Fine coal washability analysis using a laboratory concentrating table: G. William Kalb undergraduate research fellowship project report

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Abstract. Coal washability (float-sink) analysis uses heavy liquids that are a health hazard. In addition, for fine coal (-1 mm) especially, a problem with contamination by the heavy liquids arises as these fines are exposed to these chemicals for a longer time, to affect the separation. Laboratory-scale gravity concentration equipment is available to separate narrow size fractions of coal to develop washability data for a particular size fraction. This project evaluated a laboratory concentrating table for this purpose. Concerns over the validity of the initial float-sink testing limited the validation of its application in the first year of the project. Results in the second-year show promise for the use of the concentrating table, especially when comparing yields at a 10% ash level, which is typical for many US thermal coals. This paper reports on the initial findings from an undergraduate research project sponsored by the Coal Preparation Society of America.

1 Introduction

Currently the main method for evaluating the potential of coal beneficiation is laboratory washability or float-sink analysis. This is typically performed using organic liquids of known densities to allow distinct size fractions of coal to settle and be separated, though for specific gravities less than ~1.8 dissolved salts like zinc chloride ($ZnCl_2$) can be used. The organic liquids used in this analysis consist of perchloroethylene, bromoform, and tetrabromoethane. These organic liquids can have various health impacts, which shows a need for a new method of determining coal washability.

Galvin [1] reviewed options for washability analysis, indicating that the then existing Australian standard for float and sink analysis (AS4156.1-1994) was to be phased out because of the use of these toxic organic liquids. Alternative liquids and suspensions, as well as laboratory separation techniques were reviewed with pros and cons of the alternatives listed. Those techniques reviewed by Galvin [1] and some more recent developments are summarized in Table 1.

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Successful applications of jigs [2} for coarser particles and release or tree analyses [3,4] for fine particles leaves the analysis of intermediate size particles (say -2 +0.15 mm) to other technologies. For example, Callen et al. [5,6] have shown good results for the Reflux Classifier for -4 +0.045 mm particles but required the use of a correction factor for the low density/low ash region of the yield vs ash curve.

This work investigates a laboratory concentrating table to produce a fine coal washability analysis for the -1 +0.15 mm size range. This is the size upgraded by spiral concentrators in the United States and other countries. Successful application of this laboratory concentrating table will eliminate a health hazard at commercial coal laboratories, as well as at coal company and university labs. It will also eliminate the cost of chemicals and the need for storage of these materials. The purchase of a laboratory concentrating table would be a one-time expense of less than $US20,000 based on a purchase by the University lab in 2021. The cost of sieving and a three-point float-sink analysis by the commercial coal laboratory for this study was ~$US1,000, acknowledging that moisture, ash, and sulphur analyses would be conducted when using the concentrating table as well. With routine plant audits being conducted, using this unit could save lab costs for coal companies.

Table 1. Setting Word's margins.

Method	Pros	Cons	References
Salt solutions ($ZnCl_2$)	No toxicity/ environmental concerns per the reference, but known issues with fumes, corrosion of the skin and eyes and aerosol irritates the respiratory tract	Viscosity issues at higher densities; potential chemical interaction	[1]
Cesium/Potassium formate solutions	No toxicity/ environmental concerns	Absorption, especially for fines; cost for cesium formate—need for recycling	[7]
Test tube device with $ZnCl_2$	Simplified testing device compared to funnel-flask or centrifugal techniques	Will still have viscosity issues at higher densities; same issues with $ZnCl_2$ fumes and corrosion	[8]
Tungstate solutions	No toxicity/ environmental concerns per the reference but some compounds may be toxic at high concentrations	High viscosity at high density for sodium and lithium metatungstate; cost for lithium heteropolytungstates	[9]
Hematite suspensions	No toxicity/ environmental concerns	Difficult to keep suspended or to resuspend; opaque and difficult to see the particles;	[1]
Erickson Cone	No toxicity/ environmental concerns	For lump particles; washing the particles; clay breakdown	[10]

Magnetized suspensions/ferrof luids	No toxicity/ environmental concerns; one fluid to cover all densities	Further work needed on coal	[11, 12]
Water fluidization	No toxicity/ environmental concerns; only uses water	Clay breakdown; use for <4 mm particles	[5, 6, 13]
Jigging	No toxicity/ environmental concerns; only uses water	Clay breakdown; coarse particles; needs more work for fines	[1, 5, 6, 11]
Reflux Classifier	No toxicity/ environmental concerns; only uses water	Requires narrow size fractions	[3]
Reflux Classifier	No toxicity/ environmental concerns; only uses water	Hydrophobic coal fines; need technician trained in froth flotation testing	[3, 4]
Roben jig	No toxicity/ environmental concerns; only uses water; samples like prep plant products	For +0.5 mm	[2]
RhoVol	No toxicity/ environmental concerns	Possibly cost issues; needs more testing on coal; +8 mesh (+2.38 mm)	[14]

2 Methods and materials

Two Raw Coal Screen undersize samples (-1 mm) from CONSOL Energy's Bailey Central Preparation Plant in Greene County, PA, USA, were obtained for this test program. One of the samples, designated "B," was a sample collected when coal from the Bailey Mine was being processed; it was the lower ash content sample. The other sample designated "H" was of a higher ash content and was from the Harvey Mine. The coal is from the Pittsburgh seam. The samples, unfortunately, were not decanted prior to shipment, so there was a limited quantity of material to test. Following dewatering in a laboratory vacuum filter and drying, the samples were initially sieved at 28, 65, and 100 mesh (0.595, 0.212, and 0.150 mm) as narrow size fractions coarser than that being fed to froth flotation (100 mesh or 0.150 mm) were desired for the test work. There was very little -65 +100 mesh (-0.212 +0.150 mm) material, so that it was combined with the -28 +65 mesh (-0.595 +0.212 mm) fraction for testing. This resulted in the testing of two size fractions for each coal sample: +28 mesh and -28 +100 mesh (+0.595 and -0.595 +0.150 mm). Each size fraction was riffled to obtain a representative split of material that was sent to a commercial laboratory for washability or float-sink analysis at 1.40, 1.60, and 1.80 sg. The analysis is given in Table 2. Note the higher head ash analyses for the "H" samples as compared to the "B" samples and good agreement between the cumulative ash and the head ash values for the samples.

Additionally, a third combined feedstock sample was introduced and designated as "C" in the second round of testing. These samples were also not decanted before shipment, so the limited quantity of testing material was considered once more. Following dewatering in a laboratory vacuum filter and drying, the samples were sieved at 6, 35, and 100 mesh (3.36, 0.50, and 0.150 mm) as narrow size fractions, coarser than that being fed to froth flotation (100 mesh or 0.150 mm), were desired for the test work. The 6-mesh sieve was used to scalp coarse particles that made up <1% of the total sample weight. What remained was ostensibly -1mm, as before. Both size fractions were riffled to obtain a representative split of material

that was sent to a commercial laboratory for washability or float-sink analysis at 1.40, 1.60, and 1.80 sg. This analysis is given in Table 3. It should be noted that commercial coal laboratories in the US will typically only do washability analysis up to 1.80 specific gravity to avoid even more health issues with the organic liquids at higher values.

It should be noted further that the washability analysis conducted during the first year of testing by a commercial coal laboratory for the "B" and "H" seams is suspect. Literature data for the washability of other Pittsburgh seam coal samples [15] show low ash (4-5%) in the lightest gravity fractions, so the higher ash values of almost 8 % to over 10 % ash for the Float 1.40 fractions are out of line. A different coal laboratory was selected for the coal washability analysis in the second year. The low ash values of under 5% ash in the Float 1.4 fraction in the "C" washability are more comparable to literature data. Indeed, for the -28 +100 mesh (-0.595 +0.150 mm) fraction of a Pittsburgh seam coal from Pennsylvania, the Float 1.40 fraction was 4.29% ash, while that for an Ohio-based Pittsburgh seam coal was 4.48% [15].

Fine coal float-sink analysis in heavy liquids requires special care and for finer fractions, centrifuges are suggested. An interlaboratory test program conducted by the US Department of Energy in 1992 [16] had already highlighted the difficulties in conducting fine coal float-sink. There were wide differences in the ash versus yield relationships between eight laboratories using their own centrifugal float-sink technique. As commercial coal laboratories in the US lose key staff members to retirement, samples must be sent to laboratories that maintain rigorous testing procedures and offer proper training for these specialty procedures.

The remaining splits from all these fractions were then processed on a laboratory Deister concentrating table (DEISTER #15-S Laboratory Concentrating Table Package), using the "sand" deck that came with this unit (see photos in Figures 1-3) and the following set points:

Right nozzle flow rate = 0.189 L/s
Left nozzle flow rate = 0.108 L/s
Feed rate = 13.14 g/s
Height from table (which determines tilt) = 35.5 cm

Splitters on the launders then split the samples into four fractions designated "light," "medium," "medium heavy," and "heavy." All four samples were collected in buckets, decanted, and then dried. Samples were then riffled to retrieve approximately 50 g of material to then pulverize before an ash analysis using a Thermogravimetric Analyzer (TGA).

Table 2. Commercial laboratory washability analysis by size fraction for the original two coals from Bailey "B" and Harvey "H" mines (dry basis).

"B" +0.595 mm

Spec. Grav. Frac.	Fractional Data		Cumulative Data	
	Wt %	Ash (Wt %)	Wt %	Ash (Wt %)
Float 1.40	75.89	7.92	75.89	7.92
1.40 – 1.60	13.32	18.36	89.21	9.48
1.60 – 1.80	2.02	36.48	91.23	10.08
1.80 Sink	8.77	74.80	100.00	15.75
			Head Sample Ash	15.29

"B" -0.595 +0.150 mm

Spec Grav Frac	Fractional Data		Cumulative Data	
	Wt %	Ash (Wt %)	Wt %	Ash (Wt %)
Float 1.40	54.30	7.25	54.30	7.25
1.40 – 1.60	33.26	18.51	87.56	11.53
1.60 – 1.80	3.62	32.76	91.18	12.37
1.80 Sink	8.82	72.77	100.00	17.70
			Head Sample Ash	18.07

"H" +0.595 mm

Spec Grav Frac	Fractional Data		Cumulative Data	
	Wt %	Ash (Wt %)	Wt %	Ash (Wt %)
Float 1.40	56.60	10.30	56.60	10.30
1.40 – 1.60	26.18	28.28	82.78	15.99
1.60 – 1.80	5.66	33.97	88.44	17.14
1.80 Sink	11.56	79.17	100.00	24.31
			Head Sample Ash	21.04

"H" -0.595 +0.150 mm

Spec Grav Frac	Fractional Data		Cumulative Data	
	Wt %	Ash (Wt %)	Wt %	Ash (Wt %)
Float 1.40	54.52	7.90	54.52	7.90
1.40 – 1.60	22.40	20.60	76.92	11.60
1.60 – 1.80	10.12	35.90	87.04	14.42
1.80 Sink	12.96	77.56	100.00	22.61
			Head Sample Ash	21.92

Table 3. Commercial laboratory washability analysis by size fraction for the combined coal sample for the second year's sample, conducted by a different commercial lab (note that a separate head sample ash analysis by size fraction was not provided by this laboratory to check for closure though it was requested).

"C" +0.50 mm

Spec Grav Frac	Fractional Data		Cumulative Data	
	Wt %	Ash (Wt %)	Wt %	Ash (Wt %)
Float 1.40	76.02	4.66	76.02	4.66
1.40 – 1.60	7.17	18.89	83.19	5.89
1.60 – 1.80	3.23	37.28	86.42	7.06
1.80 Sink	13.58	75.54	100.00	16.36

"C" -0.50 +0.150 mm

Spec Grav Frac	Fractional Data		Cumulative Data	
	Wt %	Ash (Wt %)	Wt %	Ash (Wt %)
Float 1.40	78.07	4.77	78.07	4.77
1.40 – 1.60	7.24	16.46	85.31	5.76
1.60 – 1.80	2.54	33.56	87.85	6.57
1.80 Sink	12.15	75.09	100.00	14.89

Fig. 1. Feed to the laboratory concentrating table showing the two water addition points and vibratory feeder.

Fig. 2. Splitters allowed separation and collection of the “light” from the “medium” material along the length of the front launder.

Fig. 3. Splitters allowed the separation of the “medium heavy” from the “heavy” particles along the shorter side of the concentrating table.

3 Results and discussion

The results for the concentrating table tests are given in Tables 4-11 and compared to the float-sink results in Figures 4-9. With the limited amount of sample, it was impossible to replicate tests to confirm these results and properly quantify the statistical differences between the washability data and the concentrating table tests. However, the results are still promising and show that using a concentrating table to produce washability results for fine coal has some promise and should be continued to be evaluated. This undergraduate research program sponsored by the Coal Preparation Society of America provided some good initial results, but additional funding for a more comprehensive study must be sought for this to be accepted as a replacement for float-sink analysis.

Figures 4-7 show plots of the concentrating table results compared to the commercial laboratory float-sink results in samples "B" and "H." It can be seen that the initial concentrating table tests produced lower ash products than were achieved with the float-sink analysis, especially at similar yields. This is especially concerning for the two coarse (+28 mesh/+0.595 mm) size fractions, as it would be expected that these results for the coarser material would be more similar since it may be expected that the laboratory float-sink analysis should be more reliable for coarser fractions. However, as noted by Killmeyer et al. [16] in the US Department of Energy study there were differences between labs even for the coarse fractions tested. As described previously, the lightest fractions (Float 1.4) of the Pittsburgh seam coal typically contain less than 5% ash [15]. We are, therefore, comparing the concentrating table results to poor laboratory float-sink results. These results should be a caution for all who use commercial coal laboratories for fine coal float-sink analysis or for those conducting their own analyses without understanding all the cautions associated with this technique.

There is some concern about the data in Table 5 and Figure 5 as the "lightest" fraction from the concentrating table had a higher ash content than the next lightest or the "medium" sample as designated in this study. One possible explanation is that the sample was not thoroughly deslimed prior to testing and that finer (-0.150 mm), higher ash coal was carried into this fraction with the greater quantity of water present in the "B" sample then influencing the cumulative ash values. Unfortunately, we did not do further screening of the samples with associated ash analyses for these tests to confirm this.

Table 4. Concentrating table test results for "B" +28 mesh (+0.595 mm).

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
B+28 light	1102	26.85	4.50	26.85	4.50
B+28 med	676	16.46	4.98	43.31	4.68
B+28 med heavy	1678	40.88	8.99	84.20	6.77
B+28 heavy	649	15.80	74.57	100.00	17.49
Total	4105	100.00		**Head Sample Ash**	15.29

Table 5. Concentrating table test results for "B" -28 +100 mesh (-0.595 +0.150 mm).

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
B-28+100 light	1774	44.43	8.41	44.43	8.41
B-28+100 med	494	12.39	6.07	56.82	7.90
B-28+100 med heavy	1070	26.82	9.71	83.64	8.48
B-28+-100 heavy	653	16.36	64.33	100.00	17.62
Total	3991	100.00		**Head Sample Ash**	18.07

Table 6. Concentrating table test results for "H" +28 mesh (+0.595 mm).

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
H+28 light	2173	32.61	5.35	32.61	5.35
H+28 med	1723	25.87	5.80	58.48	5.55
H+28 med heavy	1810	27.16	15.93	72.84	7.60
H+28 heavy	957	14.36	76.36	100.00	26.27
Total	6663	100.00		**Head Sample Ash**	21.04

Table 7. Concentrating table test results for "H" -28 +100 mesh (-0.595 +0.150 mm).

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
H-28+100 light	2363	61.01	8.11	61.01	8.11
H-28+100 med	508	13.11	13.23	74.12	9.02
H-28+100 med heavy	240	6.21	32.07	80.33	10.80
H-28+100 heavy	762	19.67	79.06	100.00	24.23
Total	3873	100.00		**Head Sample Ash**	21.92

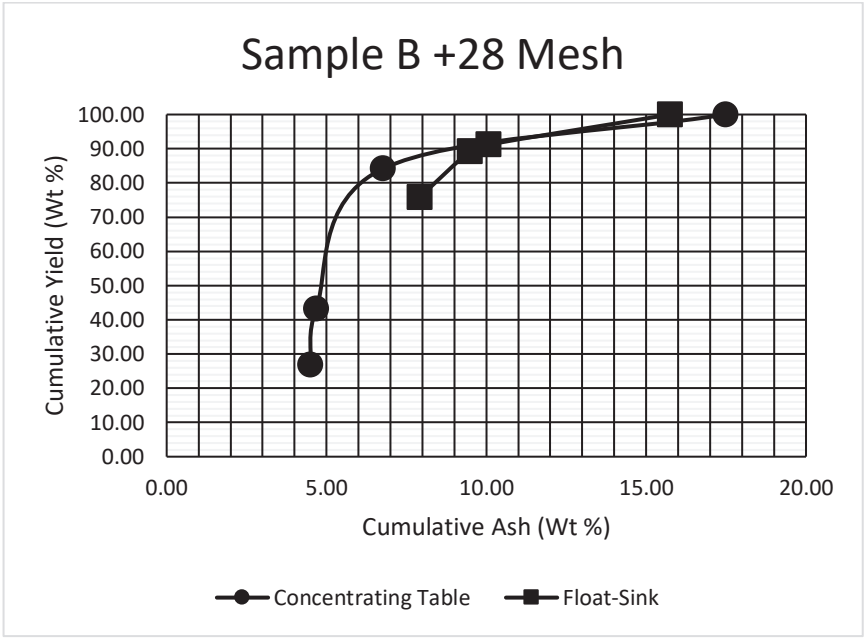

Fig. 4. Cumulative yield vs cumulative ash for the concentrating table and laboratory float-sink analysis for Sample B +28 Mesh (+0.595 mm).

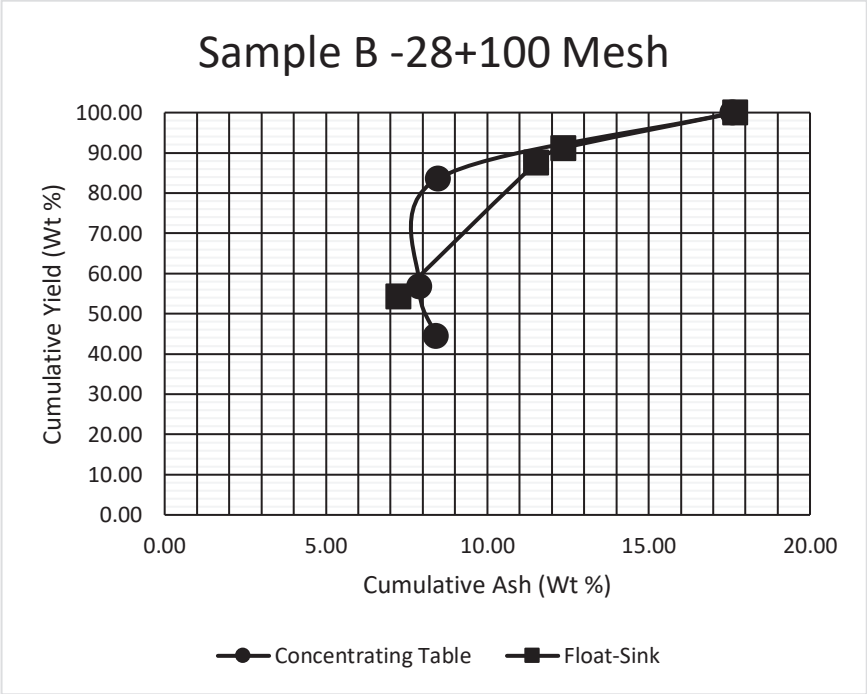

Fig. 5. Cumulative yield vs cumulative ash for the concentrating table and laboratory float-sink analysis for Sample B -28+100 Mesh
(-0.595 +0.150 mm).

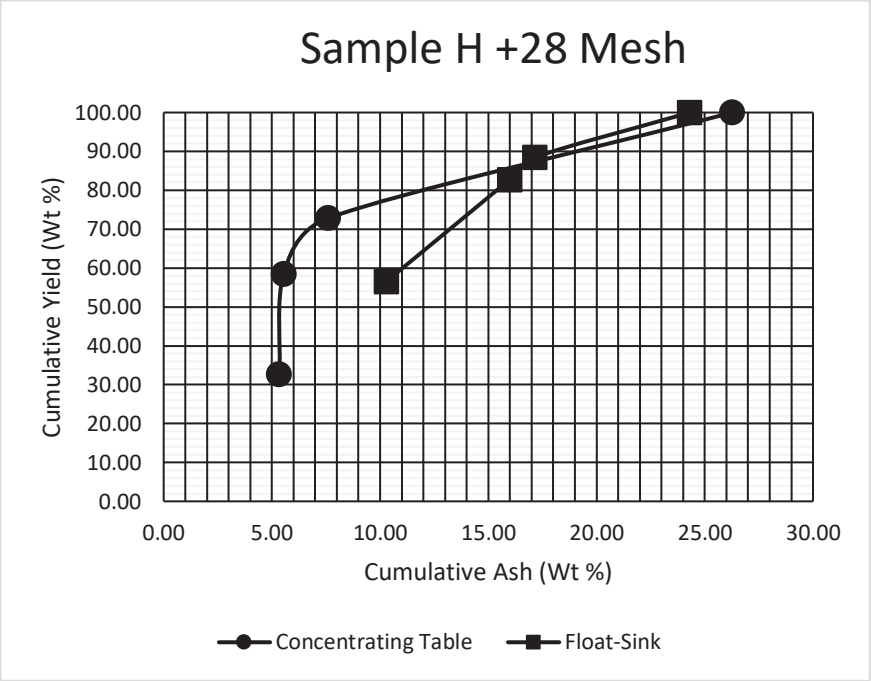

Fig. 6. Cumulative yield vs cumulative ash for the concentrating table and laboratory float-sink analysis for Sample H +28 Mesh (+0.595 mm).

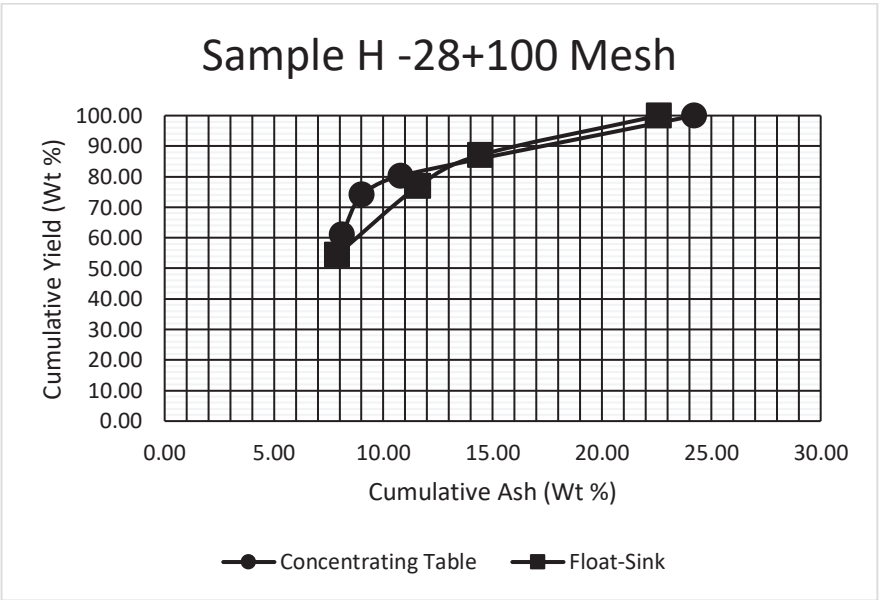

Fig. 7. Cumulative yield vs cumulative ash for the concentrating table and laboratory float-sink analysis for Sample H -28+100 Mesh (-0.595 +0.150 mm).

In the second year of testing with coal "C," a different coal laboratory was used for the float-sink analysis. As shown in Figures 8 and 9, the float-sink analysis gave an expected result. It produced a cumulative yield versus cumulative ash curve that gave the "best" result for comparison to the concentrating table tests, so it really did represent the "theoretical best" separation. Two tests were conducted with each size fraction, with one have a "smaller cut" taken for the first "lightest" fraction and the second having a "larger cut" taken for this fraction. This was accomplished by moving the cutter in the launder as shown in Figure 2. The "smaller cut" appeared to produce results more comparable to the float-sink analysis for both the coarse and fine fraction, though it appears that the light and medium fractions should be combined in these tests to better mimic the float-sink results. Again, there may be issues with some high ash slimes in the light fraction to cause the slightly higher ash in the lightest fraction.

Table 8. Concentrating table test results for "C" -6+35M (-3.36 +0.50 mm) [Small Cut].

Sample	**Wt (g)**	**Wt %**	**Ash %**	**Cumulative Wt %**	**Cumulative Ash %**
-6+35' (Small Cut) Light	1589	35.01	5.88	35.01	5.88
-6+35' (Small Cut) Medium	1321	29.10	5.69	64.11	5.79
-6+35' (Small Cut) Medium Heavy	769	16.94	13.29	81.05	7.36
-6+35' (Small Cut) Heavy	860	18.95	68.99	100.00	19.04
Total	4539	100.00			

Table 9. Concentrating table test results for "C" -6+35M (-3.36 +0.50 mm) [Large Cut].

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
-6+35' (Large Cut) Light	1591	37.38	5.41	37.38	5.41
-6+35' (Large Cut) Medium	1360	31.95	4.90	69.34	5.17
-6+35' (Large Cut) Medium Heavy	718	16.87	21.33	86.21	8.34
-6+35' (Large Cut) Heavy	587	13.79	79.36	100.00	18.13
Total	4256.	100.00			

Table 10. Concentrating table test results for "C" -35+100M (-0.50 +0.150 mm) [Small Cut].

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
-35+100' (Small Cut) Light	2364	40.79	5.56	40.79	5.56
-35+100' (Small Cut) Medium	2109	36.39	6.16	77.17	5.84
-35+100' (Small Cut) Medium Heavy	882	15.22	35.31	92.39	10.70
-35+100' (Small Cut) Heavy	441	7.61	68.83	100.00	15.12
Total	5796	100.00			

Table 11. Concentrating table test results for "C" -35+100M (-0.50 +0.150 mm) [Large Cut].

Sample	Wt (g)	Wt %	Ash %	Cumulative Wt %	Cumulative Ash %
-35+100' (Large Cut) Light	3269	53.11	6.47	53.11	6.47
-35+100' (Large Cut) Medium	1794	29.15	13.96	82.26	9.12
-35+100' (Large Cut) Medium Heavy	792	12.87	34.25	95.13	12.52
-35+100' (Large Cut) Heavy	300	4.87	69.43	100.00	15.30
Total	6155	100,00			

As spiral concentrators typically have a separating gravity of 1.7-1.8 or higher (though low density cutpoint spirals have been developed), the best comparison between the concentrating table results and the float-sink results would be at the higher ash levels on the curves in Figures 8 and 9. In the US, a typical coal specification for thermal coal would be 10% ash and for metallurgical coal at a lower value of ~8% ash. This Pittsburgh seam coal is typically sent to the thermal coal market, though it can be used in blends for metallurgical coal. The Pittsburgh seam coal fuel the early steel industry in Pittsburgh, PA, USA. Considering the difference between the cumulative yields at 10% cumulative ash for the "smaller cut" results, there is a difference of about 2 percentage points in yield. At 8% cumulative ash, the difference in yield is about 6 percentage points for the -0.5 +0.15 mm results and about 4 percentage points for the +0.5 mm results.

Additional testing with changes in the water flows, table tilt, cutter placement, and other parameters is warranted. But as a simple device for conducting fine coal float-sink analysis for comparison to a plant spiral or reflux classifier circuit, it is showing some promise. An additional advantage to using a laboratory device like the concentrating table is the ability to produce reasonable quantities of coal for further testing without the potential for contamination by reagents. As new markets develop for low ash coal, using a laboratory concentrating table can provide samples for testing in those new markets such as coal to carbon opportunities.

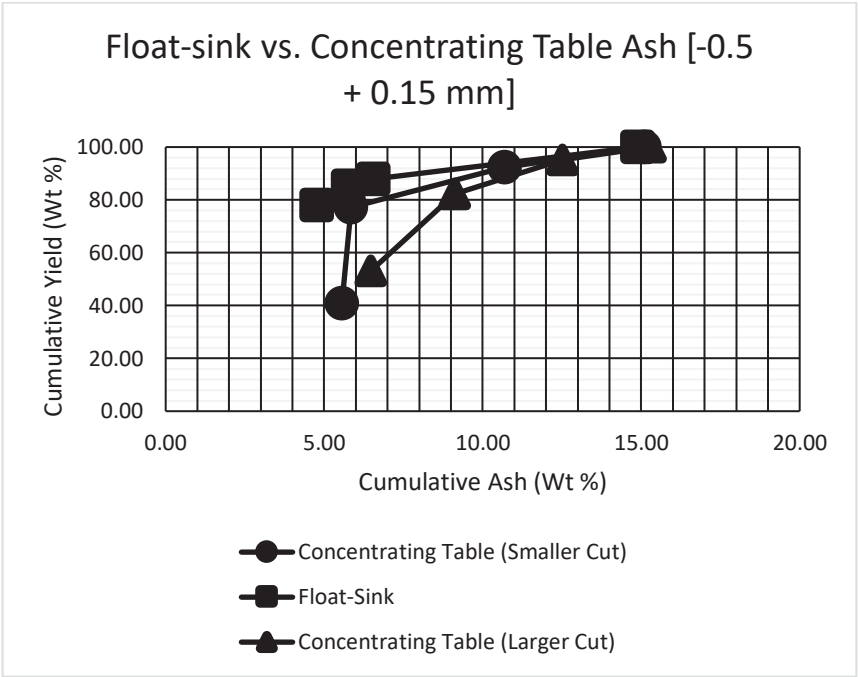

Fig. 8. Cumulative yield vs cumulative ash for the concentrating table and laboratory float-sink analysis for Sample for "C" -35+100M (-0.50 +0.150 mm).

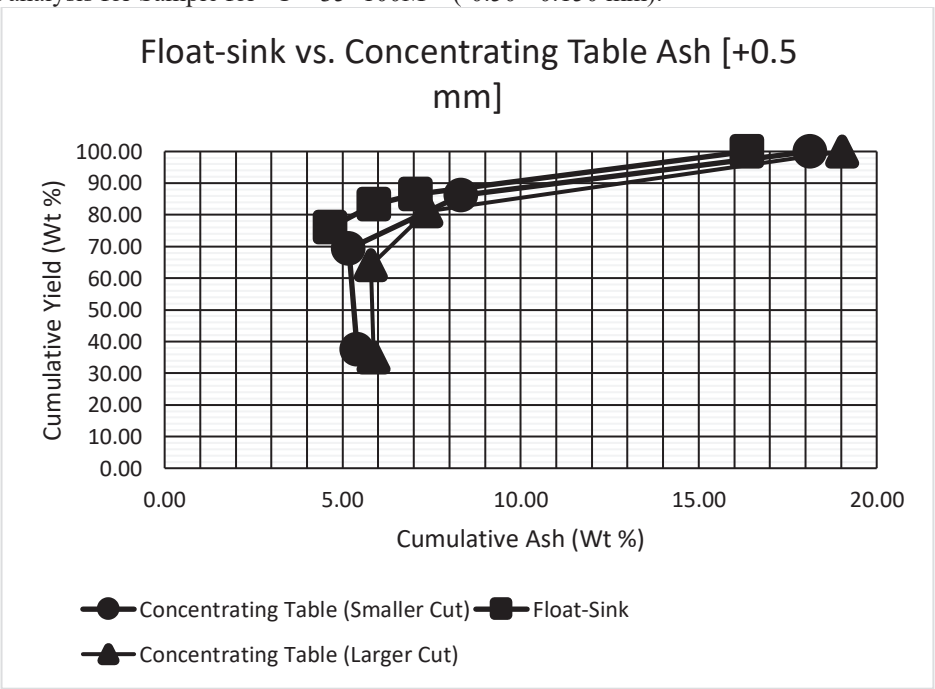

Fig. 9. Cumulative yield vs cumulative ash for the concentrating table and laboratory float-sink analysis for Sample "C" +35M (- +0.50 mm).

4 Summary and conclusions

The first-year concentrating table results clearly indicated that care must be taken when performing laboratory fine coal float-sink testing. Cautions were raised in the 1990s [16], and these issues are still relevant today. The second-year results indicate that the concentrating table can approximate the cumulative yield well (within 2 percentage points of yield) at levels of 10% ash. However, the differences in the results between the laboratory float-sink and the concentrating table diverge at lower ash levels. Since insufficient sample was obtained, replicates could not be conducted to provide a statistical analysis in this initial undergraduate research program. The results also show:

- Splitter settings matter so that some setup will need to occur when first testing the use of the concentrating table.
- Low ash products could be obtained from the concentrating table so that samples could be produced for testing future low ash coal markets without contamination by heavy liquids or salt solutions.

To further evaluate the use of a laboratory concentrating table:

- Additional larger samples must be obtained to replicate results, both for traditional float-sink analysis and for concentrating table testing. This will provide information to conduct a statistical analysis of the results to compare the float-sink results to the concentrating table results.
- The concentrating table testing must include changes in the water flows, table tilt, cutter placement, and other parameters.
- Additional coals must also be tested to determine performance.

A laboratory concentrating table is a simple device to use that is also relatively inexpensive to purchase. Initial results show some promise so that future testing is warranted.

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