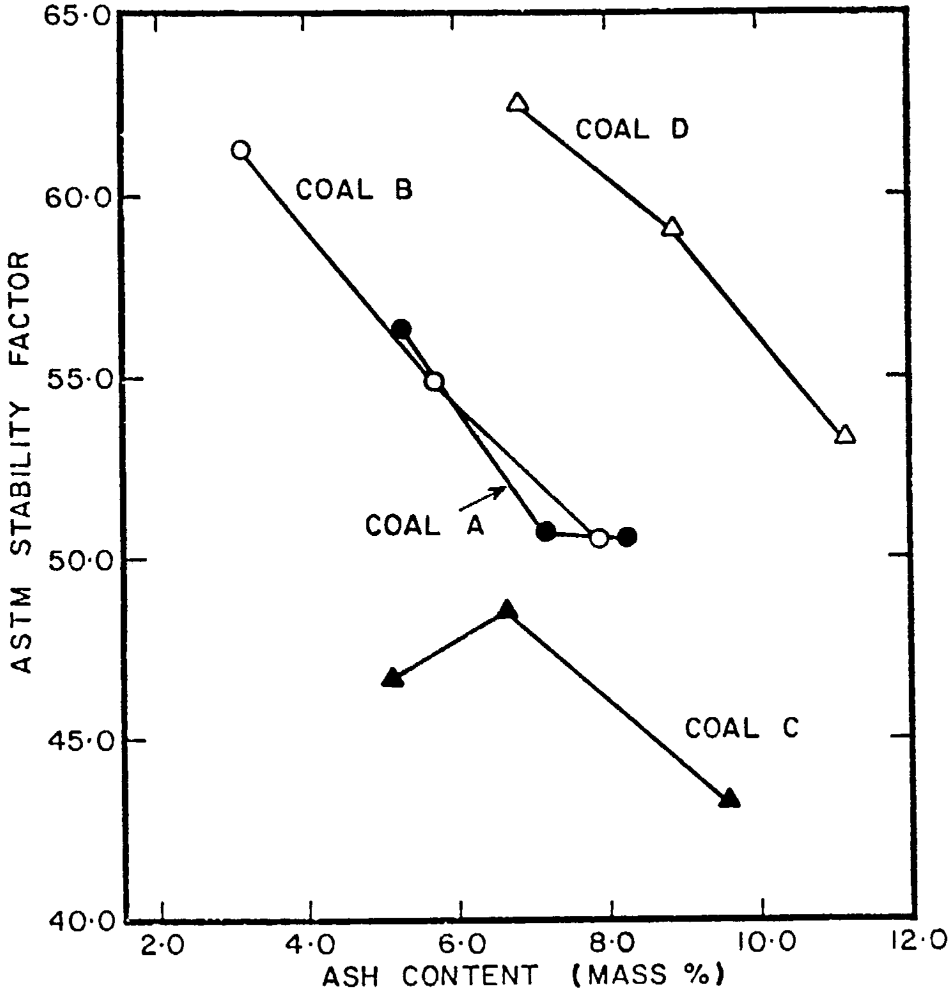

Fig. 4 - ASTM coke stability factor versus ash content of coal - 310-mm oven

COKE REACTIVITY

The reactivity of the cokes produced in the Carbolite oven were measured using the Nippon Steel Corporation test. Cokes of high reactivity to carbon dioxide are believed to be detrimental to the performance of blast furnaces, especially large furnaces, and it is therefore of interest how reactivity varies with the ash content of cokes. In the test 200g of 20-mm coke is gasified by 5 L/min of CO_2 for two hours at 1100°C, The percentage weight loss is recorded (Fig. 5) and after cooling the coke remaining is tumbled in an I-drum for 30 minutes and the amount retained on a 10-mm screen is called the 'strength after reaction'.

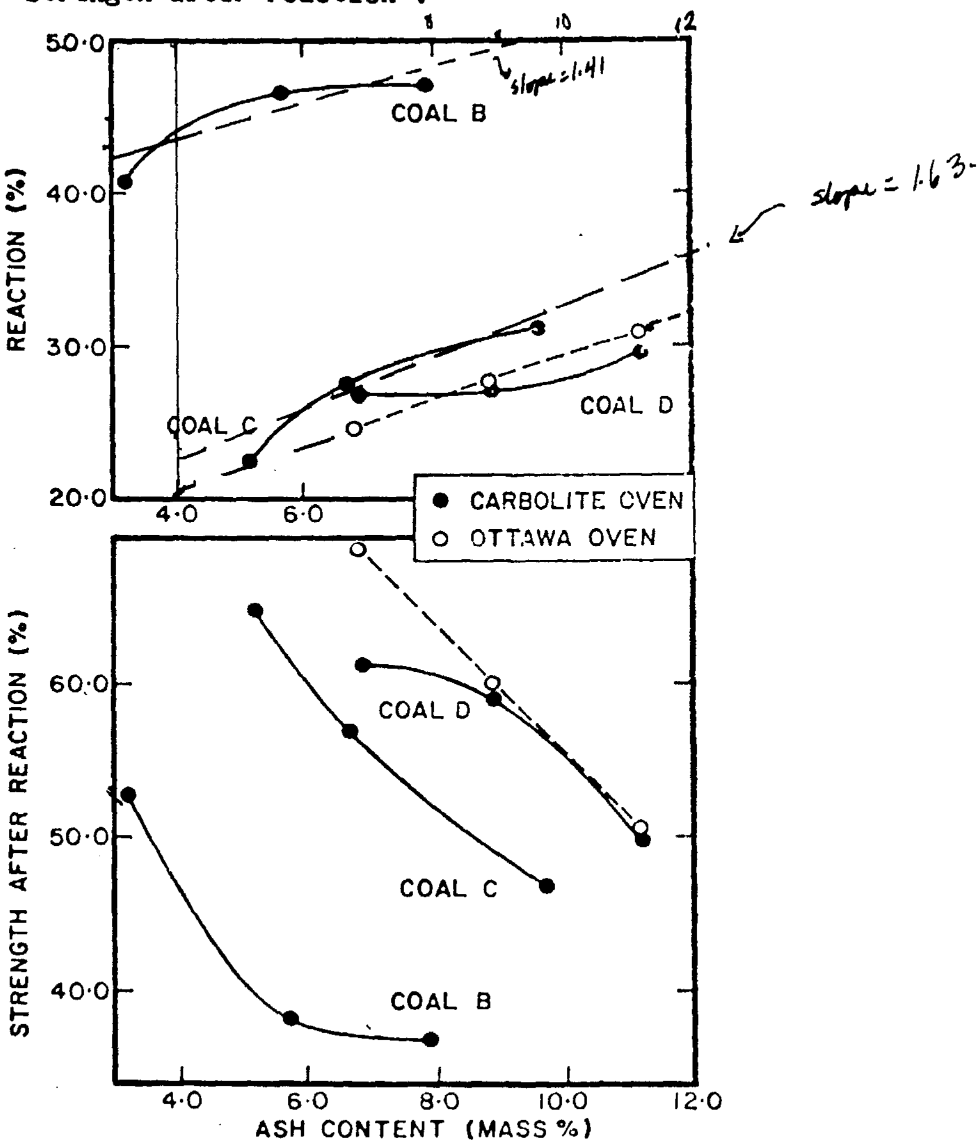

Fig. 5 - Coke reactivity; reaction % and strength after reaction versus ash content of coal

Figure 5 shows that the reactivity is higher and the strength after reaction lower, the greater the ash content of the coal (and hence coke). The broken lines in Fig. 5 for coal D are results for coke made in the Ottawa 310-mm oven and show good agreement with Carbolite oven coke. A further point of interest is the high reactivity of coke made from coal B compared to that made from coal D. Both coals are of similar rank (R_o = 1.32, 1.36 for B and D respectively) and a petrographic analysis that is not dissimilar, Table 4. However coal D does contain a broader range of vitrinite groups, Appendix B.

COKE MICROSCOPY

Cokes were examined microscopically to determine quantitatively the type of optical anisotropy present. Samples were hand-crushed to -30 mesh and mounted in cold-setting resin before grinding and polishing. Two pellets were made for each sample and five hundred areas were assessed for their optical anisotropy on each pellet. Basically two main categories are recognized. Inert or material that has not melted or softened during carbonization and is isotropic, such as fusinite and some semi-fusinite, and material that has become optically anisotropic. The latter category is divided into a number of types which describe the form of the anisotropic areas:

mosaic anisotropy:

approximately equiaxed grains of optical anisotropy, classified according to size

domain anisotropy:

large areas of optical anisotropy usually associated with mosaic anisotropy

flow anisotropy:

elongated grains of optical anisotropy

ribbon anisotropy:

long 'ribbon-like' areas of optical anisotropy of varying width

folded, creased anisotropy:

large anisotropic areas that are folded, sometimes with cracks, or appear 'creased' or undulating due to polishing relief.

Not all isotropic material present in cokes is inert. Some has melted and is identified by its irregular shape and porosity and called isotropic (reactive). As the rank of coal increases the anisotropic types present in their cokes change from isotropic to fine to coarse mosaic to flow-type (4).

Examination of the results in Table 7 for cokes made from coals B, C and D in the Carbolite oven show that the types of anisotropy occurring are not greatly changed by ash removal. (Further experience with this technique is required before it can be determined if the greater amount of mosaic anisotropy present in the high ash samples of cokes B and D and to a lesser extent C, bottom of Table 7, is significant). The amount of isotropic inerts (fusinite + semi-fusinite) is about the same for all three cokes of coal B (in agreement with CANMET coal petrography, but not laboratory B's) and for all three cokes of coal C (in agreement with both laboratories). The coke made from the low ash sample of coal D has 5% less inerts than the other two samples, again following the trend of petrographic analysis.

Table 7 - Coke microscopy - analysis of carbon anisotropy

		Coal B			Coal C			Coal D		
Coal ash content	%	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
Isotropic (reactive)	%	0.4	0.0	0.0	0.9	1.0	1.9	1.0	2.1	0.6
Very fine mosaic	%	0.4	0.4	0.9	4.1	3.2	1.7	0.4	0.1	0.2
Fine mosaic	%	9.0	6.8	9.5	23.6	15.4	17.5	5.9	7.6	7.5
Medium mosaic	%	18.0	15.1	10.8	51.9	58.8	56.6	30.7	23.4	25.6
Coarse mosaic	%	12.1	9.4	11.7	0.7	0.9	0.8	11.2	9.7	13.3
Domain anisotropy	%	3.6	13.3	11.0	2.0	3.0	4.1	2.2	0.9	1.1
Flow anisotropy	%	9.5	6.9	7.6	0.2	0.0	0.0	13.2	20.0	17.9
Ribbon anisotropy	%	2.1	0.7	1.0	0.0	0.0	0.0	0.6	1.5	2.1
Folded, creased anisotropy	%	0.2	0.0	0.6	0.2	0.3	0.1	5.0	4.5	7.1
Semi-fusinite	%	42.7	45.0	45.1	14.8	15.2	16.3	25.2	24.5	20.2
Fusinite	%	1.8	2.4	1.8	1.6	2.2	1.0	4.6	5.7	4.3
		100	100	100	100	100	100	100	100	100
Reactive carbon	%	55.5	52.6	53.1	83.6	82.6	82.7	70.2	69.8	75.5
Inert carbon	%	44.5	47.4	46.9	16.4	17.4	17.3	29.8	30.2	24.5
Types of anisotropy on inert-free basis										
Isotropic (reactive)	%	0.7	0.0	0.0	1.1	1.2	2.3	1.4	3.0	0.8
Very fine mosaic	%	0.7	0.8	1.7	4.9	3.9	2.1	0.6	0.1	0.3
Fine mosaic	%	16.3	13.0	17.9	28.3	18.6	21.2	8.4	10.9	10.0
Medium mosaic	%	32.5	28.7	20.4	62.1	71.2	68.4	43.7	33.5	33.9
Course mosaic	%	21.9	17.9	22.0	0.8	1.1	0.9	16.0	13.9	17.6
Domain anisotropy	%	6.5	25.1	20.7	2.4	3.6	5.0	3.1	1.3	1.5
Flow anisotropy	%	17.2	13.1	14.3	0.2	0.0	0.0	18.8	28.7	23.7
Ribbon anisotropy	%	3.8	1.4	1.9	0.0	0.0	0.0	0.9	2.1	2.8
Folded, creased anisotropy	%	0.4	0.0	1.1	0.2	0.4	0.1	7.1	6.5	9.4
		100	100	100	100	100	100	100	100	100
Mosaic anisotropy	%	72.1	60.4	62.0	97.2	96.0	94.9	70.1	61.4	62.6
Flow anisotropy	%	27.9	39.6	38.0	2.8	4.0	5.1	29.9	38.6	37.4

It is not easy to compare the amounts of inerts found by petrographic examination of the coal with the amounts found by examination of the coke because of the unknown volume change of the macerals during coking. (This has been attempted previously and some volume change figures are available (5)). However, when the amounts of semi-fusinite plus micrinite plus fusinite in coals B and D (37.9 - 39.2% and 35.0 - 47.7% respectively) are compared to the amount of inerts in the coke (44.5 - 47.4% and 24.5 - 30.2% respectively) it is necessary to conclude that coal D contains a much greater proportion of reactive semi-fusinite.

Finally the types of optical anisotropy and their amounts in cokes prepared from coals B and D are seen to be very similar when compared on an inert-free basis, Table 7, in accord with the similar rank (R_o) of the coals. Both have 60-70% mosaic anisotropy with medium mosaic as the predominant type but with substantial proportions of fine and coarse mosaic. The lower rank coal C has cokes with 96% mosaic anisotropy also mostly medium mosaic with some fine but little coarse mosaic.

DISCUSSION

COAL CLEANING

Maceral analysis of the coal samples revealed that coal cleaning has, in some cases, concentrated vitrinite in the cleaned product. To investigate further maceral analysis was carried out on samples taken from 13 points in the cleaning circuit during the cleaning of coal A to three ash levels. Results are given in Appendix D on an ash-free basis together with their ash content and their weight percentage of the raw coal processed.

Examination of this data shows that maceral "mass balances" do not close sufficiently accurately to make detailed statements possible. Probably some samples were not truly representative and in some cases high ash and small particle size have made petrographic analysis less precise, and in other cases impossible.

However, two definite conclusions can be drawn. Firstly, vitrinite contents are about 10% higher in the -28 mesh material of the crushed raw coal. This fraction is almost 30% of the raw coal and is fed to the water cyclone and flotation circuits, while the +28 mesh proceeds only to the heavy-media circuit. Secondly, the coal floated in the heavy media circuit is enriched in vitrinite, Table 8. The difference in the amounts of semi-fusinite in the floats and sinks increases from 5.6% for the high ash sample to 10.5% for the medium ash sample to 27.3% for the low ash sample.

Table 8 - Maceral analysis (ash free basis) of heavy-media cyclone floats and sinks for coal A

	High ash SG 1.6		Medium ash SG 1.45		Low ash SG 1.4	
	Floats	Sinks	Floats	Sinks	Floats	Sinks
Vitrinite	61.6	57.0	62.4	55.9	71.1	41.4
Exinite	0.1	0.4	0.0	0.1	0.2	0.2
Semi-fusinite	22.0	27.6	23.3	33.8	18.0	45.3
Fusinite	9.1	7.9	9.5	6.2	4.0	9.4
Macrinite	7.2	7.1	4.8	4.0	6.7	3.7

COKE QUALITY

The strength of coke made in both ovens increased as ash was removed from the coals and this was accompanied by a decrease in the mean coke size as seen in figure 6. Results in Table 6 show a similar trend for blends. Thus ash reduction leads to smaller less fractured and hence stronger coke. Ash behaving as a coke antifissurant has been noted and discussed previously by Mayer (2).

Table 9 - ASTM stability factors of cokes produced in the Carbolite oven (average) and Ottawa oven and their difference ΔS

	Coal A			Coal B			Coal C			Coal D		
	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.3
Carbolite	46.6	53.2	58.5	39.3	52.0	62.2	38.9	45.3	48.2	58.1	61.7	65.5
Ottawa	50.6	50.7	56.2	50.6	54.9	61.3	43.1	48.7	46.7	53.1	59.0	62.5
ΔS	-4.0	2.5	2.3	-11.3	-2.9	0.9	-4.2	-3.4	1.5	5.0	2.7	3.0

Table 9 compares the stability factors of coke produced in the two ovens. Although agreeing that strength increases as ash is reduced the ovens

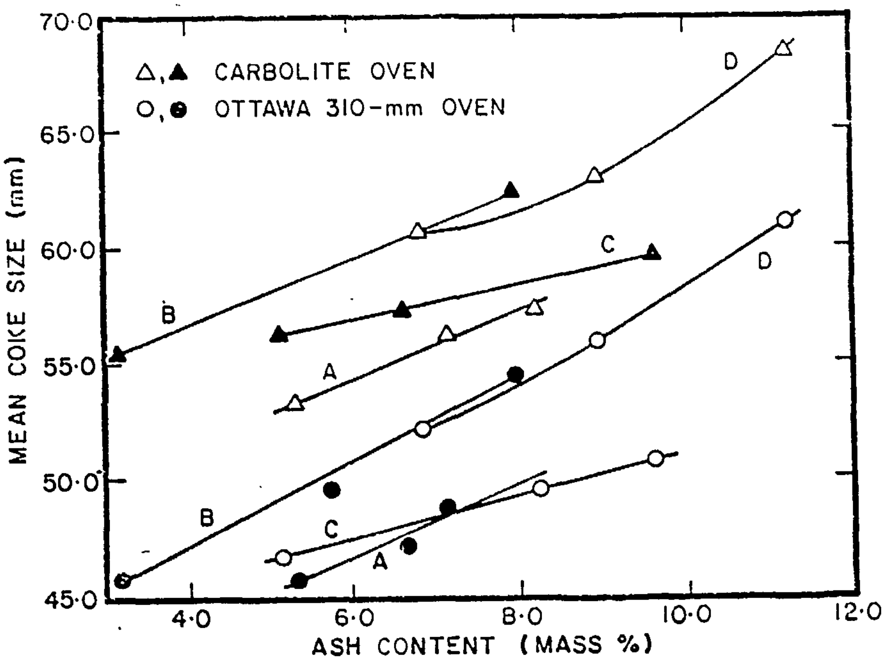

Fig. 6 - Mean coke size versus ash content of coal

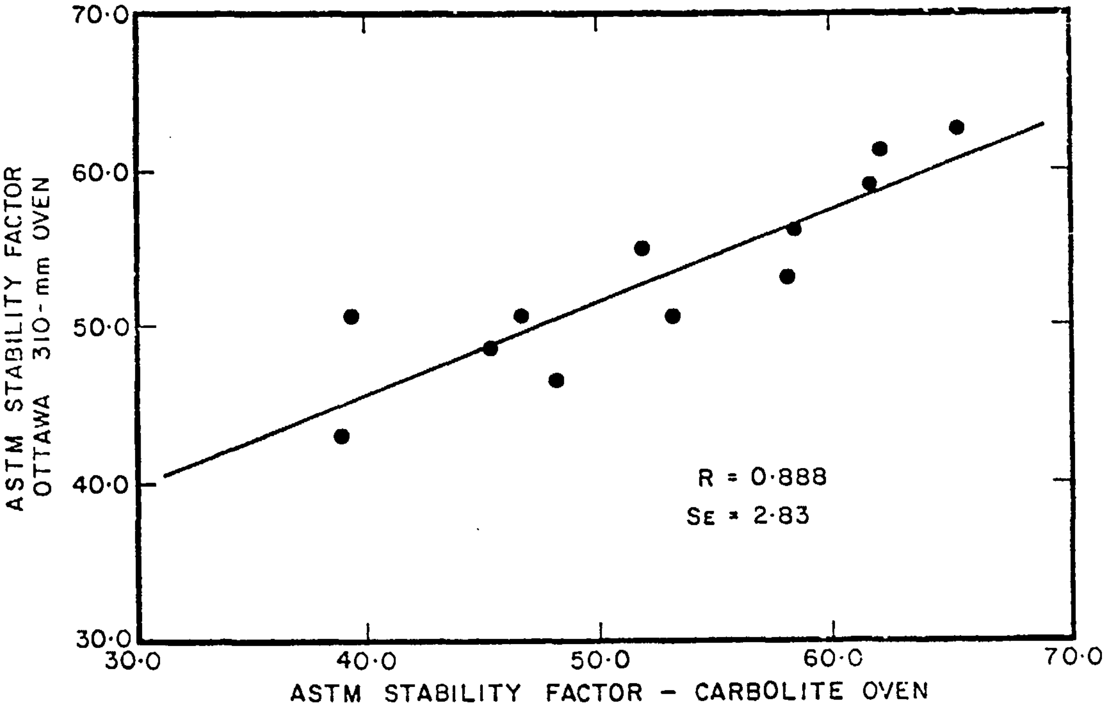

Fig. 7 - ASTM stability factors for cokes produced in Carbolite oven versus factors for cokes produced in Ottawa 310-mm oven.

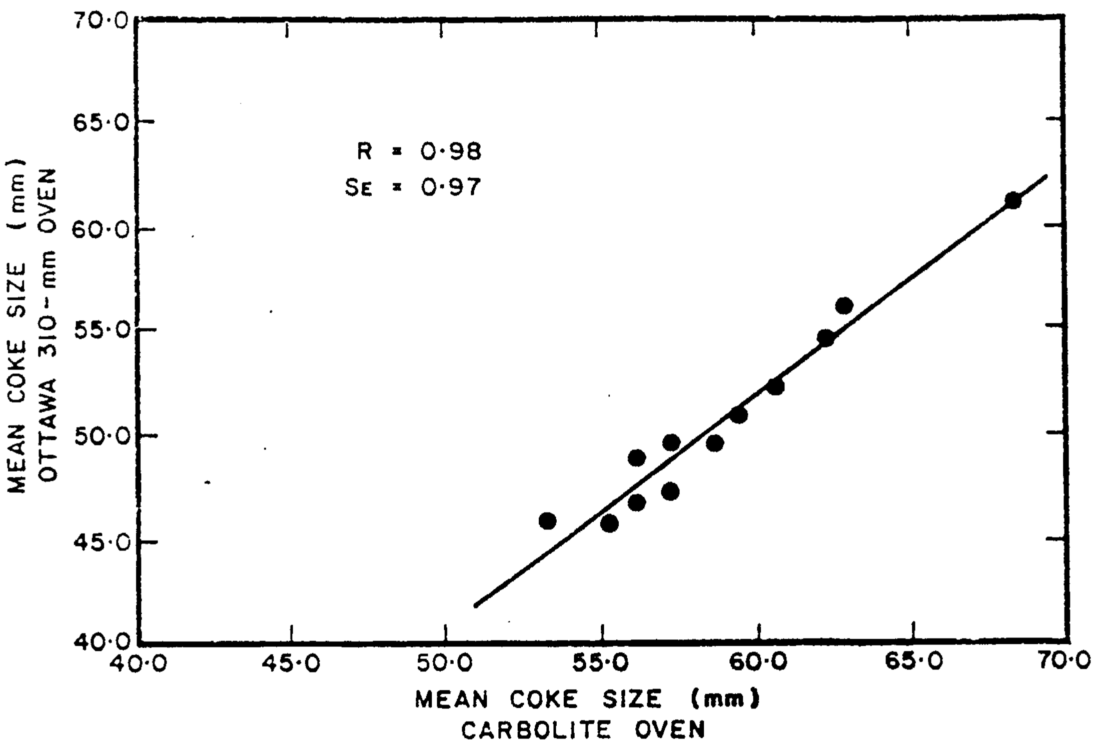

Fig. 8 - Maximum coking pressures, Carbolite oven versus Ottawa 310-mm oven

produce cokes with substantially different stability from some of the coal samples. Except for coal D the differences between the Carbolite and Ottawa oven factor, ΔS in Table 9, are negative for the high ash coal samples and positive for the low ash samples. Linear regression produces the equation

$$Y = 0.585X + 22.42$$

where X and Y are the stability factors for the Carbolite and Ottawa ovens respectively, Fig. 7. Hence the differences are largely explained by the smaller Ottawa oven producing better cokes than the Carbolite in the low stability range. The smaller oven has a levelling effect and this has been noted previously (6).

Reasons for this levelling effect are unclear but it may result from the major difference in the cokes produced in the two ovens, the coke size distribution. Figure 8 shows there is an excellent linear correlation between the mean size of coke from the two ovens and that it is about 8mm smaller for the smaller oven. This in turn is attributed to the differences in width and

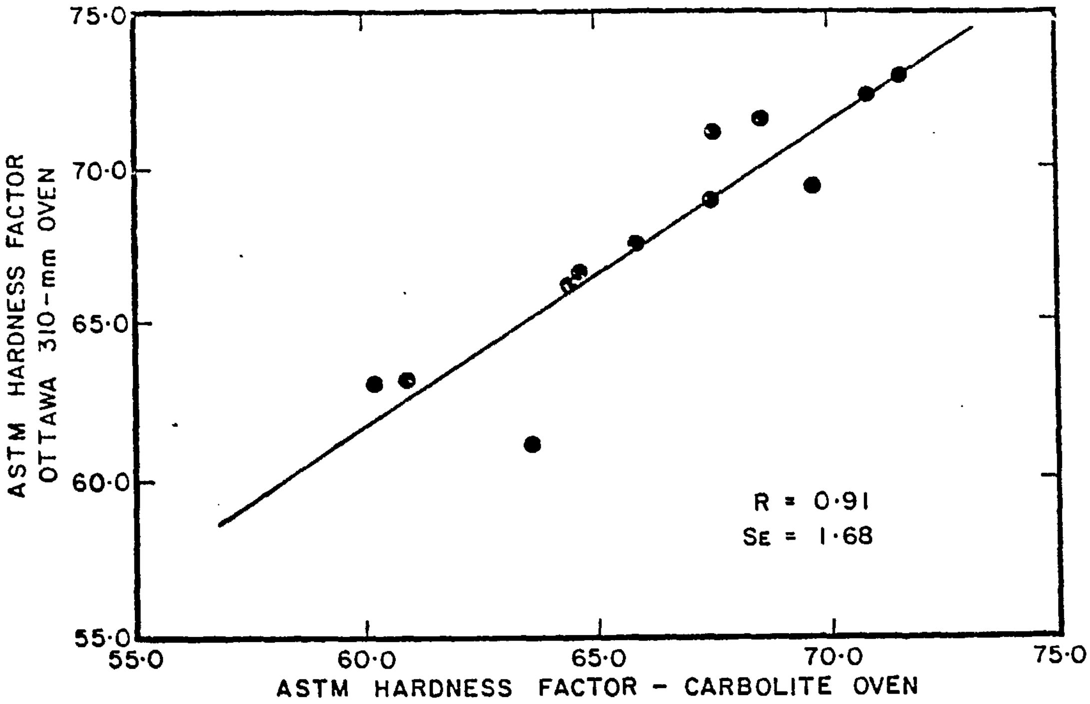

Fig. 9 - ASTM hardness factors, Carbolite oven versus Ottawa 310-mm oven

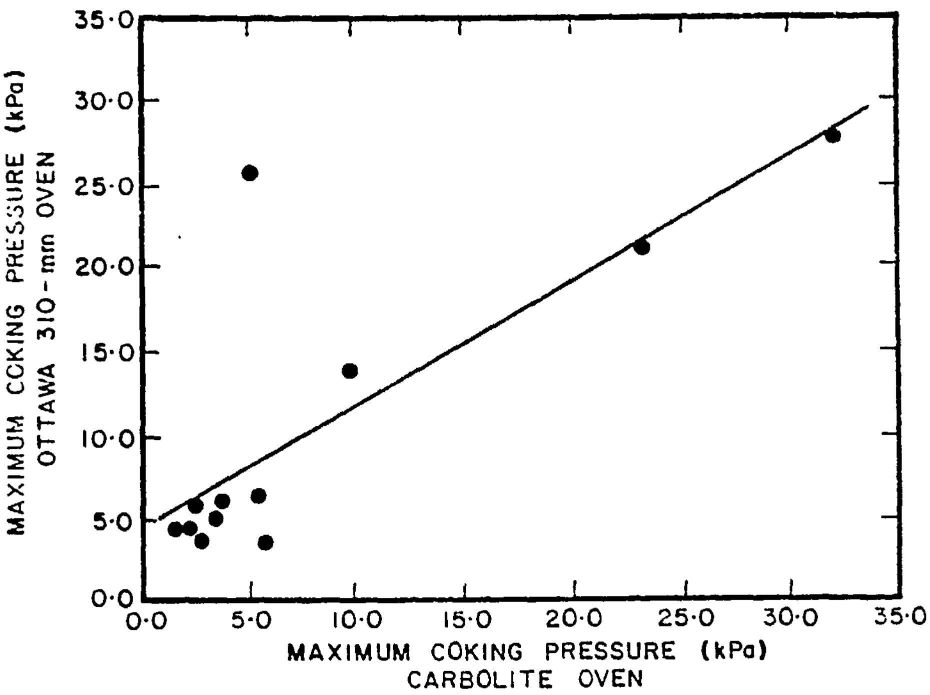

Fig. 10 - Maximum coking pressures, Carbolite oven versus Ottawa 310-mm oven

at least in part to the faster coking rate of the smaller oven, 38mm/h to a centre-temperature of 900°C compared to 33mm/h for the Carbolite oven.

Hardness factors of cokes produced in both ovens are similar. The regression line in Fig. 9 suggests the factors are on average 1.3 - 1.7 points higher for cokes made in the Ottawa oven. Maximum coking pressures developed during carbonization are also similar with one noticeable exception, Fig. 10. The lowest ash sample of coal D exerted a pressure of 25.5 kPa in the Ottawa oven but only 5.0 kPa (average) in the Carbolite oven. Pressures in both ovens were low for the high and medium ash samples and this suggests the coking pressure of the low ash sample is particularly sensitive to the carbonization conditions.

Coals B and D are of similar rank and maceral composition. Their coal and coke properties show at the same time, some remarkable similarities and differences.

The highest ash sample of B contained only 1.1% more ash than the lowest ash sample of D so direct comparison is not possible. However, the plots of maximum fluidity, melting range and to a lesser extent total dilatation (c+d) against ash content reveal that a line common to both coals may be drawn through the points. The same is true for the mean coke size for coke made in both ovens, Fig. 6. Conversely the coke stability factors are very different as can be seen in Fig. 3. Coal B at 7.9% ash has a factor of 39.3 while coal D would be expected to be 63.6 at this ash content.

Large shale particles in coal B are believed to be at least partly to blame. They were quite evident in the cokes of the two higher ash samples of this coal, but not in any of the coke samples of coal D. Coke was extensively fractured around the shale particles, and was therefore more easily broken in the drum test.

The approximate amount of shale particles larger than 1.7 mm present in the coke oven charge was measured by float/sink analysis for coals A and B (unfortunately not coal D), Table 10.

Table 10 - Shale in coke oven blends

	Coal A			Coal B		
wt % ash in coal	8.2	7.1	5.3	7.9	5.7	3.1
wt % shale +1.71	0.18	0.02	0.002	2.0	0.8	0.01

Differences in the types of anisotropic carbon in the two cokes have already been discussed. The higher inert carbon content (i.e., fusinite + semi-fusinite) of cokes from coal B may be the cause of the significantly higher reactivity of this coke.

Fractures open to the surface caused by shale particles may be a further contributing factor, but the lowest ash coke which contained few shale particles suggests the contribution is small as its reactivity is still high.

CONCLUSIONS

Reducing the ash content of the coals

- enriched their vitrinite content in comparison with other coal macerals for two of the four coals
- increased their Gieseler maximum fluidity, Ruhr dilatation and melting range. Free swelling indices were unchanged for three of the coals
- increased the maximum coking pressure of two of the coals
- increased the stability factors of cokes made from the coals, by 1.6 - 4.7 points per one percent ash reduction
- increased the coke hardness factors
- decreased the coke mean size, apparent specific gravity and reactivity to CO_2
- did not affect the types of carbon optical anisotropy present in the cokes.

ACKNOWLEDGEMENTS

The authors are grateful to J.C. Botham, former manager of CRPL, who initiated the project and provided guidance. They especially thank the companies which provided coal and the Technical Committee of the Canadian Carbonization Research Association. Dr. W.R. Leeder formerly of CANMET and now with Denison Mines Ltd. fully participated in the project while at CANMET. Mr. J. Jorgensen carried out the petrographic analysis and Mr. N.J. Ramey the coke analysis. We thank them and all staff members of CRPL.

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APPENDIX A

Summary of Coal Cleaning Data

		A			B			C			D	
Ash in raw coal			13.7			8.9			27.9			14.2	
Ash in clean coal	%	8.5	7.3	5.8	6.8	5.2	3.3	9.4	6.5	5.0	10.6	8.4	6.6
Yield clean coal	%	87.3	73.4	69.7	96.2	88.6	82.2	67.7	62.0	54.9	85.6	69.5	51.4
Heavy media circuit													
Coal fed	%	71.8	71.1	71.4	69.7	69.7	69.7	68.6	68.6	68.6	68.8	68.8	68.8
Yield clean coal	%	83.9	69.9	65.1	94.0	89.7	82.0	65.6	58.7	49.0	88.8	67.7	45.0
Ash in clean coal	%	7.9	6.0	4.3	7.7	5.6	2.9	9.2	6.2	4.1	10.6	7.6	4.8
Ash in reject	%	51.9	35.6	33.2	64.3	58.8	48.5	76.6	69.6	59.6	47.2	29.6	22.8
Water cyclone circuit													
Coal fed	%	28.2	28.9	26.8	-	30.3	30.3	31.4	31.4	31.4	31.2	31.2	31.2
Yield clean coal	%	96.4	96.3	95.6	-	99.3	98.2	89.0	84.4	81.2	95.4	91.6	83.4
Ash in clean coal	%	11.4	11.7	10.9	-	4.7	4.4	11.5	9.4	8.7	12.3	11.5	11.0
Ash in reject	%	41.9	41.4	38.3	-	47.3	38.1	64.1	59.9	54.4	51.6	42.3	29.7
Flotation circuit													
Coal fed	%	12.2	12.4	11.0	-	9.0	8.9	10.2	9.7	9.4	9.8	9.4	8.5
Yield clean coal	%	93.5	90.1	89.7	-	86.5	75.4	92.9	92.5	91.5	93.1	84.5	78.8
Ash in clean coal	%	10.9	10.2	9.4	-	3.1	2.9	9.0	8.6	8.2	10.9	10.5	9.7
Ash in reject	%	38.8	40.1	38.4	-	26.1	15.5	55.7	54.1	48.2	63.2	35.0	29.0

APPENDIX B

Ultimate and Ash Analysis (Dry Basis) of Cleaned Coal

	Coal A			Coal B			Coal C			Coal D		
Ash, %	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
Ultimate analysis												
Carbon	81.0	81.9	83.6	83.8	85.1	87.8	77.6	80.2	81.3	80.7	82.4	84.1
Hydrogen	4.8	4.9	4.9	4.4	4.6	4.7	4.9	5.2	5.2	4.4	4.6	4.8
Sulphur	0.24	0.25	0.24	0.72	0.59	0.51	0.71	0.74	0.69	0.39	0.37	0.37
Nitrogen	0.9	0.9	0.9	1.3	1.3	1.3	1.3	1.5	1.5	1.3	1.2	1.3
Ash	8.2	7.1	5.3	7.9	5.7	3.1	9.6	6.6	5.1	11.2	8.9	6.8
Oxygen (by difference)	4.9	5.0	5.1	1.9	2.7	2.6	5.9	5.8	6.2	2.0	2.5	2.6
Ash analysis												
S_1O_2	49.2	51.8	50.0	56.6	51.3	44.6	59.2	57.7	58.3	56.5	55.7	55.7
Al_2O_3	26.7	29.3	29.6	18.6	18.2	19.0	24.4	25.7	26.7	25.5	26.6	28.1
Fe_2O_3	14.4	6.7	7.7	8.8	11.4	9.3	6.0	5.2	4.8	4.8	4.1	3.8
TiO_2	1.4	1.5	1.4	0.7	0.7	0.9	1.2	1.3	1.3	1.1	1.0	1.3
P_2O_5	0.8	0.9	0.9	0.3	0.5	0.7	0.9	1.3	1.3	0.5	0.6	0.7
CaO	1.2	1.4	1.4	3.3	4.6	7.1	1.6	1.6	1.5	2.9	2.8	2.5
MgO	0.6	0.8	0.5	1.8	2.0	2.4	1.0	0.9	0.9	0.8	0.8	0.5
SO_3	0.9	1.1	1.1	3.2	5.6	8.5	0.8	0.5	0.5	3.0	3.0	1.7
Na_2O	1.7	2.0	2.2	0.6	0.9	1.7	0.1	0.1	0.1	1.7	1.8	1.8
K_2O	0.6	0.6	0.7	2.6	1.8	0.6	2.6	2.2	2.1	0.6	0.5	0.5
Vitrinite Reflectance Groups												
V7												
V8							26.7	29.0	10.9	1.0	2.3	1.9
V9							40.1	43.2	54.3	2.5	6.3	3.8
V10	3.5	1.9	3.9				3.5	2.2	7.2	0.5	-	1.9
V11	18.8	27.9	26.0	1.2						1.0	1.1	4.4
V12	35.8	31.8	31.2	18.6	19.8	17.0				4.9	1.1	12.5
V13	0.6	3.2	3.9	36.5	37.9	40.6				15.2	9.1	30.6
V14				1.7	2.4	3.0				19.6	25.1	7.5
V15										4.4	12.0	
V16												

APPENDIX C

Carbonization Results

Oven test no.		C-21	C-22	C-19	C-20	C-23	C-24	C-25	C-26	C-27	C-28	C-29	C-30
Description		Coal A 8.2% ash	Coal A 8.2% ash	Coal A 7.1% ash	Coal A 7.1% ash	Coal A 5.3% ash	Coal A 5.3% ash	Coal B 7.9% ash	Coal B 7.9% ash	Coal B 5.7% ash	Coal B 5.7% ash	Coal B 3.1% ash	Coal B 3.1% ash
CARBONIZATION CONDITIONS													
Moisture in charge	%	3.2	3.1	3.2	3.4	3.3	3.4	2.8	3.1	2.8	2.9	3.2	3.1
Minus 3 mm (6 mesh)	%	80.8	79.6	82.8	82.0	82.0	82.2	80.4	80.4	84.3	84.3	82.2	82.2
ASTM cone bulk density(wet)	kg/m^3	790	782	793	782	793	782	798	790	796	788	782	752
Coal bulk density in oven(dry)	kg/m^3	790	823	823	803	820	803	833	822	830	815	809	811
CARBONIZATION RESULTS													
Gross coking time	h:min	16:39	15:52	16:56	17:11	16:59	17:09	16:53	16:58	17:07	17:10	17:00	16:22
Final centre temperature	°C	1067	1076	1062	1056	1054	1060	1051	1080	1054	1062	1059	1122
Time to 900°C centre temp.	h:min	13:39	12:52	13:56	14:11	13:59	14:09	13:53	13:58	14:07	14:10	14:00	13:22
Time to 1000°C centre temp.	h:min	14:36	14:00	14:59	15:18	15:03	15:05	15:02	14:44	15:06	15:10	15:04	13:56
Maximum wall pressure	kPa	1.6	2.8	1.2	4.2	3.2	3.5	12.8	6.5	27.1	19.4	27.8	36.5
Coke yield	%	72.3	71.7	73.4	70.0	72.6	69.1	71.7	72.9	73.5	73.8	72.9	73.2
COKE SCREEN ANALYSIS													
(cumulative % retained on)													
102 mm sieve		-	-	-	-	-	-	-	-	-	-	-	-
76		21.5	18.3	13.9	14.4	10.0	8.7	26.2	27.0	20.3	19.5	10.2	9.5
51		63.5	57.6	59.3	60.6	50.7	57.0	68.6	67.6	61.8	61.7	56.6	56.7
38		82.8	77.8	83.6	83.8	81.3	81.7	83.5	82.8	83.2	81.7	87.0	84.6
25		91.3	88.6	92.7	91.6	92.2	92.0	94.3	93.4	93.6	93.3	95.9	94.9
19		93.0	90.5	94.1	93.1	93.6	93.6	95.8	94.7	95.6	95.3	97.0	96.5
13		93.6	91.4	94.6	94.0	94.4	94.3	96.6	96.1	96.6	96.4	97.6	97.2
Percentage -13 mm (breeze)	%	6.4	8.6	5.2	6.0	5.6	5.7	3.4	3.9	3.4	3.6	2.4	2.8
Mean coke size	mm	58.7	55.9	56.1	56.1	52.8	53.8	62.5	62.0	58.9	58.4	55.6	54.9
COKE PROPERTIES													
Apparent specific gravity		0.97	0.98	0.98	0.95	0.96	0.94	0.95	0.95	0.94	0.93	0.92	0.91
Proximate analysis (db); ash	%	11.1	11.2	9.7	9.5	7.8	7.9	9.3	9.1	6.4	6.7	4.1	4.1
volatile matter	%	1.8	1.4	1.4	2.0	1.4	1.2	1.8	1.7	1.5	1.5	1.4	1.2
fixed carbon	%	87.1	87.4	88.9	88.5	90.8	90.9	88.9	89.2	92.1	91.8	94.5	94.7
Sulphur (db)	%	0.23	0.21	0.23	0.24	0.23	0.22	0.57	0.57	0.53	0.56	0.49	0.49
ASTM COKE TUMBLER TEST													
Stability factor	%	47.6	45.6	53.9	52.5	59.3	57.6	39.5	39.0	51.6	52.3	63.0	61.4
Hardness factor	%	59.8	60.5	63.1	64.0	68.1	66.8	67.6	67.4	69.0	68.2	70.7	71.0
JIS COKE TUMBLER TEST													
30 revs 50 mm sieve	%												
25 mm sieve	%												
15 mm sieve	%	90.1	89.4	92.3	92.5	93.1	92.5	88.5	88.5	91.9	91.8	94.9	94.5
150 revs 50 mm sieve	%												
25 mm sieve	%												
15 mm sieve	%	75.1	75.0	79.9	80.2	82.9	81.1	74.7	73.8	80.1	80.1	85.6	85.4

Oven test no.		C-31	C-33	C-34	C-35	C-36	C-37	C-39	C-40	C-41	C-42	C-43	C-44
Description		Coal C 9.6% ash	Coal C 9.6% ash	Coal C 6.6% ash	Coal C 6.6% ash	Coal C 5.1% ash	Coal C 5.1% ash	Coal D 11.2% ash	Coal D 11.2% ash	Coal D 8.9% ash	Coal D 8.9% ash	Coal D 6.3% ash	Coal D 6.3% ash
CARBONIZATION CONDITIONS													
Moisture in charge	%	3.3	3.9	3.1	3.1	3.0	3.1	3.0	2.8	2.8	2.8	2.6	2.5
Minus 3 mm (6 mesh)	%	83.5	83.5	82.6	82.6	91.7	91.7	79.0	79.0	79.5	79.5	87.6	87.6
ASTM cone bulk density(wet)	kg/m^3	778	777	790	783	786	783	788	793	790	785	785	793
Coal bulk density in oven(dry)	kg/m^3	815	822	820	819	822	820	830	825	827	823	827	819
CARBONIZATION RESULTS													
Gross coking time	h:min	16:53	16:51	17:27	17:24	17:30	17:02	16:55	15:55	15:32	16:04	17:02	17:07
Final centre temperature	°C	1097	1096	1067	1061	1082	1056	1065	1092	1110	1065	1112	1059
Time to 900°C centre temp.	h:min	13:53	13:51	14:27	14:24	14:30	14:02	13:55	12:55	12:32	13:04	14:02	14:07
Time to 1000°C centre temp.	h:min	14:35	14:30	15:18	15:36	15:05	14:34	14:49	13:41	13:15	14:14	14:31	15:05
Maximum wall pressure	kPa	3.3	3.4	2.8	8.2	3.2	4.1	6.8	4.6	2.0	0.9	2.5	7.4
Coke yield	%	68.3	69.2	69.5	69.3	69.3	70.6	74.8	75.0	76.3	77.5	76.7	75.5
COKE SCREEN ANALYSIS													
(cumulative % retained on)													
102 mm sieve		1.2	3.2	0.0	0.0	1.3	0.0	10.6	14.6	4.6	4.7	1.7	1.0
76		21.0	19.7	14.9	11.2	13.0	9.4	32.0	36.8	23.2	28.7	18.9	16.0
51		66.0	66.5	61.6	65.4	62.9	57.3	76.4	78.3	69.9	72.7	71.0	71.2
38		83.7	84.1	84.3	88.0	86.4	85.6	88.0	89.2	85.6	88.2	90.5	89.7
25		92.8	93.3	94.9	95.2	95.5	94.5	93.0	93.8	93.7	93.8	95.9	95.2
19		95.2	95.4	96.1	96.6	96.8	96.4	94.0	94.9	95.0	94.9	96.6	96.0
13		96.3	96.4	96.9	97.3	97.5	97.2	94.8	95.6	95.8	95.7	97.1	95.8
Percentage -13 mm (breeze)	%	3.7	3.6	3.1	2.7	2.5	2.8	5.2	4.4	4.2	4.3	2.9	3.2
Mean coke size	mm	59.2	59.7	56.9	57.4	57.4	54.9	66.8	69.9	61.7	64.0	61.2	59.9
COKE PROPERTIES													
Apparent specific gravity		0.91	0.93	0.90	0.89	0.89	0.89	1.04	1.04	1.00	1.01	0.98	0.96
Proximate analysis (db); ash	%	13.2	13.2	9.3	9.3	7.1	7.2	13.0	13.0	10.6	10.6	8.5	8.5
volatile matter	%	1.7	1.5	1.8	1.6	1.3	1.3	1.5	1.8	1.5	1.6	1.4	1.8
fixed carbon	%	85.1	85.3	88.9	89.1	91.6	91.5	85.5	85.2	87.9	87.8	90.1	89.7
Sulphur (db)	%	0.60	0.60	0.59	0.58	0.57	0.54	0.34	0.33	0.29	0.30	0.28	0.26
ASTM COKE TUMBLER TEST													
Stability factor	%	39.1	38.7	44.3	46.2	47.9	48.4	57.7	58.5	61.1	62.3	66.1	64.9
Hardness factor	%	61.4	60.1	64.6	64.6	63.8	64.9	65.5	66.3	69.3	70.0	71.9	71.3
JIS COKE TUMBLER TEST													
30 revs 50 mm sieve	%												
25 mm sieve	%												
15 mm sieve	%	89.7	89.2	92.1	92.6	93.4	93.0	92.8	92.8	93.5	94.1	95.5	94.8
150 revs 50 mm sieve	%												
25 mm sieve	%												
15 mm sieve	%	74.5	73.0	79.4	79.8	80.5	80.7	81.7	81.9	83.0	84.0	86.1	85.8

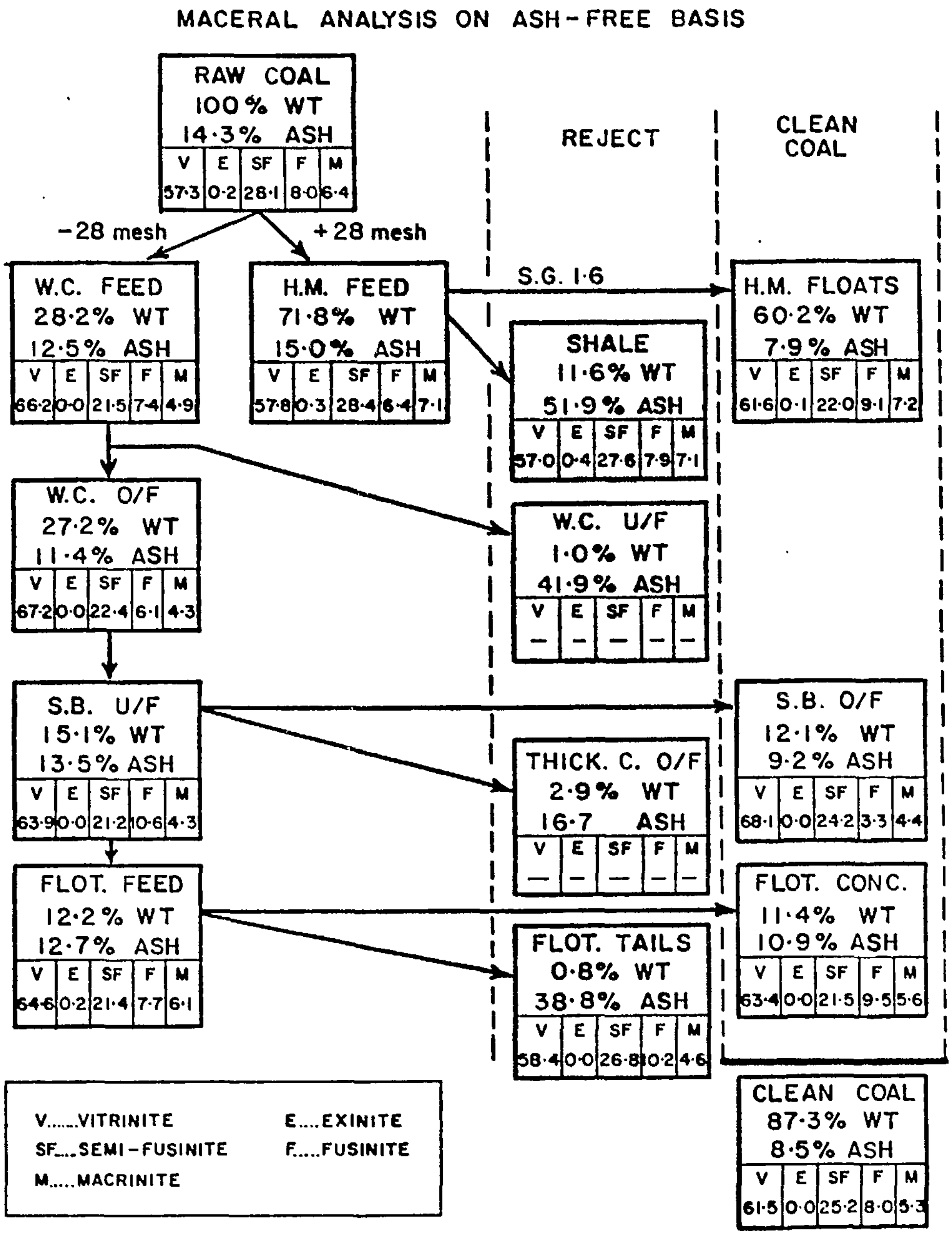
Oven test no.		772	771	773	775	774*	785	779	784	789	787	788
Description		Coal A 8.2% ash	Coal A 7.1% ash	Coal A 5.3% ash	50% A 8.2% ash 37.5%E 12.5%F	50% A 5.3% ash 37.5%E 12.5%F	Coal B 7.9% ash	Coal B 5.7% ash	Coal B 3.1% ash	50% B 7.9% ash 37.5%E 12.5%F	50% B 5.7% ash 37.5%E 12.5%F	50% B 3.1% ash 37.5%E 12.5%F
CARBONIZATION CONDITIONS												
Moisture in charge	%	3.0	3.0	2.8	2.8	3.0	3.0	2.8	3.0	3.0	3.0	3.0
Minus 3 mm (6 mesh)	%	89.5	88.4	91.0	-	-	88.8	89.3	88.9	-	-	-
ASTM cone bulk density(wet)	kg/m^3	-	-	-	-	-	-	777	-	777	775	777
Coal bulk density in oven(dry)	kg/m^3	788	780	786	782	788	783	774	778	783	772	745
CARBONIZATION RESULTS												
Gross coking time	h:min	9:20	9:10	9:10	9:15	9:00		9:05	8:55	9:05	9:00	8:55
Final centre temperature	°C	1082	1077	1071	1082	1066		1066	1060	1077	1060	1060
Time to 900°C centre temp.	h:min	7:45	7:55	8:00	7:45	7:45		7:55	7:55	7:40	8:00	7:55
Time to 1000°C centre temp.	h:min	-	-	-	-	-		-	-	-	-	-
Maximum wall pressure	kPa	4.3	3.6	5.6	4.0	6.5	13.8	21.0	27.6	22.6	14.1	19.2
Coke yield	%	76.9	76.4	76.2	75.7	75.4	79.7	79.3	79.1	76.7	75.4	76.1
COKE SCREEN ANALYSIS												
(cumulative % retained on)												
102 mm sieve		0.6	0.0	0.0	0.7	0.4	2.6	0.6	0.0	0.0	0.3	0.0
76		7.8	5.3	3.2	6.3	4.1	15.8	5.9	2.3	6.0	5.8	3.5
51		43.3	40.9	32.4	45.2	42.1	51.6	42.5	33.1	47.2	47.0	46.8
38		71.8	72.8	65.8	75.9	72.8	73.5	71.6	63.9	78.4	75.6	75.8
25		91.7	92.8	92.6	94.9	94.2	92.7	93.5	93.5	94.3	94.2	94.6
19		93.5	94.6	95.2	96.7	96.3	95.8	96.0	96.2	96.3	96.4	96.7
13		94.3	95.4	95.9	97.6	97.3	96.8	97.1	97.1	97.1	97.2	97.5
Percentage -13 mm (breeze)	%	5.7	4.6	4.1	2.4	2.7	3.2	2.9	2.9	2.9	2.8	2.5
Mean coke size	mm	49.5	48.8	45.7	50.8	49.0	54.4	49.5	45.7	51.1	50.8	50.3
COKE PROPERTIES												
Apparent specific gravity		0.966	0.939	0.936	0.921	0.911	0.939	0.915	0.924	0.892	0.862	0.857
Proximate analysis (db); ash	%	10.9	9.5	7.6	8.1	6.1	8.7	6.3	3.8	7.0	5.5	4.3
volatile matter	%	1.2	1.2	1.2	1.4	1.5	1.9	2.1	2.1	1.5	1.5	1.5
fixed carbon	%	87.9	89.3	91.2	90.5	92.4	89.4	91.6	94.1	91.5	93.0	94.2
Sulphur (db)	%	0.23	0.21	0.23	0.53	0.51	0.48	0.41	0.37	0.66	0.57	0.52
ASTM COKE TUMBLER TEST												
Stability factor	%	50.6	50.7	56.2	56.9	58.5	50.6	54.9	61.3	55.3	57.0	59.0
Hardness factor	%	63.0	61.1	68.9	68.7	69.7	71.1	71.5	72.3	69.3	68.0	68.5
JIS COKE TUMBLER TEST												
30 revs 50 mm sieve	%	17.5	25.2	15.0	16.5	15.0	16.0	6.0	11.9	13.8	23.4	17.8
25 mm sieve	%	86.5	86.1	71.8	88.4	88.6	82.1	83.3	88.4	86.6	89.6	87.8
15 mm sieve	%	92.8	91.9	94.4	94.1	94.9	92.3	93.1	94.6	93.5	94.4	94.7
150 revs 50 mm sieve	%	2.5	6.3	5.6	3.3	6.8	3.0	1.7	4.5	4.5	8.3	8.0
25 mm sieve	%	70.2	68.4	69.5	72.3	70.0	58.2	63.5	72.4	70.7	74.2	73.0
15 mm sieve	%	80.4	79.5	84.2	83.8	80.7	80.5	82.0	85.5	82.6	83.7	84.0

Oven test no.		797	796	795	801	802	800	811	812	813	817	815	816
Description		Coal C 9.6% ash	Coal C 6.6% ash	Coal C 5.1% ash	75% C 9.6% ash 25% F	75% C 6.6% ash 25% F	75% C 5.1% ash 25% F	Coal D 11.2% ash	Coal D 8.9% ash	Coal D 6.8% ash	50% D 11.2% ash 37.5%E 12.5%F	50% D 8.9% ash 37.5%E 12.5%F	50% D 6.8% ash 37.5%E 12.5%F
CARBONIZATION CONDITIONS													
Moisture in charge	%	3.1	3.0	3.1	3.6	3.1	2.9	2.8	2.8	2.8	2.3	3.0	2.3
Minus 3 mm (6 mesh)	%	90.3	87.6	89.8	-	-	-	84.3	87.7	88.3	-	-	-
ASTM cone bulk density(wet)	kg/m^3	780	775	775	801	825	809	793	769	775	769	777	769
Coal bulk density in oven(dry)	kg/m^3	790	794	775	812	830	803	806	806	814	812	780	806
CARBONIZATION RESULTS													
Gross coking time	h:min	9:10	9:00	9:10	9:30	9:30	9:40	9:15	9:15	9:05	8:55	9:05	9:20
Final centre temperature	°C	1071	1049	1071	1071	1054	1071	1077	1060	1060	1043	1043	1060
Time to 900°C centre temp.	h:min	8:10	8:10	8:05	8:15	8:35	8:25	7:45	8:05	7:50	7:50	7:55	8:10
Time to 1000°C centre temp.	h:min	-	-	-	-	-	-	-	-	-	-	-	-
Maximum wall pressure	kPa	4.9	6.4	5.9	10.5	14.9	13.4	3.4	4.3	25.5	8.4	7.4	19.2
Coke yield	%	72.1	72.5	70.0	76.2	74.8	73.9	80.2	80.9	80.4	77.5	77.4	76.5
COKE SCREEN ANALYSIS													
(cumulative % retained on)													
102 mm sieve		0.0	0.0	0.2	0.0	0.0	0.5	7.4	2.8	0.0	1.8	0.9	0.0
76		5.0	3.1	2.6	7.9	5.3	5.5	25.7	14.1	10.2	11.3	9.6	6.1
51		47.9	37.7	34.2	52.5	48.9	47.1	63.1	57.3	47.2	55.5	52.2	46.7
38		77.0	70.6	68.3	80.2	78.3	79.5	81.1	79.4	78.1	80.5	78.7	79.9
25		93.3	92.6	92.5	94.9	95.1	95.5	93.4	94.1	94.4	94.9	95.0	94.5
19		95.7	95.5	95.4	96.2	96.4	96.8	94.7	95.3	95.9	96.5	96.6	96.1
13		96.9	96.5	96.6	96.5	97.2	97.5	95.4	96.0	96.7	97.2	97.5	97.0
Percentage -13 mm (breeze)	%	3.1	3.5	3.4	3.1	2.8	2.5	4.6	4.0	3.3	2.8	2.5	3.0
Mean coke size	mm	50.8	47.2	46.2	52.8	51.3	51.6	61.0	55.9	52.1	54.9	53.3	51.3
COKE PROPERTIES													
Apparent specific gravity		0.916	0.891	0.874	0.927	0.914	0.907	1.030	0.982	0.956	0.987	0.922	0.906
Proximate analysis (db); ash	%	13.1	9.3	7.3	11.3	8.5	7.2	13.1	10.8	8.9	9.1	7.6	7.2
volatile matter	%	1.3	1.4	1.4	1.2	1.0	1.3	1.1	1.6	2.1	0.9	0.9	0.7
fixed carbon	%	85.6	89.3	91.3	87.5	90.5	91.5	85.8	87.6	89.0	90.0	91.5	92.1
Sulphur (db)	%	0.61	0.53	0.58	0.59	0.58	0.57	0.35	0.21	0.19	0.57	0.56	0.53
ASTM COKE TUMBLER TEST													
Stability factor	%	43.1	48.7	46.7	55.4	57.8	57.8	53.1	59.0	62.5	58.7	61.8	61.0
Hardness factor	%	63.2	65.6	66.3	68.3	69.7	68.5	67.6	69.4	72.9	69.5	69.5	71.1
JIS COKE TUMBLER TEST													
30 revs 50 mm sieve	%	17.3	6.0	4.1	27.4	14.5	20.2	23.5	34.9	29.3	27.5	24.8	24.7
25 mm sieve	%	82.3	83.4	82.5	88.4	85.7	87.9	85.7	89.4	91.1	90.2	90.0	90.5
15 mm sieve	%	91.7	92.3	92.3	93.7	94.3	94.4	92.4	93.3	94.9	94.0	94.5	94.6
150 revs 50 mm sieve	%	0.8	0.5	0.0	6.1	4.5	2.2	8.2	9.4	15.4	9.2	10.0	6.8
25 mm sieve	%	61.8	64.9	60.5	71.7	68.2	75.6	70.7	75.4	79.0	77.3	76.4	78.0
15 mm sieve	%	77.4	79.7	79.7	82.5	83.9	86.6	81.0	82.1	86.0	84.8	84.3	85.0

APPENDIX D

Petrographic analysis of samples from coal cleaning circuits

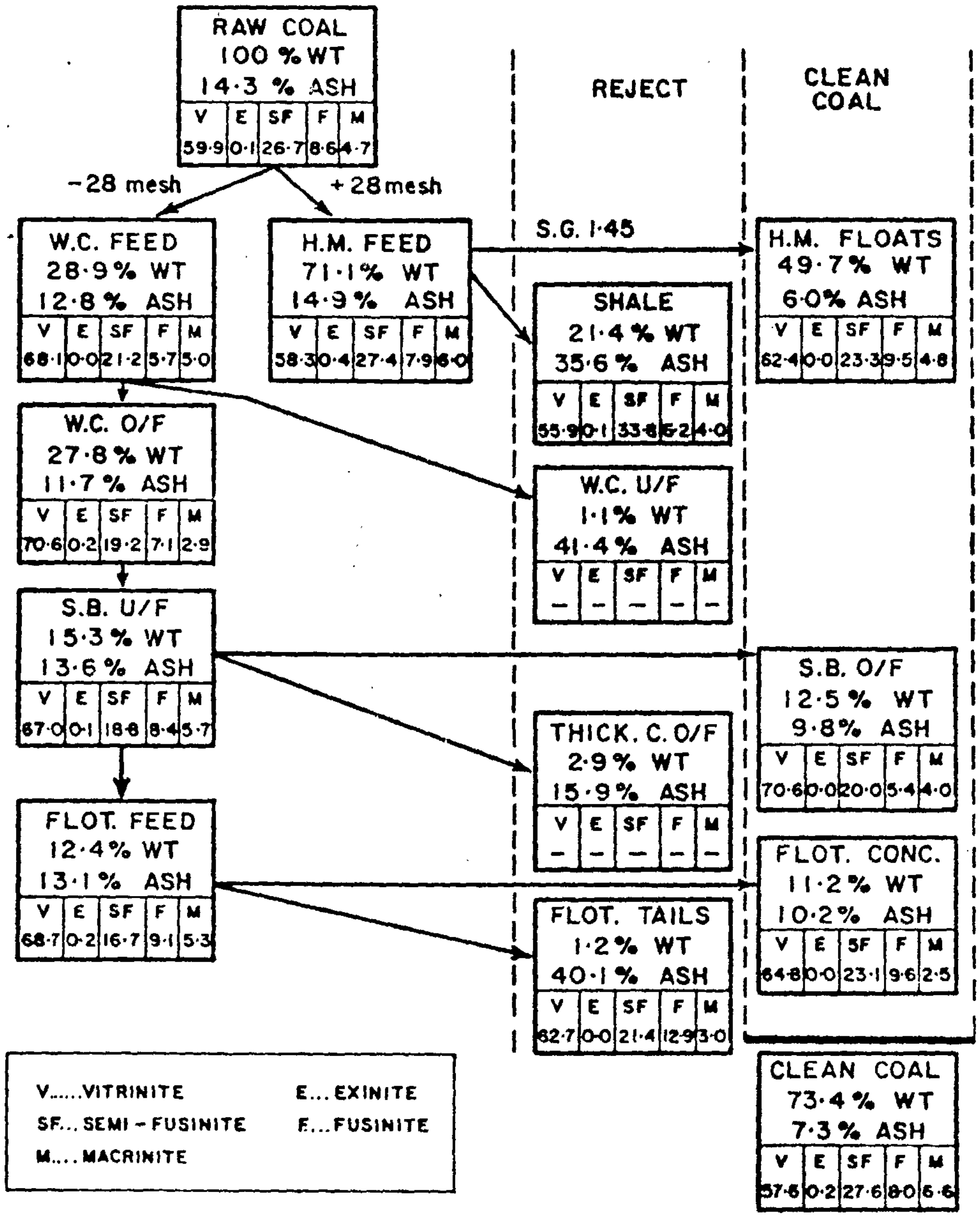
HIGH ASH



APPENDIX D (Cont'd)

MEDIUM ASH

MACERAL ANALYSIS ON ASH-FREE BASIS



APPENDIX D (Cont'd)

LOW ASH