Final Report

IDENTIFICATION OF REE IN SOME ALASKAN COAL AND ASH SAMPLES

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DISCLAIMER

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SUMMARY

The scope of this work includes the investigation of rare earth elements in some selected coal and ash samples from Alaska. Two coal samples collected from the Healy coal mine and the Wishbone Hill region were investigated for size and density effects on the partition of REE elements. Screen analysis and float-sink tests were conducted on selected size fractions. In addition, ash samples from the University of Alaska Fairbanks (UAF) power plant were examined for REEs. The results showed that REEs were primarily distributed in high density float fractions especially from sp.gr 1.7 and upward. It was found that Wishbone Hill coal has higher REE content than that of Healy coal. The REE contents of both coals correlate well with the total amount of ash. No significant difference was observed between bottom ash and fly ash when corrected for volatile matter.

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1. INTRODUCTION

Global concerns surrounding stable access to mineral supplies have led many countries to re-assess indigenous resources, particularly of the ‘critical’ metals (so labeled because of their growing economic importance and the higher risk of supply shortage). In addition to improving knowledge of primary mineral deposits, the potential for resource recovery from waste materials is attracting considerable attention.

Rare-earth elements, metals, and alloys are used in common consumer goods such as computer memory devices, DVDs, rechargeable batteries, cell phones, vehicle catalytic converters, magnets, fluorescent lighting, and many more. The demand for REEs used in these goods has surged over the past two decades. Many rechargeable batteries are made with rare-earth compounds. Rechargeable lanthanum–nickel–hydride (La–Ni–H) batteries are gradually replacing nickel–cadmium (Ni–Cd) batteries in computer and communications applications and could eventually replace lead-acid batteries in automobiles[1].

Several pounds of rare-earth compounds are required for batteries that power electric vehicles and hybrid-electric vehicles. Rare-earth compounds are also used for powerful magnets in a wide range of products, from computer hard drives to wind turbines. As concerns for energy independence, climate change, and other issues impact the sale of electric vehicles and “green” energy systems like wind turbines and solar power panels, the demand for rare-earth compounds is expected to increase dramatically. Rare earths are also used as catalysts, phosphors, and polishing compounds. These are used in areas such as air pollution control, illuminated screens on electronic devices, and optical-quality glass. Demand for all of these products is expected to rise.

Rare-earth elements play an essential role in National Defense. Night-vision goggles, precision-guided weapons, and other defense technology rely on various rare-earth metals. Rare-earth metals are key ingredients for radar systems, avionics, and satellites [2-5]. REEs are divided into two major groups: LREE, light rare earth elements: Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd; also known as the cerium group. HREE, heavy rare earth elements: Y, Tb, Dy, Ho, Er, Tm, Yb, and Lu; also known as the yttrium group [6, 7]. Coal can be a source for both of these groups.

Recent research indicates that some forms of coal are significantly enriched with certain critical REE metals (8). Moreover, coals with high REE concentrations were recently discovered in Far Eastern areas, such as Kuznetsky, and some other Russian coal basins. These coals are now being actively studied as a new source of REE [9, 10]. A recent study from China looks at how different trace elements (including numerous REEs) partition in various size fractions of Antaibao coal. It is clear that the REEs, phosphorous, and thorium all have their high concentrations in the particle sizes 0.5 to 3 mm, and 6 to 25 mm. This suggests that REEs are often present as a phosphate such as monazite [11, 12].

In the US, Ekmann [12] in a REE prospective analysis identified four regions of particular interest, namely the Central Appalachian Basin (CentAPP), the Southern Appalachian Basin (SoAPP), the San Juan Basin (RckyMtn4Crnrs), and the Powder River Basin (PRB) by using the USGS COALQUAL database. He reported that REE contents were 930 ppm for RckyMtn4Crnrs, 950 ppm for CentAPP, 953 ppm for PRB, and 966 ppm for SoAPP. In general, it was found that monazite was the most likely mineral form in which to find rare earths in coal formations. Cerium correlates well with the total amount of ash and with non-REE elements such as chromium (Cr), scandium (Sc), hafnium (Hf), lithium (Li), tantalum (Ta), vanadium (V) and lead (Pb). The rare earth element, Dysprosium, also correlated well to the presence of other rare earth elements, to the total ash, and to ash related elements such as lithium (Li), thorium (Th), vanadium (V), zirconium (Zr), chromium (Cr) and lead (Pb) [12,13].

2. OBJECTIVES OF THE RESEARCH

Leonardo Technologies, Inc., (LTI), contractor to the U.S. Department of Energy, has been looking at Alaskan coal in terms of REE content. LTI is also interested in investigations into combustion products (FA, FBA) from Alaskan power plants to assess the enrichment of REE into different streams and perhaps REE groupings in these streams. Systematic investigations of REE in Alaskan coal and coal ash have not been performed to date. Therefore this investigation aimed to address these questions.

The main objectives of this research included: (A) collection of 2 coal samples from one commercially operating coal mine and one from potentially commercial coal mining activity in Alaska as well as 1 fly ash sample from a power plant, depending on the availability of quality samples and access. (B) Conducting lab screening and float-sink, magnetic and flotation tests to ascertain the distributions of REEs in terms of size and specific gravity. (C) Analyze the selected samples for Proximate plus S and 13REE+Y+Sc content with ICP. (D) Prepare a final report to LTI on the findings.

3. COAL SAMPLES AND THEIR ORIGIN

Two previously identified coal samples were from the Healy (The Central Nenana) and the Wishbone Hill (Southern Alaska-Cook Inlet) coal regions.

The Central Alaska-Nenana coal province is centrally located on the north side of the Alaska Range. It has accounted for more than one-half of the coal mined in Alaska and is the only province in Alaska currently being mined. This coal province is in the northern foothills of the Alaska Range, extending from about 50 mi (80 km) west to 50 mi (80 km) east of the Alaska Railroad. It consists of several synclinal basins partly detached from each other by erosion of coal-bearing rocks.

The collected Healy coal sample (No.4 coal bed) was from the Suntrana formation which consists of sandstones, siltstones, mudstones, carbonaceous shales, and coal. Coal beds are interbedded with carbonaceous shales and have a combined thickness ranging from 1.6 to 65 ft (0.5 to 20m) [14, 15].

The Wishbone Hill district belongs to Matanuska field and is in Southern Alaska-Cook Inlet region. The Matanuska coalfield is the most important Paleocene coalfield in Alaska because it contains high-rank minable coal beds. Wishbone Hill coal district is on the north side of the coalfield between Moose and Granite Creeks. More than 20 coal beds, with thicknesses exceeding 3 ft, are known in the Wishbone Hill coal district [16]. Structures in the Matanuska coalfield are typically complex. The doubly plunging Wishbone Hill syncline has beds that dip up to 40˚ and the structure is cut by two sets of transverse faults [15]. Structural complications on its northwest flank make the coal beds in some structural blocks difficult to mine and preclude meaningful estimation of reserves [17]. The Wishbone Hill sample used in our test program was from Jonesville coal zone and was handpicked from the exposed oblique-slip fault outcrop.

4. EXPERIMENTAL METHODOLOGY

The collected samples, more than 200kg each, were mixed thoroughly and divided by using cone and quartering method. After that, representative samples were crushed by using jaw and roll crushers in order to provide representative subsamples for further physical separation and sample characterization in accordance with the standards prescribed in ASTM D-4371. All of the samples were subdivided separately into three size fractions. Float-sink tests were conducted for coarse sizes at the different specific gravities between 1.30 and 2.0 in 20 liter buckets. The test solutions were prepared by using anhydrous zinc chloride (99% pure) up to sp.gr. 2. LMT (lithium meta-tungstate) was used for preparation of sp.gr. 2.2 at MIRL Labs (UAF).

The fine fraction (-100 mesh) was later subjected to flotation and magnetic separation tests. The magnetic separation was twofold as dry high intensity and wet high intensity separation using Carpco separators. The flotation tests were done using fuel oil and a frother at pH7 in MIRL Labs at UAF.

After the tests, the samples were air dried and subsequently split into subsamples to be sent for proximate (ASTM D3172) and sulfur (ASTM D4239) analysis by ALS Global, Canada. Also REE content including Y and Sc was analyzed using ICP-AES and ICP-MS at ALS Coal and ALS Global in Richmond and Vancouver Canada laboratories according to the ALS accredited ME-4ACD81 method. All of the REE concentrations reported in this document are on a whole-coal basis.

Furthermore, some samples were also collected from UAF power plant as fly-ash, bottom ash and cinders. These samples were also analyzed for their REE content at ALS global laboratories.

5. RESULTS AND DISCUSSION

After homogenization and size reduction, the two different coal type samples namely Healy and Wishbone Hill were screened separately into three size fractions as coarse sizes ¼ in. x 30 mesh and 30 mesh x 100 mesh, and as fines 100 mesh x 0. The representative samples of the prepared material from each coal type were characterized for proximate analysis and float sink analysis.

Table 1 - Size-by-size analysis of the Healy coal sample

Healy					
Mesh Size		**% Weight**	**% Moisture**	**Dry Wt %**	**Ash%**
	+1/4"	2.39	18.04	2.38	19.21
-1/4"	+30M	85.72	17.98	85.27	20.55
-30M	+100M	9.34	14.52	9.69	29.40
-100M		2.55	13.64	2.67	31.33
TOTAL		**100.00**	**17.55**	**100.00**	**21.66**

Table 2 - Size-by-size analysis of the Wishbone Hill coal sample

Wishbone Hill					
Mesh Size		**% Weight**	**% Moisture**	**Dry Wt %**	**Ash%**
	+1/4"	9.72	3.90	9.75	49.93
-1/4"	+30M	80.09	4.20	80.07	44.18
-30M	+100M	8.93	4.24	8.93	55.48
-100M		1.25	3.70	1.26	60.97
TOTAL		**100.00**	**4.17**	**100.00**	**45.96**

From the above tables, the initial representative sample characterization showed that the majority of the screened sample, about 87.65% and 89.82% is over 30 mesh in size for Healy and Wishbone Hill coals respectively. Only a very small amount about 2.67% for the Healy and 1.26% for the Wishbone Hill being fine fraction and below 100 mesh in size.

The Healy sample had a high inherent moisture content of around 18% with a dry ash % of around 22%. The Wishbone Hill sample had very low moisture content around 4% with a very high dry ash% around 46%.

5.1. Washability Tests

After weighing the individual fractions the washability analysis was conducted for coarse sizes at the following specific gravities of interest i.e 1.30, 1.50, 1.60, 1.70, 1.80, 2.00, and 2.20.

The float sink analysis (Table 3 and 4) yielded similar results for the Healy and the Wishbone hill coals, the difference with the size analysis values can be attributed to the inherent variability of the feed coal, however these differences are well within the margin of error.

Table 3 - Float-Sink data of the Healy coal sample

Healy -1/4"+30Mesh

Washability SINK	FLOAT	% Weight	% Moisture	Dry Wt. %	Ash %	Volatile Matter	Fixed Carbon	Total Sulfur	Cum. Wt	Cum Ash	Cum Sulfur
FLOAT	1.3	38.26	9.18	38.38	11.89	41.85	37.08	0.43	38.38	11.89	0.43
1.3	1.5	44.17	10.22	43.80	21.09	38.39	30.30	0.56	82.18	16.79	0.50
1.5	1.6	3.81	13.98	3.62	28.47	35.49	22.06	0.39	85.80	17.29	0.49
1.6	1.7	1.91	7.61	1.95	38.24	31.90	22.25	0.32	87.75	17.75	0.49
1.7	1.8	0.64	7.83	0.65	52.70	26.16	13.31	0.15	88.40	18.01	0.49
1.8	2	6.79	8.65	6.85	62.00	20.91	8.44	0.10	95.25	21.17	0.46
2	2.2	3.73	2.74	4.01	77.47	14.95	4.84	0.06	99.26	23.44	0.44
2.2	Sink	0.69	2.60	0.74	88.19	11.07	0.00	0.03	100.00	23.93	0.44
Total		**100.00**	**9.46**	**100.00**	**23.93**	**37.07**	**29.59**	**0.44**			

Healy -30Mesh+100Mesh

Washability SINK	FLOAT	% Weight	% moisture	Dry Wt. %	Ash %	Volatile Matter	Fixed Carbon	Total Sulfur	Cum.Wt	Cum Ash	Cum Sulfur
FLOAT	1.3	0.14	10.05	0.14	10.27	45.40	34.28	0.45	0.14	10.27	0.45
1.3	1.5	19.15	13.58	19.11	13.09	45.78	27.55	0.24	19.26	13.07	0.24
1.5	1.6	35.39	13.23	35.46	17.58	43.18	26.01	0.30	54.71	15.99	0.28
1.6	1.7	23.84	19.40	22.19	20.76	40.72	19.12	0.27	76.90	17.37	0.28
1.7	1.8	0.82	9.80	0.86	53.08	26.56	10.56	0.20	77.76	17.76	0.28
1.8	2	5.05	9.51	5.28	58.08	28.55	3.86	0.12	83.04	20.33	0.27
2	2.2	4.77	8.33	5.04	59.50	30.99	1.18	0.09	88.09	22.57	0.26
2.2	Sink	10.84	4.80	11.91	83.11	4.98	0.00	0.03	100.00	29.78	0.23
Total		**100.00**	**13.40**	**100.00**	**29.78**	**37.05**	**19.13**	**0.23**			

Healy +1/4" x 0 (Composite)

Washability SINK	FLOAT	% Weight	% Moisture	Dry Wt. %	Ash %	Volatile Matter	Fixed Carbon	Total Sulfur	Cum. Wt	Cum Ash	Cum Sulfur
FLOAT	1.3	37.79	8.25	34.05	11.89	41.85	37.08	0.43	34.05	11.89	0.00
1.3	1.5	43.85	9.75	40.79	20.66	38.79	30.15	0.54	74.85	16.67	0.49
1.5	1.6	4.21	24.33	7.39	22.26	39.88	24.31	0.34	82.23	17.17	0.48
1.6	1.7	2.18	30.95	4.33	27.58	37.28	20.34	0.29	86.56	17.69	0.47
1.7	1.8	0.65	8.39	0.68	52.77	26.23	12.84	0.16	87.23	17.96	0.47
1.8	2	6.76	8.44	6.62	61.62	21.65	7.99	0.10	93.86	21.04	0.44
2	2.2	3.74	3.65	4.06	74.74	17.38	4.28	0.06	97.92	23.27	0.42
2.2	Sink	0.82	9.59	2.08	84.66	6.67	0.00	0.03	100.00	24.55	0.42
Total		**100.00**	**9.93**	**100.00**	**24.55**	**37.09**	**28.39**	**0.42**			

Table 4 - Float-Sink data of the Wishbone Hill coal sample

Wishbone Hill -1/4"+30Mesh

Washability SINK	FLOAT	% Weight	% moisture	% Dry Weight	Ash %	Volatile Matter	Fixed Carbon	Total Sulfur	Cum. Wt	Cum Ash	Cum Sulfur
FLOAT	1.3	34.65	2.81	34.61	6.09	36.93	54.17	0.50	34.61	6.09	0.50
1.3	1.5	9.36	3.98	9.24	28.81	30.96	36.25	0.38	43.85	10.88	0.47
1.5	1.6	5.05	3.64	5.01	42.23	26.56	27.57	0.29	48.86	14.09	0.46
1.6	1.7	4.40	3.41	4.37	51.08	23.90	21.61	0.23	53.23	17.12	0.44
1.7	1.8	2.59	2.56	2.60	62.51	19.76	15.17	0.15	55.82	19.24	0.42
1.8	2	7.57	2.47	7.59	74.73	16.20	6.60	0.08	63.41	25.88	0.38
2	2.2	8.12	2.26	8.16	78.38	14.41	4.95	0.06	71.57	31.86	0.35
2.2	Sink	28.26	2.13	28.43	81.33	14.01	2.53	0.04	100.00	45.93	0.26
Total		**100.00**	**2.72**	**100.00**	**45.93**	**24.92**	**26.44**	**0.26**			

Wishbone Hill -30Mesh+100Mesh

Washability SINK	FLOAT	% Weight	% moisture	% Dry Weight	Ash %	Volatile Matter	Fixed Carbon	Total Sulfur	Cum. Wt	Cum Ash	Cum Sulfur
FLOAT	1.3	28.10	9.28	26.78	9.52	31.29	49.91	0.34	26.78	9.52	0.34
1.3	1.5	2.16	5.06	2.15	30.81	29.19	34.94	0.37	28.93	11.10	0.34
1.5	1.6	0.31	3.92	0.31	43.84	25.47	26.77	0.32	29.24	11.45	0.34
1.6	1.7	0.68	4.15	0.69	50.74	23.92	21.19	0.26	29.92	12.35	0.34
1.7	1.8	2.35	2.85	2.39	75.51	14.48	7.16	0.09	32.32	17.03	0.32
1.8	2	0.51	2.98	0.52	72.37	15.18	9.47	0.11	32.84	17.91	0.32
2	2.2	7.19	7.29	7.01	71.64	17.19	3.88	0.05	39.84	27.36	0.27
2.2	Sink	58.70	2.44	60.16	83.11	12.09	2.36	0.03	100.00	60.90	0.13
Total		**100.00**	**4.80**	**100.00**	**60.90**	**18.15**	**16.26**	**0.13**			

Wishbone Hill +1/4" x 0 (Composite)

Washability SINK	FLOAT	% Weight	% moisture	% Dry Weight	Ash %	Volatile Matter	Fixed Carbon	Total Sulfur	Cum. Wt	Cum Ash	Cum Sulfur
FLOAT	1.3	34.49	3.26	33.28	6.37	36.47	53.82	0.49	33.28	6.37	0.49
1.3	1.5	9.27	3.73	8.53	28.86	30.91	36.22	0.38	41.81	10.96	0.47
1.5	1.6	5.00	3.34	4.54	42.24	26.55	27.56	0.29	46.34	14.02	0.45
1.6	1.7	4.35	3.17	4.00	51.07	23.90	21.60	0.23	50.34	16.96	0.43
1.7	1.8	2.59	2.57	2.58	63.74	19.26	14.41	0.14	52.92	19.24	0.42
1.8	2	7.48	2.27	6.90	74.71	16.19	6.62	0.08	59.82	25.64	0.38
2	2.2	8.12	2.70	8.08	77.78	14.66	4.86	0.06	67.90	31.84	0.34
2.2	Sink	28.70	2.42	32.10	81.67	13.64	2.50	0.04	100.00	47.84	0.24
Total		**100.00**	**2.93**	**100.00**	**47.84**	**24.11**	**25.14**	**0.24**			

The washability plots (Figure1-4) reveal that it is possible to effectively achieve a product with ash content around 15% with relative yields of around 60 % and 50% for the Healy and Wishbone Hill coals with required densities around 1.45 and 1.65 respectively.

Apart from proximate and sulfur analyses for each sink-float density fractions, the samples were analyzed for their respective 13 REE+Y+Sc contents on whole sample basis. The results are summarized in the Tables 5-7 and in Figures 5-10.

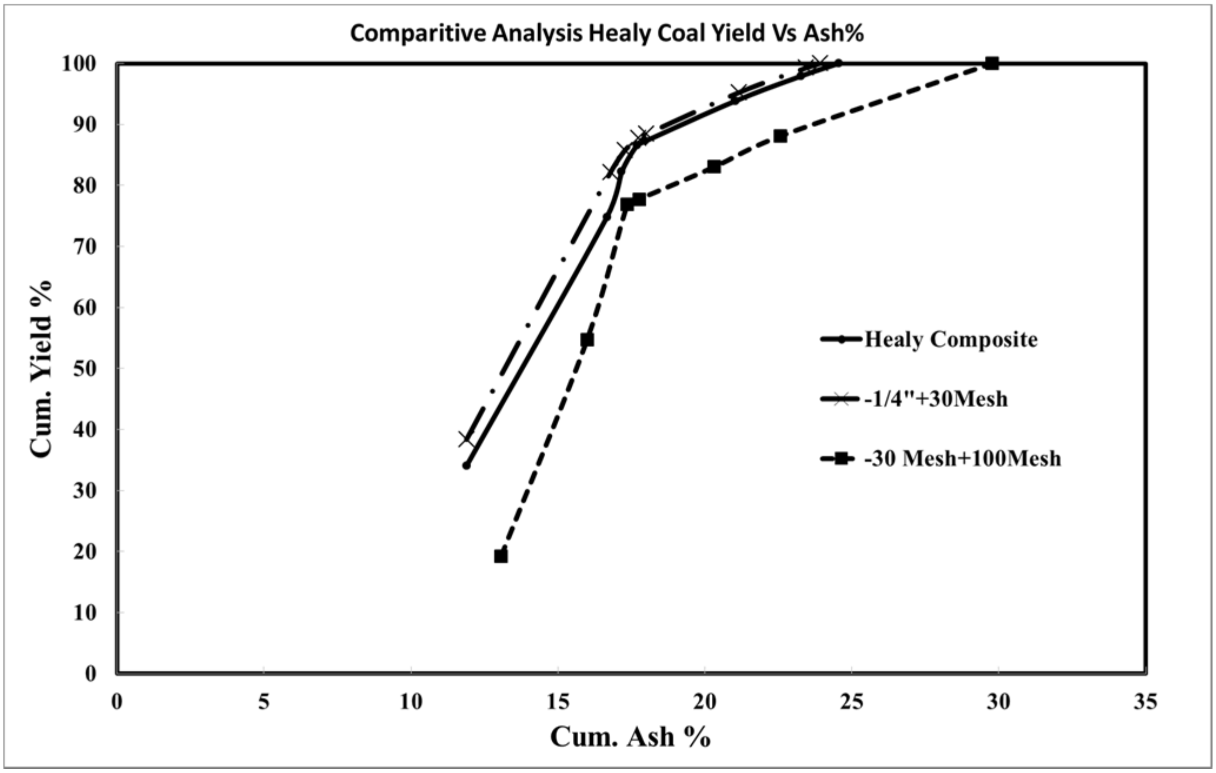

Figure 1 - Washability curves of the Healy coal sample

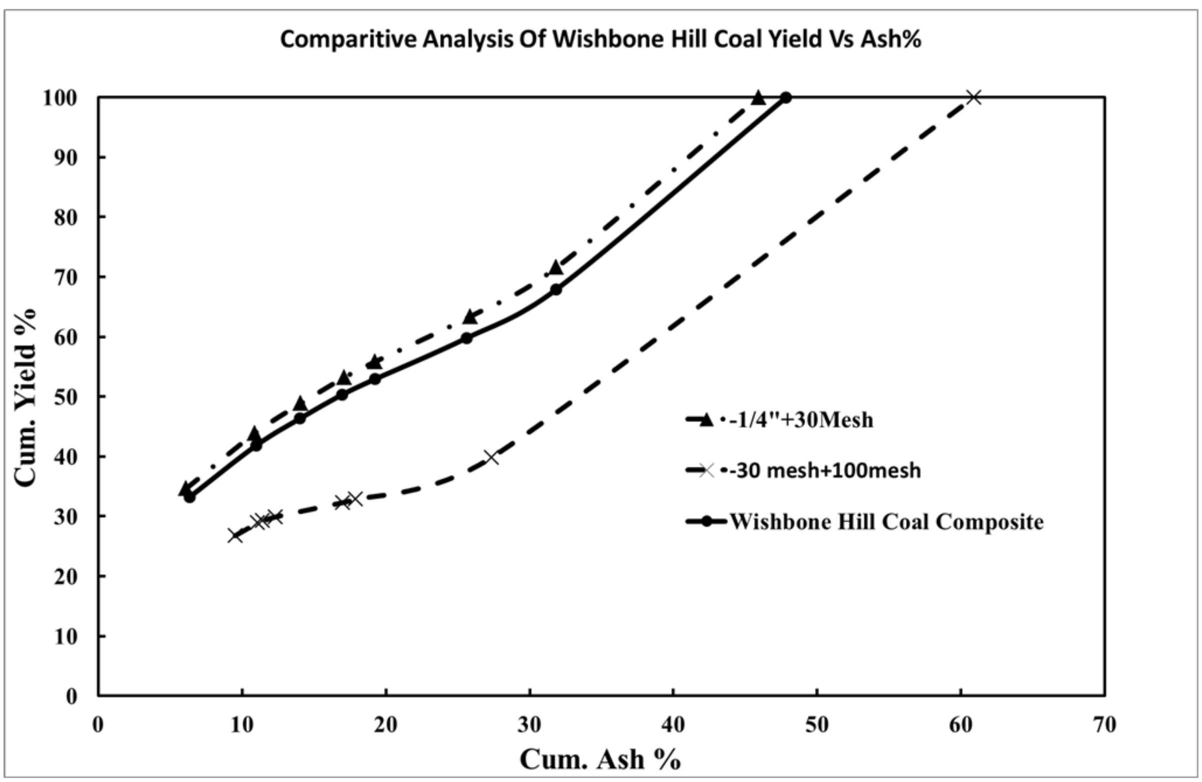

Figure 2 - Washability curves of the Wishbone Hill coal sample

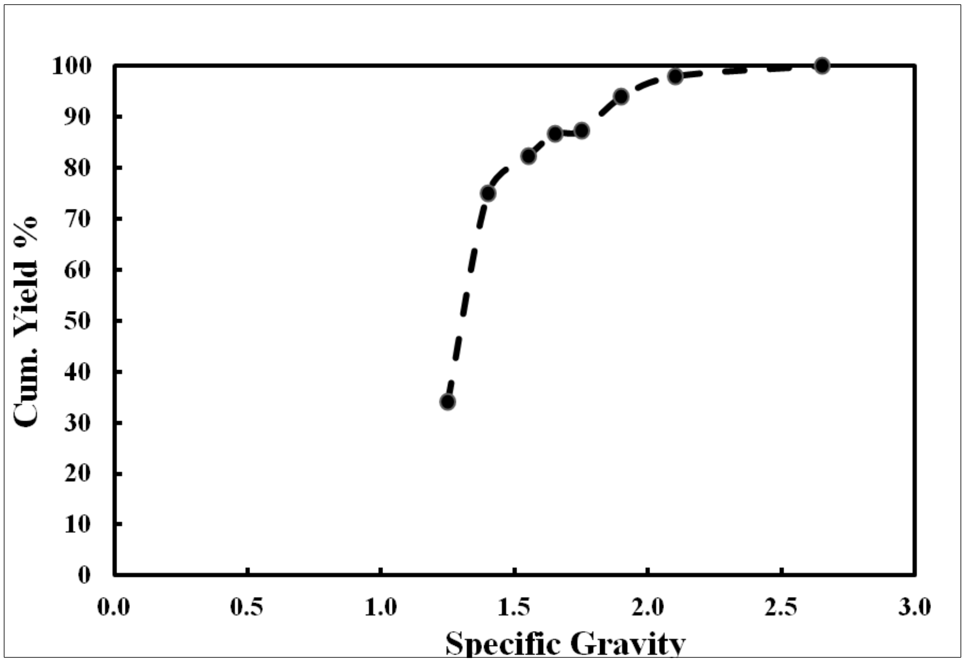

Figure 3 – Cumulative yield % to float versus specific gravity for the Healy coal sample

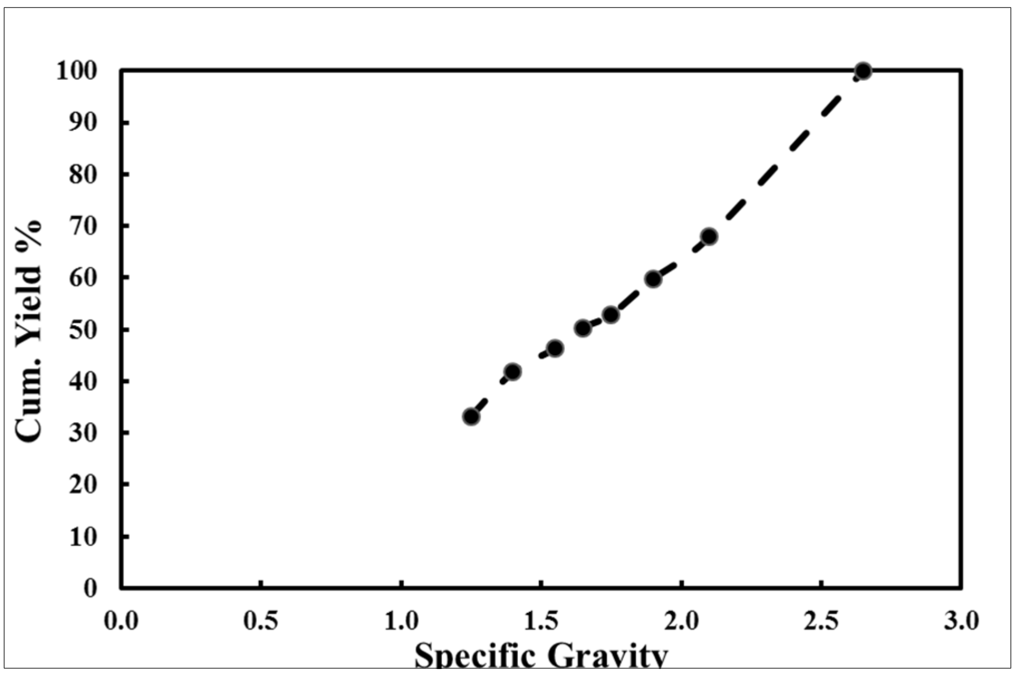

Figure 4 – Cumulative yield % to float versus specific gravity for the Wishbone Hill coal sample

Table 5 – REE analysis of the Healy coal sample with size and density fractions (all data reported on "Whole Coal" basis)

Mesh Size		Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho	Er	Tm	Yb	Lu
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	+1/4"	5.70	16.55	34.06	4.10	15.80	3.68	0.84	3.42	16.82	0.53	3.12	0.64	1.79	0.24	1.63	0.24
-1/4"	**+30M**	7.17	17.00	35.20	4.20	15.99	3.73	0.80	3.31	17.03	0.52	3.04	0.62	1.69	0.26	1.58	0.24
-30M	**+100M**	7.69	18.70	37.58	4.46	16.99	3.88	0.77	3.43	17.41	0.51	3.11	0.63	1.92	0.27	1.63	0.24
-100M		8.58	20.63	41.59	4.92	18.65	4.10	0.93	3.70	18.98	0.58	3.53	0.70	1.91	0.27	1.83	0.25

Healy -1/4"+30Mesh

Washability		Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho	Er	Tm	Yb	Lu
SINK	FLOAT	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FLOAT	1.3	3.40	8.57	17.30	2.01	8.55	2.06	0.44	1.96	9.71	0.29	1.60	0.33	0.92	0.13	0.81	0.12
1.3	1.5	4.61	16.80	33.81	4.02	16.19	3.70	0.77	3.42	16.63	0.54	2.99	0.60	1.62	0.25	1.56	0.24
1.5	1.6	5.43	21.61	42.40	4.85	19.81	4.14	0.94	3.78	18.01	0.57	3.26	0.65	1.85	0.29	1.64	0.26
1.6	1.7	5.09	22.47	42.27	4.90	19.33	4.12	0.92	3.78	17.81	0.59	3.09	0.70	1.77	0.28	1.87	0.25
1.7	1.8	6.49	24.88	44.05	4.97	19.16	3.97	0.81	3.17	16.45	0.50	2.95	0.61	1.73	0.28	1.79	0.25
1.8	2	9.80	28.64	49.72	5.92	21.92	4.35	0.85	3.49	17.30	0.49	3.15	0.69	1.92	0.28	1.88	0.31
2	2.2	13.00	32.34	58.33	6.91	24.70	4.65	0.95	3.72	19.91	0.63	3.60	0.80	2.16	0.35	2.33	0.37
2.2	Sink	11.20	53.87	130.71	16.62	66.66	15.78	1.85	14.19	64.61	2.43	13.49	2.53	6.47	0.97	4.81	0.56
Total		**4.94**	**15.68**	**30.81**	**3.64**	**14.58**	**3.27**	**0.68**	**2.97**	**14.58**	**0.46**	**2.58**	**0.53**	**1.44**	**0.22**	**1.36**	**0.21**

Healy -30Mesh+100Mesh

Washability		Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho	Er	Tm	Yb	Lu
SINK	FLOAT	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FLOAT	1.3	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS
1.3	1.5	2.16	9.15	15.44	1.84	7.59	1.83	0.39	1.72	8.12	0.25	1.39	0.28	0.74	0.12	0.70	0.10
1.5	1.6	4.39	13.43	20.75	2.42	10.27	2.42	0.52	2.26	10.91	0.33	1.87	0.41	1.07	0.16	0.96	0.15
1.6	1.7	4.03	15.69	26.26	3.05	12.50	2.70	0.63	2.56	11.77	0.37	2.24	0.45	1.26	0.20	1.11	0.17
1.7	1.8	5.99	29.31	45.26	5.10	19.78	4.27	0.77	3.21	16.19	0.50	3.02	0.60	1.65	0.26	1.68	0.26
1.8	2	5.23	25.58	40.63	4.70	17.67	3.32	0.63	2.73	14.33	0.42	2.54	0.54	1.53	0.24	1.61	0.22
2	2.2	4.62	19.87	35.37	4.09	15.38	2.90	0.62	2.34	13.53	0.37	2.41	0.53	1.53	0.26	1.52	0.23
2.2	Sink	4.41	14.38	25.58	3.02	10.67	2.33	0.41	1.67	11.29	0.30	1.90	0.41	1.08	0.17	1.10	0.17
Total		**3.95**	**14.31**	**23.50**	**2.74**	**11.02**	**2.44**	**0.52**	**2.19**	**10.96**	**0.33**	**1.93**	**0.41**	**1.10**	**0.17**	**1.03**	**0.15**

Table 6 – REE analysis of the Wishbone Hill coal sample with size and density fractions (all data reported on "Whole Coal" basis)

Mesh Size		Sc ppm	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm	Eu ppm	Gd ppm	Y ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm
	+1/4"	13.51	19.12	39.12	4.79	18.44	4.37	0.93	4.10	23.07	0.69	3.88	0.86	2.58	0.37	2.55	0.35
-1/4"	+30M	14.44	16.11	36.09	4.27	18.39	4.31	0.87	3.96	20.58	0.65	3.81	0.81	2.34	0.38	2.18	0.30
-30M	+100M	13.57	18.29	39.94	4.62	19.59	4.52	0.98	4.23	21.71	0.62	3.78	0.82	2.16	0.36	2.27	0.34
-100M		13.55	19.55	42.79	5.13	21.04	4.94	1.15	4.89	25.36	0.77	4.56	1.01	2.78	0.43	2.59	0.39

Wishbone Hill -1/4"+30Mesh

Washability		**Sc**	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Y**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
SINK	FLOAT	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FLOAT	1.3	7.09	4.75	10.64	1.30	5.70	1.42	0.34	1.74	13.03	0.30	2.05	0.48	1.37	0.24	1.50	0.23
1.3	1.5	11.92	15.31	31.93	3.80	15.80	3.68	0.75	3.64	19.40	0.57	3.38	0.74	2.11	0.35	2.17	0.33
1.5	1.6	13.30	19.02	41.37	4.92	20.75	4.43	0.89	4.25	21.37	0.63	3.94	0.84	2.35	0.36	2.27	0.36
1.6	1.7	13.34	21.02	46.31	5.55	22.46	4.84	1.08	4.86	22.83	0.71	4.32	0.91	2.41	0.39	2.33	0.35
1.7	1.8	15.40	23.09	49.53	5.98	24.38	5.57	1.04	5.09	23.54	0.76	4.39	0.93	2.50	0.40	2.49	0.35
1.8	2	17.11	25.59	55.06	6.67	27.30	6.55	1.24	5.52	27.06	0.94	5.27	1.09	2.73	0.43	2.71	0.37
2	2.2	19.51	25.36	54.30	6.32	26.42	6.34	1.31	5.80	28.53	0.90	5.27	1.10	2.87	0.48	2.71	0.41
2.2	Sink	17.68	24.08	51.69	6.26	25.43	5.87	1.27	5.56	27.28	0.91	5.09	1.05	2.85	0.45	2.55	0.40
Total		**13.12**	**16.39**	**35.32**	**4.25**	**17.54**	**4.09**	**0.87**	**3.97**	**21.12**	**0.64**	**3.80**	**0.81**	**2.21**	**0.36**	**2.15**	**0.33**

Wishbone Hill -30Mesh+100Mesh

Washability		Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho	Er	Tm	Yb	Lu
SINK	FLOAT	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FLOAT	1.3	7.17	4.21	8.49	1.03	4.68	1.20	0.30	1.44	11.21	0.26	1.77	0.42	1.21	0.21	1.31	0.20
1.3	1.5	10.60	15.50	33.06	3.98	16.73	3.76	0.85	3.79	18.68	0.57	3.38	0.75	1.99	0.33	1.89	0.31
1.5	1.6	12.15	21.26	44.07	5.28	21.08	5.02	1.01	4.60	21.92	0.65	4.12	0.86	2.45	0.38	2.36	0.36
1.6	1.7	9.16	23.75	49.65	5.87	24.50	5.49	1.09	4.99	22.89	0.69	4.52	0.87	2.45	0.39	2.36	0.34
1.7	1.8	16.66	25.94	55.29	6.59	27.13	6.13	1.25	5.46	25.31	0.80	4.93	0.95	2.87	0.40	2.29	0.35
1.8	2	10.60	26.27	54.21	6.62	26.12	6.11	1.28	5.72	25.06	0.84	4.72	1.00	2.48	0.42	2.53	0.39
2	2.2	11.84	22.03	46.82	5.46	23.29	5.01	1.03	4.67	22.82	0.69	4.32	0.88	2.56	0.39	2.44	0.36
2.2	Sink	19.86	23.49	49.66	5.80	24.61	5.04	1.26	5.04	24.53	0.79	4.48	0.98	2.54	0.40	2.70	0.38
Total		**15.48**	**18.12**	**38.22**	**4.48**	**19.07**	**4.02**	**0.98**	**4.03**	**20.72**	**0.63**	**3.73**	**0.81**	**2.18**	**0.35**	**2.28**	**0.33**

Table 7 – REE analysis of the Healy and the Wishbone Hill composite coal samples with size and density fractions (all data reported on "Whole Coal" basis)

Healy Coal +1/4" x 0 (Composite)

Washability		**Sc**	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Y**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
SINK	FLOAT	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FLOA	1.3	3.45	8.67	17.56	2.04	8.66	2.08	0.45	1.98	9.84	0.29	1.63	0.34	0.94	0.13	0.83	0.12
1.3	1.5	4.55	16.50	33.10	3.94	15.84	3.62	0.76	3.35	16.31	0.53	2.94	0.59	1.59	0.25	1.53	0.24
1.5	1.6	5.33	16.86	30.36	3.47	14.21	3.08	0.73	2.84	13.90	0.42	2.45	0.50	1.40	0.21	1.28	0.20
1.6	1.7	4.83	18.50	33.02	3.82	15.16	3.24	0.77	3.02	14.29	0.45	2.55	0.55	1.46	0.23	1.46	0.20
1.7	1.8	6.43	25.39	44.15	4.98	19.21	4.00	0.80	3.17	16.40	0.49	2.96	0.61	1.72	0.27	1.77	0.25
1.8	2	9.48	28.39	48.98	5.82	21.57	4.26	0.83	3.42	17.05	0.48	3.10	0.68	1.89	0.28	1.86	0.30
2	2.2	12.0	30.84	55.56	6.57	23.56	4.43	0.91	3.55	19.12	0.59	3.45	0.77	2.08	0.34	2.24	0.36
2.2	Sink	7.74	32.23	73.36	9.20	36.08	8.45	1.07	7.37	35.64	1.27	7.20	1.37	3.54	0.53	2.80	0.35
Total		**4.96**	**15.70**	**30.48**	**3.60**	**14.38**	**3.22**	**0.67**	**2.93**	**14.41**	**0.45**	**2.56**	**0.52**	**1.43**	**0.22**	**1.35**	**0.20**

Wishbone Hill Coal +1/4" x 0 (Composite)

Washability		**Sc**	**La**	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Y**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**
SINK	FLOAT	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
FLOA	1.3	7.09	4.72	10.47	1.28	5.61	1.41	0.34	1.71	12.93	0.30	2.03	0.48	1.37	0.24	1.50	0.23
1.3	1.5	11.8	15.36	32.00	3.82	15.81	3.68	0.76	3.64	19.42	0.57	3.37	0.74	2.11	0.35	2.18	0.33
1.5	1.6	13.2	19.08	41.43	4.93	20.75	4.44	0.89	4.25	21.40	0.63	3.94	0.84	2.36	0.36	2.28	0.36
1.6	1.7	13.2	21.11	46.41	5.56	22.49	4.85	1.08	4.86	22.86	0.71	4.32	0.91	2.41	0.39	2.33	0.35
1.7	1.8	15.5	23.39	50.10	6.04	24.63	5.62	1.06	5.13	23.73	0.77	4.44	0.93	2.54	0.40	2.48	0.35
1.8	2	17.0	25.71	55.16	6.69	27.27	6.55	1.24	5.52	27.11	0.94	5.26	1.09	2.74	0.43	2.73	0.37
2	2.2	18.8	25.19	53.75	6.26	26.13	6.23	1.29	5.69	28.11	0.88	5.18	1.08	2.86	0.47	2.71	0.41
2.2	Sink	17.9	24.43	51.85	6.27	25.30	5.75	1.28	5.47	27.18	0.89	4.98	1.05	2.87	0.45	2.66	0.40
Total		**13.3**	**16.85**	**36.04**	**4.33**	**17.81**	**4.12**	**0.89**	**4.00**	**21.32**	**0.65**	**3.81**	**0.82**	**2.25**	**0.36**	**2.21**	**0.33**

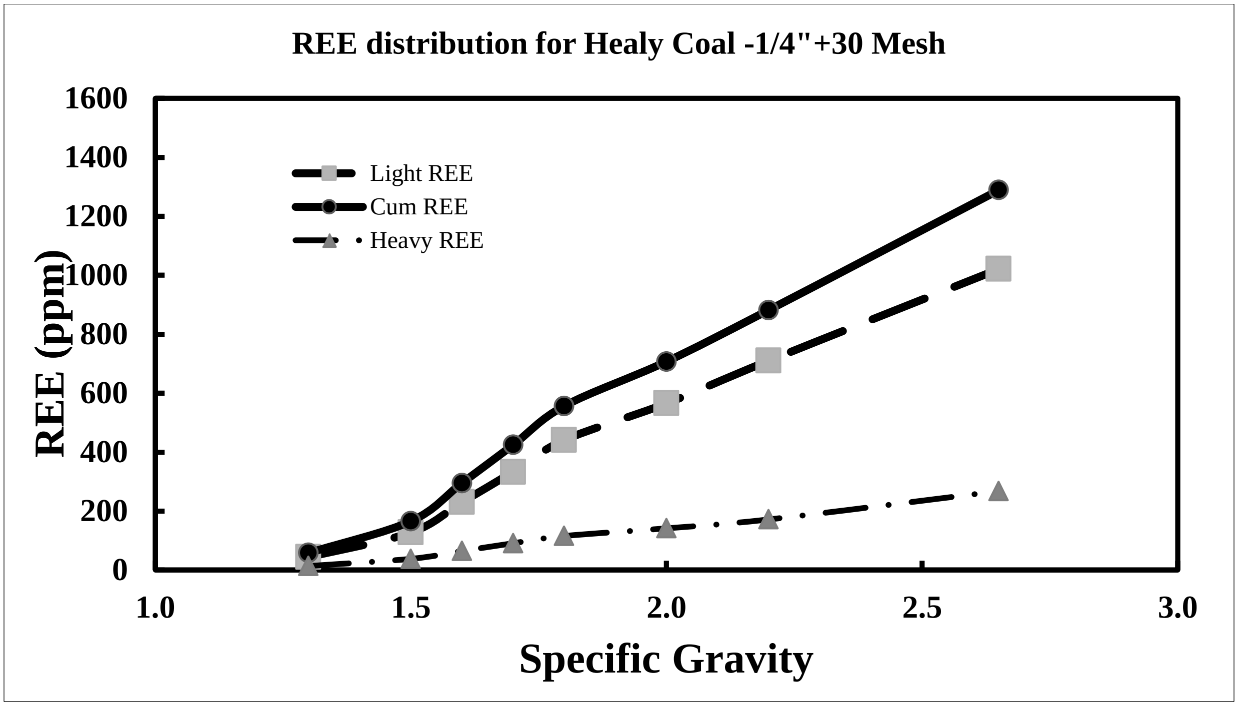

Figure 5 – Cumulative REE % vs. specific gravity for Healy sample (-1/4”+30#) on whole coal basis.

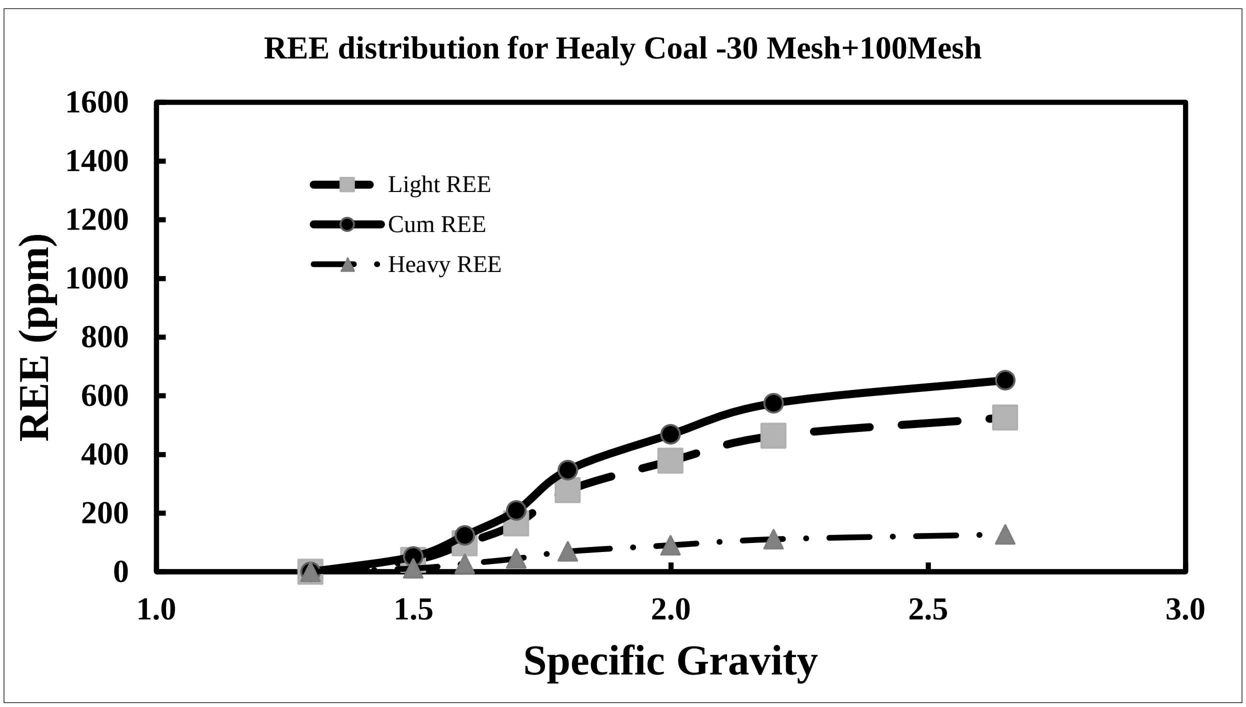

Figure 6 – Cumulative REE % vs. specific gravity for Healy sample (-30+100#) on whole coal basis.

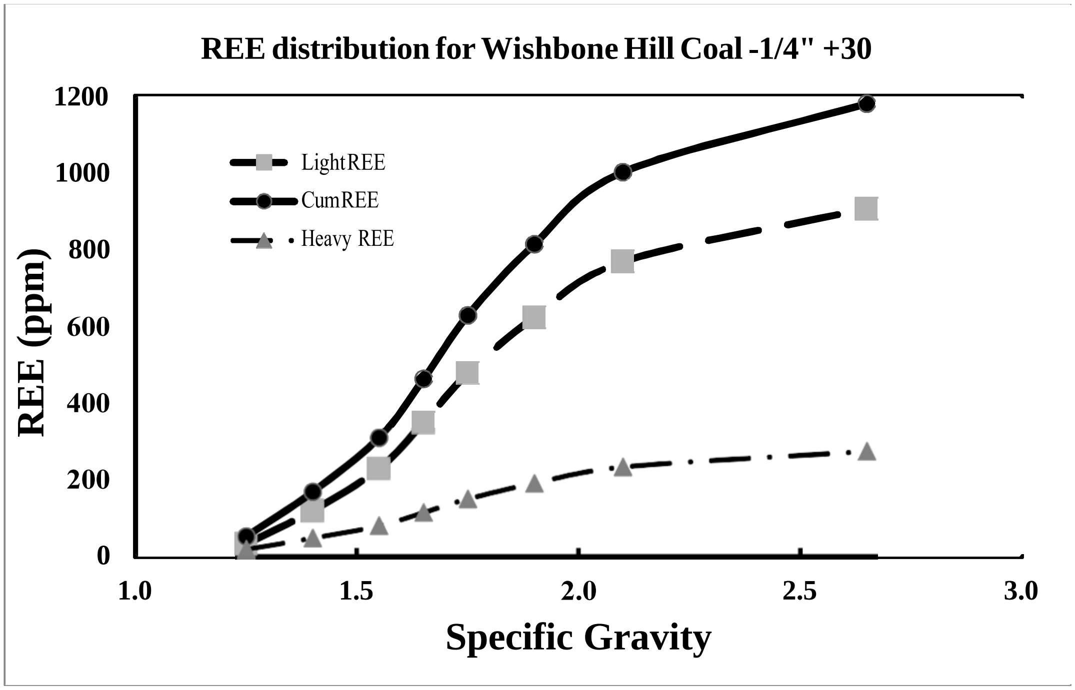

Figure 7 – Cumulative REE % vs. specific gravity for Wishbone Hill sample (-1/4”+30#) on whole coal basis.

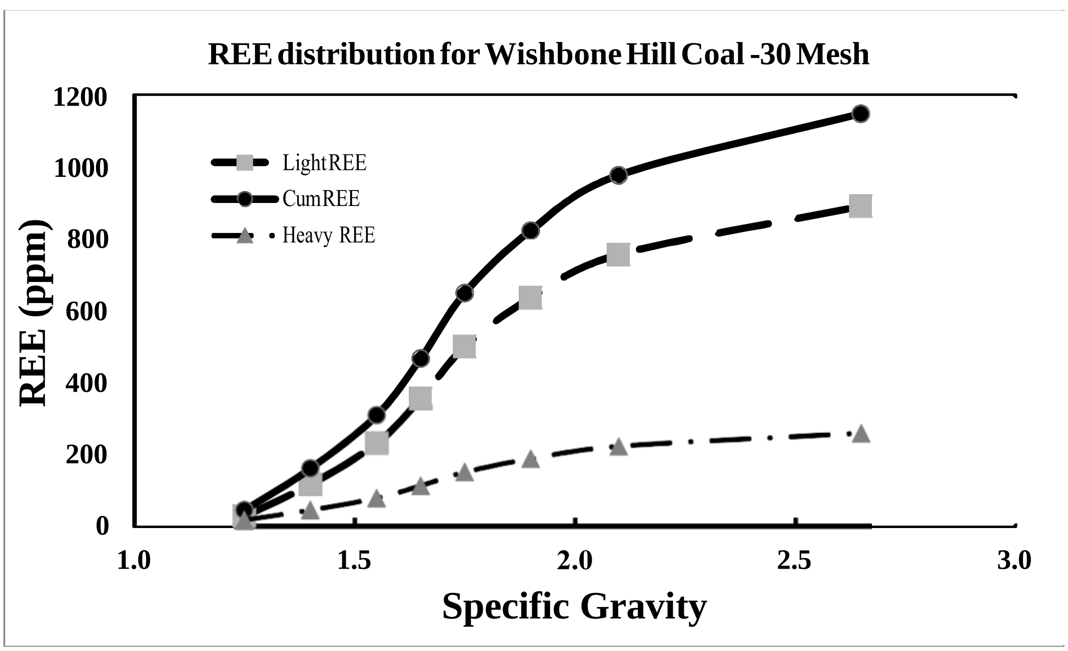

Figure 8 – Cumulative REE % vs. specific gravity for the Wishbone Hill sample (-30+100#) on whole coal basis.

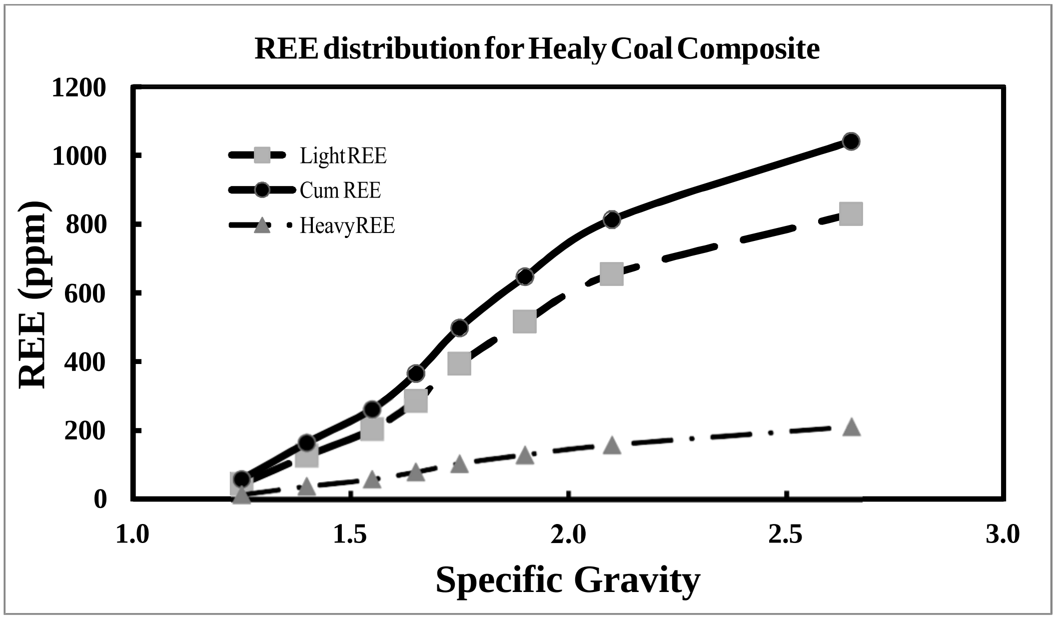

Figure 9 – Cumulative REE % versus specific gravity for Healy composite sample on whole coal basis.

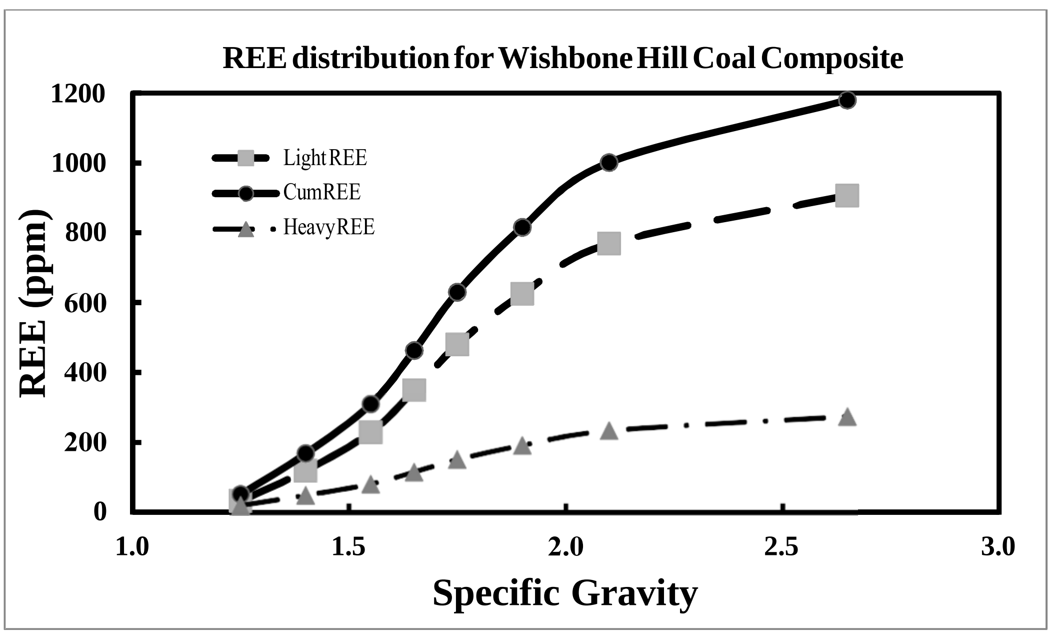

Figure 10 – Cumulative REE % versus specific gravity for the Wishbone Hill composite sample on whole coal basis.

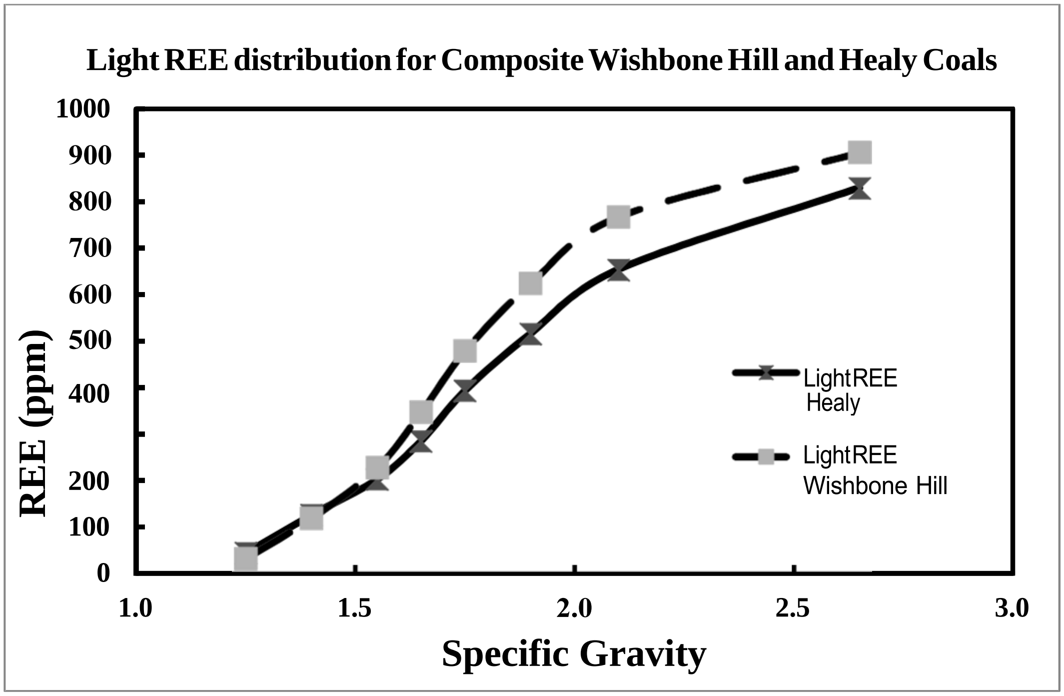

Figure 11 – Comparison of Cumulative LREE % versus specific gravity for two composite samples on whole coal basis.

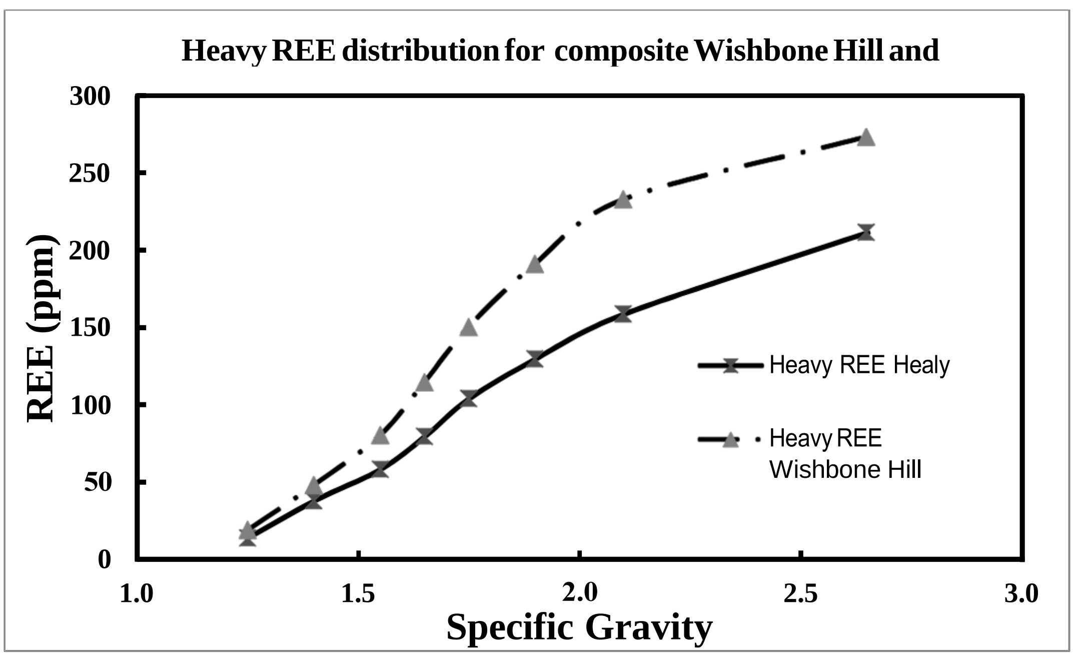

Figure 12 – Comparison of Cumulative HREE % versus specific gravity for two composite samples on whole coal basis.

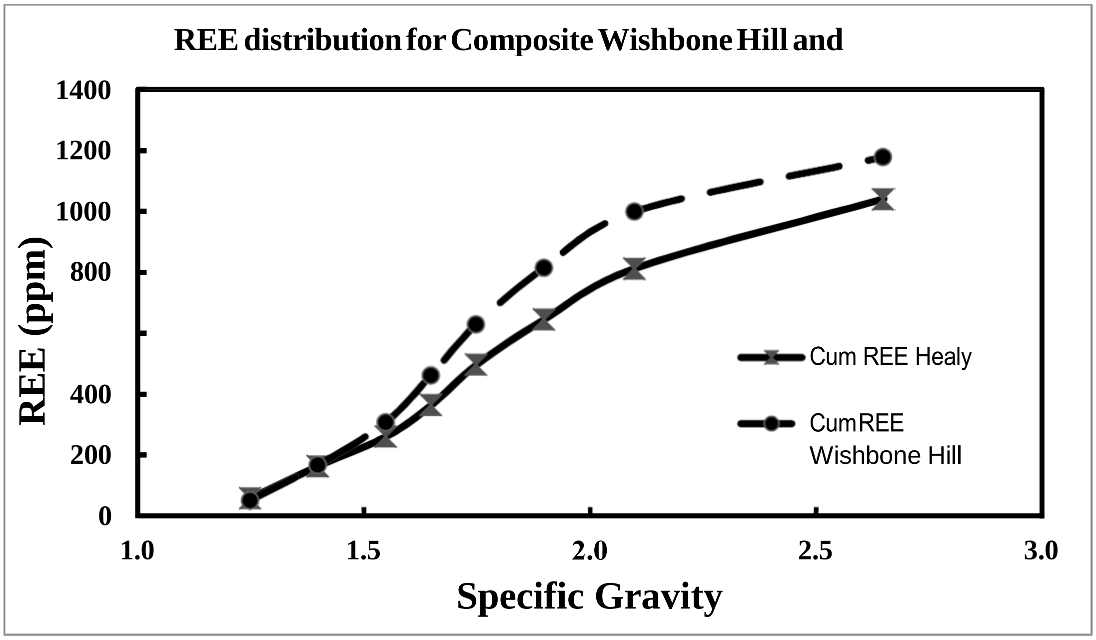

Figure 13 – Comparison of Total REE % versus specific gravity for two composite coal samples

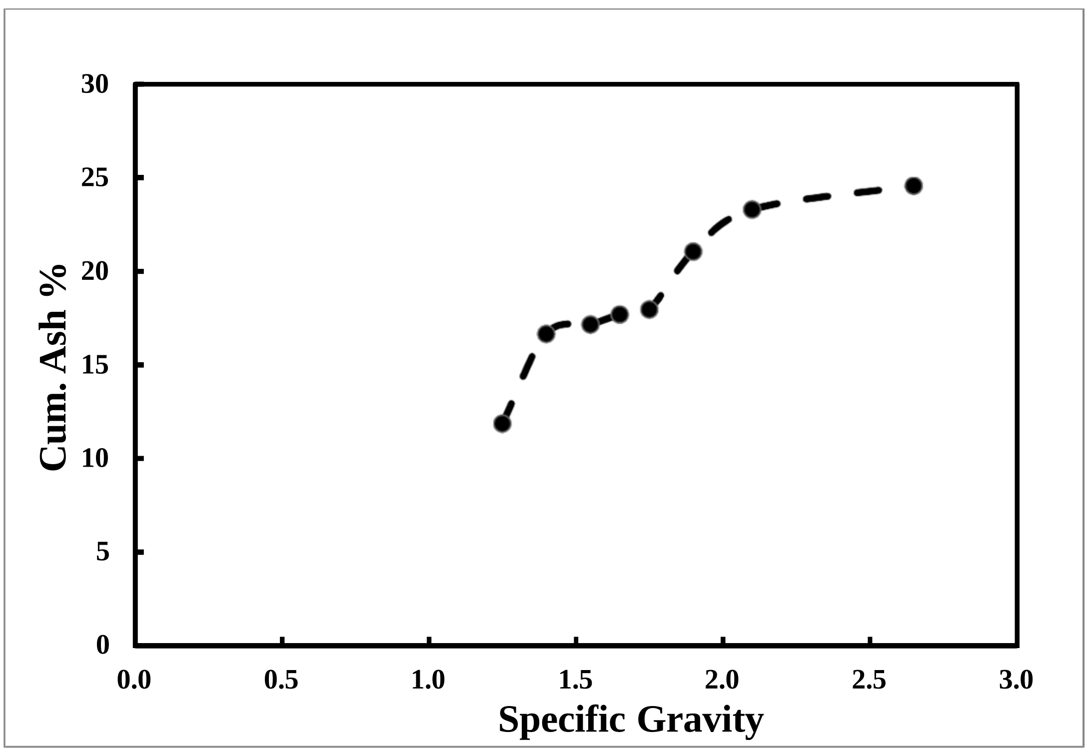

Figure 14 – Cumulative Ash % versus specific gravity for the Healy coal sample

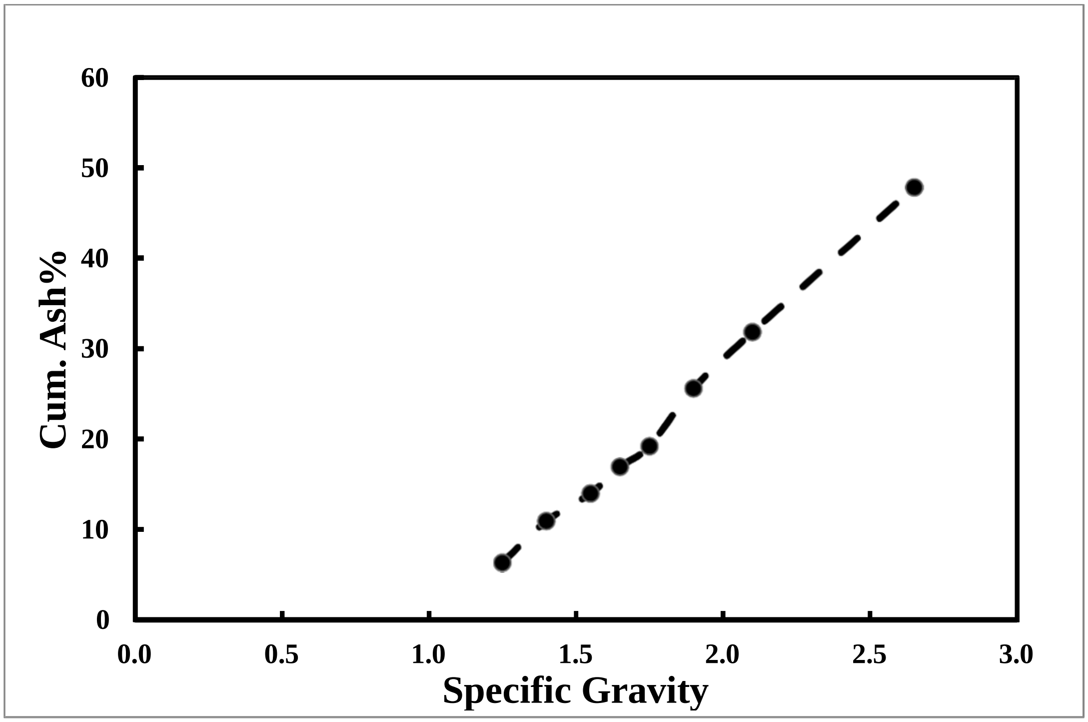

Figure 15 – Cumulative Ash % versus specific gravity for the Wishbone Hill coal sample

5.2. Magnetic and Flotation Tests on fines (-100 mesh)

5.2.1. Dry High Intensity Magnetic Separation (Carpco)

The highest field strength (3 Amperes) was used at 20 rpm rotor speed and at splitter blade setting of 4. However, no distinct separation was observed for either coal types after several iterations. Therefore, these tests were abandoned.

5.2.2. Wet High Intensity Magnetic Separation (Carpco)

As indicated in Table 8, magnetic fractions from both coals appear to be very small compared to non-magnetics (especially for Healy fines which is around 1 %). The Wishbone Hill magnetic fraction is about 12 %. For both coals high ash fractions were found to be reporting to magnetics. Conversely sulfur was retained in non-magnetics together with fixed carbon and volatile matter.

Table 8 – Wet High Intensity Magnetic Separation (WHIMS) of the Healy and the Wishbone Hill coal samples (-100# fractions)

	Sample Weight(g)	Non-mags (g)	Mags (g)	% Non-Mags	% Mags
Healy Coal	148	147.1	0.9	99	1
Wishbone Hill Coal	185	163.2	21.8	88	12
			Proximate Analysis		
	Moisture air dried %	**Ash air dried %**	**Volatile Matter air dried %**	**Fixed Carbon air dried %**	**Total Sulphur air dried %**
Healy coal Magnetics	NSS	48.59	NSS	NSS	NSS
Healy coal Non-Mags	9.42	32.78	44.75	13.05	0.52
Wishbone Hill Magnetics	1.53	74.78	23.69	0.00	<0.01
Wishbone Hill Non-Mags	3.71	58.38	20.77	17.14	0.18

*NSS – Not sufficient sample

Table 9 – REE distributions after Wet High Intensity Magnetic Separation (WHIMS) of the Healy and the Wishbone Hill samples (-100# fractions) on whole coal basis

					LREE			
	Sc ppm	**La ppm**	**Ce ppm**	**Pr ppm**	**Nd ppm**	**Sm ppm**	**Eu ppm**	**Gd ppm**
Healy coal Magnetics	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS
Healy coal Non-Mags	6.68	20.95	42.52	4.94	20.09	4.20	0.98	4.03
Wishbone Hill Magnetics	29.56	19.18	43.95	5.44	23.65	6.98	1.83	8.31
Wishbone Hill Non-Mags	14.81	20.36	43.69	5.37	21.54	5.02	1.08	4.39
					HREE			
	Y ppm	**Tb ppm**	**Dy ppm**	**Ho ppm**	**Er ppm**	**Tm ppm**	**Yb ppm**	**Lu ppm**
Healy coal Magnetics	NSS	NSS	NSS	NSS	NSS	NSS	NSS	NSS
Healy coal Non-Mags	18.83	0.58	3.38	0.69	2.09	0.29	1.80	0.30
Wishbone Hill Magnetics	50.90	1.34	8.55	1.87	5.34	0.78	4.79	0.70
Wishbone Hill Non-Mags	23.02	0.68	4.33	0.88	2.41	0.39	2.52	0.37

*NSS – Not sufficient sample

From Table 9 Wishbone Hill fines contain higher Sc in non-magnetics than that of Healy coal. LREE are similarly distributed between magnetics and non- magnetics for Wishbone Hill fines except Sc, Sm and Gd which were richer in magnetics. This trend is similarly observed for HREE content of the Wishbone Hill. HREE appear to be preferentially reporting to magnetic fractions.

5.2.3. Flotation

Flotation of the fines for both coals was conducted under similar conditions using fuel oil collector (0.45kg/t), Aerofroth 88 frother (20 ppm) at 7% solids concentration by weight. The pH level was maintained at 7. The collector was conditioned for 14 minutes, frother conditioning 1 min with flotation time of 3 minutes and collection at every 30 seconds. There were no depressants used.

Table 10 – Flotation of the Healy and the Wishbone Hill samples (-100# fractions) on whole coal basis

	Sample Wt(g)	Tailings(g)	Floats(g)
Healy Coal	135.5	86.7	30.8
Wishbone Coal	135.5	87.4	38.8

Proximate Analysis					
	Moisture air dried %	Ash air dried %	Volatile Matter air dried %	Fixed Carbon air dried %	Total Sulfur air dried %
Healy Float	7.55	21.94	35.63	34.88	0.56
Healy Tailings	9.97	34.13	33.37	22.53	0.57
Wishbone Float	3.41	26.50	29.93	40.16	0.39
Wishbone Tailings	2.73	74.24	17.50	5.53	0.03

As shown in Table 10, the floated fraction has a significantly lower ash content than the tailings. The tailings have a higher ash content especially for the Wishbone Hill tailings, around 74%, with correspondingly reduced volatiles and fixed carbon. Healy tailings reveal that sulfur and volatiles were equally distributed between tailings and floats. Flotation tests produced relatively low yield under the given set of conditions. Healy sample did not respond well to the test as evident from the relative proximity of the ash values between the floats and sinks.

Table 11 shows the distribution of LREE and HREE between floats and tailing fractions of the Healy and Wishbone Hill fines after flotation separation. As expected both LREE and HREE concentrated more in tailings than float fractions. This finding is more pronounced for Wishbone Hill fines. This follows the same trend as indicated in the washability data.

Table 11 – REE distributions after flotation of the Healy and the Wishbone Hill samples (-100# fractions) on whole coal basis

	LREE							
	Sc ppm	**La ppm**	**Ce ppm**	**Pr ppm**	**Nd ppm**	**Sm ppm**	**Eu ppm**	**Gd ppm**
Healy Float	6.63	16.95	34.15	3.98	15.93	3.43	0.78	3.26
Healy Tailings	8.70	22.38	44.68	5.26	20.92	4.35	1.00	4.23
Wishbone Hill Float	9.00	11.19	23.76	2.91	12.01	2.83	0.65	3.09
Wishbone Hill Tailings	18.82	26.66	56.70	7.01	28.31	6.68	1.29	6.22
	HREE							
	Y ppm	**Tb ppm**	**Dy ppm**	**Ho ppm**	**Er ppm**	**Tm ppm**	**Yb ppm**	**Lu ppm**
Healy Float	16.56	0.51	2.99	0.60	1.60	0.22	1.50	0.22
Healy Tailings	21.87	0.65	3.87	0.83	2.34	0.31	2.10	0.34
Wishbone Hill Float	18.76	0.48	2.98	0.70	1.97	0.31	1.95	0.31
Wishbone Hill Tailings	33.80	0.96	6.06	1.33	3.52	0.47	3.22	0.46

5.2.4. REE content of ash samples from UAF Power Plant

Fly ash (flue-ash is one of the residues generated in coal combustion and contains very fine particles that rise with the flue gases. Fly ash is captured by electrostatic precipitators and filtration equipment. On the other hand Bottom ash (coal ash) is removed from the bottom of the furnace. Depending upon the source and makeup of the coal being burned, the components of fly ash vary considerably.

The ash samples from UAF plant were three types namely, fly-ash (FA), bottom ash (BA) and cinders (C, residue left from incomplete combustion of coal). Their proximate and sulfur analysis is given in Table 12. REE contents are tabulated in Table 13.

Table 12 –UAF power plant products

	Proximate Analysis				
	Moisture air dried %	**Ash air dried**	**Volatile air dried %**	**Fixed air dried %**	**Total air dried %**
BA	0.09	99.63	0.28	0.00	<0.01
FA	1.95	84.17	7.84	6.04	1.71
C	3.54	67.17	7.23	22.06	0.24

Table 13 – REE distributions of UAF power plant products on ash basis

	LREE							
	Sc ppm	**La ppm**	**Ce ppm**	**Pr ppm**	**Nd ppm**	**Sm ppm**	**Eu ppm**	**Gd ppm**
BA	23.89	31.86	66.11	7.41	30.37	6.36	1.58	6.28
FA	20.74	26.35	56.60	6.40	26.96	5.94	1.44	5.83
C	17.63	20.38	42.03	4.82	19.60	4.33	1.09	4.15
	HREE							
	Y ppm	**Tb ppm**	**Dy ppm**	**Ho ppm**	**Er ppm**	**Tm ppm**	**Yb ppm**	**Lu ppm**
BA	32.56	0.98	5.91	1.25	3.56	0.53	3.34	0.49
FA	29.72	0.96	5.45	1.13	3.00	0.47	2.87	0.48
C	21.37	0.64	4.03	0.83	2.31	0.35	2.13	0.37

As seen from Table 12, incomplete combustion residue, Cinders (C), expectedly contained large amounts of fixed carbon and volatiles with around 67% ash product. Fly-ash (F) had also retained some carbon and volatile matter with high concentrations of sulfur. Conversely bottom ash (BA) had very small amounts of volatile matter and sulfur, around 99% ash with no carbon in it.

Trends of REE contents of the power plant products in Table 13 revealed that bottom ash (BA) had relatively higher contents of both LREE and HREE. However, the differences in concentrations distributed between the products are relatively low especially between BA and FA when adjusted for volatiles content.

6. CONCLUSIONS

- The representative sample characterization showed that the majority of the screened sample, about 87.65% and 89.82% is over 30 mesh in size for Healy and Wishbone Hill coals respectively. Only a very small amount about 2.67% for the Healy and 1.26% for the Wishbone Hill is fine fraction and below 100 mesh in size.
- The Healy sample had a high inherent moisture content of around 18% with a dry ash % of around 22%. The Wishbone Hill sample had very low moisture content around 4% with a very high dry ash% around 46%.
- REE content of the Wishbone Hill coal is higher than that of Healy coal. HREE and LREE report to higher density fractions. The REE content of both coals correlate well with the total amount of ash. Also the coals were comparatively richer in Light REE content as compared to HREE.
- Wet high intensity magnetic separation tests on -100 mesh fractions showed that Wishbone Hill fines contain higher Sc in non-magnetics than that of Healy coal. LREE elements are similarly distributed between magnetics and non- magnetics for Wishbone Hill fines except Sc, Sm and Gd which were richer in magnetics. This trend is valid for the HREE content of the Wishbone Hill in that HREE elements appear to be preferentially reporting to magnetic fractions.
- Flotation tests on -100 mesh fines revealed that both LREE and HREE concentrated more in tailings than float fractions. This finding is more pronounced for Wishbone Hill fines. This follows the same trend as indicated in the washability tests that inorganic part of these Alaskan coals is much richer in rare earth elements than those of organic material.
- Trends of REE content of the power plant products revealed that both the bottom ash (BA) and fly ash (FA) had similar contents of both LREE and HREE when adjusted for the volatiles content.

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