

Producing Clean Coal from Western Canadian Coalfields using the Water-Based Roben Jig Process

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Introduction

In British Columbia (BC), the occurrence of coal is well known and relatively predictable. Several known thermal coalfields exist, as well as two major metallurgical coalfields, the Kootenay and Peace River coalfields (BC Geological Survey, 1992). The challenge isn't in 'finding' the coal, it is in evaluating the coal as a resource for various applications during the exploration stage.

During the exploration phase of coal-mine development, the evaluation of metallurgical coal for resulting coke quality is often determined using small-mass (2–15 kg) samples collected from drillcores. Drilling is the least expensive method of obtaining representative coal-seam samples when compared to developing test pits or adits. If a larger bulk sample is required, it is sometimes possible to use several 6-inch drill-program cores. However, depending on the thickness of the seam, even this may be cost prohibitive, as a large number of drillholes would need to be used to collect the required large coal mass (i.e., several tonnes). This latter amount would need to be collected to conduct pilot-scale carbonization test work for evaluating its coking potential.

Coal samples from the exploration phase are prepared by screening and washing the coal for further quality testing. The float-and-sink procedure used in coal-washability studies is the process where ash/mineral matter is removed from the coal. The coarser coal is processed using mixtures

of organic liquids (i.e., white spirit, perchloroethylene (PCE) and methylene bromide) in this procedure, while the finest fraction is cleaned by a process called froth flotation. During the float-and-sink process, the coal sample is separated at relative densities (specific gravity, sg)—white spirit/PCE for 1.4 sg, PCE for 1.6 sg and PCE/methylene bromide for 1.8 sg—that produce clean-coal samples at different ash contents typical of what would be produced in a commercial coal-washing plant.

Project economics are based on the results of the float-and-sink testing, including information on the yield of clean coal as well as the quality of the cleaned coal and resulting coke quality. The coking characteristics for a metallurgical-coal deposit are mandatory in evaluating project economics (i.e., expected price for the clean coal). It is critical to ensure that coal/coking properties are correctly assessed from drillcore samples in order to properly evaluate project economics.

Background

For years, the primary concern in the handling and use of organic liquids, such as perchloroethylene (PCE), was the safety risk associated with human exposure. Perchloroethylene is a known carcinogen, posing a safety hazard for laboratory operators, and therefore must be handled carefully. Figure 1 shows a laboratory technician working in a specially designed fume hood wearing personal protective equipment, including a respirator mask.

A number of investigations and ensuing observations about how PCE may impact coal-sample coking quality have also been identified and noted. Campbell (2010) at ALS Coal Technology (Riverview, Australia) found that organic liq-

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Figure 1. Operator working with organic liquids in a specially designed fume hood.

uids could interfere with the properties of interest for a coal producer or end user. Iveson and Galvin (2010) comprehensively examined the effects of organic liquids on coking properties of coal in an Australian Coal Association Research Program project and subsequently published their findings (Iveson and Galvin, 2012). They concluded that PCE had, on one hand, a negative effect on the coking properties of lower rank and lower fluidity coking coals but, on the other hand, a negligible or possibly even a small positive effect on the coke reactivity index (CRI) and coke strength after reaction (CSR) of cokes resulting from coals with relatively good initial coking properties. The latter observation pertaining to a positive impact of PCE on coke quality had been reported earlier by DuBroff et al. (1985) at Inland Steel (East Chicago, Indiana). Their patent outlined a process for improving the quality of some metallurgical coke, produced from coals with high inert content that had produced coke of lower-than-expected stability when compared to the coal rank. They studied several medium-volatile bituminous coal samples that had been soaked and agitated in a PCE bath prior to carbonization. For some of the coals, the resultant coke showed improved stability index, increased hardness index, decreased reactivity and increased tumble strength. It was also found that the carbonization time was decreased. The hypothesis was that the PCE reacted with certain macerals in the coal, producing a “solvent induced reaction product” residue on the coal particles that was highly reactive. In some cases, this reaction product was thought to ‘increase’ the reactivities:inerts ratio at the coal-particle surfaces (DuBroff et al., 1985).

Contrary to what the Inland Steel patent outlines, Iveson and Galvin found that the negative effect of PCE treatment/exposure was shown to be more significant when coal had high inertinite content (>40%). These coals produced lower strength coke as a result of being exposed to PCE. In fact, for coals with high inertinite content, CRI was increased (an adverse effect) by an average of 15% and CSR

values decreased by an average of 25% (also an adverse effect) when the coal had been exposed to PCE prior to coking. This effect was more pronounced after the coal had aged for more than 16 weeks (oxidized). The explanation proposed by Iveson and Galvin was that the high porosity of inertinite, namely semifusinite and fusinite, enabled greater access of PCE to the interior of the coal particles (Iveson and Galvin, 2012).

The evidence that organic liquids, as discussed previously, affect the coking properties of low-fluidity Australian coals implies that western Canadian coals, known to have moderate fluidity levels, could be affected in a similar way. Many Canadian geologists have also found that cleaned coal samples from drillcore often had lower caking/coking properties than bulk or production coal samples. Based on these observations, the Canadian Carbonization Research Association (CCRA) undertook a program to investigate the impact of organic solvents used in float-and-sink procedures on the coal and coke properties of a western Canadian coal sample with higher inertinite content (Holuszko et al., 2017).

This study looked at the effects of perchloroethylene on coal rheology and coke quality. It was found that an 80% decrease in Gieseler maximum fluidity occurred in the perchloroethylene-treated coal immediately following treatment, when compared to the control sample. The coke resulting from the treated sample showed a 16-point decrease in CSR when compared to the control sample. These two coal- and coke-quality parameters (i.e., Gieseler maximum fluidity and CSR) are key when evaluating coal resources and reserves. The ramifications of using the wrong numbers for the above-mentioned parameters when determining product characteristics for sale are severe and could result in project abandonment or false overvaluing of the property.

After the initial study outlined above, the CCRA also completed an exploratory study that examined an alternative to organic liquids when processing coal. A jig (Roben Jig, previously called ‘Boner Jig’) was used to clean coal using only water, and the resulting coal- and coke-quality characteristics were compared to coal that was processed using the traditional organic-chemical washing process. It was found that clean-coal product could be produced that was similar to that generated using the organic liquids. It is believed that, due to the coal type used in this phase study, the perchloroethylene had no negative effect on the coal-rheology and coke-strength parameters. Although this study has not yet been published, its findings are important because it demonstrates that the Roben Jig can be used to produce clean-coal composites similar in all aspects to those produced by traditional float-and-sink methods. The coal used in this work was a relatively ‘easy to clean’ coal, in that the particles high in mineral matter could be easily separated

from the coal. However, as not all coals wash as easily, it is important to test the Roben Jig on a wide variety of coal types.

Objectives

The objective of this project was to verify that the Roben Jig can be used commercially to wash a broad range of coal types to ultimately produce representative clean-coal composites for coal and coke analysis. This is beneficial to the coal industry for the following reasons:

- It would eliminate the potential negative effects of perchloroethylene and other organic liquids on coal- and coke-quality parameters.
- It would reduce the exposure of lab technicians/operators to carcinogenic organic liquids.

Experimental Methodology

Four coal types (coals A, B, C, D) from British Columbia were tested in this project. One sample originated from a northeastern BC coalfield and the other three originated from southeastern BC coalfields (Figure 2). All samples were collected in an undiluted, raw state from active mining faces.

Upon receipt of the coal samples at the GWIL Industries–Birtley Coal & Minerals Testing Laboratory (Calgary, AB), staff removed the coal from the sealed drums and left it to air-dry overnight. As-received and air-dried weights were reported. The coal was then screened through a 12.5 mm sieve and the oversize was hand-knapped to pass. All coal was sized at -12.5 mm. The entire sample was then split into two size fractions: -12.5×0.25 mm and -0.25 mm. The coarse size fraction (-12.5×0.25 mm) was then split into two samples. One sample was washed in organic liquids and the other was washed using the Roben Jig. The -0.25 mm coal was treated in the same way and was cleaned using the ASTM D5114-90(2010)¹ froth flotation of coal method.

Float-and-Sink and Jigging Methods

This project evaluated clean-coal products resulting from two washing methods: traditional ‘float-and-sink’ using organic liquids, and separation using the Roben (previously referred to as ‘Boner’) Jig. The specific gravity of a coal particle is dependent on the mineral-matter content and maceral composition. Coal particles containing the lowest mineral-matter content will float when separated in a 1.30 sg liquid, whereas those with the highest mineral-matter content are separated at 1.80 sg.

¹References to the relevant ASTM methods can be found at the end of the ‘References’ section.

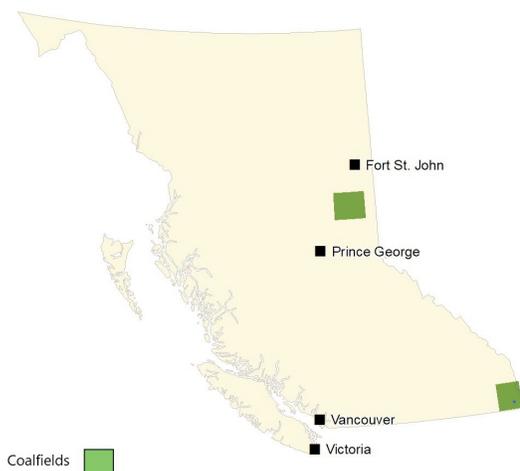


Figure 2. Locations of the coalfields in northeastern and southeastern British Columbia from which the coal samples used in this project originated.

The ASTM D4371-06(2012) float-and-sink method was used in this project. This technique fractionates coal and mineral-matter particles based on particle density by allowing particles to settle in organic-liquid mixtures with a known specific gravity. Mixtures of white spirits, perchloroethylene and methylene bromide are used to produce various media densities ranging from 1.30 to 1.80 sg (Figure 3).

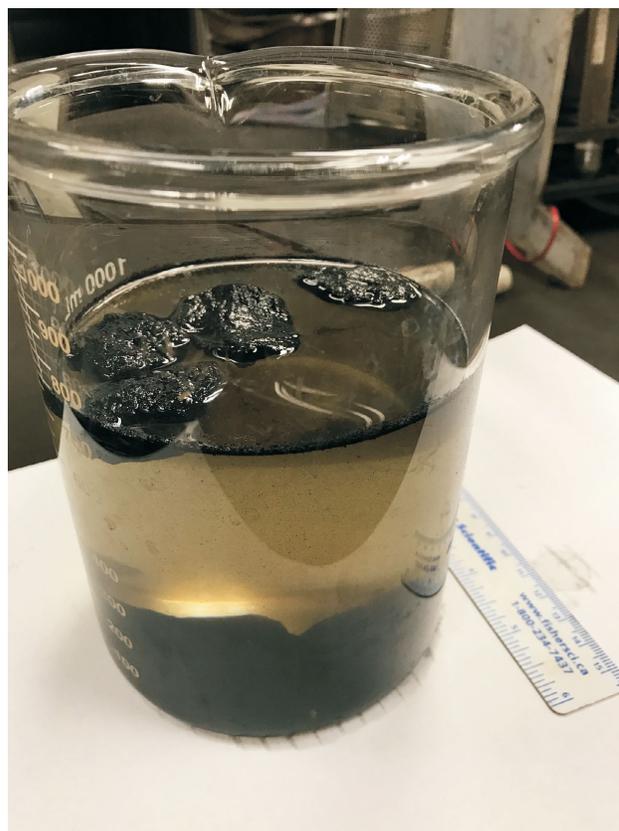


Figure 3. Coal particles floating in perchloroethylene (PCE, 1.6 sg).

The Roben Jig is a device that allows the separation of coal particles based on density to occur as the coal is jiggled up and down in a column of water (Figure 4). Although a published standard (ASTM, ISO, Australian Standards) does not exist for the use of the Roben Jig, the procedure described here was developed by the inventor. Approximately 15 kg of -12.5×0.25 mm coal and tracers (glass marbles) of a known specific gravity (2.70) were added to the jig tube with a 0.25 mm screen at the bottom. This mesh base allows water to enter during the jig downstroke, as well as allowing particle sorting during the jig upstroke. This tube, with coal added, was gently lowered into the jig vessel. Water level was adjusted so that it was approximately 100 mm above the level of the coal. The Jig tube was attached to the pneumatic jiggling mechanism. Once turned on, this mechanism moved the jig tube up and down. The downstroke was rapid to suspend particles individually, whereas the upstroke was slower to allow the particles to sort according to density. The jiggling time was 15 minutes. When the jig cycle was complete, the coal sample was presumed to have been sorted into a density-continuum column: heaviest material (discard) at the bottom grading to lightest (best) coal at the top.

After jiggling was completed, the jiggling tube was lifted from the jig vessel, thus allowing the water to drain from the coal. A sample pusher was inserted in the jig tube and pressed to allow more water to drain. The entire tube was

then inverted to allow the coal to be pushed upward. Once the jig tube was inverted and the screen removed, the marbles were visible, as they had the heaviest specific gravity. This was evidence that the jiggling was successful. A tray was attached to the top of the tube and the sample pusher was rotated, causing the coal to be pushed above the jig tube and allowing the operator to scrape off the layer (Figure 5). The layer was carefully scraped into the apparent relative density (ARD) basket. Note that, because the jig tube was inverted after jiggling, the first fraction collected was the highest density (heaviest or highest ash content). The thickness of the layers was dictated by the size distribution of the coal and by how many fractions one expected to remove from the sorted column. As the wet ARDs were calculated immediately, the depth of the layers could be increased or decreased to obtain a range of ARDs and subsequent range of ash contents.

Each wet coal layer was weighed and air dried, and a dry ARD calculated. Samples were then prepared for laboratory testing. Similar ARDs were added together before preparation, or tested first to confirm ash results. The calculated ARD is an average for that layer.

Each coal sample was washed using both the jig method and the organic liquids method, thus yielding two clean-coal composites per coal type. Each of these samples was analyzed at the GWIL Industries–Birtley Coal & Minerals



Figure 4. Roben Jig equipment used in this study.



Figure 5. Inverted Roben Jig with coal slice ready to be removed.

Testing Laboratory for yield (percent), proximate analysis, free swelling index (FSI), specific gravity (sg), total sulphur, Hardgrove Grindability Index (HGI), calorific value (kcal/kg), mercury, ultimate analysis, mineral analyses of the ash, phosphorus in coal (percent, calculated), Gieseler maximum fluidity, Ruhr dilatation, ash fusion (oxidizing and reducing), chlorine, fluorine, alkali extraction–light transmittance test, Sapozhnikov X and Y indices, and caking index (G). Petrographic analysis of the coal was carried out at both CanmetENERGY (Ottawa, ON) and David E. Pearson & Associates Ltd. (Victoria, BC).

Carbonization

The clean-coal composites for coals A–D (~20 kg each) generated by the float-and-sink washing with organic liquids and the Roben Jig washing with water were received at CanmetENERGY in Ottawa between May 12 and June 29, 2017. Upon receipt, the composite samples were air-dried in the open air of the laboratory for 12 hours, homogenized and screened through a nest of sieves, ranging from +6.35 mm down to –0.5 mm, for measuring the size distribution and for preparing the charges for coking in CanmetENERGY’s 12 kg capacity carbonization sole-heated oven, as per ASTM D2014-97(2010), to measure the level of expansion/contraction.

The following section provides a description of the features and operating conditions for carbonization of coal in the sole-heated oven at CanmetENERGY, including the preparation of coke samples from coals A–D for CSR evaluation, following a procedure developed at CanmetENERGY (MacPhee et al., 2013). Figure 6 presents a schematic diagram of a sole-heated oven and Figure 7 a photo of the sole-heated oven used in this project.

Sole-Heated Oven (ASTM D2014-97(2010))

A 12 kg quantity of coal (75–100% –3.35 mm or –6 mesh) was divided equally and each half-charge loaded into a chamber approximately 280 mm in width, length and depth of a double-chambered oven. A weighted piston applied a constant force corresponding to a pressure of 15.2 kPa (2.2 psi) to the top of the coalbed (thickness in the 76–90 mm range), which was heated from below according to a prescribed temperature program. The sole temperature was raised from 554 to 950°C at a heating rate of 0.9–1°C/min during the test. The movement of the load was continuously monitored during the test, which was complete when the temperature at the top of the coalbed reached 500°C (normally after a period of 6–7 hours). The measured expansion or contraction of the sample was converted to a reference base of 833 kg/m³ (52 lbs./cu. ft.) and 2% moisture.

After carbonization, semi-coke was removed from the sole-heated oven and reheated. This treatment heated the semi-coke to 1100°C in nitrogen gas to complete the annealing of the coke.

Cokes from the sole-heated oven were assessed for apparent specific gravity (ASG) and hot-strength properties, including CSR and CRI following the ASTM D5341 / D5341M-14 standard, and analyzed for proximate (moisture, ash, volatile matter, fixed carbon), sulphur and carbon forms/textures using an optical microscope.

The ASG of coke is defined as the ratio of the mass of a volume of dry coke to the mass of an equal volume of water. Coke ASG varies with the rank and ash content of the coal carbonized, the bulk density of the coal charge in the oven, the carbonization temperature and the coking time (Price and Gransden, 1987). In this project, the ASG values of cokes were determined following a method developed at CanmetENERGY and related to the ASTM D167-93(2004) and ISO 1014:1985 standards.

According to ASTM D5341 / D5341M-14, the CRI is the percent weight loss of the coke sample after reaction in CO₂ at 1100°C for 2 hours. The cooled, reacted coke was then

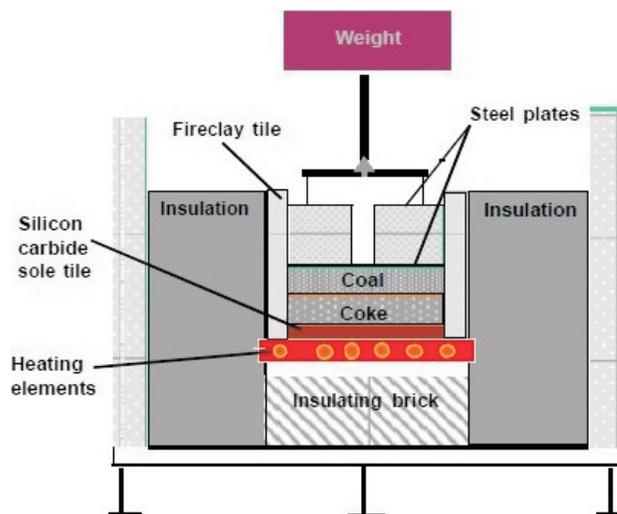


Figure 6. Schematic diagram of the CanmetENERGY sole-heated oven.



Figure 7. CanmetENERGY sole-heated oven (12 kg capacity) used in this study.

tumbled in an I-drum for 600 revolutions at 20 rpm. The cumulative percent of +9.5 mm coke after tumbling is denoted as the CSR.

Microscopic analysis of the textures was also performed on the sole-heated cokes to measure the carbon forms. This technique is extremely useful for understanding the behaviour of coal during coking and for interpreting pressure-generation and coke-quality results.

Carbon-form analysis in this project was carried out using a combination of the US Steel method (Gray and DeVanney, 1986) and the CanmetENERGY method, which is based on work carried out by H. Marsh in 1978-1981 and published in the book *Introduction to Carbon Science* (Edwards et al., 1989). A single point count is made for each measured field of view. For each field, the stage is rotated in order to determine the carbon form of highest possible rank. Normally, 500 point counts are performed on a sample. Each carbon form is derived from an assumed parent coal V-type. From the coke-texture analysis, one can determine the effective coal reflectance (%Ro).

Results

Coal and coke analytical results were analyzed to determine the following:

- Was the Roben Jig capable of producing a clean-coal composite similar to that of organic liquids for use in coal and coke evaluation?
- Did perchloroethylene have any impacts on coal rheology, coke strength and coke size?
- Was there misplaced material (higher ash particles contaminating lower ash/specific gravity slices) in the jig-produced sample, and at what specific gravity fraction did the misplaced material occur?
- Did the misplaced material affect coal and coke quality?

Roben Jig Versus Float-and-Sink Clean-Coal Quality

For all samples tested, the Roben Jig was successful in creating a clean-coal sample similar to that of the float-and-sink method but with better rheology.

Table 1 shows the comparison of some basic coal-quality parameters between the clean coals produced by the jig and the float-and-sink (FS) methods. Most of the clean-coal quality characteristics of the samples produced from both methods compared very closely. Values for ash, volatile matter, fixed carbon, sulphur, free swelling index, calorific value, fluorine, mercury and specific gravity, as well as most Hardgrove Grindability Index values, matched well, thus proving that the jig was useful in creating comparable clean-coal samples. One unexpected result was the increase in Hardgrove Grindability Index in the float-and-sink coal

samples compared to the jig-washed sample. Potential causes for this result will be researched at a later date.

For all coal types, the dilatation and fluidity were lower in the float-and-sink-washed samples than in the jig-washed samples. This was expected and was due to the perchloroethylene suppressing the rheology of the coal. The jig was successful in providing a more accurate measurement of the dilatation and fluidity of these samples. Only small differences were seen in the caking index (G) and the Sapozhnikov X and Y indices.

Fluidity refers to coal's plasticity during carbonization, where it changes from a solid material to a fluid (plastic) state and then to a fused porous solid (coke) during cooling. High fluidity is beneficial in the coke-making process. Dilatation determines the swelling properties of coal when heated under standard conditions. The caking index (G) is determined through a laboratory test that measures the caking capacity of a sample of coal to ascertain how well it binds or fuses together. A higher G index indicates greater caking capacity. The Sapozhnikov Y index is a measure of the maximum thickness of the plastic mass when the coal is heated to the peak temperature and before it resolidifies. This measure is similar to the free swelling index and the level of Gieseler maximum fluidity.

As expected, chlorine levels were highly elevated in all float-and-sink coal samples due to residual perchloroethylene remaining on the coal surface and within pore spaces.

Coal petrography is a microscopic technique used to determine a coal's degree of coalification and amount and category of macerals. These macerals can be categorized as reactives or inerts. Reactive macerals are those that burn readily during combustion and those that become plastic during carbonization in the coke oven. Inert macerals are those that are not reactive. The mean max vitrinite reflectance and the amounts of vitrinite, semifusinite, total reactives and total inerts were very comparable between the samples prepared using the jig and the float-and-sink method.

When comparing the clean-coal quality characteristics, it is apparent that the Roben Jig was able to provide a representative clean-coal sample with more realistic values of chlorine, fluidity and dilatation than the float-and-sink-washed sample. It is also evident that exposure to perchloroethylene caused a decrease in fluidity and dilatation in all four coal samples.

Clean-Coal Carbonization

For coals A–D, the percentage of the coal that was <3.35 mm ranged between 77% for coal C and 88% for coal B (Table 2). This indicates that coal B and coal C are the finest and coarsest coals, respectively, of the four coals tested.

Table 1. Clean-coal quality parameters (air-dried basis) for coal types A, B, C and D.

Clean-coal quality parameter (air-dried basis)	Coal A		Coal B		Coal C		Coal D	
	FS	JIG	FS	JIG	FS	JIG	FS	JIG
Moisture (%)	0.99	0.97	2.15	0.56	0.50	0.26	1.05	0.90
Ash (%)	5.74	5.88	8.54	9.70	8.42	8.35	10.95	10.85
Volatile matter (%)	31.76	31.95	23.19	23.52	24.41	24.96	22.14	22.35
Fixed carbon (%)	61.51	61.20	66.12	66.22	66.67	66.43	65.86	65.90
Sulphur (%)	0.46	0.51	0.41	0.42	0.55	0.56	0.30	0.31
Free swelling index	8.5	8.5	7.75	7.5	8.5	8.5	3.5	4.5
Calorific value (cal/g)	7955	7971	7750	7763	7874	7864	7496	7487
Chlorine (ppm)	3906	271	21450	949	733	472	4600	962
Fluorine (ppm)	224	225	118	115	92	134	93	93
Mercury (ppb)	32	24	38	31	86	85	53	55
Hardgrove grindability index	87	82	147	118	81	80	79	78
Specific gravity (sg)	1.30	1.31	1.37	1.36	1.35	1.34	1.39	1.37
Max fluidity (ddpm)	1647	1972	57	257	405	488	2	4
Ruhr dilatation:								
% contraction	24	27	24	21	23	25	20	16
% dilatation	111	139	3	33	93	103	-	-
% total dilatation	135	166	27	54	116	128	-	-
% SD 2.5	120	154	2	29	86	96	-	-
Caking index (G)	96	98	78	82	93	92	35	46
Sapozhnikov Y index	17.0	17.5	14.5	15.0	18.5	18.0	6.5	7.0
Petrography:								
Vitrinite reflectance (mean max)	0.94	0.94	1.22	1.23	1.20	1.21	1.17	1.17
Maceral analysis:								
Vitrinite (%)	68.7	64	38	46.3	60.6	62.9	41.3	43.4
Semifusinite (%)	9.7	12	24.1	18	13.9	12.8	21.6	20.9
Total reactives (%)	84.4	82.8	62.9	65.1	75.3	76.1	63.5	65.1
Inerts:								
Semifusinite (%)	9.7	12	24.1	18	13.9	12.8	21.6	20.9
Total inerts (%)	15.6	17.2	37.1	34.9	24.7	23.9	36.5	34.9

Abbreviation: ddpm, dial divisions per minute

Table 2. Size distribution in the sole-heated oven charges, and reference contraction values obtained from the sole-heated oven coke tests, for coals A–D.

Description	Units	Coal A		Coal B		Coal C		Coal D	
		Float-sink	Jig	Float-sink	Jig	Float-sink	Jig	Float-sink	Jig
Index		26152	26153	26164	26165	26209	26210	26240	26241
Coal pulverization, sole-heated oven charge:									
<i>Sieve analysis, cumulative</i>									
6.30 mm	%	4.62	4.15	3.77	4.02	12.74	8.40	8.26	8.54
3.35 mm	%	19.41	17.93	10.77	12.26	25.24	20.90	22.90	20.24
1.70 mm	%	36.12	34.85	20.96	24.37	42.24	38.09	39.05	36.71
0.85 mm	%	52.39	52.87	32.45	39.02	58.72	56.65	53.20	54.07
0.50 mm	%	63.49	65.07	41.39	50.20	69.20	68.76	62.64	66.07
Passing 3.35 mm	%	80.59	82.07	89.23	87.74	74.76	79.10	77.10	79.76
Sole-heated oven:									
Test date		25-May-17	26-May-17	01-Jun-17	02-Jun-17	28-Jun-17	29-Jun-17	20-Jul-17	19-Jul-17
Expansion/contraction value (%)		-20.8	-20.5	-22.3	-17.9	-6.6	-9.4	-19.8	-17.2

Contraction levels ranged from -21 for coal A to approximately -8 for coal C. In actuality, coals A, B and D exhibited very similar contraction, in the range -18 to -21. The type of washing medium, namely float-and-sink and Roben Jig, did not influence the level of contraction for the individual coals as it remained essentially unchanged.

The low volatile-matter content remaining in the cokes, 0.65–1.08%, provides clear evidence that the coals were essentially fully carbonized by a combination of coking in the sole-heated oven and heat-treatment of the resulting semi-coke to 1100°C under N₂ to complete the annealing of the coke. Figure 8 shows coke made by carbonizing coal C, washed via float-and-sink, in the sole-heated oven and after annealing to 1100°C. The coke reveals a number of cracks/fissures, which develop as the result of contraction due to loss of volatile matter as the semi-coke is heated above resolidification (Jenkins et al., 2010). In a sole-heated oven, fissures propagate from the bottom of the oven toward the top as coking progresses.



Figure 8. Coke made by carbonizing coal C, cleaned using the float-and-sink method, in the sole-heated oven.

The apparent specific gravity (ASG) of coke ranged between 1.01 (coals A and C) and 1.15 (coal D). As stated earlier, the rank and ash content of the carbonized coal dictates the coke ASG. The low ash content in coal A (5.8%) generates the coke with the lowest ASG coke, whereas the high

ash content in coal D (10.9%) leads to the coke with the highest ASG.

As shown in Figure 9, the CSR values for coals A, C and D washed using the traditional float-and-sink method were

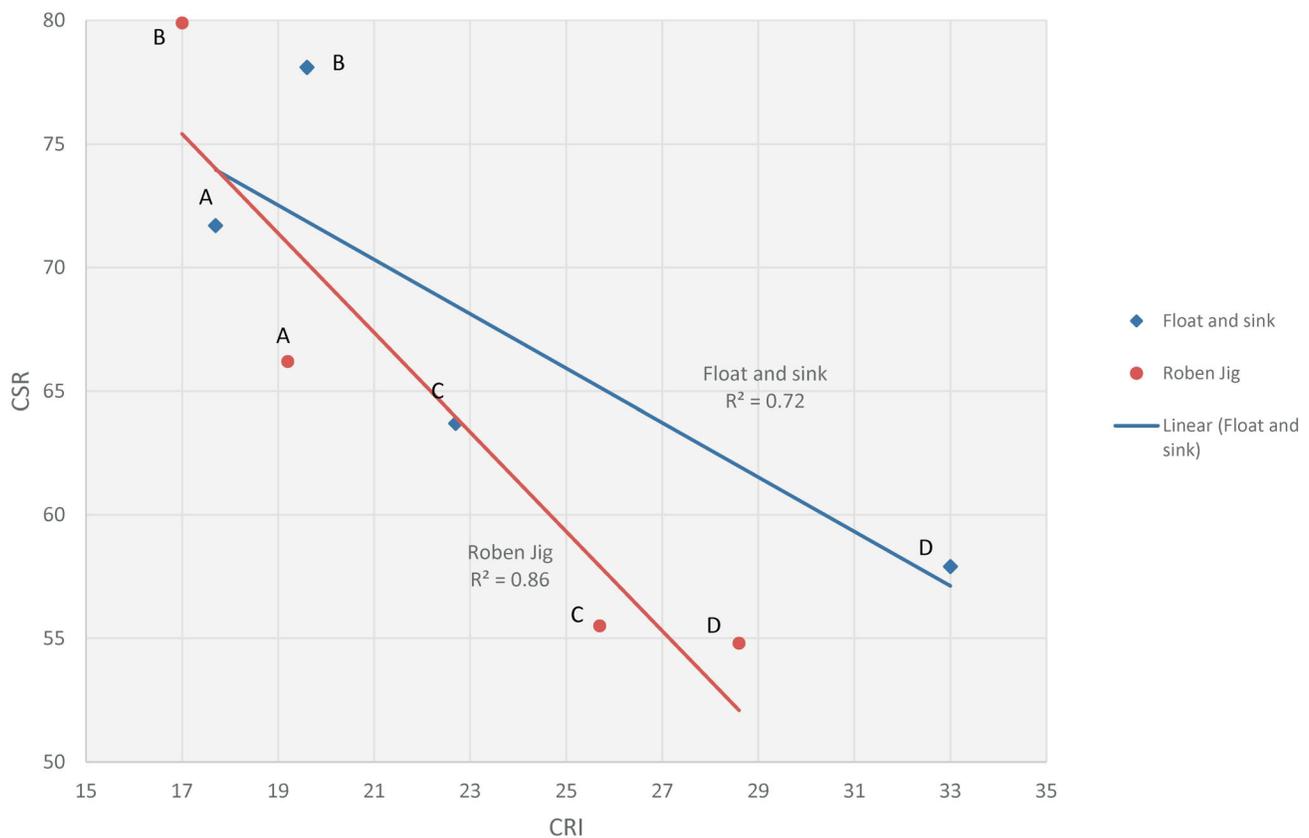


Figure 9. Plots of coke strength after reaction (CSR) versus coke reactivity index (CRI) for coals A–D.

higher than the values for these same coals washed using the water-based Roben Jig. Coal B, on the other hand, has a slightly higher CSR value when washed using the Roben Jig, compared to float-and-sink method. The CSR values for the four coals examined are in the order $B > A > C > D$. The high CSR and low CRI results for coal B appear to be dictated by its low ash basicity index of 0.049.

The most common classification of coal is based on rank, which refers to the degree of coalification that has occurred. The rank of a coal is determined primarily by the depth of burial and temperature to which the coal was subjected over time. Examination of carbon forms in coke, after a coal is transformed into a coke, provide a true measure of the degree of coalification, or rank, of the coal, which is its effective coking rank (Roeff). Results for coke textures/carbon forms (C forms) are given in Table 3. A close exami-

nation of the data indicates that the washing medium does not influence the development of textures during coal to coke transformation for coals A–D. In fact, the fractions of reactive and inert textures in the cokes are found to be similar for coals washed by the traditional float-and-sink method with organic liquids and by the Roben Jig using water. This is also supported by the fact that the ‘effective’ coking rank (Roeff) for the individual coals washed in the two media are very similar, except perhaps for coal C, which shows slightly stronger C forms and an Roeff value of 1.37 for jig washing compared to 1.32 for float-and-sink washing. It is quite revealing and interesting to note that the effective coking ranks of coals A–D, based on carbon forms measured in the cokes, are appreciably higher than the ranks determined from coal petrography (Ro). These Roeff and Ro values are 1.14 versus 0.94 for coal A, 1.42 versus 1.20 for coal B, 1.32 versus 1.21 for coal C, and 1.27

Table 3. Coke analytical data for cokes produced from coals A–D, including chemistry (proximate and sulphur), coke strength after reaction (CSR) and coke reactivity index (CRI), and coke textures/carbon forms.

Description	Unit	Coal A		Coal B		Coal C		Coal D	
		Float-sink	Jig	Float-sink	Jig	Float-sink	Jig	Float-sink	Jig
Index		26152	26153	26164	26165	26209	26210	26240	26241
Coke analyses:									
<i>Proximate analysis (db)</i>									
Ash	%	7.88	8.10	10.89	10.90	10.55	10.40	13.81	13.55
Volatile matter	%	0.71	1.08	0.70	0.86	0.65	0.69	1.07	0.81
Fixed carbon	%	91.41	90.82	88.40	88.24	88.80	88.90	85.12	85.64
Sulphur	%	0.38	0.41	0.30	0.31	0.46	0.45	0.24	0.26
Coke properties:									
Apparent specific gravity		1.051	1.009	1.085	1.096	1.018	1.005	1.157	1.145
Coke Strength after reaction (CSR)		71.7	66.2	78.1	79.9	63.7	55.5	57.9	54.8
Coke reactivity index (CRI)		17.7	19.2	19.6	17.0	22.7	25.7	33.0	28.6
Coke textural analysis:									
<i>Reactive textures</i>									
Isotropic	%	0.8	1.4	1.6	0.7	1.3	1.2	1.9	1.4
Very fine mosaic	%	1.2	2.4	0.0	0.0	0.6	0.2	0.5	1.3
Fine mosaic	%	13.3	12.2	0.0	0.3	1.0	0.8	1.3	1.4
Medium mosaic	%	58.8	57.7	2.5	3.1	23.4	13.1	20.5	21.7
Coarse mosaic	%	2.8	1.3	2.6	3.1	8.2	4.1	10.0	6.0
Elongated fine flow	%	6.9	12.8	6.6	4.5	29.3	24.7	8.4	7.2
Elongated medium flow	%	0.4	0.4	50.3	52.1	14.9	30.0	8.0	13.3
Elongated coarse flow	%	0.0	0.0	5.1	3.5	0.7	1.9	2.2	2.6
Domain flat flow	%	0.0	0.0	0.2	0.0	0.1	0.3	0.3	0.6
Domain undulating	%	0.0	0.0	0.8	0.3	0.9	0.1	0.7	1.2
Domain ribbon	%	0.0	0.0	0.0	0.0	0.3	0.0	0.5	0.0
<i>Inert textures</i>									
Fusinite	%	0.2	0.5	1.7	0.8	1.1	1.2	1.3	1.9
Semifusinite	%	15.4	11.1	26.7	31.2	17.5	21.3	43.4	39.8
Unidentified inerts	%	0.2	0.1	1.9	0.4	0.5	0.9	0.9	1.0
Altered vitrinite	%	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.6
Total mosaic	%	76.9	75.0	6.7	7.2	34.5	19.4	34.2	31.8
Total flows	%	7.3	13.2	62.0	60.1	44.9	56.6	18.6	23.1
Total domains	%	0.0	0.0	1.0	0.3	1.3	0.4	1.5	1.8
Total coke inerts	%	15.8	11.7	30.3	32.4	19.3	23.5	45.7	43.3
Coke mosaic size index		2.11	2.14	3.07	3.01	2.72	2.85	2.66	2.65
Estimated Ro of coal	%	1.13	1.14	1.42	1.42	1.32	1.37	1.27	1.27

versus 1.17 for coal D. This finding indicates that coals A–D actually produce stronger C forms than would be expected based on coal petrography v-type measurements.

The coke mosaic size index (CMSI) values for the coals washed in the two media are also very similar. CMSI is a mathematical method to summarize the carbon-form analysis (Coin, 1982). The higher the CMSI, the higher the rank based on carbon forms measured. In the present study, the CMSI values of the four coals are in the order $B > C > D > A$.

The CSR values of three of the four coals washed in the two types of media revealed that the float-and-sink method gives a slightly better result than the water-based jig method. It was also found that the washing medium (organic versus inorganic) does not influence the development of textures during the coal to coke transformation for the four coals. Also, coking rank based on carbon forms measured in the cokes is appreciably higher for each coal than rank determined from coal petrography, indicating that these coals produce stronger C forms than expected based on coal petrography v-type measurements.

Washability

Coal A

Figure 10 provides clean-coal curves produced from the float-and-sink procedure and the jig procedure for coal A.

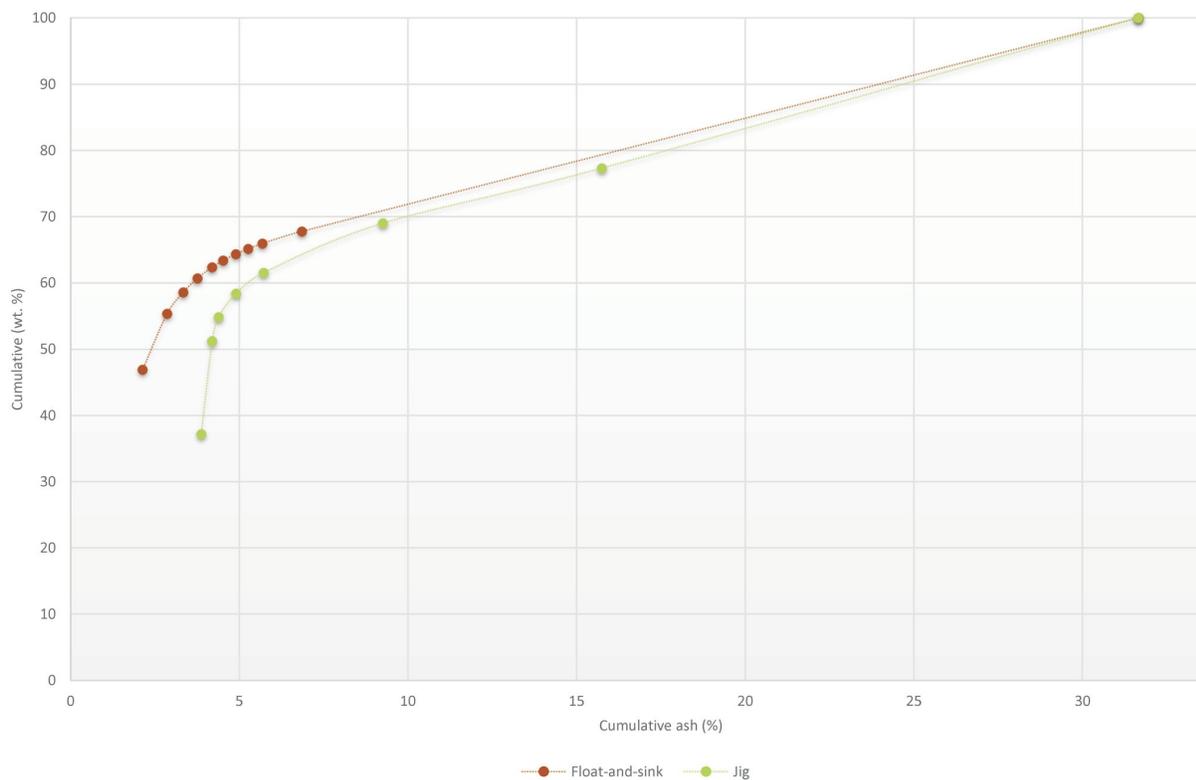


Figure 10. Clean-coal curve for coal A washed by the float-and-sink and jig procedures.

Figures 11 and 12 provide correlations between density of separation and cumulative ash, and density of separation and cumulative yield, respectively, for clean coal from tests using the two procedures.

The Jig was able to produce a low-ash clean-coal sample (below 5% ash) but at a much lower yield than the float-and-sink method. While it was easy to obtain a coal concentrate at 2% ash with a 47% yield using the float-and-sink procedure, the jig was only able to provide a concentrate with double the ash content (3.87% ash) at a 37% yield. The Roben Jig always provided products with higher ash content compared to a similar density of separation for the float-and-sink method. The greatest disparities were observed in clean-coal products below 10% ash (Figure 10). This coal seems to be somewhat easy to wash.

Coal B

It was difficult to obtain lower than 10% ash product using the jig procedure since the ash did not vary much within the first five relative density slices (Figures 13 and 14). When comparing the densities of the floats, the Jig clean coal resulted in higher ash values compared to the same density floats in the float-and-sink procedure (Figure 14 and 15). This coal seemed to be easy to wash (by float-and-sink); however, compared to coal A, it provided lower yields at 5% and 10% ash.

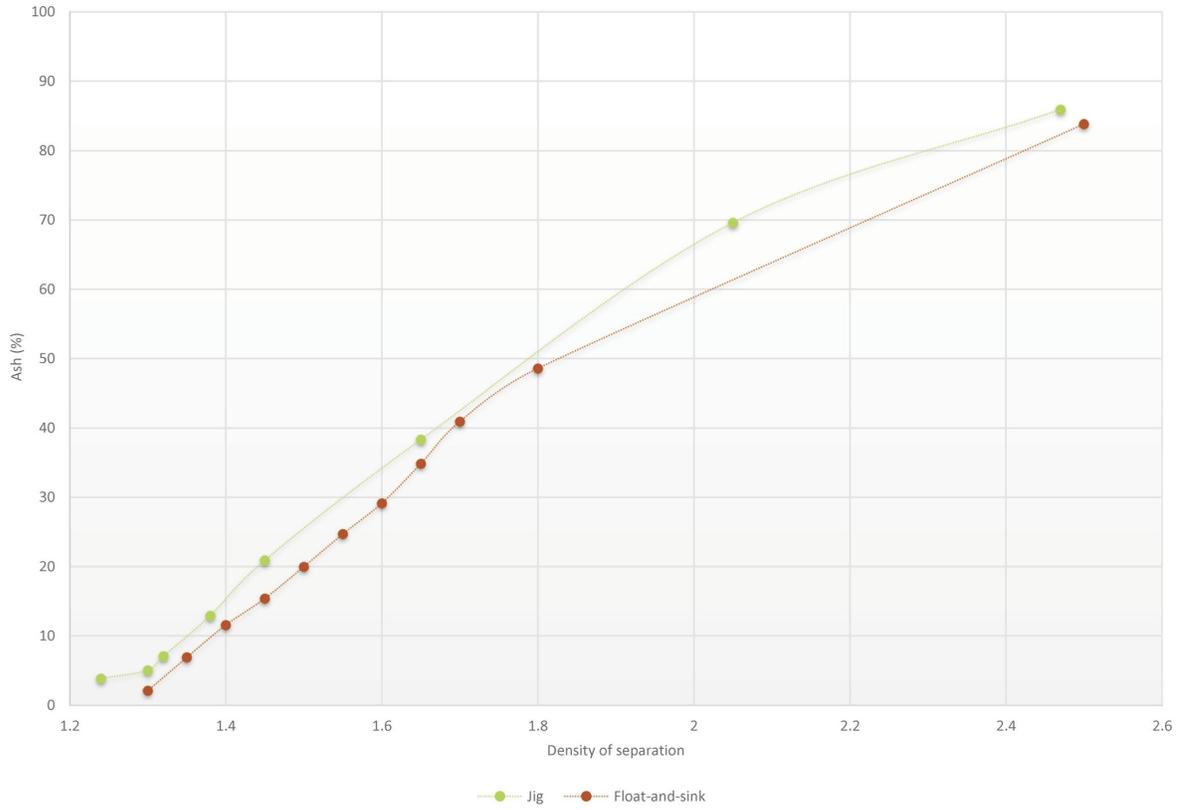


Figure 11. Density of separation (specific gravity and apparent relative density) versus ash in density fractions for coal A washed by the float-and-sink and jig procedures.

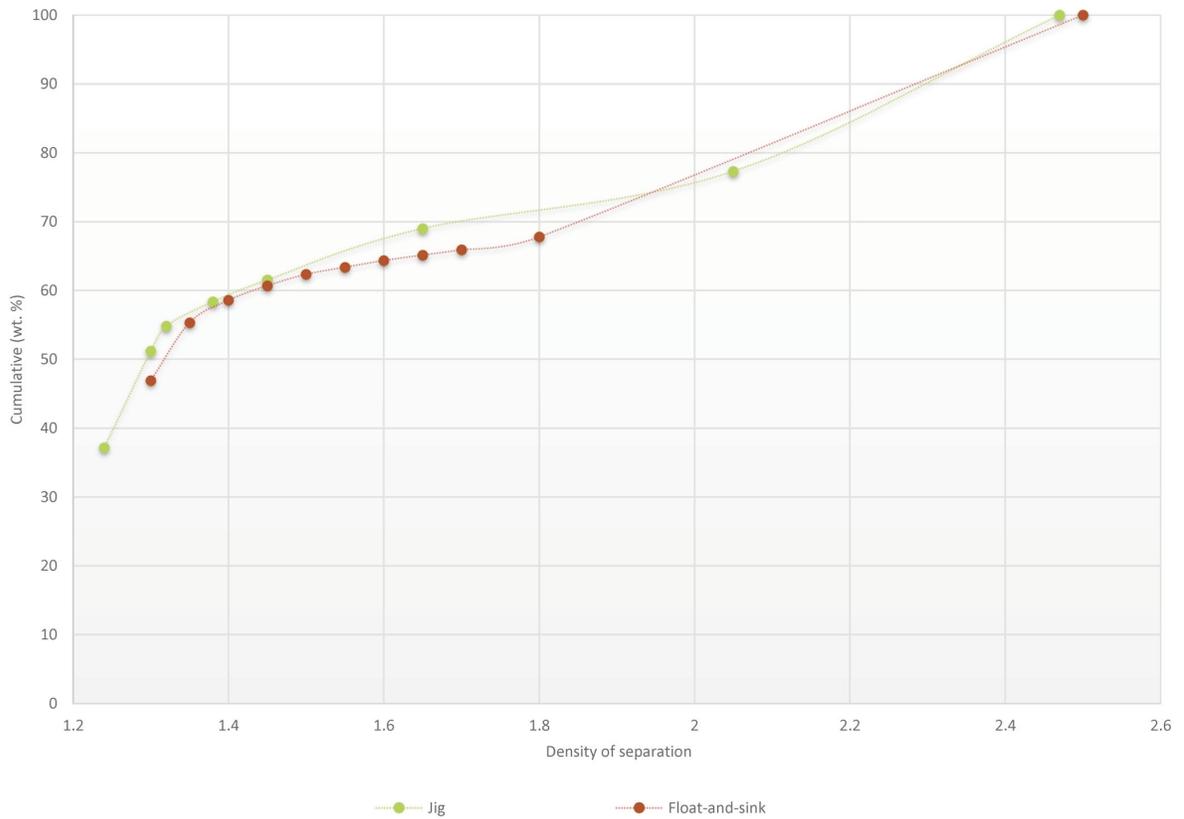


Figure 12. Density of separation versus cumulative yield of clean coal washed by the float-and-sink and jig procedures.

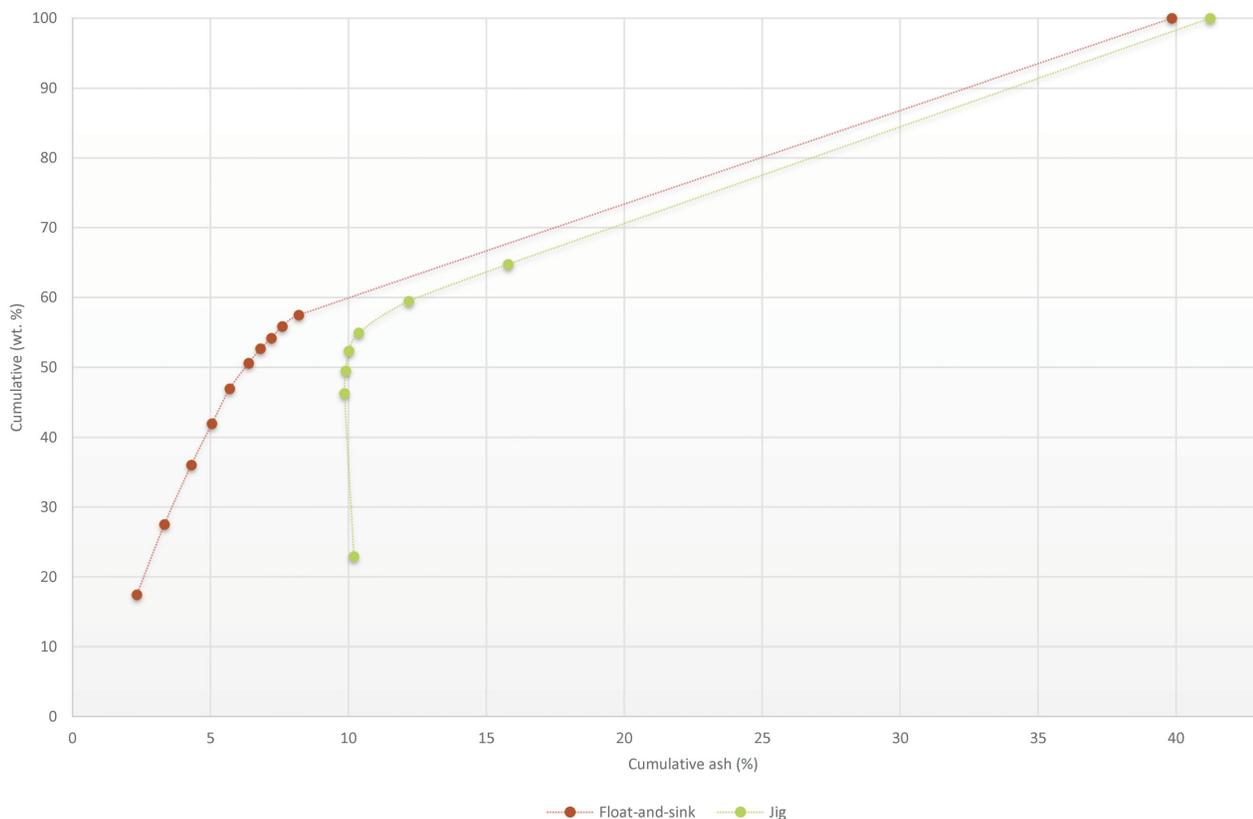


Figure 13. Clean-coal curve for coal B washed by the float-and-sink and jig procedures.

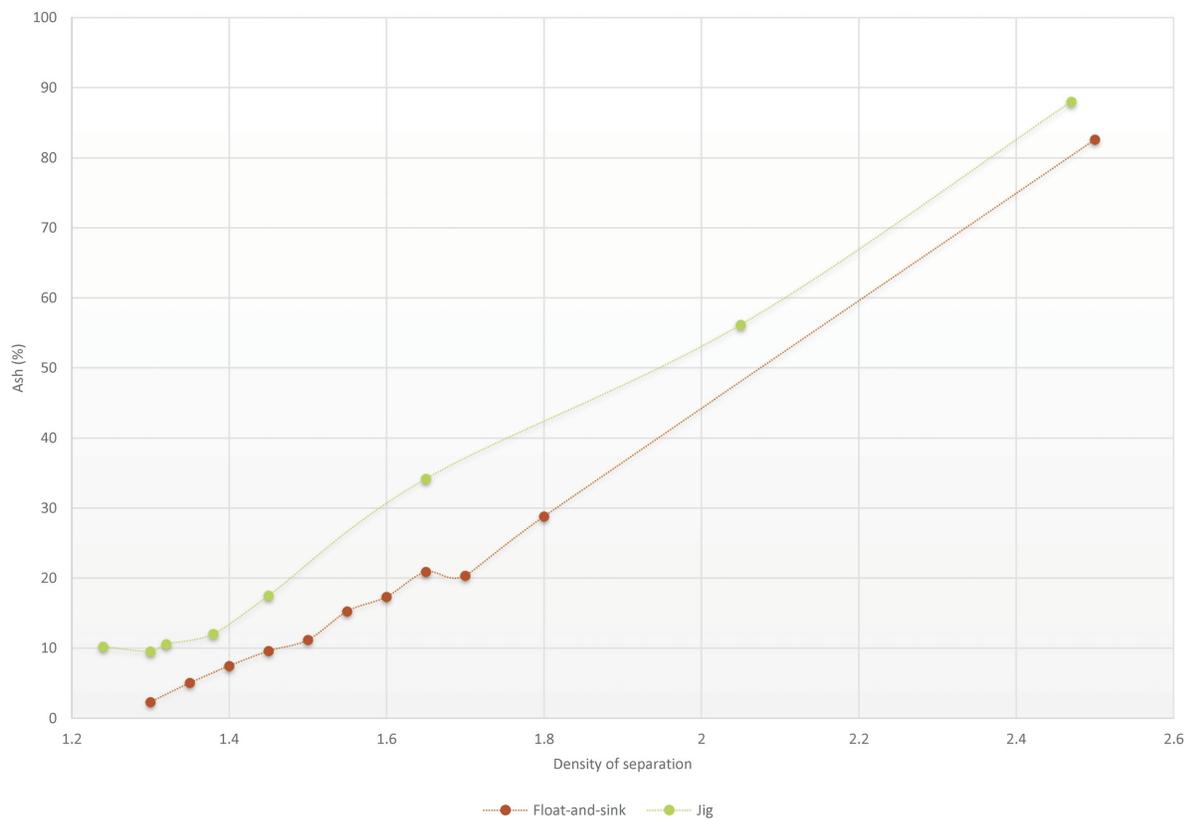


Figure 14. Density of separation (specific gravity and apparent relative density) versus ash in density fractions for coal B washed by the float-and-sink and jig procedures.

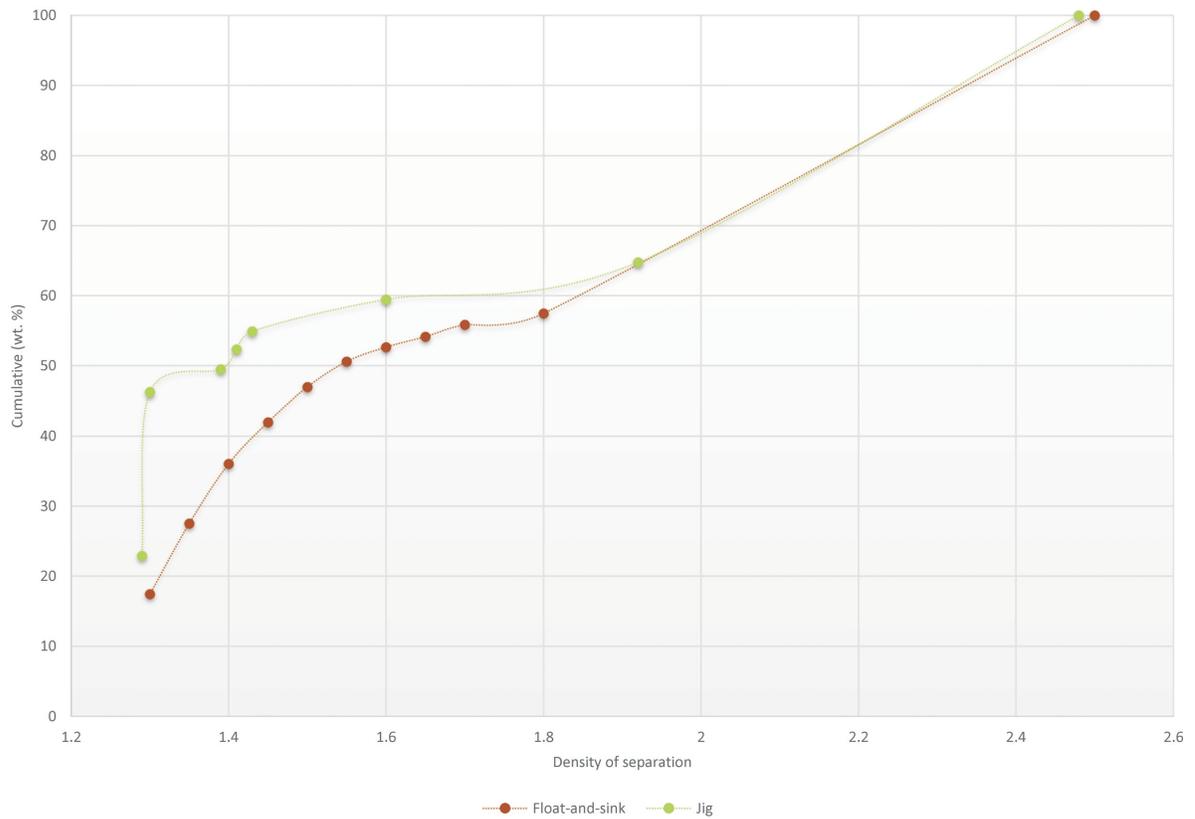


Figure 15. Density of separation versus cumulative yield of clean coal washed by the float-and-sink and jig procedures.

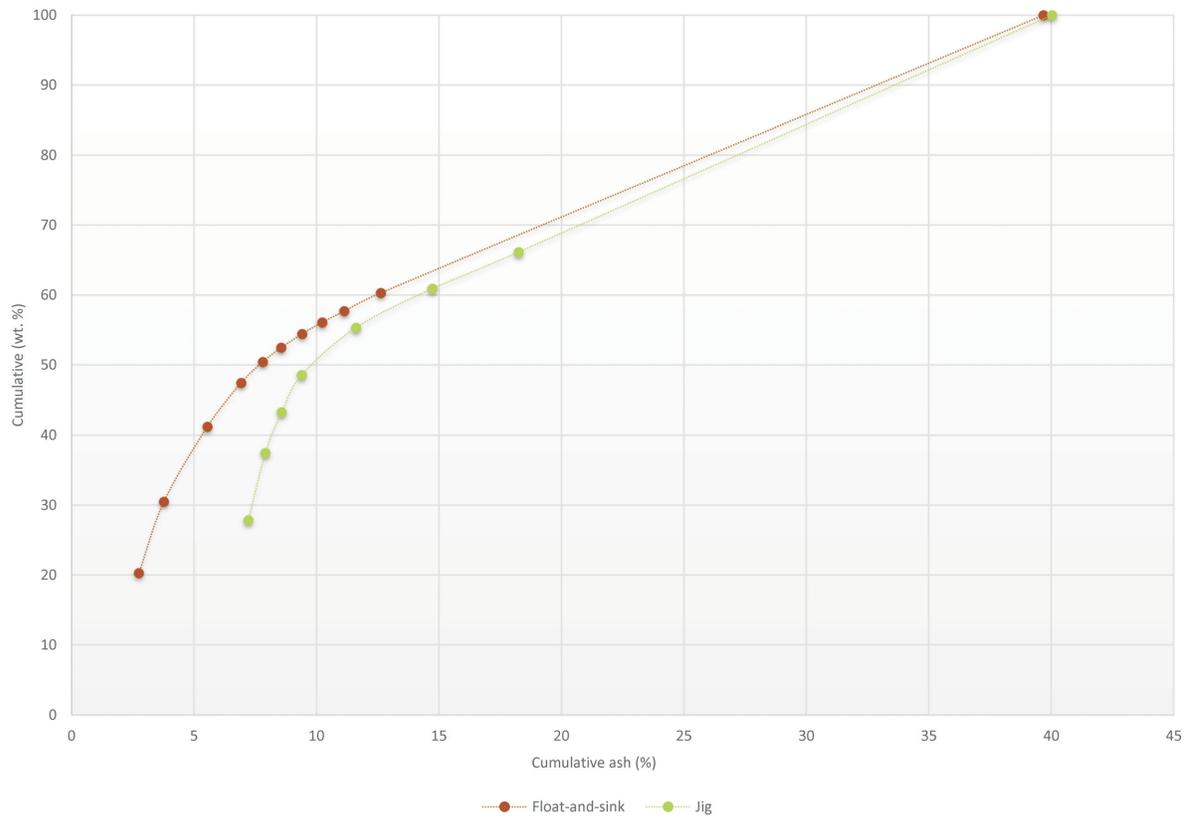


Figure 16. Clean-coal curve for coal C washed by the float-and-sink and jig procedures.

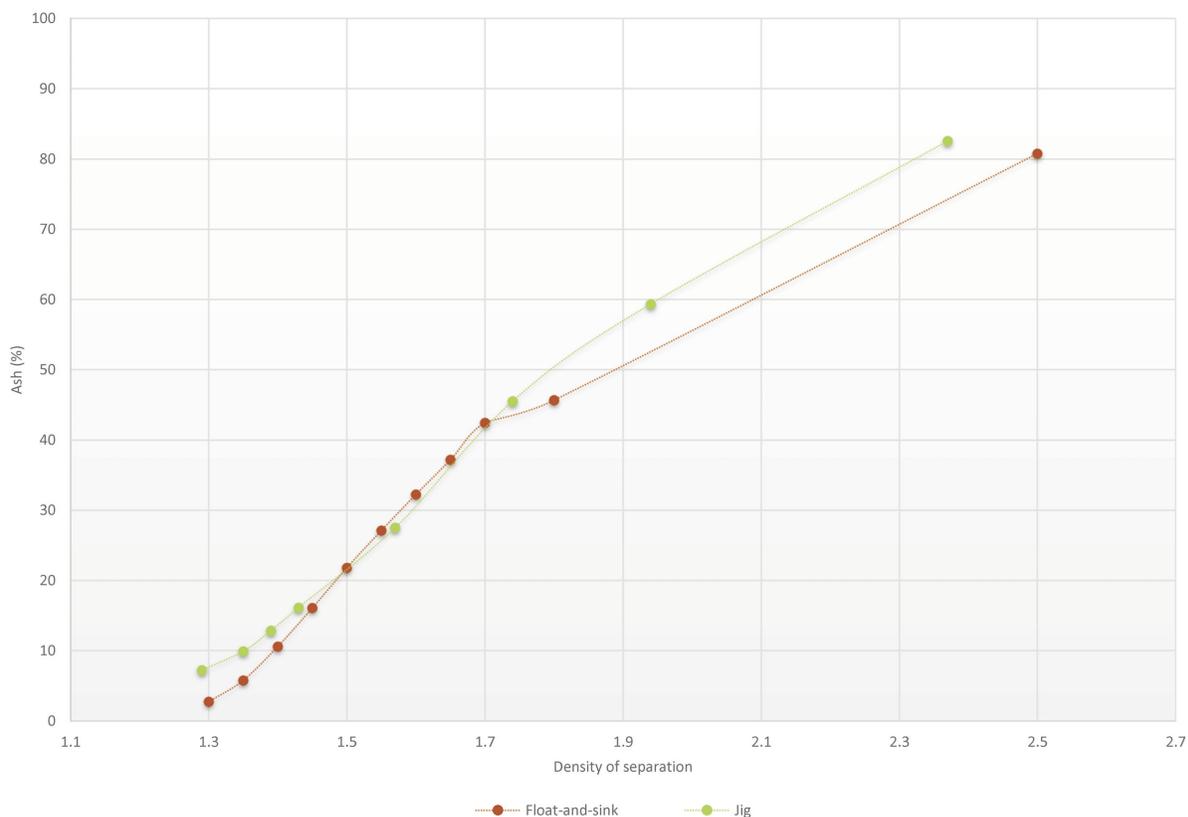


Figure 17. Density of separation (specific gravity and apparent relative density) versus ash in density fractions for coal C washed by the float-and-sink and jig procedures.

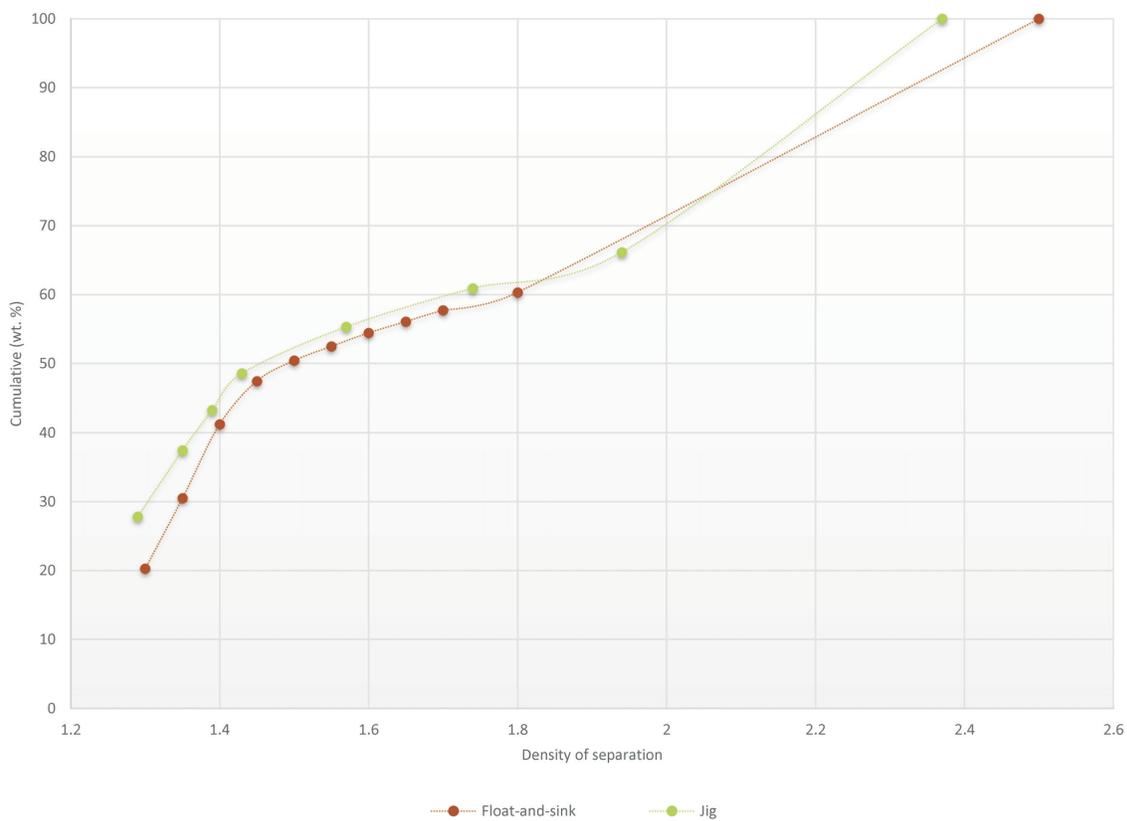


Figure 18. Density of separation versus cumulative yield of clean coal washed by the float-and-sink and jig procedures.

Coal C

Clean-coal curves produced from the float-and-sink and jig procedures for coal C are compared in Figure 16. Figures 17 and 18 provide correlations between density of separation and cumulative ash, and density of separation and cumulative yield, respectively, of clean coal from tests using the two procedures.

Using jig procedure, it was not possible to obtain lower than 5% ash content at the same yield of clean-coal product as from the float-and-sink procedure. However, like coals A and B, yield of product with 10% ash was comparable to that obtained from the float-and-sink procedure. Yield of clean coal was higher with higher ash at every density cut. This coal was more difficult to wash than coals A and B, based on the washability assessment and the much lower yields at 5% and 10% ash content.

Coal D

Clean-coal curves produced from the float-and-sink and jig procedures for coal D are compared in Figure 19. Figures 20 and 21 provide correlations between density of separation and cumulative ash, and density of separation and cumulative yield, respectively, of clean coal from tests using the two procedures.

Coal D exhibited the greatest differences between coal products produced from the jig procedure and the float-

and-sink procedure, even at higher than 10% ash products. It seems that it was not possible to obtain coal with lower than 8.87% ash. This sample seems to be difficult to wash, since even the float-and-sink procedure failed to produce a high yield of low-ash coal.

Each of the coal samples tested exhibited different washability characteristics when assessed using the standard float-and-sink procedure. Coal A was the easiest to wash, followed by coals B and C, and coal D was the most difficult to wash. The float-and-sink procedure reflects ideal conditions for gravity separation, and coal D could be deemed the most difficult to wash by gravity methods.

The Roben Jig was used in this study to produce a clean-coal concentrate comparable in quality to that produced by the float-and-sink procedure. In general, it was possible to obtain similar yields of clean-coal product with 10% ash from coals A, B and C using both procedures. However, it was not easy to obtain lower ash products (i.e., less than 5% ash) with the jig procedure either at all or at a yield comparable to that of the float-and-sink procedure. Coal D was deemed to be difficult to wash by the float-and-sink procedure and showed the greatest variability in the results obtained from the two washing procedures.

Since the jig procedure segregates particles by size and density, the stratification of feed containing coal particles

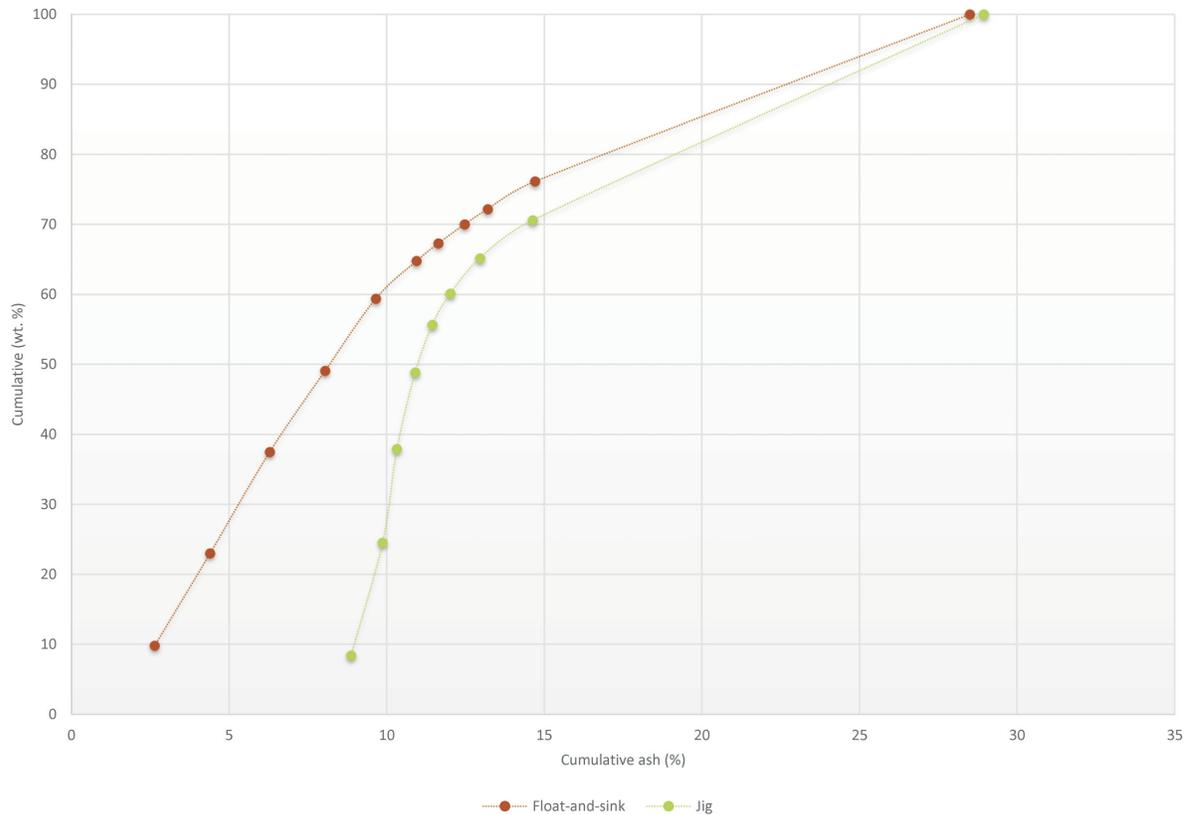


Figure 19. Clean-coal curve for coal D washed by the float-and-sink and jig procedures.

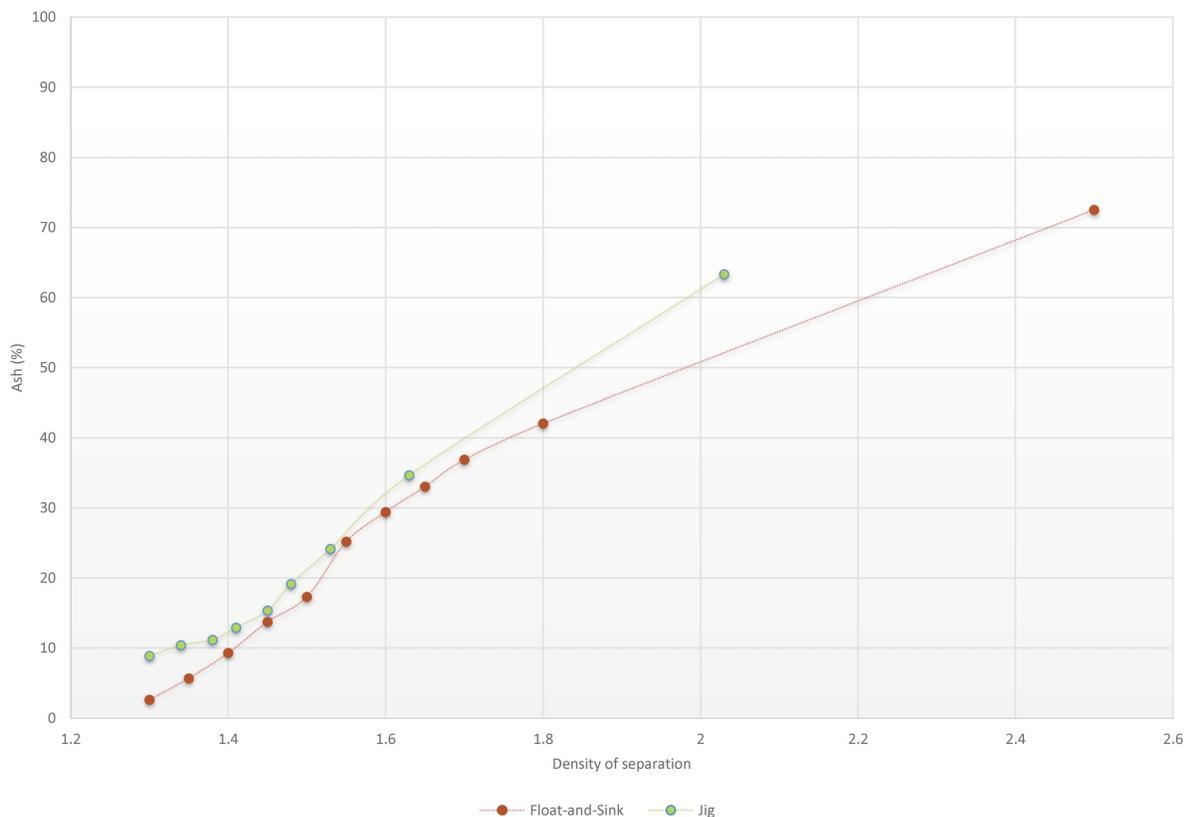


Figure 20. Density of separation (specific gravity and apparent relative density) versus ash in density fractions for coal D washed by the float-and-sink and jig procedures.

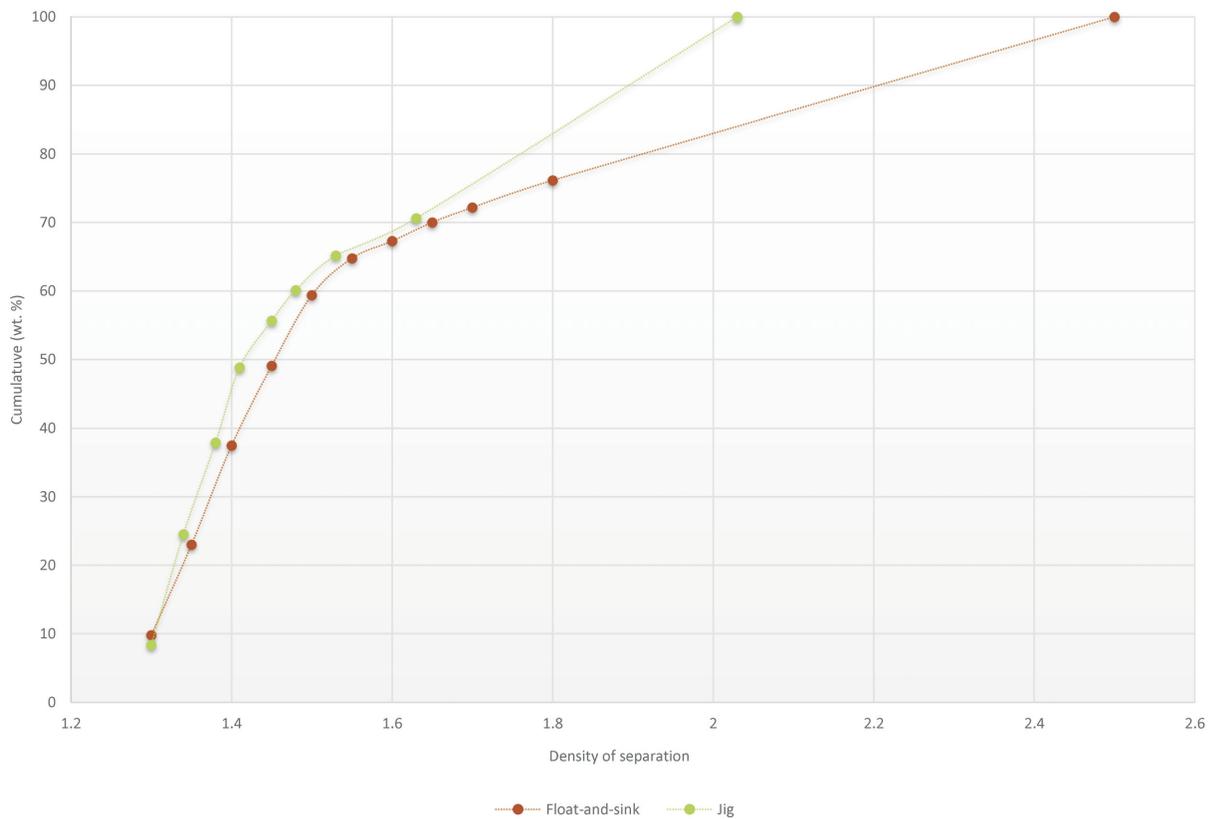


Figure 21. Density of separation versus cumulative yield of clean coal washed by the float-and-sink and jig procedures.

of intermediate density (middling matter) would pose the greatest challenge for the preparation of a clean-coal sample of similar quality by this method. Also, liberated mineral matter could be entrained within the layers of segregated clean coal and increase the ash and yield within each density cut. Even though coals A, B and C had similar washability patterns as determined by the float-and-sink procedure, they showed different trends when washed on the jig, which could indicate that such mineral-matter characteristics as liberation, clay content and content of fine coal could contribute to these outcomes. This aspect needs to be researched further to delineate the effects of possible clay entrainment and/or misplacement of middling matter during the jigging process.

Conclusion

The Canadian coal industry needs a reliable method of washing small-scale metallurgical coal samples where the exposure of both the coal sample and the laboratory technicians to perchloroethylene and other toxic organic liquids can be eliminated. This study evaluated the use of the Roben Jig in satisfying these requirements.

When comparing the clean-coal quality characteristics, it is apparent that the water-based Roben Jig was able to produce a clean-coal sample that had more realistic values of chlorine, fluidity and dilatation than the sample produced by the float-and-sink procedure. It is also evident that the exposure of the coal to perchloroethylene (in the float-and-sink process) caused a decrease in fluidity and dilatation in all four coal samples.

Coke resulting from three of the four coals was evaluated for coke strength after reaction (CSR), which revealed that the float-and-sink clean coal gave a slightly better result than the water-based jig method. It was also found that the washing medium (perchloroethylene or water) did not influence the development of textures during the coal to coke transformation for coals A–D. Also, the coking ranks, based on carbon forms measured in the cokes from all four coals, are appreciably higher than those determined from coal petrography, indicating that these coals produce stronger carbon forms than would be expected based on coal petrography v-type measurements.

Because of the jigging action and subsequent known movement of particles, there was a possibility that coal particles would be misplaced (i.e., fall within a layer of differing specific gravity). Previous work, using ‘easy to wash’ coal, showed that the Roben Jig worked well to produce representative clean coal samples. Even though coals A, B and C had similar washability patterns from the float-and-sink procedure, they showed different trends when washed in the Roben Jig, which could indicate that such mineral-matter characteristics as liberation, clay content and content of fine coal could contribute to these outcomes. Since the

clean-coal quality characteristics were very similar for the samples produced by the two washing methods, it is possible that, if there is misplaced material, it is not significantly affecting the coal quality. This phase of research involving the Roben Jig is nearing its conclusion and will be wrapped up by November 2017. More test work needs to be done on identifying and characterizing any misplaced material that may occur, as well as ‘fine tuning’ the methodology of the jig procedure.

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