Kentucky Geological Survey
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Metallurgical Coal Resources in Eastern Kentucky

Cortland F. Eble and Gerald A. Weisenfluh

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Metallurgical Coal Resources in Eastern Kentucky

Cortland F. Eble and Gerald A. Weisenfluh

Executive Summary

This study assessed eight of the principal low-ash, low-sulfur coal beds of the Eastern Kentucky Coal Field. Low ash and sulfur contents are the minimum requirements for use in metallurgical applications. The Eastern Kentucky Coal Field is a mature mining region, and these results show the extent of that historical development. Most of the resources of optimal thickness (greater than 42 in.) have been mined out; more recent development is in thinner coals that require mining of additional rock (roof or floor or both), resulting in higher mining and processing costs. The eight beds assessed contained original resources of 11.4 billion tons that are greater than 28 in. thick. Remaining resources are 5.5 billion tons, 48 percent of original resources. However, only 17 percent of remaining coal is thicker than 42 in. If all the remaining resource could be mined at a recovery rate of 50 percent, the resources would provide another 35 years of mining at 70 million tons per year. Given the numerous challenges of access, seam continuity, roof quality, and coal quality, it is unlikely that this level of resource extraction can be achieved.

Although these resources undoubtedly contain deposits with quality suitable for metallurgical applications, this study does not address the specific magnitude of those resources. Given the small quantities of specialty coal required relative to steam-coal consumption, such resources could be available for many decades.

Coal is used by the metallurgical industry to produce coke. Coke, a very carbon-dense material, serves principally as a reducing agent when heated with iron ore to produce steel. This contrasts with steam coal, which is burned to produce electricity. Metallurgical coal has more narrow operating parameters than steam coal. The coal must be low in ash (less than 10 percent) and sulfur (less than 1.0 percent) and, ideally, should have a volatile matter content between 22 and 31 percent (dry, ash-free basis). The organic components of the coal should also have an acceptable mixture of reactive and inert components, with a mixture of 70 to 80 percent reactive and 20 to 30 percent inert components being preferable. Furthermore, the rank (level of coal metamorphism) of the coal should be greater than or equal to 0.82 Ro max, with higher reflectance values (greater than or equal to 0.95 Ro max) being preferred. Metallurgical coals in the high-volatile bituminous rank should exhibit broad ranges of plasticity (greater than or equal to 75) and dilatation (greater than or equal to 100). Ash acid/base ratios should exceed 3.5 and the phosphorus content of the ash should be minimal (less than or equal to 0.06 percent). Predicted coke strength after reaction values should be greater than or equal to 45.

Coal samples examined during the course of this study (n=87) were found to be low in ash yield (average, 9.8 percent; range, 1.2 to 41.6 percent, dry basis). Run-of-mine samples commonly contained 20 to 50 percent ash. Although many samples were low in sulfur content (average, 1.4 percent; range, 0.3 to 5.2 percent, dry basis), sulfur variability was found to be quite high. In higher-sulfur coal samples, much of the sulfur was found to exist as very small (less than 10 μ), highly disseminated pyrite grains. These are not easily removed by coal-preparation techniques, making the identification of low-sulfur mining resources prior to extraction very important. Volatile-matter contents of the eastern Ken-

tucky coal samples analyzed ranged between 35.8 and 47.0 percent (average, 40.0 percent, dry, ash-free basis).

The average plastic range of 20 selected samples was 69 (range, 40 to 94), with an average dilatation of 67 (range, 2 to 194). Average ash acid/base ratio was 5.7 (range, 1.9 to 12.3), and average phosphorus content was 0.05 (range, 0.02 to 0.2). The average reflectance of coal samples was 0.89 Ro max, with an observed range between 0.77 and 0.98. Reactive components in the 20 selected samples averaged 79.7 percent (range, 71.7 to 91.8 percent), and inert components averaged 20.3 percent (range, 8.2 to 28.3 percent). Predicted coke strength after reaction value averaged 40.3, and ranged from 18 to 51.

Although many parameters (on an average basis) for the analyzed coals fall outside limitations proposed for coking-coal consideration, no single parameter qualifies or disqualifies a coal from metallurgical consideration. Results indicate that many eastern Kentucky coals can be used as metallurgical feedstock, though primarily through blending with other coals (mainly low-volatile bituminous). Furthermore, low-ash, low-sulfur eastern Kentucky coal appears to be of prime consideration as pulverized coal injection coal. PCI coal is primarily used as a heat source, and since many samples analyzed during the course of this study had calorific values in excess of 14,000 Btu/lb (average, 13,617; range, 11,236 to 15,001, dry basis), many eastern Kentucky coals should have application to the PCI coal market.

Part 1: Eastern Kentucky Coal Resources for Metallurgical Markets

Introduction

Estimating remaining resources for metallurgical-grade coal requires site-specific data on sulfur and ash contents, as well as other chemical and petrographic properties generally not available to public agencies. This study made the assumption that very low sulfur and ash contents are a minimum requirement for the various types of metallurgical feedstocks, and proposed to update earlier assessments of remaining coal resources for beds known to contain such qualities. An assessment of this kind would identify resources with potential for metallurgical applications, but not necessarily specific mineable reserves with known qualities. The resulting resource maps and tables would highlight counties in eastern Kentucky that have the greatest potential for expanding production in these markets.

Although there are many coal beds in the Eastern Kentucky Coal Field, those with significant low-sulfur and low-ash resources are mainly found in the stratigraphically lower part of the geologic sequence (Fig. 1). Coals between the Lower Elkhorn and Fire Clay have the greatest areal development, are known to contain high-quality coal, and with the exception of the Upper Elkhorn No. 1, were previously assessed for remaining resources during the National Coal Resource Assessment program (Ruppert and others, 2002; Tewalt and others, 2002). Updating these estimates involved a compilation of mining data since 2002 and recalculation of remaining resources by county. The four coal beds below the Lower Elkhorn are commonly cited as sources of coal for specialty markets, but were not assessed in the 2002 study because of their limited regional extent. These beds have very localized development in eastern Kentucky—mainly in the southeastern part of the region. New assessments of original and remaining resources were prepared for these beds in Pike County, where they are actively being mined. Some of the beds contain a small amount of resources in other counties, but it was beyond the scope of this study to prepare a complete assessment for each of them.

The objective of this resource study was to prepare original and remaining resource calculations for eight coal beds known to contain significant low-sulfur and low-ash resources. Remaining resources are aggregated by total coal thickness, in 14-in. increments, and by county of location. Resource maps have been prepared to illustrate the geographic distribution of potentially mineable resources and general statements about the accessibility of the resources are made.

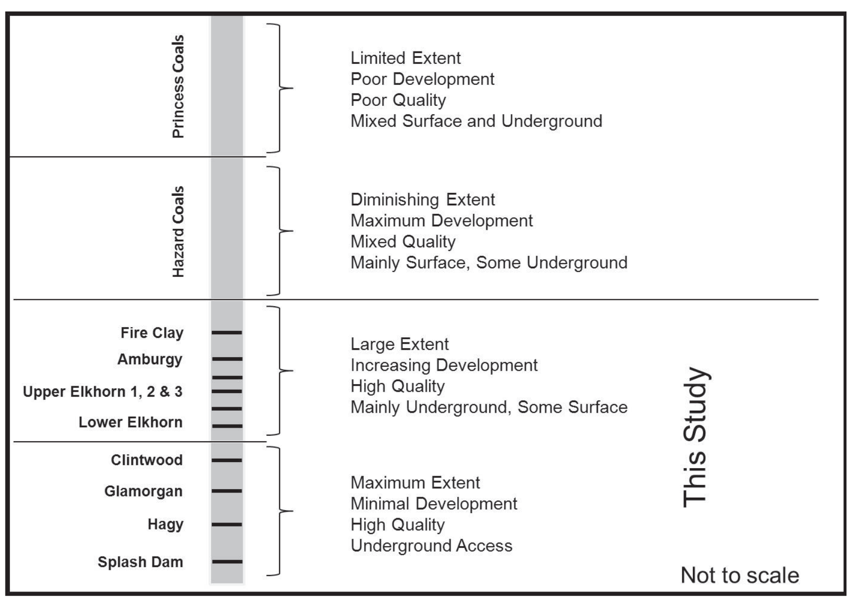


Figure 1. Stratigraphic context of the major coals of eastern Kentucky with respect to resource development and accessibility.

Methods

The geologic extent of each coal horizon, known as the "outcrop," was compiled from published geologic quadrangle maps for the entire Eastern Kentucky Coal Field, or in some cases, for the part of the field where the bed was recognized and mapped. Isopleth maps of total coal thickness were prepared using measurements from field observations and coal-exploration borehole records on file at the Kentucky Geological Survey. All available data were plotted on base maps, coal-bed discontinuities were identified, and thickness contours were manually interpolated from the data. Contour lines were digitized to form polygonal areas representing 14-in. intervals of total coal thickness, and corresponding tonnages for the areas were calculated using an average midpoint thickness for each range and an average coal density of 1.32 (1,800 short tons per acre/ft). The coal-thickness polygons were intersected with the coal-bed outcrop to remove areas where the coal has been eroded by streams during geologic time. The result is a GIS-based map of original resources.

Historical and active coal-mine outlines were accessed from minemaps.ky.gov in May 2012. Because the digitized mine outlines contain many internal blocks of unmined coal that would not be considered an available resource, the mine areas were processed with a buffering operation to eliminate those blocks and to add a perimeter safety barrier that would also not be available for future mining. The final, processed mined-out-area layer was intersected with the original-coal-resource layer so that unmined areas could be tabulated by thickness category and county. Both original and remaining resources were calculated, and percentages of remaining coal determined for each coal bed, county, and thickness interval.

Results

Overburden and Resource Accessibility

Figure 2 shows the basin structure of the Eastern Kentucky Coal Field. The field is separated into two distinct basins by the Pine Mountain Thrust Fault. North of the fault, the strata form a broad syncline, with beds dipping toward the central axis drawn on the map. A second narrow syncline is formed south of Pine Mountain, with the axis in the central part of the area. This latter area is named the Upper Cumberland Basin. The axial parts of each basin have the highest overburden thickness, but overburden also generally increases to the south as a result of greater surface elevations approaching Pine Mountain (Fig. 3). Using this basic structural information, accessibility to the resource by mine type can be generally classified as below drainage, underground drift (near drainage), and surface. Figure 4 shows an example for the Lower Elkhorn coal, where the pink area is below drainage, the gray area is mainly underground-drift accessible, and the boundary between white and gray would be surface-mine accessible. Actual mine development is affected by fluctuations in market price and other local variables, and therefore it is difficult to place the tabulated resources in such categories with a high level of confidence. Rather, in the following sections, general statements will be made in regard to the likely access method for the areas of remaining resources.

Resource availability is also dependent on total coal thickness. In this study, resources greater than 14 in. were measured in increments of 14 in. Coal less than 28 in. thick is generally not mine-

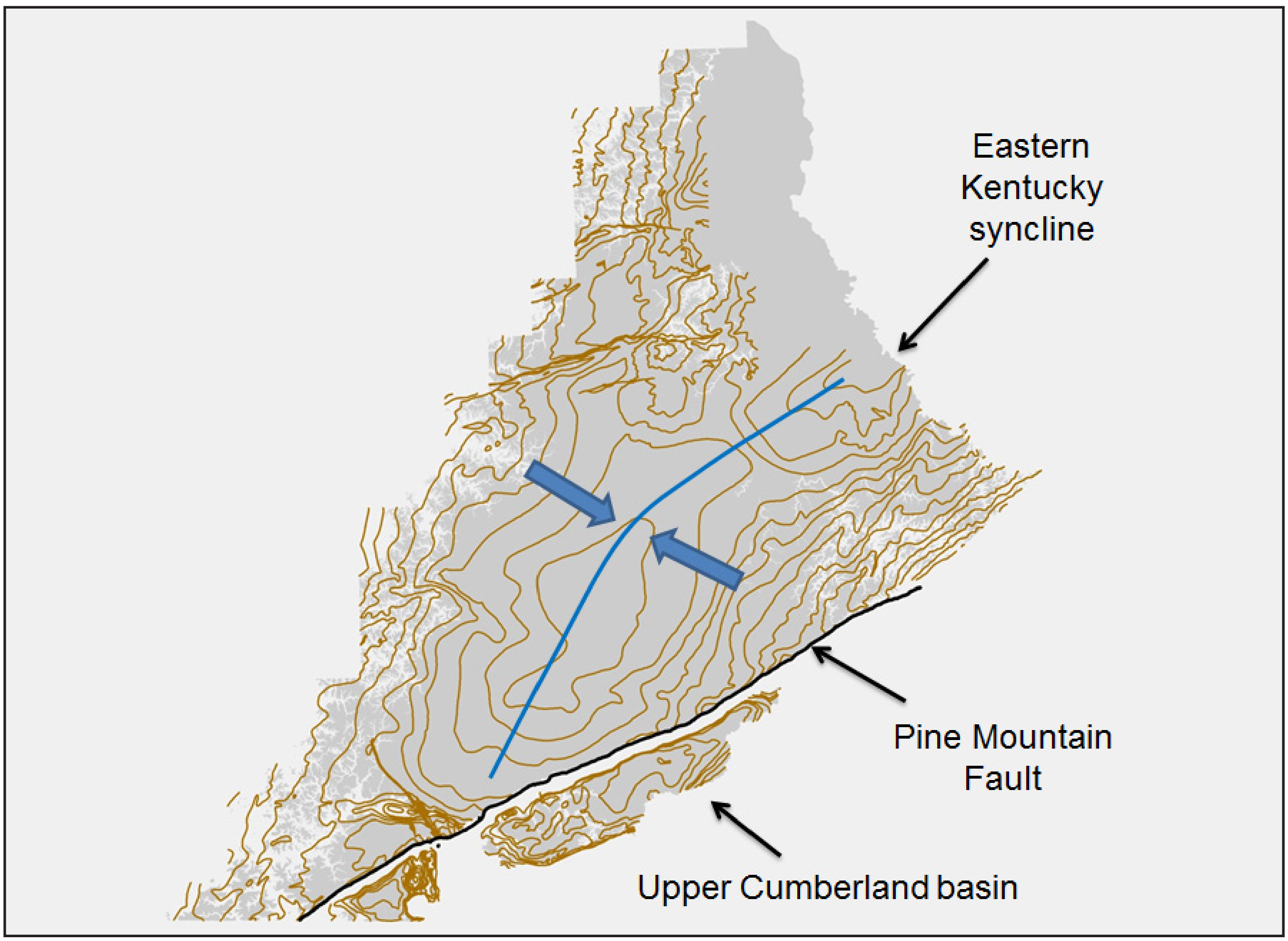


Figure 2. Structure contours for the Lower Elkhorn coal bed illustrating the two basins of the Eastern Kentucky Coal Field separated by the Pine Mountain Thrust Fault.

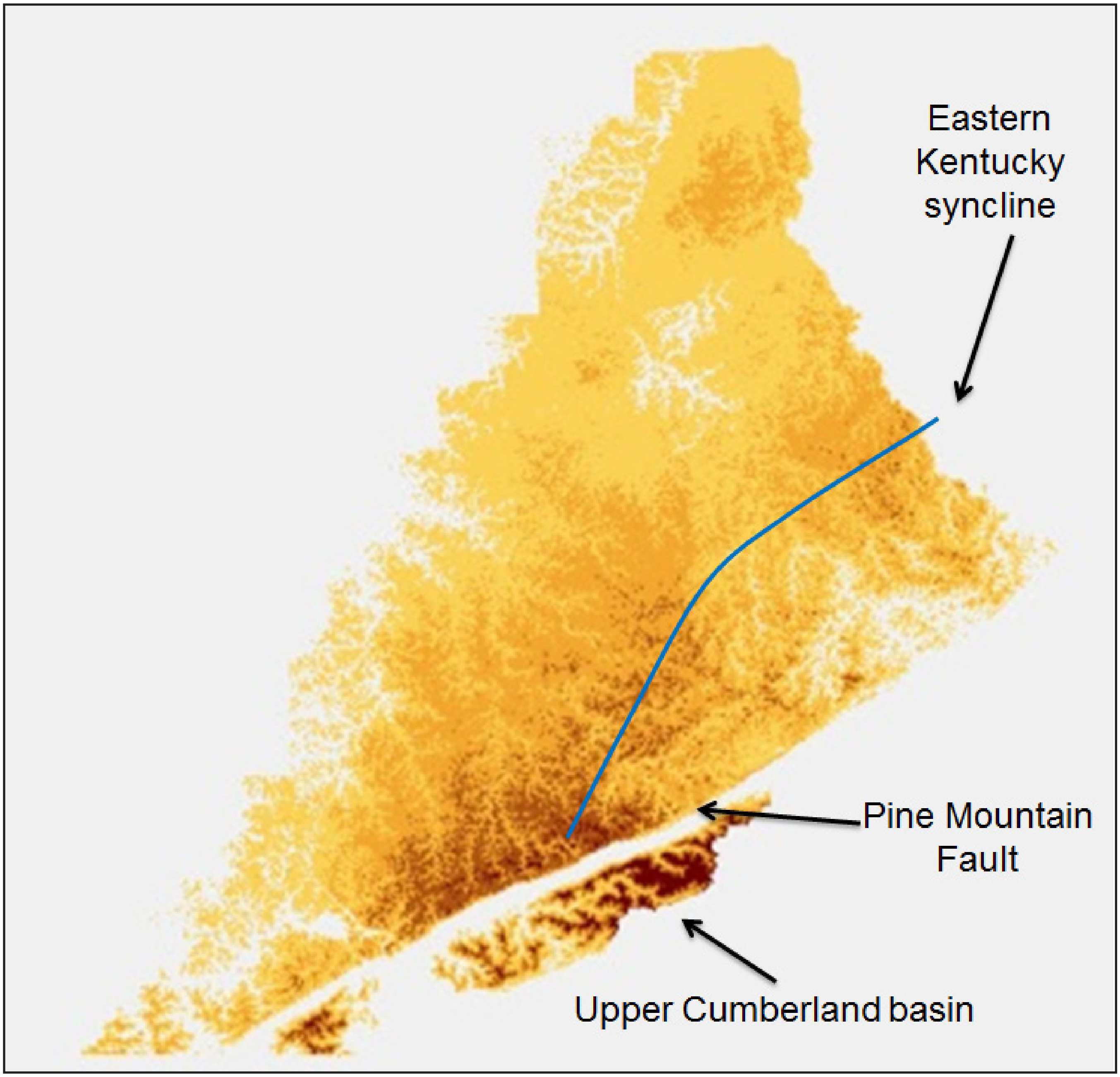


Figure 3. Overburden thickness for the Lower Elkhorn coal. Darker colors indicate greater thickness of overburden in the center of the Eastern Kentucky Syncline, increasing toward the Pine Mountain Fault, and reaching maximum heights in the Upper Cumberland Basin.

able by underground methods, and constitutes a significant part of the tabulated resource. Coal thicker than 42 in. is optimal for most of the mine equipment used for underground mining in the region. Underground mines with coal between 28 and 42 in. thick typically require mining of roof or floor rock to maintain minimum clearance, but this decreases productivity and increases processing costs. The thinnest category of coal is technically available for surface mining, but very little of that coal has been developed by any method.

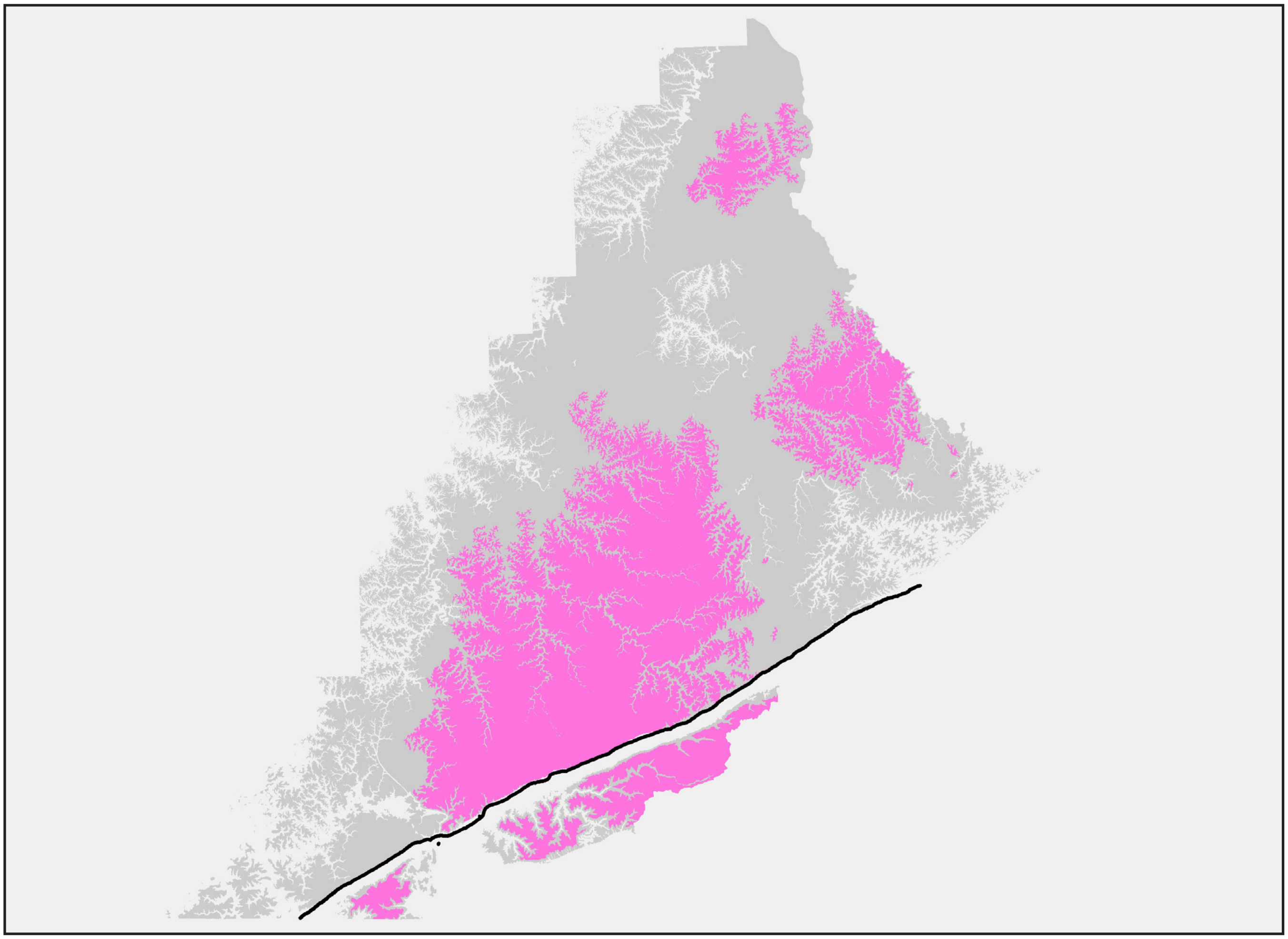


Figure 4. Outcrop extent of the Lower Elkhorn coal bed, showing mine accessibility to the resource. Areas in pink are below drainage and have no surface access. Gray areas are proximal to surface outcrops and can be accessed by surface and underground drift mines.

Fire Clay Coal

Original resources for the Fire Clay coal are shown in Table 1 and Figure 5. The main coal body occurs in Letcher, Knott, Perry, and Leslie Counties, with lesser amounts of coal in surrounding areas. Although the maximum coal thickness is more than 80 in. (Pike County), 62 percent of the coal is between 28 and 56 in., with 40 percent of that being in the 28- to 42-in. category. Of the original 4.2-billion-ton resource, 66 percent is thicker than 28 in., but only 26 percent is thicker than 42 in. One-third of the measured resource is too thin to be economically extracted.

Mined-out and remaining resources are illustrated in Figure 6, where dark blue color indicates mined-out areas and light blue color indicates active mines. The map shows that the core of the main coal body has been extensively developed, leaving marginal areas, mainly less than 42 in. thick. Approximately 1 billion tons of coal greater than 28 in. remains (39 percent of original), but only 16 percent of coal greater than 42 in. remains. Most of the remaining coal is proximal to surface outcrops, providing access by underground drift methods.

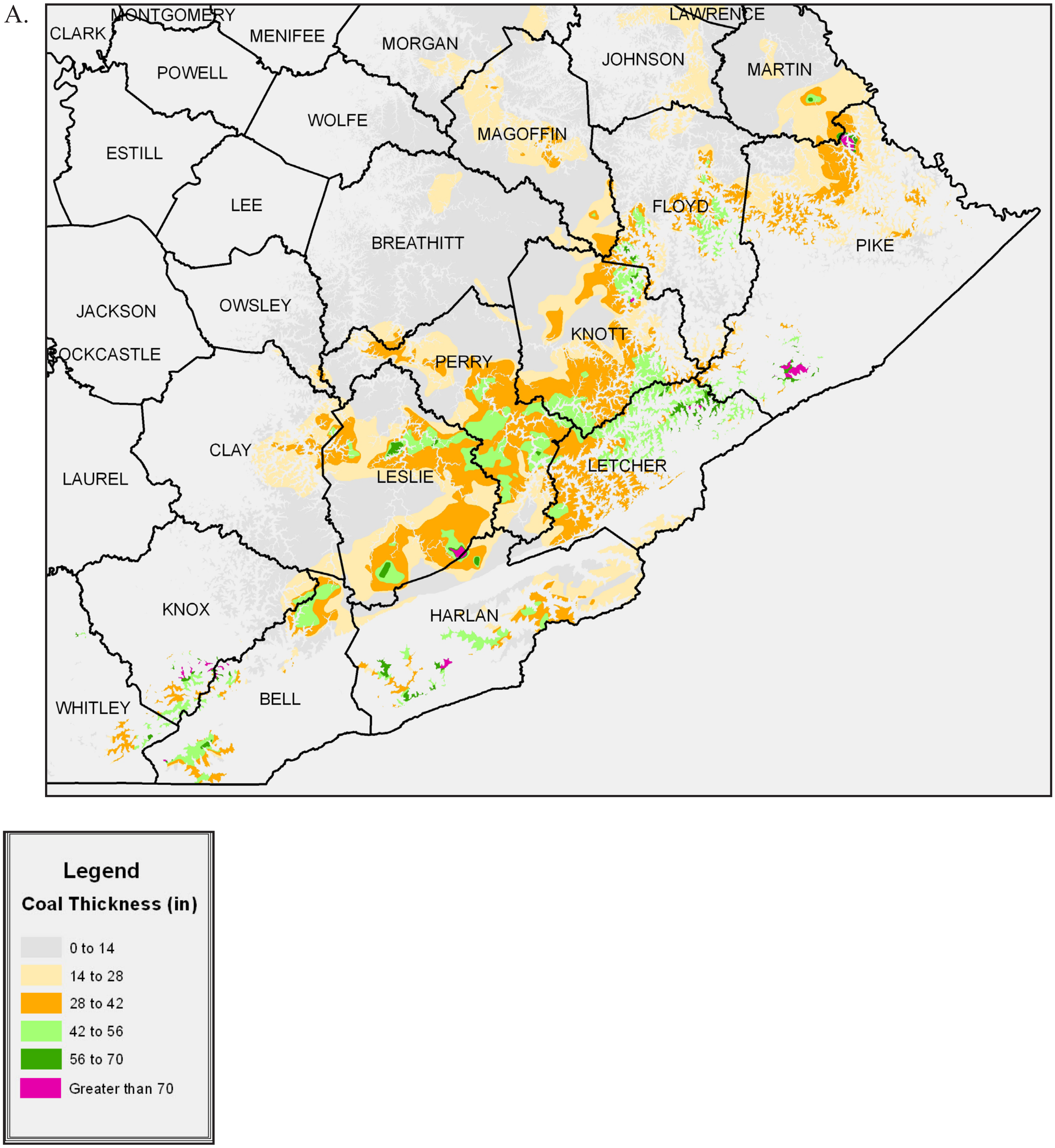
Table 1. 2012 original and remaining coal resources for the Fire Clay coal (million tons).

County		*14–28*	*28–42*	*42–56*	*56–70*	*70–84*	*Total*	*> 28*	*> 42*
Bell	Original	31.9	67.6	91.4	7.5	3.8	202.1	170.2	102.7
	Remaining	28.0	29.8	15.1	0.7	0.0	73.6	45.6	15.8
	% Remaining	87	44	16	9	1	36	26	15
Breathitt	Original	53.3	8.6	–	–	–	61.9	8.6	–
	Remaining	53.2	7.4	–	–	–	60.6	7.4	–
	% Remaining	99	86	–	–	–	97	86	–
Carter	Original	4.2	1.3	–	–	–	5.5	1.3	–
	Remaining	4.2	1.3	–	–	–	5.5	1.3	–
	% Remaining	100	100	–	–	–	100	100	–
Clay	Original	81.8	27.9	2.2	–	–	112.0	30.2	2.2
	Remaining	80.3	16.3	0.0	–	–	96.6	`16.3	0.0
	% Remaining	98	58	0	–	–	86	54	0
Elliott	Original	13.8	–	–	–	–	13.8	–	–
	Remaining	13.8	–	–	–	–	13.8	–	–
	% Remaining	100	–	–	–	–	100	–	–
Floyd	Original	49.0	93.2	58.6	3.7	–	204.6	155.6	62.3
	Remaining	46.1	68.7	25.9	0.1	–	140.8	94.8	26.0
	% Remaining	94	73	44	3	–	68	60	41
Harlan	Original	109.8	82.4	62.6	23.4	8.4	286.6	176.8	94.4
	Remaining	104.8	38.8	13.7	6.4	2.4	166.1	61.3	22.5
	% Remaining	95	47	21	27	28	57	34	23
Johnson	Original	76.9	–	–	–	–	76.9	–	–
	Remaining	75.3	–	–	–	–	75.3	–	–
	% Remaining	97	–	–	–	–	97	–	–
Knott	Original	120.2	290.0	138.1	3.0	1.4	552.6	432.4	142.4
	Remaining	116.9	129.1	14.7	0.3	0.1	261.1	144.3	15.1
	% Remaining	97	44	10	9	8	47	33	10
Knox	Original	17.4	17.8	33.0	6.1	6.2	80.5	63.1	45.3
	Remaining	17.2	12.9	9.4	2.2	0.2	41.9	24.7	11.8
	% Remaining	98	72	28	35	2	52	39	26

Table 1. 2012 original and remaining coal resources for the Fire Clay coal (million tons).

County		*14–28*	*28–42*	*42–56*	*56–70*	*70–84*	*Total*	*> 28*	*> 42*
Lawrence	Original	32.3	–	–	–	–	32.3	–	–
	Remaining	32.3	–	–	–	–	32.3	–	–
	% Remaining	100	–	–	–	–	100	–	–
Leslie	Original	214.2	371.7	119.9	23.3	9.1	738.1	524.0	152.3
	Remaining	200.3	164.9	7.6	0.9	0.8	374.5	174.1	9.2
	% Remaining	93	44	6	3	8	50	33	6
Letcher	Original	26.3	185.0	167.7	29.2	1.4	409.6	383.4	198.3
	Remaining	25.6	76.9	12.2	1.4	0.3	116.4	90.8	13.9
	% Remaining	97	41	7	4	22	28	23	7
Magoffin	Original	149.1	40.1	0.9	–	–	190.0	41.0	0.9
	Remaining	148.7	35.3	0.6	–	–	184.7	36.0	0.6
	% Remaining	99	88	74	–	–	97	87	74
Martin	Original	110.8	29.8	6.2	3.8	0.1	150.6	39.8	10.1
	Remaining	110.5	27.9	6.0	2.0	–	146.5	36.0	8.1
	% Remaining	99	93	97	54	0	97	90	80
Morgan	Original	48.4	–	–	–	–	48.4	–	–
	Remaining	48.4	–	–	–	–	48.4	–	–
	% Remaining	100	–	–	–	–	100	–	–
Owsley	Original	5.9	1.5	–	–	–	7.4	1.5	–
	Remaining	5.9	1.5	–	–	–	7.4	1.5	–
	% Remaining	100	100	–	–	–	100	100	–
Perry	Original	133.7	275.0	188.6	1.3	–	598.6	464.9	189.9
	Remaining	129.4	141.7	43.5	0.3	–	314.9	185.5	43.8
	% Remaining	96	51	23	24	–	52	39	23
Pike	Original	138.3	164.6	19.3	15.5	28.7	366.4	228.1	63.5
	Remaining	130.3	142.2	1.5	2.6	1.3	277.8	147.5	5.3
	% Remaining	94	86	7	16	4	75	64	8
Whitley	Original	0.9	14.5	7.8	2.2	–	25.5	24.6	10.1
	Remaining	0.9	14.3	4.8	0.6	–	20.4	19.6	5.3
	% Remaining	93	98	60	24	–	80	79	52
TOTAL	Original	1,418.2	1,670.9	896.2	118.9	59.1	4,163.4	2,745.2	1,074.3
	Remaining	1,372.0	909.0	155.1	17.5	5.0	2,458.6	1,086.6	177.6
	% Remaining	96	54	17	14	8	59	39	16

A.



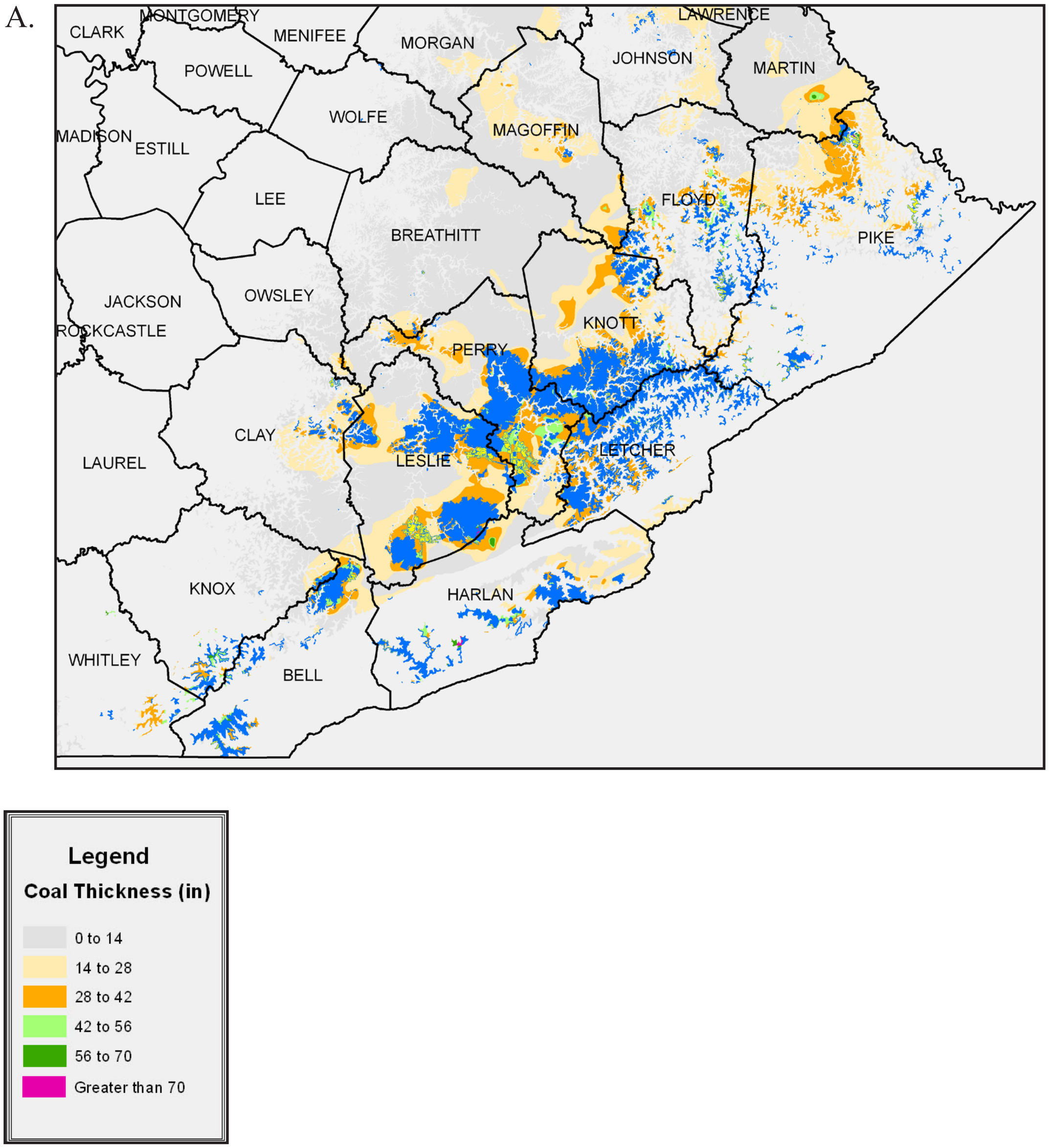
B.

Thickness Range	14–28	28–42	42–56	56–70	> 70
Original Resources	1,418,286,822	1,670,936,332	896,231,208	118,921,549	59,146,367

Totals	> 28	Total
Original Resources	2,745,235,457	4,163,522,279

Figure 5. Original resources of the Fire Clay coal in eastern Kentucky. A. Areal distribution. B. Estimated original resources in short tons.

A.



B.

Thickness Range	14–28	28–42	42–56	56–70	> 70
Mined Resources	46,219,670	761,933,425	741,123,930	101,417,089	54,144,143
Remaining Resources	1,372,067,152	909,002,907	155,107,278	17,504,461	5,002,225
Remaining Percentage	97	54	17	15	8

Totals	> 28	Total
Mined Resources	1,658,618,586	1,704,838,256
Remaining Resources	1,086,616,871	2,458,684,023
Remaining Percentage	40	59

Figure 6. Remaining coal resources of the Fire Clay coal in eastern Kentucky. Mined-out coal shown in dark blue (abandoned) and yellow (active) colors. A. Areal distribution. B. 2012 estimated remaining resources of the Fire Clay coal in short tons.

Upper Elkhorn No. 3 and Kellioka Coal

Original resources for the Upper Elkhorn No. 3 coal are shown in Table 2 and Figure 7. The main coal body north of Pine Mountain is located in Letcher, Knott, Floyd, and Pike Counties. South of the Pine Mountain Fault, where the equivalent bed is named Kellioka, the resource is best developed in northeastern Harlan County. As with the Fire Clay coal, the largest part of the mineable resource is in the 28- to 42-in. category. Only 45 percent of the original resource is thicker than 28 in., because of a greater extent of thin coal on the margin of the coal body. Coal thicker than 42 in., mainly in eastern Letcher and Knott Counties and southern Floyd County, comprises only 17 percent of the resource.

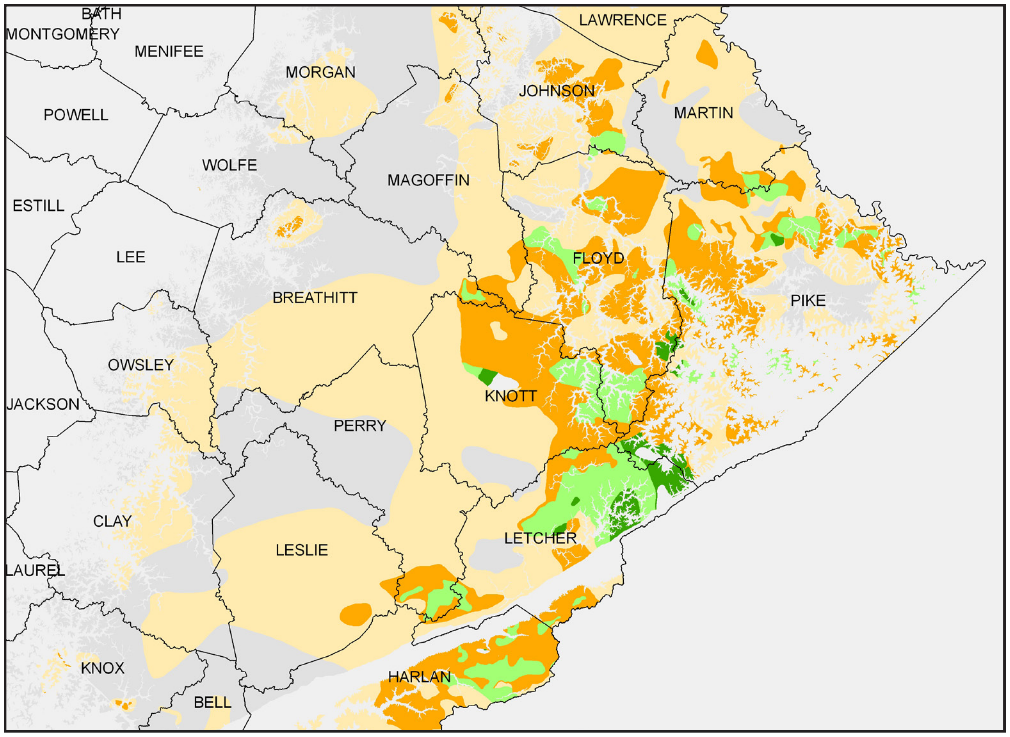
Mined-out and remaining resources are shown in Figure 8. As with the Fire Clay, most of the remaining coal thicker than 28 in. is in marginal areas adjacent to existing mines. Much of that coal is technically below drainage, but could have limited access from adjacent outcrops. Approximately half of the greater-than-28-in. resource remains, but only 22 percent of coal thicker than 42 in. is available.

Table 2. 2012 original and remaining coal resources for the Upper Elkhorn No. 3 coal (million tons).

County		*14–28*	*28–42*	*42–56*	*56–70*	*70–84*	*Total*	*> 28*	*> 42*
Bell	Original	120.5	8.2	–	–	–	128.8	8.2	–
	Remaining	120.2	6.5	–	–	–	126.7	6.5	–
	% Remaining	99	79	–	–	–	98	79	–
Breathitt	Original	507.1	28.0	12.5	–	–	547.6	40.5	12.5
	Remaining	507.1	21.9	5.4	–	–	534.5	27.3	5.4
	% Remaining	100	78	43	–	–	97	67	43
Carter	Original	17.8	–	–	–	–	17.8	–	–
	Remaining	17.7	–	–	–	–	17.7	–	–
	% Remaining	99	–	–	–	–	99	–	–
Clay	Original	216.0	–	–	–	–	216.0	–	–
	Remaining	214.4	–	–	–	–	214.4	–	–
	% Remaining	99	–	–	–	–	99	–	–
Elliott	Original	25.9	–	–	–	–	25.9	–	–
	Remaining	25.8	–	–	–	–	25.8	–	–
	% Remaining	99	–	–	–	–	99	–	–
Floyd	Original	272.1	470.9	161.4	23.6	10.2	938.2	666.1	195.2
	Remaining	258.5	273.4	24.6	3.9	6.7	567.2	308.6	35.2
	% Remaining	95	58	15	16	65	60	46	18
Harlan	Original	258.4	296.3	140.0	0.2	4.1	699.1	440.7	144.4
	Remaining	255.8	250.7	75.9	0.1	3.4	585.9	330.1	79.4
	% Remaining	98	84	54	35	82	83	74	54
Johnson	Original	216.3	129.8	33.5	–	–	379.7	163.4	33.5
	Remaining	211.8	69.4	4.7	–	–	285.9	74.1	4.7
	% Remaining	97	53	14	–	–	75	45	14
Knott	Original	335.5	403.1	92.8	15.4	32.4	879.3	543.8	140.6
	Remaining	333.8	288.1	6.0	4.8	21.3	654.0	320.2	32.1
	% Remaining	99	71	6	31	65	74	58	22
Knox	Original	54.0	3.8	–	–	–	57.8	3.8	–
	Remaining	54.0	3.8	–	–	–	57.8	3.8	–
	% Remaining	100	100	–	–	–	100	100	–

Table 2. 2012 original and remaining coal resources for the Upper Elkhorn No. 3 coal (million tons).									
County		*14–28*	*28–42*	*42–56*	*56–70*	*70–84*	*Total*	*> 28*	*> 42*
Lawrence	Original	240.9	–	–	–	–	240.9	–	–
	Remaining	240.2	–	–	–	–	240.2	–	–
	% Remaining	99	–	–	–	–	99	–	–
Lee	Original	0.1	–	–	–	–	0.1	–	–
	Remaining	0.1	–	–	–	–	0.1	–	–
	% Remaining	100	–	–	–	–	100	–	–
Leslie	Original	491.9	35.0	–	–	–	526.9	35.0	–
	Remaining	491.9	35.0	–	–	–	526.9	35.0	–
	% Remaining	100	100	–	–	–	100	100	–
Letcher	Original	203.0	167.1	328.2	121.9	23.8	844.0	641.0	473.9
	Remaining	195.4	112.9	53.1	2.7	0.5	364.6	169.2	56.4
	% Remaining	96	67	16	2	2	43	26	11
Magoffin	Original	238.3	54.7	0.0	–	–	293.0	54.7	0.0
	Remaining	238.3	44.3	0.0	–	–	282.5	44.3	0.0
	% Remaining	99	80	100	–	–	96	80	100
Martin	Original	274.0	67.7	15.7	–	–	357.5	83.5	15.7
	Remaining	273.8	51.4	0.6	–	–	325.8	52.0	0.6
	% Remaining	99	75	4	–	–	91	62	4
Morgan		175.5	8.3	–	–	–	183.8	8.3	–
		174.2	5.8	–	–	–	180.0	5.8	–
		99	69	–	–	–	97	69	–
Owsley		112.9	0.1	–	–	–	112.9	0.1	–
		112.9	0.1	–	–	–	112.9	0.1	–
		100	100	–	–	–	100	100	–
Perry		361.7	65.6	44.5	–	–	471.8	110.1	44.5
		361.7	63.9	22.5	–	–	448.1	86.4	22.5
		99	97	50	–	–	94	78	50
Pike		298.3	504.6	180.5	72.1	14.9	1,070.5	772.2	267.5
		275.4	324.3	50.7	7.5	0.3	658.2	382.8	58.5
		92	64	28	10	2	61	49	21
Whitley		0.4	–	–	–	–	0.4	–	–
		0.4	–	–	–	–	0.4	–	–
		100	–	–	–	–	100	–	–
Wolfe		9.4	0.1	–	–	–	9.5	0.1	–
		9.4	0.1	–	–	–	9.5	0.1	–
		100	100	–	–	–	100	100	–
TOTAL		4,430.0	2,243.5	1,009.2	233.2	85.4	8,001.4	3,571.4	1,327.9
		4,372.8	1,551.5	243.6	19.0	32.2	6,219.1	1,846.3	294.8
		98	69	24	8	37	77	51	22

A.



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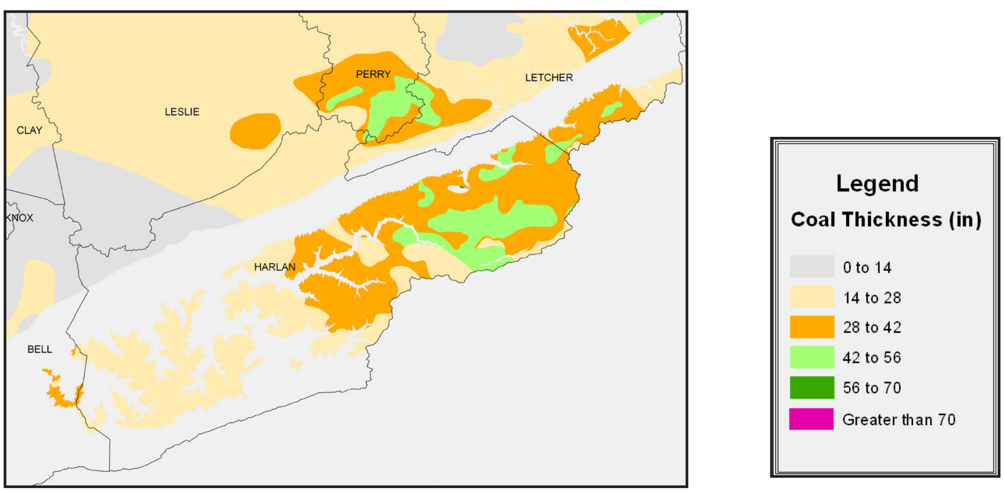


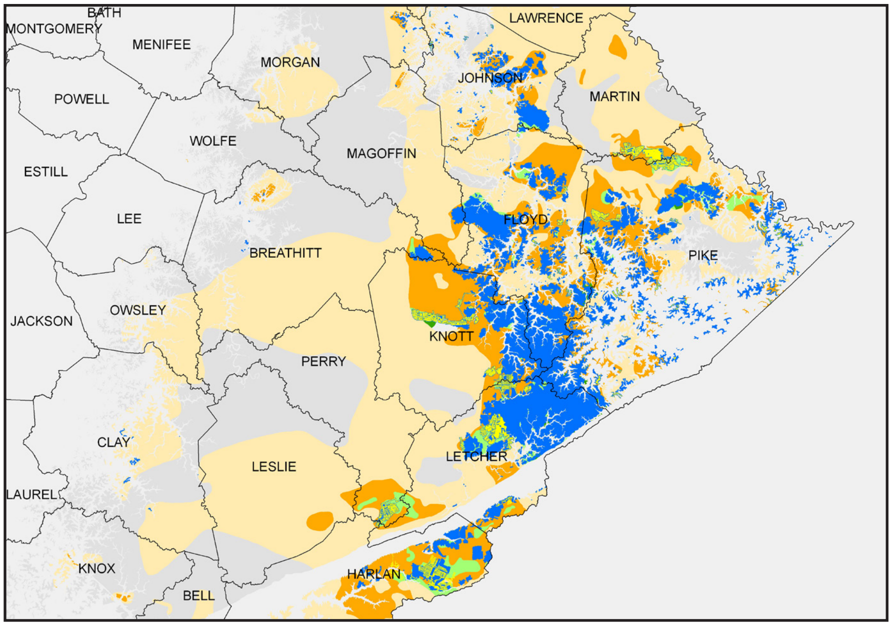
C.

Thickness Range	14–28	28–42	42–56	56–70	> 70
Original Resources	4,430,246,300	2,243,588,954	1,009,248,615	233,232,807	85,429,323

Totals	> 28	Total
Original Resources	3,571,499,700	8,001,746,000

Figure 7. Original resources of the Upper Elkhorn No. 3 coal in eastern Kentucky. A. Main coal field. B. Kellioka coal in the Upper Cumberland Basin. C. Estimated original resources for the Upper Elkhorn No. 3 coal horizon in short tons.

A.



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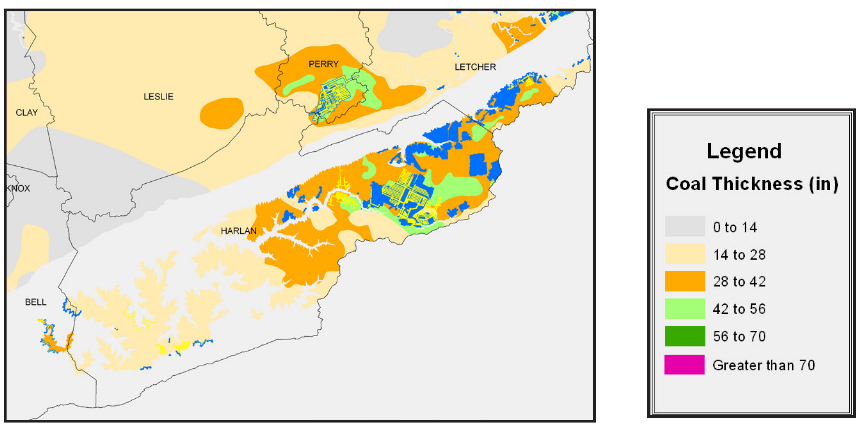


C.

Thickness Range	14–28	28–42	42–56	56–70	> 70
Mined Resources	57,242,434	692,023,378	765,598,937	214,203,034	53,258,018
Remaining Resources	4,373,003,866	1,551,565,576	243,649,678	19,029,773	32,171,305
Remaining Percentage	99	69	24	8	38

Totals	> 28	Total
Mined Resources	1,725,083,367	1,782,325,801
Remaining Resources	1,846,416,333	6,219,420,199
Remaining Percentage	52	78

Figure 8. Remaining resources of the Upper Elkhorn No. 3 coal in eastern Kentucky. Mined-out coal shown in dark blue (abandoned) and yellow (active) colors. A. Main coal field. B. Kellioka coal in the Upper Cumberland Basin. C. 2012 estimated remaining resources for the Upper Elkhorn No. 3 coal horizon in short tons.

Upper Elkhorn No. 2 Coal

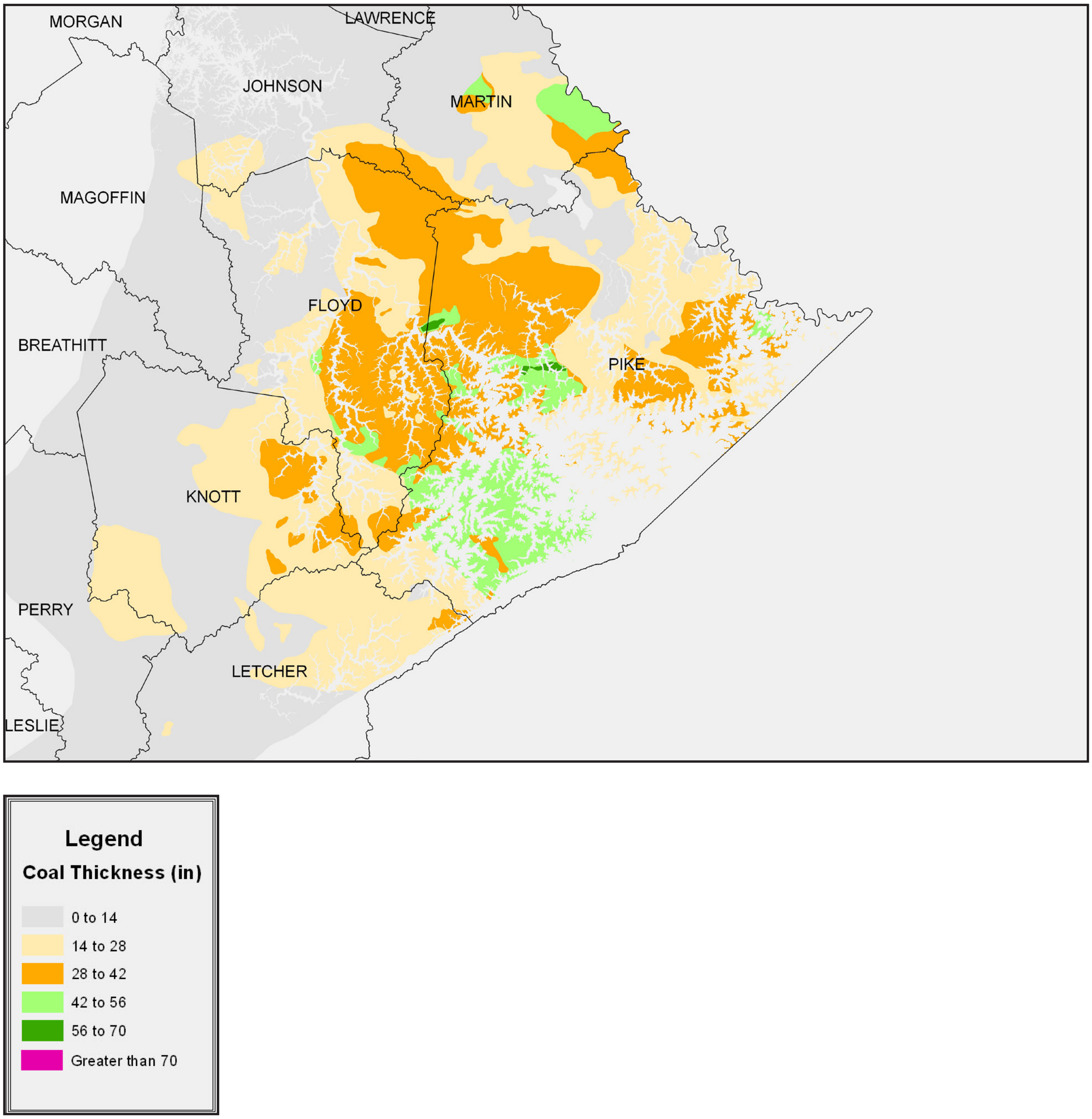
Resources for the Upper Elkhorn No. 2 coal were only assessed north of Pine Mountain, because the equivalent coal in the Upper Cumberland Basin could not be determined. Original resources are shown in Table 3 and Figure 9. The main coal body is a northwest-oriented elongate area centered in Pike and Floyd Counties. Peripheral, thinner deposits are found in eastern Pike, Martin, and Knott Counties. The coal is best developed in southwestern Pike County, where it is thicker than 42 in. Of the original 2.9-billion-ton resource, 58 percent (1.7 billion tons) is thicker than 28 in., but only 16 percent is thicker than 42 in.

Mined-out and remaining resources are shown in Figure 10. With the exception of one mine in western Martin County, all the mines have been in the southern part of the coal body, where the resource is found near present drainage and is generally thicker. Remaining coal is mainly in northern Pike and Floyd Counties and eastern Martin County. Those areas are largely below drainage, and the coal is somewhat thin for that method of development. About 1 billion tons of coal thicker than 28 in. remains, much of which is less than 42 in. thick.

Table 3. 2012 original and remaining coal resources for the Upper Elkhorn No. 2 coal (million tons).

County		*14–28*	*28–42*	*42–56*	*56–70*	*Total*	*> 28*	*> 42*
Floyd	Original	233.5	434.7	37.2	1.4	706.8	473.3	38.6
	Remaining	228.5	259.6	13.5	0.3	502.0	273.4	13.8
	% Remaining	97	59	36	19	71	57	35
Johnson	Original	52.1	26.3	–	–	78.4	26.3	–
	Remaining	50.1	24.9	–	–	75.0	24.9	–
	% Remaining	96	94	–	–	95	94	–
Knott	Original	263.5	87.4	–	–	350.9	87.4	–
	Remaining	262.7	49.5	–	–	312.1	49.5	–
	% Remaining	99	56	–	–	88	56	–
Letcher	Original	195.0	8.7	–	–	203.8	8.7	–
	Remaining	194.2	8.5	–	–	202.7	8.5	–
	% Remaining	99	97	–	–	99	97	–
Magoffin	Original	5.6	–	–	–	5.6	–	–
	Remaining	5.6	–	–	–	5.6	–	–
	% Remaining	100	–	–	–	100	–	–
Martin	Original	125.6	73.2	83.5	–	282.3	156.7	83.5
	Remaining	125.4	57.6	83.5	–	266.6	141.1	83.5
	% Remaining	99	78	100	–	94	90	100
Perry	Original	29.1	–	–	–	29.1	–	–
	Remaining	29.1	–	–	–	29.1	–	–
	% Remaining	100	–	–	–	100	–	–
Pike	Original	305.9	606.4	336.3	12.2	1,260.9	954.9	348.5
	Remaining	279.2	467.5	74.3	5.4	826.5	547.2	79.8
	% Remaining	91	77	22	44	65	57	22
TOTAL	Original	1,210.4	1,236.8	457.0	13.6	2,917.7	1,707.4	470.6
	Remaining	1,174.8	867.6	171.4	5.7	2,219.5	1,044.7	177.1
	% Remaining	97	70	37	41	76	61	37

A.



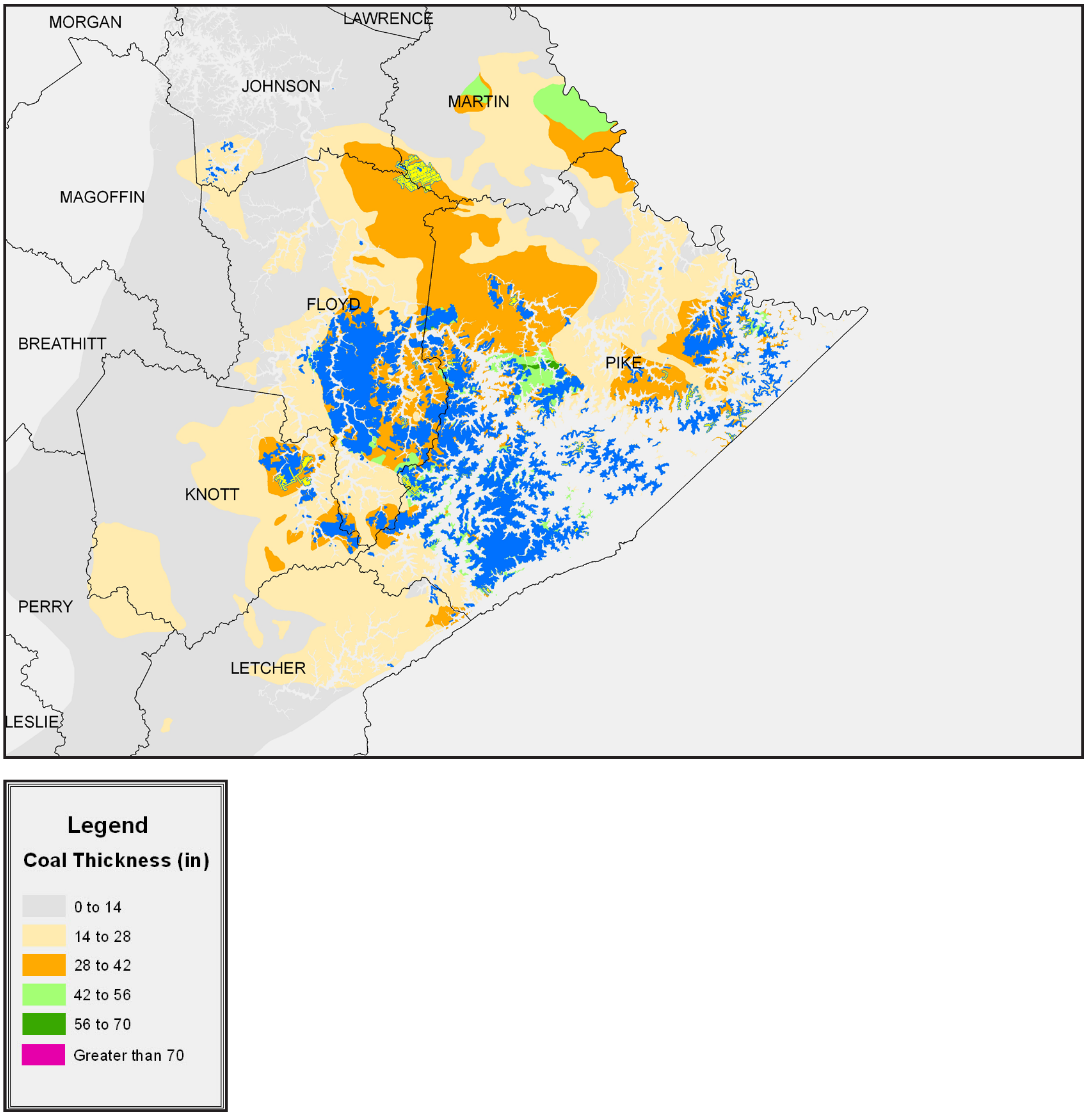
B.

Thickness Range	14–28	28–42	42–56	56–70
Original Resources	1,210,363,618	1,236,803,002	457,077,399	13,631,125

Totals	> 28	Total
Original Resources	1,707,511,526	2,917,875,145

Figure 9. Original resources of the Upper Elkhorn No. 2 coal in eastern Kentucky. A. Main coal body north of the Pine Mountain Fault. B. Estimated original resources for the Upper Elkhorn No. 2 coal in short tons.

A.



B.

Thickness Range	14–28	28–42	42–56	56–70
Mined Resources	35,573,038	369,198,124	285,614,080	7,910,287
Remaining Resources	1,174,790,580	867,604,878	171,463,319	5,720,838
Remaining Percentage	97	70	38	42

Totals	> 28	Total
Mined Resources	662,722,491	698,295,529
Remaining Resources	1,044,789,035	2,219,579,616
Remaining Percentage	61	76

Figure 10. Remaining resources of the Upper Elkhorn No. 2 coal in eastern Kentucky. Mined-out coal shown in dark blue (abandoned) and yellow (active) colors. A. Main coal field. B. 2012 estimated remaining resources for the Upper Elkhorn No. 2 coal horizon in short tons.

Lower Elkhorn Coal

Original resources for the Lower Elkhorn coal are shown in Table 4 and Figure 11. There are three distinct parts to the Lower Elkhorn resource. The main body is located in eastern Pike County and southern Martin County (Fig. 11A). The bed is sometimes called Pond Creek in this area. Also north of Pine Mountain is a smaller body in Bell, Knox, and Whitley Counties, where the coal is known as Blue Gem. The third resource area lies

Table 4. 2012 original and remaining coal resources for the Lower Elkhorn coal (million tons).

County		*14–28*	*28–42*	*42–56*	*56–70*	*70–84*	*Total*	*> 28*	*> 42*
Bell	Original	208.8	159.7	2.3	–	–	370.7	161.9	2.3
	Remaining	207.3	96.7	1.5	–	–	305.4	98.2	1.5
	% Remaining	99	60	65	–	–	82	60	65
Breathitt	Original	20.7	11.3	3.6	–	–	35.7	15.0	3.6
	Remaining	19.1	8.5	1.1	–	–	28.6	9.6	1.1
	% Remaining	92	74	30	–	–	80	63	30
Floyd	Original	194.9	–	–	–	–	194.9	–	–
	Remaining	194.9	–	–	–	–	194.9	–	–
	% Remaining	100	–	–	–	–	100	–	0
Harlan	Original	280.6	379.3	79.5	37.2	25.6	802.2	521.6	142.3
	Remaining	275.1	295.7	79.1	37.2	25.6	712.7	437.6	141.9
	% Remaining	98	77	99	100	100	88	83	99
Johnson	Original	7.8	–	–	–	–	7.8	–	–
	Remaining	7.8	–	–	–	–	7.8	–	–
	% Remaining	100	–	–	–	–	100	–	0
Knox	Original	240.0	34.0	3.9	–	–	278.0	37.9	3.9
	Remaining	198.7	29.0	3.5	–	–	231.1	32.4	3.5
	% Remaining	95	85	87	–	–	83	85	87
Laurel	Original	0.7	–	–	–	–	0.7	–	–
	Remaining	0.7	–	–	–	–	0.7	–	–
	% Remaining	100	–	–	–	–	100	–	0
Lee	Original	1.4	0.8	0.3	–	–	2.5	1.1	0.3
	Remaining	1.4	0.8	0.3	–	–	2.5	1.1	0.3
	% Remaining	100	100	100	–	–	100	100	100
Letcher	Original	59.7	78.4	8.9	56.1	5.5	208.6	148.9	70.5
	Remaining	59.5	70.9	4.5	9.2	–	144.1	84.6	13.7
	% Remaining	99	90	50	16	–	69	56	19
Martin	Original	289.6	54.6	25.0	17.1	1.8	388.1	98.5	43.9
	Remaining	289.3	48.7	5.7	0.0	–	343.7	54.4	5.7
	% Remaining	99	89	22	0	0	88	55	12
McCreary	Original	15.3	–	–	–	–	15.3	–	–
	Remaining	15.3	–	–	–	–	15.3	–	–
	% Remaining	100	–	–	–	–	99	–	0
Owsley	Original	1.0	0.5	0.3	–	–	1.8	0.8	0.3
	Remaining	1.0	0.5	0.3	–	–	1.8	0.8	0.3
	% Remaining	100	100	100	–	–	100	100	100
Pike	Original	297.3	388.8	864.3	471.8	15.3	2,037.4	1,740.1	1,351.3
	Remaining	293.6	241.0	64.9	25.6	0.8	625.8	332.2	91.2
	% Remaining	98	61	7	5	4	30	19	6

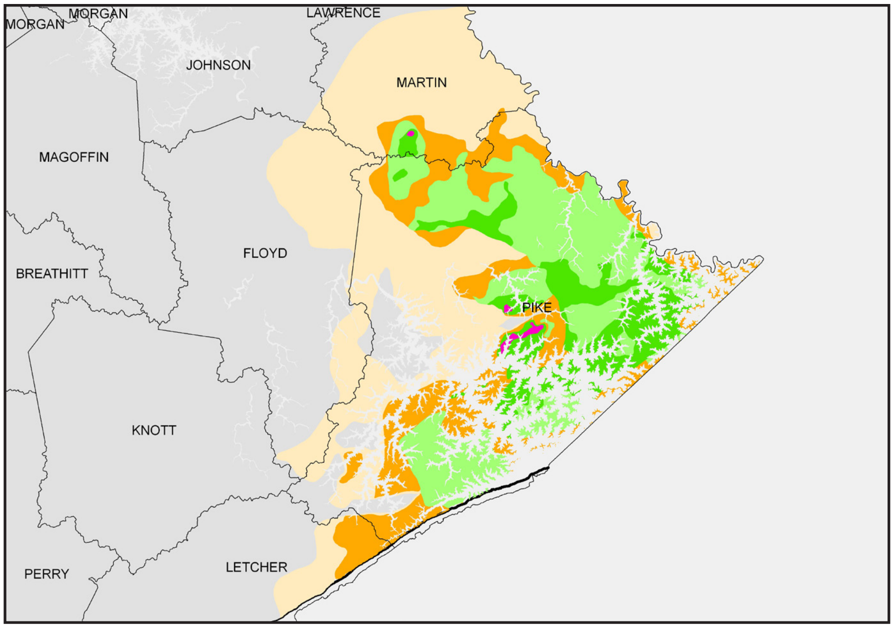
Table 4. 2012 original and remaining coal resources for the Lower Elkhorn coal (million tons).

County		*14–28*	*28–42*	*42–56*	*56–70*	*70–84*	*Total*	*> 28*	*> 42*
Whitley	Original	272.5	94.	–	–	–	281.9	9.4	–
	Remaining	238.1	7.3	–	–	–	245.4	7.3	–
	% Remaining	93	77	–	–	–	87	77	0
Wolfe	Original	5.9	1.4	–	–	–	7.3	1.4	–
	Remaining	5.9	1.4	–	–	–	7.3	1.4	–
	% Remaining	100	100	–	–	–	100	100	0
TOTAL	Original	1,896.1	1,118.3	988.1	582.2	48.2	4,632.9	2,736.8	1,618.5
	Remaining	1,807.5	800.3	160.8	72.0	26.4	2,867.1	1,059.6	259.2
	% Remaining	98	71	16	12	61	61	38	16

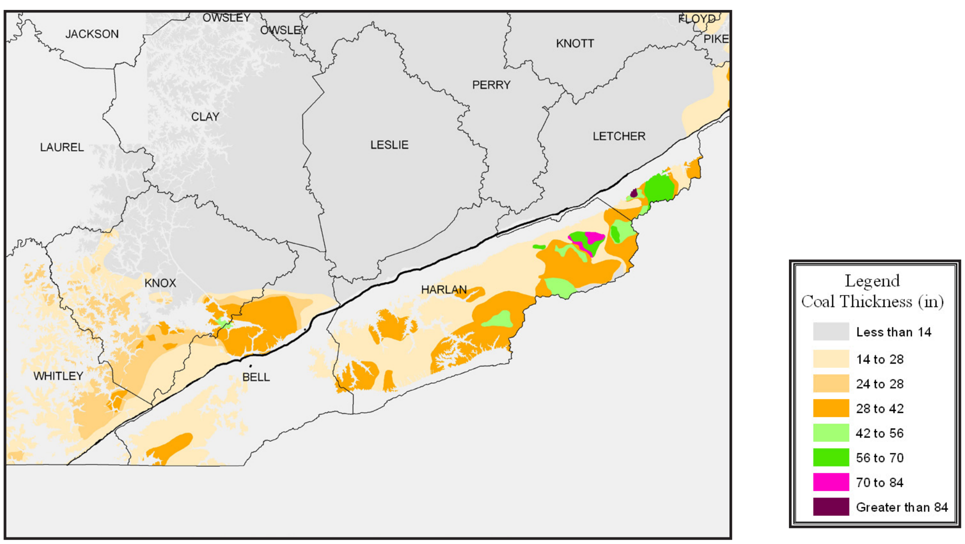
in the Upper Cumberland Basin, where the coal is known as the Imboden or Path Fork (Fig. 11B). The Pond Creek coal in Pike and Martin Counties constitutes over half of the total resource (2.4 billion tons), and about 30 percent of that is thicker than 42 in. The Blue Gem resource area has much thinner coal, but the high quality of this coal permits the practice of using thin-seam miners to extract coal as thin as 24 in. The Upper Cumberland resource area has several thick coal bodies, but most of the area is less than 42 in. thick. Total original resources for the three areas are 4.6 billion tons, with 2.7 billion tons thicker than 28 in.

Mined-out and remaining resources are shown in Figure 12. Again, the core of the Pond Creek coal deposit has been largely depleted, with remaining resources located on the periphery. Most of the remaining coal is less than 42 in. thick. Areas in Letcher and western Pike Counties are accessible by underground drift mines, whereas those in northern Pike and southern Martin Counties are only accessible by existing or new slope and shaft mines. In the Upper Cumberland area, development of the Imboden and Path Fork coals has been at both ends of the syncline, where the coal is at shallower depths. Remaining coal in this sub-basin is below drainage, with greater overburden and dominated by coal less than 42 in. thick. Previous development of the Blue Gem resource is characterized by many small underground and surface mines near the outcrop belt and a few larger mines. For all Lower Elkhorn coal resource areas, approximately 1 billion tons of coal thicker than 28 in. remains, with only 259 million tons thicker than 42 in.

A.



B.



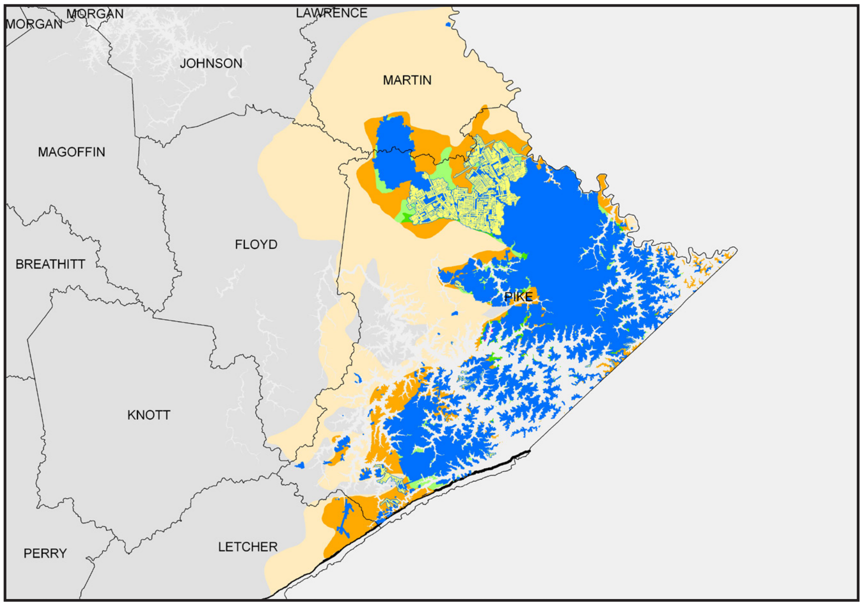
C.

Thickness Range	14–28	24–28	28–42	42–56	56–70	70–84	> 84
Original Resources	1,638,197,167	258,085,366	1,118,477,631	988,183,866	582,248,414	42,684,807	5,505,362

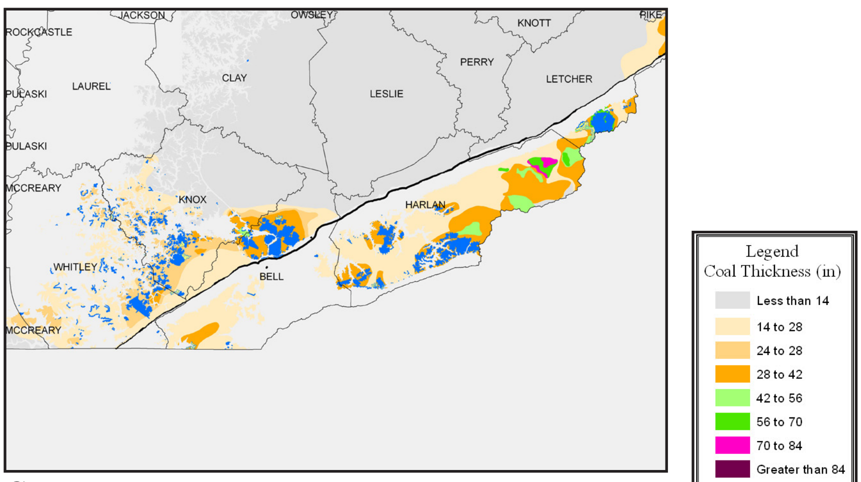
Totals	> 28	Total
Original Resources	2,737,100,080	4,633,382,613

Figure 11. Original resources of the Lower Elkhorn coal in eastern Kentucky. A. Pond Creek coal resources in Pike and Martin Counties. B. Imboden and Path Fork coal resources in the Upper Cumberland Basin, and Blue Gem coal resources in Bell, Knox, and Whitley Counties. C. Estimated original resources for the Lower Elkhorn coal horizon in short tons.

A.



B.



C.

Thickness Range	14–29	24–28	28–42	42–56	56–70	70–84	> 84
Mined Resources	29,820,704	58,765,638	317,959,355	827,294,192	510,180,359	16,295,788	5,505,362
Remaining Resources	1,608,376,463	199,319,728	800,518,276	160,889,674	72,068,055	26,389,019	–
Remaining Percentage	98	77	72	16	12	62	0

Totals	> 28	Total
Mined	1,677,235,056	1,765,821,398
Remaining Resources	1,059,865,025	2,867,561,216
Remaining Percentage	39	62

Figure 12. Remaining resources of the Lower Elkhorn coal in eastern Kentucky. Mined-out coal areas shown in dark blue (abandoned) and yellow (active) colors. A. Pond Creek coal. B. Upper Cumberland Basin and Blue Gem coal. C. 2012 estimated remaining coal resources for the Lower Elkhorn coal in short tons.

Pike County Assessment

Four coal beds containing low-sulfur and -ash coal were assessed in Pike County, where they have been produced for specialty coal products. These beds are the Clintwood, Glamorgan, Hagy, and Splash Dam (see Fig. 1). Equivalent coals occur in small quantities in other counties, especially near Pine Mountain, but could not be assessed because of insufficient data and time. In Pike County, most of the resources associated with these lower coal beds are in the southern part of the county adjacent to the Virginia border. Original and remaining resources are shown in Figures 13 through 16 and Tables 5 through 8, respectively. Combined original resources for the four beds, where thicker than 28 in., are 660 million tons. This relatively modest amount is because of the limited areal extent of the coal deposits. Remaining resources are 428 million tons, or 65 percent of original resources.

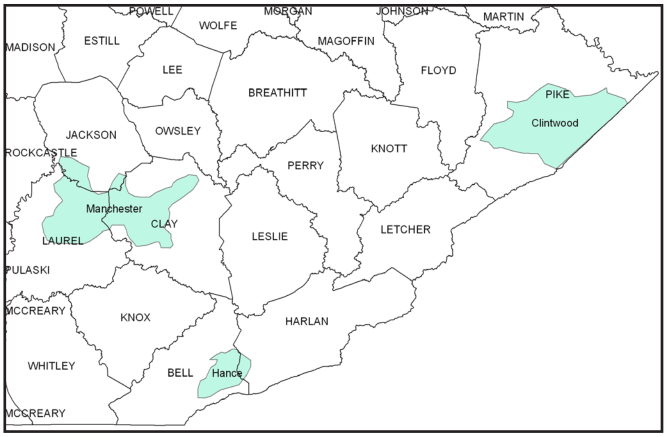
The Clintwood coal horizon (also known as the Hance and Manchester) occurs throughout eastern Kentucky, but areas containing mineable thickness are limited to a few counties (Fig. 13A). In Pike County, development of the Clintwood coal bed (Fig. 13B) has been primarily in coal thicker than 42 in., which is now largely depleted. Remaining coal (Fig. 14) on the northern edge of the coal body constitutes the largest block of uninterrupted resource, but it is entirely below drainage. Existing mines have not developed into this area, suggesting limitations from seam height and depth of cover. Remaining coal on the west side of the deposit is proximal to the outcrop and could be developed by drift mines. However, individual mine areas between streams are relatively small, precluding development of large contiguous mines. Remaining resources thicker than 28 in. are 149 million tons (Fig. 14B, Table 5).

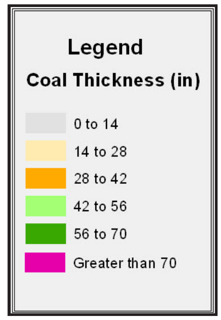
The Glamorgan coal bed is limited to two areas: Pike County, where it is also known as the Millard coal, and Bell County, where it is known as the Mason coal (Fig. 15A). Although the coal bed persists throughout Pike County, mineable areas are limited to small individual pods, mainly in the southeastern third of the county (Fig. 15B). Most of those areas are proximal to outcrop access. Almost all of the individual deposits have some mine development, but coal, mainly less than 42 in. thick, remains in most of them (Fig. 16A). Remaining resources thicker than 28 in. are 159 million tons (Fig. 16B, Table 6).

The Hagy coal bed is restricted to the southeastern corner of Pike County. As with the Glamorgan, the Hagy is characterized by relatively small pods of coal thicker than 28 in., but very little thicker than 42 in. (Figs. 17A, B). Mine development has been limited mainly to one of the coal bodies along the Virginia border, where there is outcrop access (Fig. 18A). Remaining resources thicker than 28 in. are 80 million tons (Fig. 18B, Table 7).

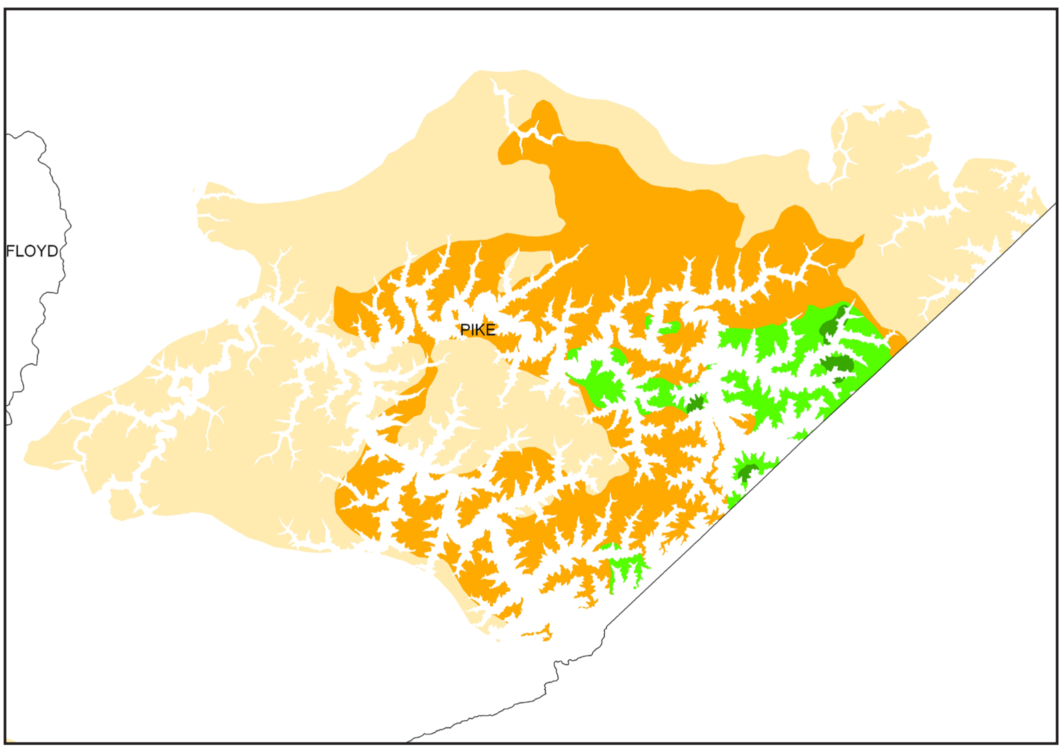
The Splash Dam coal is best developed along the Virginia border, but it occurs in three distinct coal bodies in different parts of eastern Kentucky. Only 30 percent of the assessed resource is thicker than 28 in., and there are no resources thicker than 42 in. (Figs. 19A, B). Most of the areas of coal thicker than 28 in. have been developed, and only 40 million tons remains (Figs. 20A, B, Table 8).

A.





B.



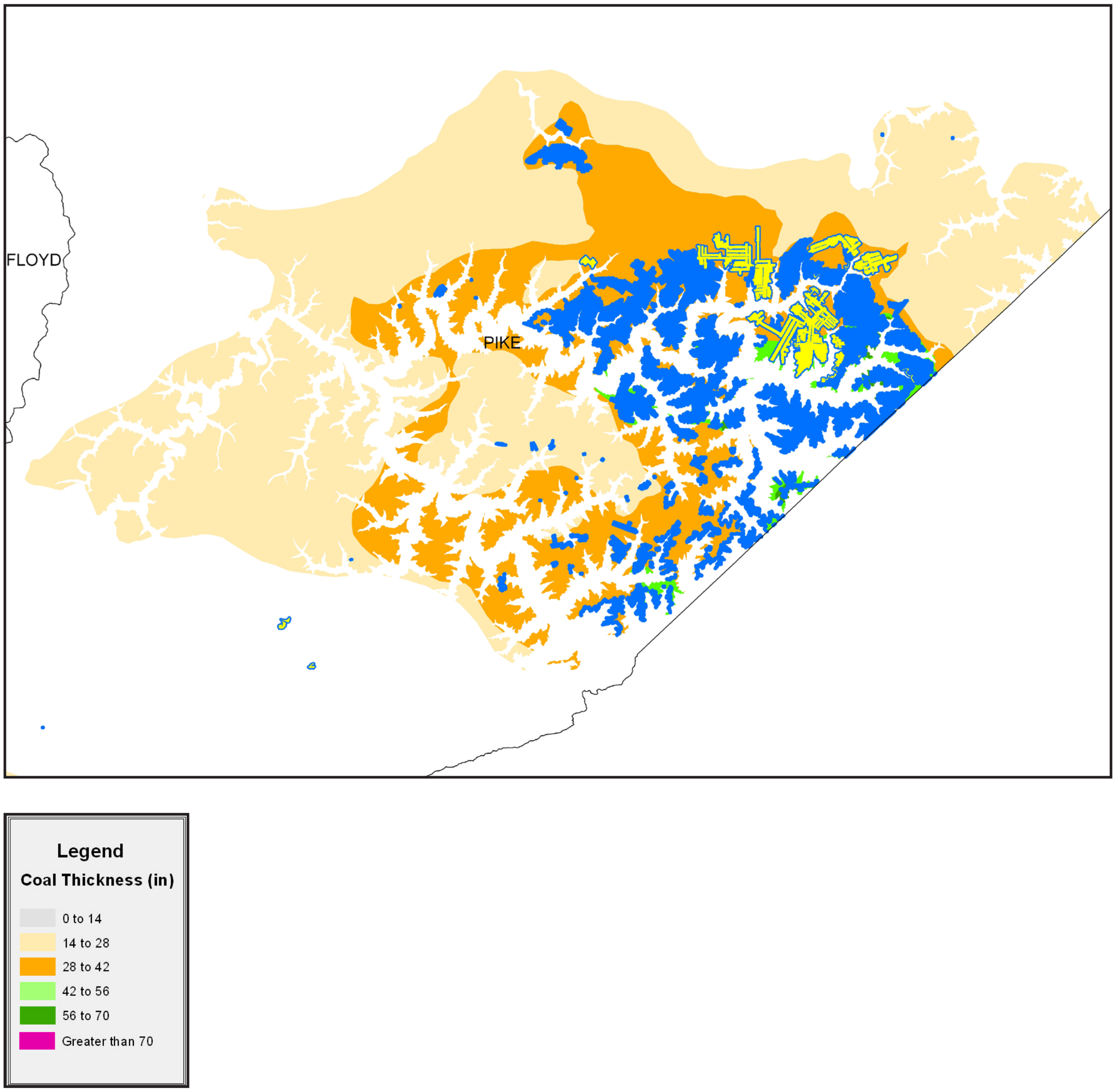
C.

Thickness Range	14–28	28–42	42–56	56–70
Original Resources	249,642,547	210,542,663	45,874,843	5,904,341

Totals	> 28	Total
Original Resources	262,321,847	511,964,394

Figure 13. Original resources of the Clintwood coal in eastern Kentucky. A. Resource areas for the three equivalent coal beds for this horizon: Clintwood, Manchester, and Hance coals. B. Original resources of the Clintwood coal in southwestern Pike County. C. Estimated original resources of the Clintwood coal in southeastern Pike County in short tons.

A.



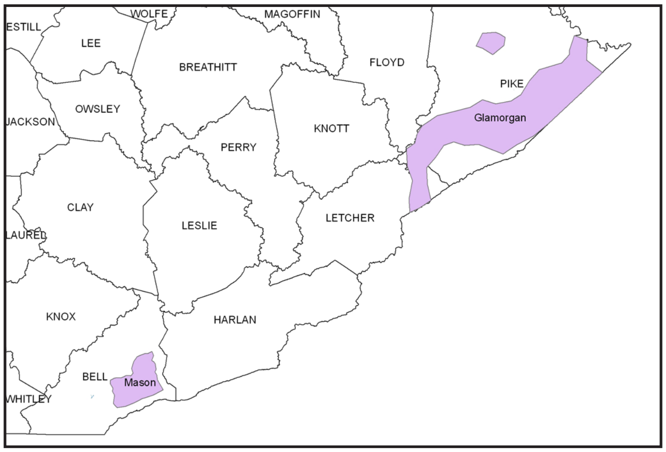
B.

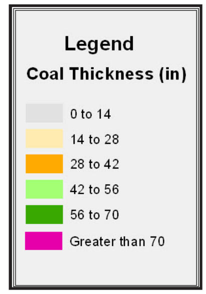
Thickness Range	14–28	28–42	42–56	56–70
Mined Resources	605,816	67,689,987	40,345,760	4,981,993
Remaining Resources	249,036,732	142,852,676	5,529,082	922,348
Remaining Percentage	100	68	12	16

Totals	> 28	Total
Mined Resources	113,017,740	113,623,556
Remaining Resources	149,304,107	398,340,839
Remaining Percentage	57	78

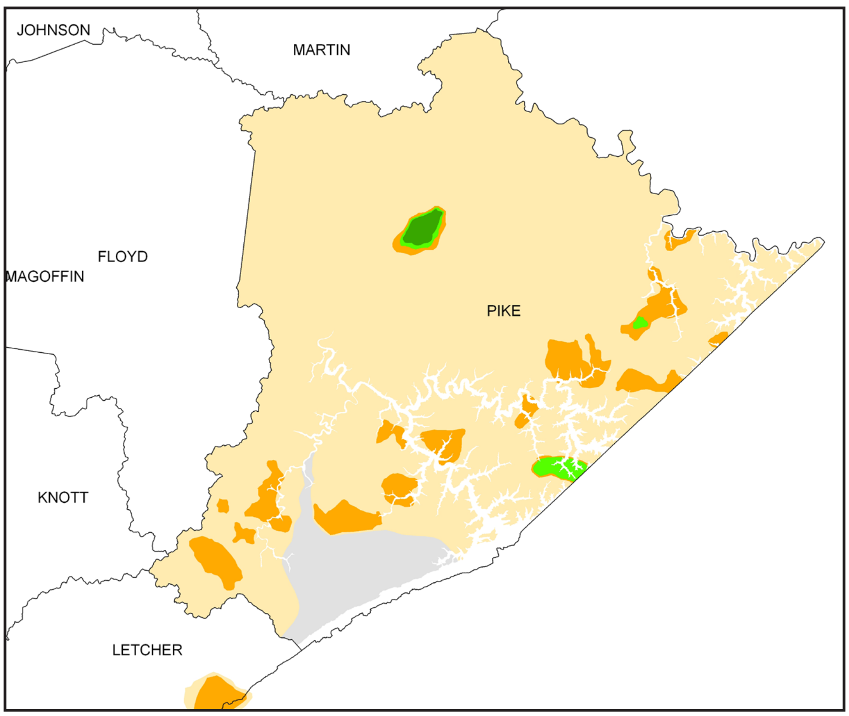
Figure 14. Remaining resources of the Clintwood coal in southeastern Pike County. Mined-out coal areas shown in dark blue (abandoned) and yellow (active) colors. A. Areal distribution in Pike County. B. 2012 estimated remaining coal resources for the Clintwood coal in Pike County in short tons.

A.





B.



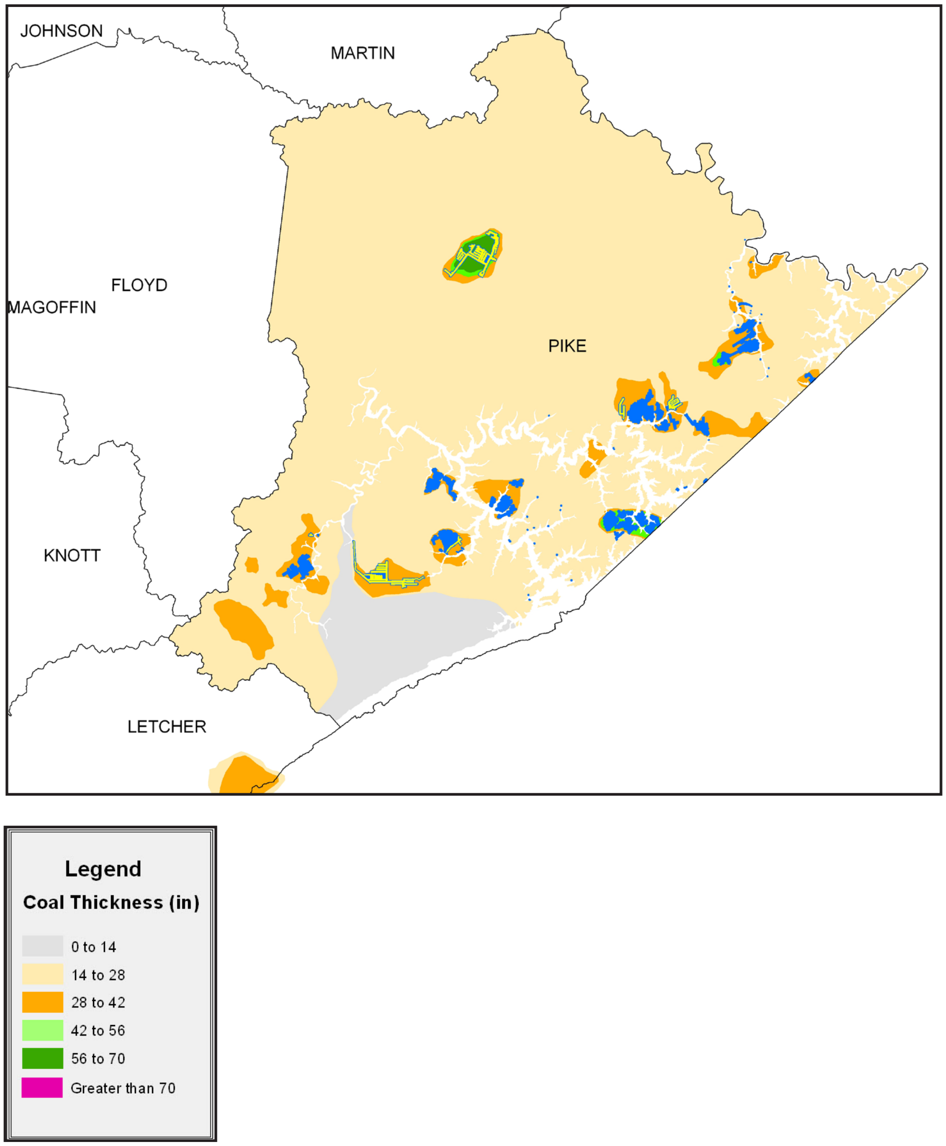
C.

Thickness Range	14–28	28–42	42–56	56–70
Original Resources	1,287,186,568	185,347,600	21,463,975	18,930,004

Totals	> 28	Total
Original Resources	225,741,579	1,512,928,146

Figure 15. Original coal resources of the Glamorgan coal in eastern Kentucky. A. Resource areas for the two equivalent coal beds for this horizon: Glamorgan (Millard) and Mason. B. Original resources of the Glamorgan coal in southeastern Pike County. C. Estimated original resources of the Glamorgan coal in southeastern Pike County in short tons.

A.



B.

Thickness Range	14–28	28–42	42–56	56–70
Mined Resources	1,971,807	43,078,113	14,447,410	9,239,441
Remaining Resources	1,285,214,761	142,269,487	7,016,565	9,690,563
Remaining Percentage	100	77	33	51

Totals	> 28	Total
Mined Resources	66,764,964	68,736,771
Remaining Resources	158,976,615	1,444,191,376
Remaining Percentage	70	95

Figure 16. Remaining resources of the Glamorgan coal in Pike County. Mined-out coal areas shown in dark blue (abandoned) and yellow (active) colors. A. Areal distribution in Pike County. B. 2012 estimated remaining coal resources for the Glamorgan coal in Pike County in short tons.

Table 5. 2012 original and remaining coal resources for the Clintwood coal in Pike County (million tons).

Thickness	*14–28*	*28–42*	*42–56*	*56–70*	*Total*	*> 28*	*> 42*
Original	249.6	210.5	45.9	5.9	512	262	52
Remaining	249.0	142.9	5.5	0.9	398	149	6
Remaining %	99	67	12	15	77	56	12

Table 6. 2012 original and remaining coal resources for the Glamorgan coal in Pike County (million tons).

Thickness	*14–28*	*28–42*	*42–56*	*56–70*	*Total*	*> 28*	*> 42*
Original	1,279.0	185.3	21.5	18.9	1,505	226	40
Remaining	1,277.0	142.3	7.0	9.7	1,436	159	17
Remaining %	99	76	32	51	95	70	41

Table 7. 2012 original and remaining coal resources for the Hagy coal in Pike County (million tons).

Thickness	*14–28*	*28–42*	*42–56*	*Total*	*> 28*	*> 42*
Original	485.3	94.7	4.6	585	99	5
Remaining	484.1	78.3	1.9	564	80	2
Remaining %	99	82	40	96	80	40

Table 8. 2012 original and remaining coal resources for the Splash Dam coal in Pike County (million tons).

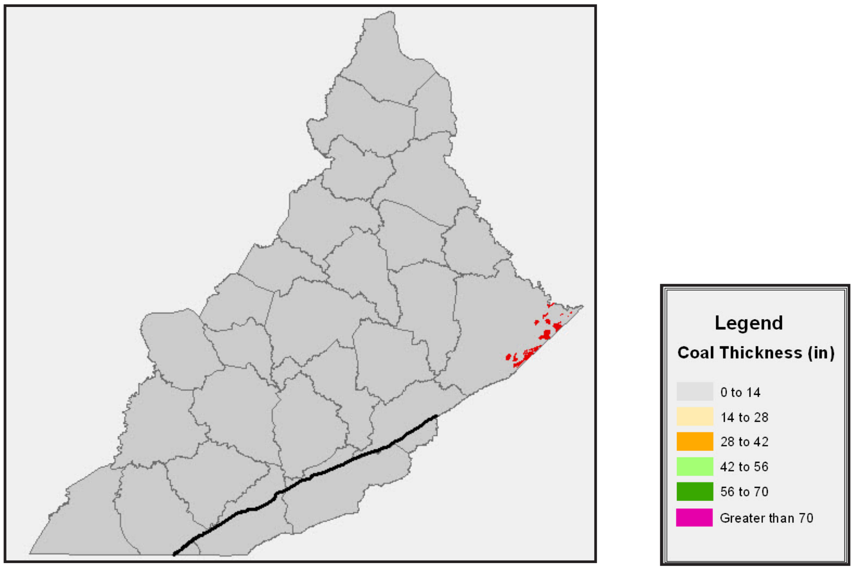
Thickness	*14–28*	*28–42*	*Total*	*> 28*	*> 42*
Original	224.8	73.0	298	73	–
Remaining	223.8	40.3	264	40	–
Remaining %	99	55	88	55	–

Summary

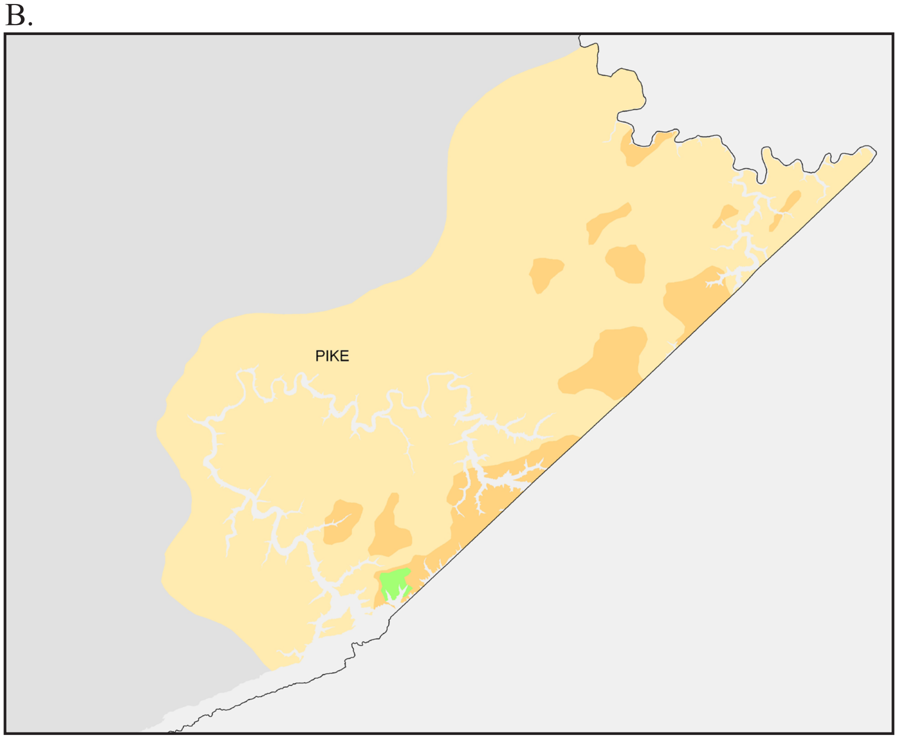
This study assessed most of the principal coal beds of eastern Kentucky possessing significant low-sulfur and low-ash quality—minimum requirements for use in metallurgical applications. The Eastern Kentucky Coal Field is a mature mining region, and these results show the extent of that historical development. Most of the resources of optimal thickness (greater than 42 in.) have been mined, and recent development is in thinner coals that require mining of additional rock, resulting in higher mining and processing costs. The eight beds assessed contained original resources of 11.4 billion tons that are greater than 28 in. thick. Remaining resources are 5.5 billion tons, 48 percent of original resources. However, only 17 percent of remaining coal is thicker than 42 in. If all the remaining resource could be mined at a recovery rate of 50 percent, the resource would provide another 35 years of mining at 70 million tons per year. Given the numerous challenges of access, seam continuity, roof quality, and coal quality, it is unlikely that this level of resource extraction can be achieved.

Although these resources undoubtedly contain deposits with quality suitable for metallurgical applications, this study does not address the specific magnitude of those resources. Given the small quantities of specialty coal required relative to steam-coal consumption, such resources could be available for many decades.

A.



B.



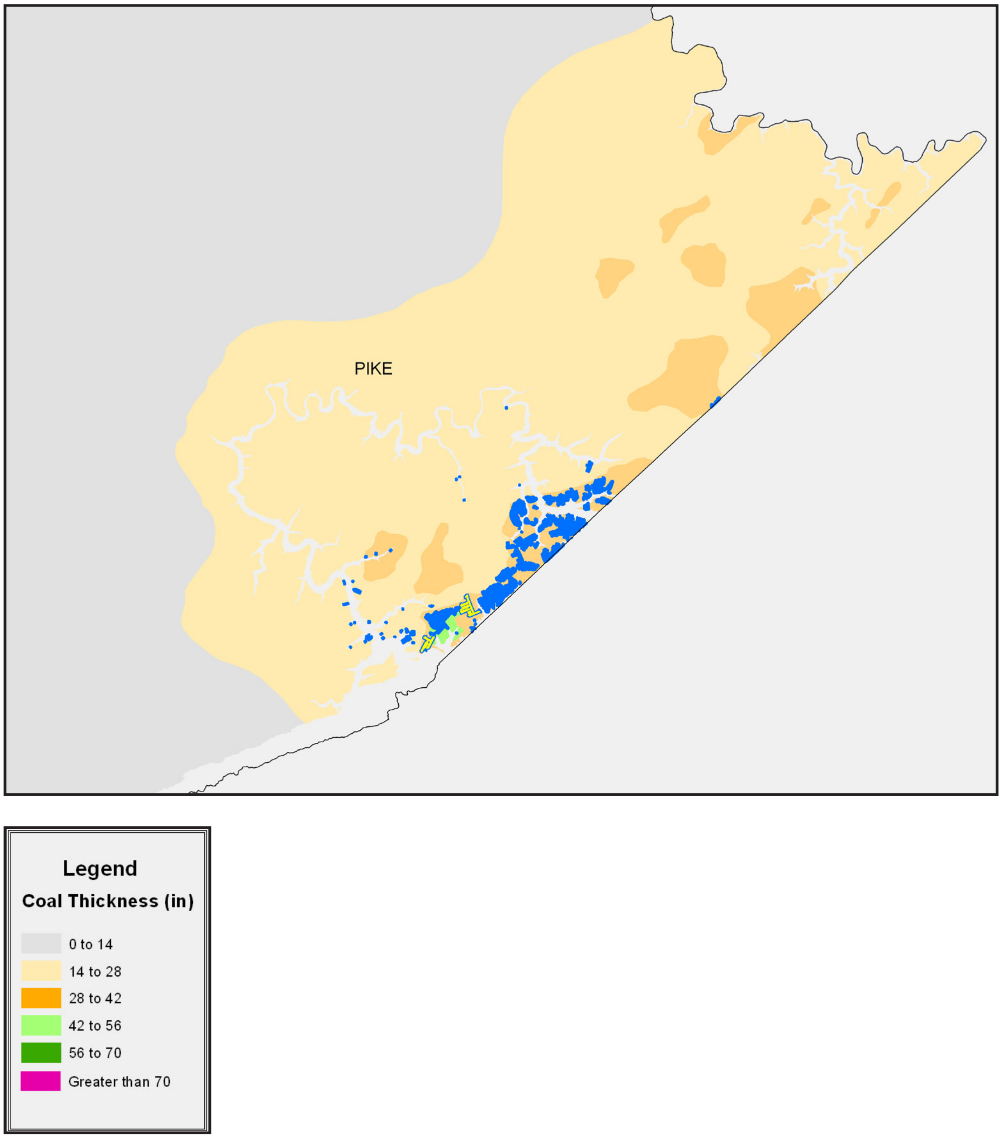
C.

Thickness Range	14–28	28–42	42–56
Original Resources	485,329,977	94,673,670	4,624,860

Totals	> 28	Total
Original Resources	99,298,530	584,628,507

Figure 17. Original coal resources of the Hagy coal in eastern Kentucky. A. Resource areas for the Hagy horizon. B. Original resources of the Hagy coal in southeastern Pike County. C. Estimated original resources of the Hagy coal in southeastern Pike County in short tons.

A.



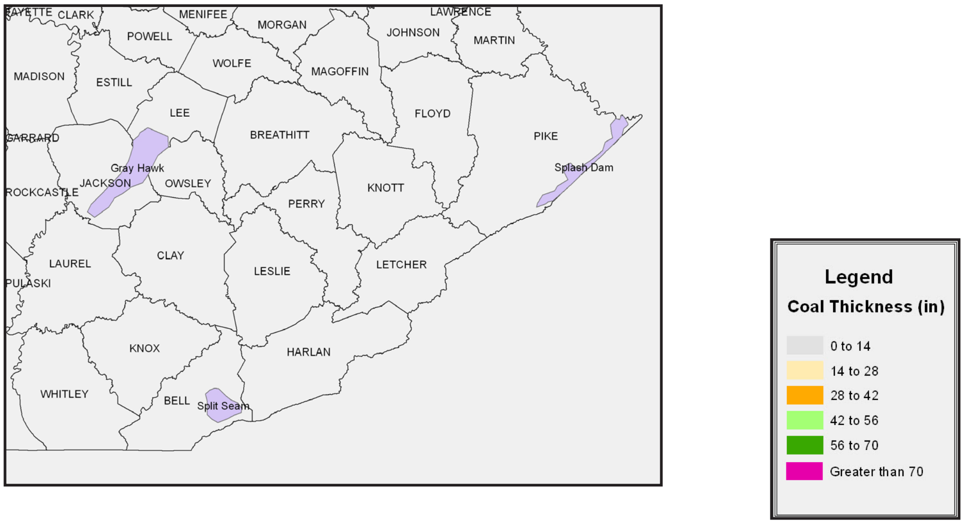
B.

Thickness Range	14–28	28–42	42–56
Mined Resources	1,262,883	16,381,685	2,728,793
Remaining Resources	484,067,094	78,291,985	1,896,067
Remaining Percentage	100	83	41

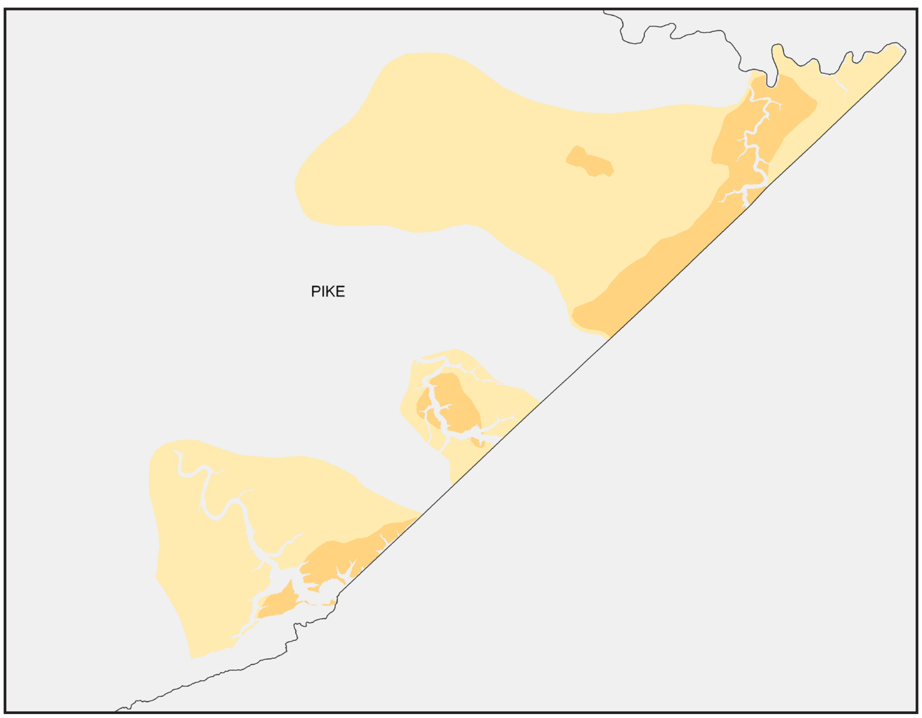
Totals	> 28	Total
Mined Resources	19,110,479	20,373,362
Remaining Resources	80,188,052	564,255,146
Remaining Percentage	81	97

Figure 18. Remaining resources of the Hagy coal in Pike County. Mined-out coal areas shown in dark blue (abandoned) and yellow (active) colors. A. Areal distribution in Pike County. B. 2012 estimated remaining coal resources for the Hagy coal in Pike County in short tons.

A



B.



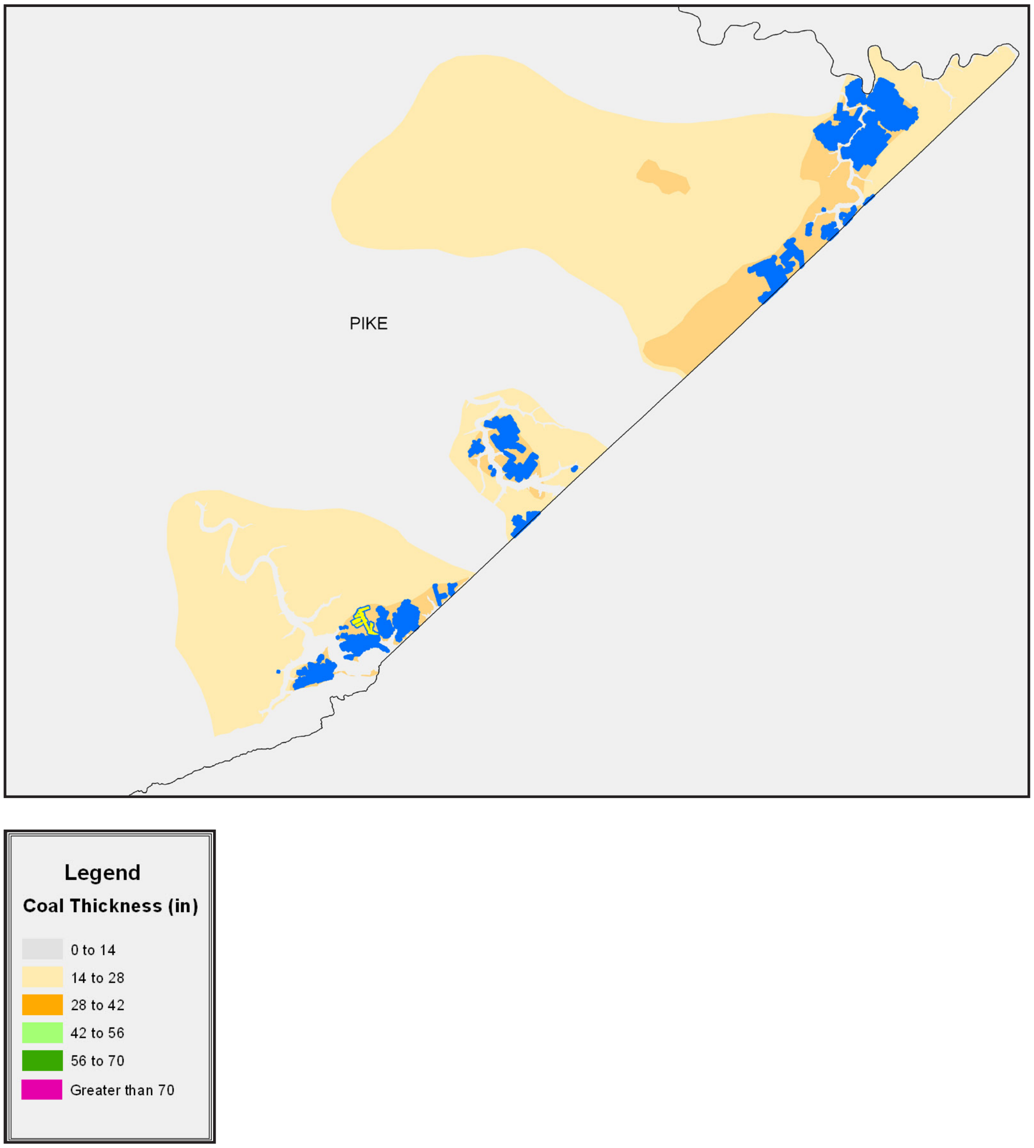
C.

Thickness Range	14–28	28–42
Original Resources	224,765,715	72,960,660

Totals	> 28	Total
Original Resources	72,960,660	297,726,375

Figure 19. Original resources of the Splash Dam coal in eastern Kentucky. A. Resource areas for the three equivalent coal beds for this horizon: Splash Dam, Split Seam, and Gray Hawk. B. Original resources of the Splash Dam coal in southeastern Pike County. C. Estimated original resources of the Splash Dam coal in southeastern Pike County in short tons.

A.



B.

Thickness Range	14–28	28–42
Mined Resources	990,471	32,640,728
Remaining Resources	223,775,244	40,319,932
Remaining Percentage	100	55

Totals	> 28	Total
Mined Resources	32,640,728	33,631,199
Remaining Resources	40,319,932	264,095,176
Remaining Percentage	55	89

Figure 20. Remaining resources of the Splash Dam coal in Pike County. Mined-out coal areas shown in dark blue (abandoned) and yellow (active) colors. A. Areal distribution in Pike County. B. 2012 estimated remaining coal resources for the Splash Dam coal in Pike County in short tons.

Part 2: Metallurgical Coal Characterization

Introduction

Most of the coal produced from eastern Kentucky has been, and continues to be, used by the electric-utility industry because of its low sulfur content. As such, a significant amount of eastern Kentucky coal is so-called "compliance coal," which can be burned without flue-gas desulfurization to control sulfur dioxide (SO_2) emissions. In 2010, coal production from eastern Kentucky was 68.1 million tons, down from the 74.7 million tons of coal produced in 2009 (Energy Information Administration, 2011). Most (86.8 percent) was consumed by electric utilities in 25 states. Although only a small amount (992,000 tons) of eastern Kentucky coal was used domestically for the production of steel, a greater amount (4.5 million tons) was exported to other countries, primarily for use in the metallurgical industry.

As the electric-utility industry continues to expand its use of flue-gas desulfurization (scrubbers), which allows less expensive, high-sulfur coal to be used, and expand its use of natural-gas generation capacity, the demand for low-sulfur eastern Kentucky coal in the electric-utility market is likely to decline. If utilities continue to switch from low-sulfur to higher-sulfur coal, alternative markets such as metallurgical coal will have to be found to keep production levels in eastern Kentucky from drastically decreasing.

Steam Coal

Steam coal is used primarily by the electric-utility industry as a heat source to produce very high-temperature, high-pressure steam to drive turbines with attached generators. Most power plants in Kentucky use coal in pulverized air injection furnaces to accomplish this. In this type of furnace, coal is crushed to a fine powder in large ball mills, and injected into a furnace with preheated air. Inside the furnace, the coal-air mixture ignites, producing a significant amount of heat (typically 2,000 to 2,400°F). The walls of the furnace are lined with a series of water tubes; water enters the furnace and exits as superheated steam.

Coal-quality specifications for steam power plants vary according to facility design. Principal factors are moisture, ash and sulfur content, and calorific (heating) value, although other parameters are important as well. Coal from eastern Kentucky has long been valued by the electric-utility industry as a high-Btu, low-sulfur fuel source, factors that make it "compliance" coal. Compliance coal is coal that emits less than or equal to 1.2 lb of SO_2 per million Btu when burned. All of the coal mined in eastern Kentucky can be used as steam coal, although only part of it qualifies as compliance coal.

Metallurgical Coal

Metallurgical coal has more narrow operational parameters than steam coal. Probably foremost, the coal must be low in ash (less than 10 percent) and sulfur (less than 1 percent) content. Volatile-matter contents should approach those exhibited by a medium-volatile bituminous coal (22 to 31 percent, on a dry, ash-free basis). Volatile matter in coal represents the organic fraction of the coal that is driven off at 950°C under inert (no oxygen) conditions. The volatile-matter contents of eastern Kentucky coals vary from about 35 to 45 percent (dry, ash-free basis). Although this is higher than the ideal amount of volatile matter required for coking coal, some eastern Kentucky coal can be successfully blended with low-volatile coals (coals that have volatile-matter contents between 14 and 22 percent, dry, ash-free basis) to produce a product with medium-volatile characteristics. Blending is a very common practice in the steel industry, since naturally occurring medium-volatile bituminous coal is in short supply worldwide.

Coal to Coke

Coke is produced by heating coal in an oxygen-deficient furnace. As the coal is heated, it becomes soft and plasticizes (in effect, melts). Volatile material is progressively lost as the fluidity of the coal increases. With most coals, this transition occurs between 350 and 450°C. At higher temperatures, the coal progressively loses its fluidity and hardens into a carbon-dense material referred to as coke. Metallurgical coke is produced in contained furnaces (ovens) that vary in size, but typically are 6 m high × 15 m deep × 0.5 m wide. A furnace of this size holds a charge of 15 to 30 tons of coal. The furnace is progressively heated to about 1,000°C for 18 hours, during which the conversion from coal to coke takes place (Crelling, 2008).

Proper recognition and quantification of macerals (coal petrography) in coal is important in the production of high-grade coke. Metallurgical coal must have an acceptable ratio of reactive versus inert components to produce high-grade coke. Reactive components in coal include vitrinite and liptinite macerals. Inert components in coal include inertinite and mineral matter (ash). Calculations are used to generate indices that help predict the quality of the resulting coke. These include composition balance index, strength index, and stability factor.

Materials and Methods

Coal samples were collected from active mines, preparation plants, and outcrop locations. A total of 102 individual samples (87 coal and 15 carbonaceous partings, and high-ash run-of-mine samples) were collected and analyzed for this study. Samples were first crushed to –8 mesh (particle top size, 2.36 mm) and split to obtain four representative subsamples. For selected samples, one subsample was sealed in an airtight container and sent to Coal Tech Petrographic Associates Inc. for Gieseler plasticity, Audibert-Arnu dilatation, and free-swelling index analysis. This was done as quickly as possible, because these analyses are very sensitive to coal oxidation. One subsample was further reduced in size to –20 mesh (particle top size, 850 μ) for petrographic analysis. Another was pulverized to –60 mesh (particle top size, 250 μ) for proximate, calorific value, total carbon/sulfur, and X-ray fluorescence analysis. All unused sample material and petrographic pellets used during the course of this study are stored at the Kentucky Geological Survey, University of Kentucky. Location data are shown in Appendix 1 of this report.

Coal Petrography

Petrographic pellets were constructed by mixing 3 to 5 g of –20 mesh coal with epoxy resin, and then pouring the coal-epoxy mixture into 3.2-cm-diameter phenolic ring forms. Upon hardening, the pellets were ground using 400- and 600-grit papers, and polished using 1.0 and 0.3 μ alumina suspensions and 0.05 μ colloidal silica. Maceral percentages were determined by 500 point counts for each sample. All counts were done on a mineral-matter-free basis. Vitrinite-reflectance measurements are based on 50 individual measurements of collotelinite for each sample, using an oil immersion objective (40X), a reflectance standard of 0.95 Ro, and a peak wavelength transmittance of 546 nm. Random measurements were taken; Ro max was calculated by multiplying the average Ro random measurements by 1.066 (Ting, 1978). All coal petrographic data are shown in Appendix 2 of this report.

Proximate Analysis

Proximate analysis was performed on a Leco TGA 701 thermogravimetric analyzer in accordance with ASTM International test method D-5142-09 (ASTM International, 2009a). The following furnace temperatures were used:

- Moisture: 107°C
- Volatile matter: 950°C
- Ash: 750°C

Percent fixed carbon is calculated by: 100 – (percent moisture + percent volatile matter + percent ash).

Total Carbon and Sulfur

Total carbon/sulfur analysis was performed on a Leco SC-432 carbon sulfur analyzer in accordance with ASTM International test method D-4239-08 (ASTM International, 2009b). Results are presented on a dry (moisture-free) basis.

Calorific Value

Calorific values were determined on a Leco AC-500 bomb calorimeter in accordance with ASTM International test method D-5865-07a (ASTM International, 2009c). Results are presented as Btu/lb, on a dry (moisture-free) basis. All proximate, total carbon/sulfur, and calorific value data are shown in Appendix 3 of this report.

Elemental Analyses

The abundance of 12 major- and minor-element oxides and 18 selected trace elements in coal ash were determined on a Bruker AXS S4 Pioneer X-ray fluorescence (wavelength) unit in accordance with ASTM International test method D-4326-04 (ASTM International, 2009d). This unit was also used to determine the abundance of chlorine in coal samples. All elemental data are reported on a dry (moisture-free) basis. All elemental data are shown in Appendix 4 of this report.

Gieseler Plastometry

The Geiseler plastometer measures the plastic properties of a coal through the use of a constant-torque stirring apparatus. A coal sample is placed in a heating crucible that increases the amount of heat very slowly and regularly (3°C/min). The stirring rod rests inside the coal sample in the crucible. As the coal is heated, it begins to soften and the stirring rod begins to turn. The rate of turning is expressed in dial divisions per minute. At 0.5 ddpm, the initial softening temperature is recorded. With increasing temperature, the coal becomes more fluid, and the stirring rod turns more quickly. The temperature at which the maximum turn rate occurs (maximum fluidity) is recorded as the maximum fluid temperature. With further temperature increase, the coal fluidity begins to decrease, until a point is reached where the stirring rod stops turning, and the coal resolidifies. This point is designated as the solidification temperature. The temperature range from the initial softening point to the solidification point is referred to as the plastic range of the coal. In general, high plastic ranges are preferable for coking coals. Although high-volatile-rank coals generally have high maximum fluidity (high ddpm numbers), a considerable amount of variation is to be expected for coals in this rank range (Zimmerman, 1979; Kevin DeVanney, Coal Tech Petrographics Inc., personal communication, 2011). The ASTM International test method for Gieseler plastometry is D-2639-08 (ASTM International, 2009e).

Audibert-Arnu Dilatation

This test measures the swelling and contraction properties of a coal sample. In practice, powdered coal is inserted into a narrow tube that has calibration markings. Once in place, the coal "pencil" is capped by a steel rod (piston) that slides into the tube directly on top of the coal. As the apparatus is heated, the rod moves. The following readings of rod displacement from the original position are recorded:

- T1: temperature at which the piston has moved 0.5 mm (=softening temperature)
- T2: temperature where the piston reaches its lowest point (=contraction temperature)
- T3: temperature where the piston reaches its highest point (=maximum dilatation).

Maximum dilatation and contraction are recorded in percent. Contraction percentages may be recorded as positive or negative. Audibert-Arnu dilatation methods in this study conform to International Standards Organization test method 349. The ASTM International test method for coal dilatation is D-5515-97 (ASTM International, 2009f). All plasticity and associated metallurgical coal rating data are shown in Appendix 5 of this report.

Results

Mineral Matter and Ash

All coal contains some inorganic material in the form of mineral matter (Table 9). Upon combustion, mineral matter is converted to ash. Although coal mineral matter and coal ash are closely related, they are not identical terms. This is the result of certain mineral phases, namely sulfides

Table 9. Summary of basic coal-quality data (n=87).

Parameter	*Average*	*Maximum*	*Minimum*
Ash (%, dry)	9.8	41.6	1.2
Total sulfur (%, dry)	1.4	5.2	0.3
Volatile matter (%, dry)	36.5	44.5	23.6
Fixed carbon (%, dry)	54.6	63.6	31.9
Total carbon (%, dry)	76.3	90.6	47.7
Calorific value (Btu/lb, dry)	13,617	15,001	11,236

and carbonates, being destroyed during the high-temperature (750°F) ashing process. Thus, coal has a mineral-matter content and a corresponding ash yield. Mineral-matter content can be calculated from ash-yield data using the Parr formula, where:

mineral matter = (1.08 × ash) + (0.55 × total sulfur).

Ash yields are vitally important in the coke-making process. Coal beds must generally contain less than 10 percent ash to be considered as candidates for metallurgical coal. Lower ash-yield values (less than 8 percent) are preferred. Achieving a low-ash product is a two-fold process. Coals for metallurgical consideration should be naturally low in ash. Further reduction is possible through coal-preparation (beneficiation) procedures. Increasingly thin coal (less than 40 in.) being mined in eastern Kentucky has resulted in some portion of the adjacent roof or floor rock being mined with the coal, in order to provide sufficient operating room within the mine. As such, virtually all eastern Kentucky coal that is mined underground is beneficiated post-mining. Data acquired during the course of the present work indicates that the run-of-mine product coming out of active mines routinely contains 20 to 50 percent ash. By contrast, washed coal, collected from preparation facilities, is routinely less than 10 percent in ash.

Sulfur

Sulfur in coal occurs as pyritic sulfur, sulfatic sulfur, and organic sulfur. The sum of these components equals total sulfur content (i.e., total sulfur = pyritic sulfur + sulfatic sulfur + organic sulfur). The sulfur content of metallurgical coal is critical, because an upper limit of about 1.3 percent (dry basis) is considered acceptable; sulfur contents less than 1.0 percent are preferable (Kevin DeVanney, Coal Tech Petrographics Inc., personal communication, 2011). Although the coal beds sampled for this study were selected in part because of their overall low ash and sulfur contents, variability between and within individual beds can be considerable. For example, 19 samples of Upper Elkhorn No. 3 coal collected and analyzed for this study showed a range of total sulfur content from 0.72 to 5.16 percent (average, 2.0 percent, raw coal, dry basis; n = 19). At one Upper Elkhorn No. 3 location, closely spaced bench samples (from top to base) were collected. The distribution of sulfur (range, 0.63 to 8.39 percent) at this location is highly disparate:

Depth (in.)	*% Total S*
0.0–0.7 (top of coal)	8.39
0.7–1.2	0.63
1.2–1.7	0.67
1.7–2.3	0.85
2.3–3.3 (parting)	0.06
3.3–3.8	1.42
3.8–4.3 (base of coal)	0.79
4.3 (full-channel sample)	1.97
beneficiated samples (average, 4)	1.25

This type of sulfur distribution in eastern Kentucky coal is not atypical, with the top parts of the coal often having higher sulfur contents than the rest of the bed. Because all of the coal, and some roof or floor rock, must be removed in the mining process, coal-preparation techniques are relied on to reduce ash and sulfur contents. An analysis of four washed-coal fractions from the mine where bench-scale samples were collected indicated an average total sulfur content of 1.25 percent for the washed coal. This represents a reduction of sulfur by about 37 percent.

Although coal preparation is effective in removing some sulfur from the coal, petrographic analysis indicates that much of the sulfur in the tested samples occurs as very small grains of pyrite (less than 10 μ), finely disseminated throughout the organic matrix. Although the specific gravities of pyrite and coal are disparate (coal has a specific gravity less than or equal to 1.5; pyrite has a specific gravity of 5.0), this type of distribution makes removal through coal preparation extremely difficult (and costly). Since sulfur in coal (both organic and inorganic sulfur) is dominantly associated with the organic fraction of coal, the progressive removal of sulfur during the beneficiation process also results in a progressive loss of coal product (i.e., decreased recovery).

Elements in Coal Ash

Selected samples were analyzed for 12 element oxides and 18 trace elements (Table 10). For metallurgical coals, the relative proportion of acid elements to basic elements is an important factor. Acidic elements include aluminum (as Al_2O_3), silicon (as SiO_2), and titanium (as TiO_2). Basic elements include calcium (as CaO), iron (as Fe_2O_3), magne-

Table 10. Summary of major-element oxide concentrations in coal ash (n=45).

Parameter	Average	Maximum	Minimum
Aluminum oxide (Al_2O_3)	27.7	34.5	12.4
Barium oxide (BaO)	0.1	0.4	0.1
Calcium oxide (CaO)	2.6	8.1	0.8
Ferric oxide (Fe_2O_3)	11.4	48.5	3.0
Magnesium oxide (MgO)	1.0	2.5	0.6
Phosphorus pentoxide (P_2O_5)	0.2	0.9	0.1
Potassium oxide (K_2O)	2.3	3.4	0.8
Silicon dioxide (SiO_2)	47.9	58.2	22.5
Sodium oxide (Na_2O)	0.6	2.2	0.2
Strontium oxide (SrO)	0.2	0.8	0.0
Sulfur trioxide (SO_3)	2.3	8.8	0.3
Titanium dioxide (TiO_2)	1.4	2.1	0.5
TOTAL	97.6	99.1	95.8
Acid/base ratio	4.9	12.3	0.6
P in ash	0.04	0.2	0.02

sium (as MgO), potassium (as K_2O), and sodium (as Na_2O). Basic elements, in particular, have been found to have a serious impact on the coke-making process, causing decreased burden permeability and lower productivity. For these reasons, high acid/base ratios are preferable. Values greater than or equal to 3.5 are cited as acceptable; values greater than or equal to 6.0 are considered preferable (Kevin DeVanney, Coal Tech Petrographics Inc., personal communication, 2011). Samples that were analyzed for element oxide concentrations (n=45) for this study had an average acid/base ratio of 4.9 (range, 0.6 to 12.3). Phosphorus is another element of concern, because it has an adverse effect on iron, and ultimately, steel quality. Acceptable upper limits of 0.03 to 0.06 percent have been cited by Gray and others (1978) and Zimmerman (1979). Samples collected for this study had an average phosphorus content of 0.04 percent (range, 0.02 to 0.2). Trace elements may be of concern, though mainly from an environmental standpoint.

Coal Petrology

Coal, though homogenous in macroscopic appearance, is actually a very complex mixture of organic components, called macerals, and inorganic components (mineral matter). Macerals are analogous to the minerals that make up rocks, and are classified according to their level of reflectance and morphology when viewed in reflected light. Figures 21 through 24 provide examples (photographs) of coal macerals. The organic components of bituminous coal follow.

Vitrinite. Vitrinite is usually the most abundant maceral in eastern Kentucky coals, commonly comprising 70 percent or more of the coal. Vitrinite represents the coalified parts of ancient vegetation that were woody (e.g., trunks, stems, and roots) or wood-like (e.g., bark). Three broad subgroups of vitrinite are recognized—telovitrinite, detrovitrinite, and gelovitrinite—depending on how well the original plant material was preserved. Well-preserved woody parts of plants usually produce telovitrinite; more poorly preserved parts generally produce detrovitrinite or gelovitrinite. Vitrinite maceral terminology is as follows:

- vitrinite
- telovitrinite
  - telinite
  - collotelinite
- detrovitrinite
  - collodetrinite
  - vitrodetrinite
- gelovitrinite
  - gelinite
  - corpogelinite

In reflected light, with an oil-immersion objective, vitrinite group macerals are collectively distinguished by their medium gray color and reflectance. Individual maceral identification is based on morphological characteristics. As a group, vitrinite represents one of the reactive components of metallurgical coal. Coal samples (samples with ash yields less than 50 percent, dry basis) analyzed in this study (Table 11) had an average vitrinite content of 72.0 percent, and ranged from 27.6 to 93.2 percent (mineral-matter-free basis). The majority of the vitrinite occurred as telovitrinite, with

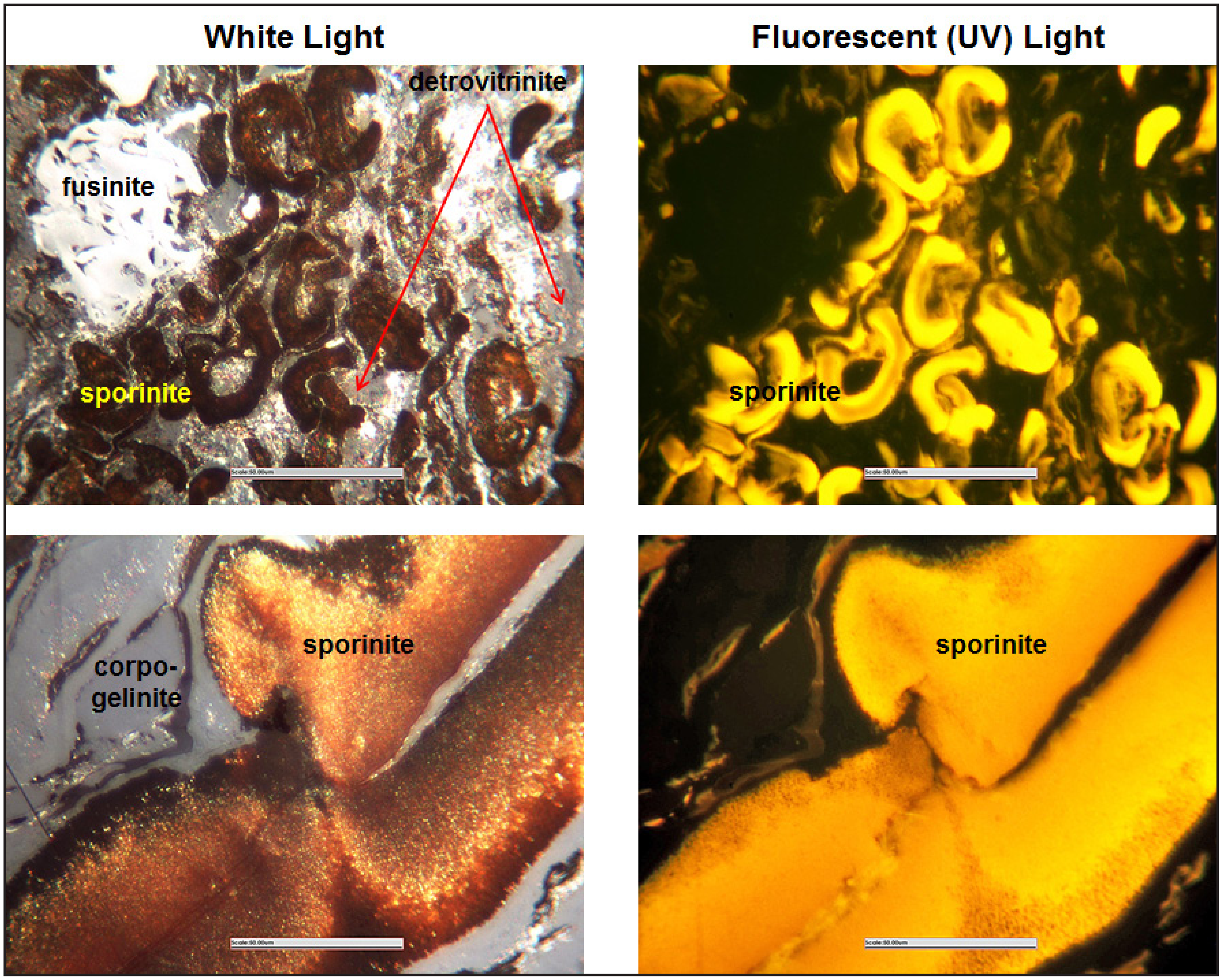


Figure 21. Examples of macerals in eastern Kentucky coal (1 of 4). The scale bar in each photo is 50 μ.

the average telovitrinite/(detrovitrinite + gelovitrinite) ratio being 3.1 (range, 0.4 to 7.5).

Liptinite. Liptinite group macerals include spores, pollen, cuticles, resins, and other hydrogen-rich plant components. They are recognized by their low reflectance, dark brown to black color, characteristic morphology, and fluorescence in ultraviolet light. Liptinite macerals in coal samples averaged 12.1 percent and ranged from 5.2 to 30.4 percent (mineral-matter-free basis). Liptinite, like vitrinite, is a reactive component in coal.

Inertinite. Inertinite macerals in coal represent plant materials that have become oxidized, either through charring (wildfire) or biodegradation. In reflected light, inertinite macerals display a higher level of reflectance than either vitrinite or liptinite macerals, appearing white (as opposed to gray/vitrinite or brown-black/liptinite). Individual maceral identification is largely morphology-based. Inertinite macerals in coal samples averaged 15.9 percent, and ranged from 1.6 to 42.0 percent (mineral-matter-free basis).

One inertinite maceral, semifusinite, is unique in that it has a reflectance in between that of vitrinite and other inertinite macerals. In metallurgical coal, semifusinite is treated as being partially reactive and partially inert. All other inertinites are classified as being inerts. Although the amount of semifusinite considered to be reactive in the coke production process varies among workers, a one-third reactive to two-thirds inert ratio is commonly

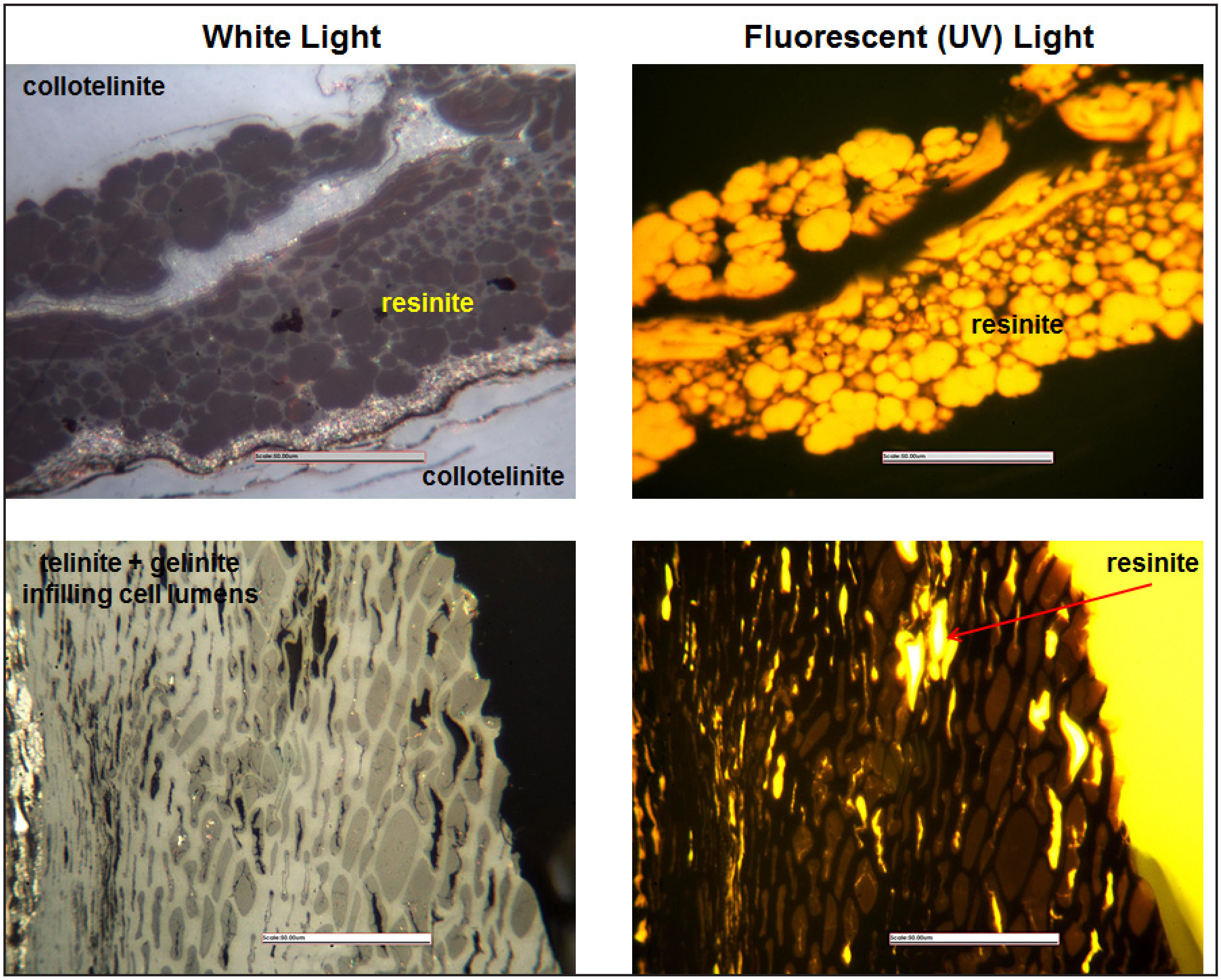


Figure 22. Examples of macerals in eastern Kentucky coal (2 of 4). The scale bar in each photo is 50 µ.

used (Gray and others, 1978; Bustin and others, 1983). This ratio has been adopted in the present work.

The following petrographic rating factors were calculated for 20 samples that were tested for plastic properties (Gieseler plastometry and Audibert-Arnu dilatation):

- composition balance index
- strength index
- rank index
- predicted coke strength after reaction.

Several techniques have been developed to use coal petrographic data to determine the quality of coke that a particular coal or blend of coals will produce; these have been summarized in Mackowski (1977). All of the available published techniques share two common premises. The first is that for each particular rank of coal, expressed as V-types, there is an optimal mix of reactive components relative to inert components. The second premise recognizes that optimal mix calculations or ratios vary with rank. Reactive components include vitrinite, liptinite, and some semi-inertinite (usually semifusinite). Inert components include inertinite, mineral matter, and some semi-inertinite. The optimal mix has been compared to the mixing of concrete (Schapiro and others, 1961), whereby the reactive components act as the cement, and the inert components serve as the sand or gravel. In this study, the method of Schapiro and others (1961)

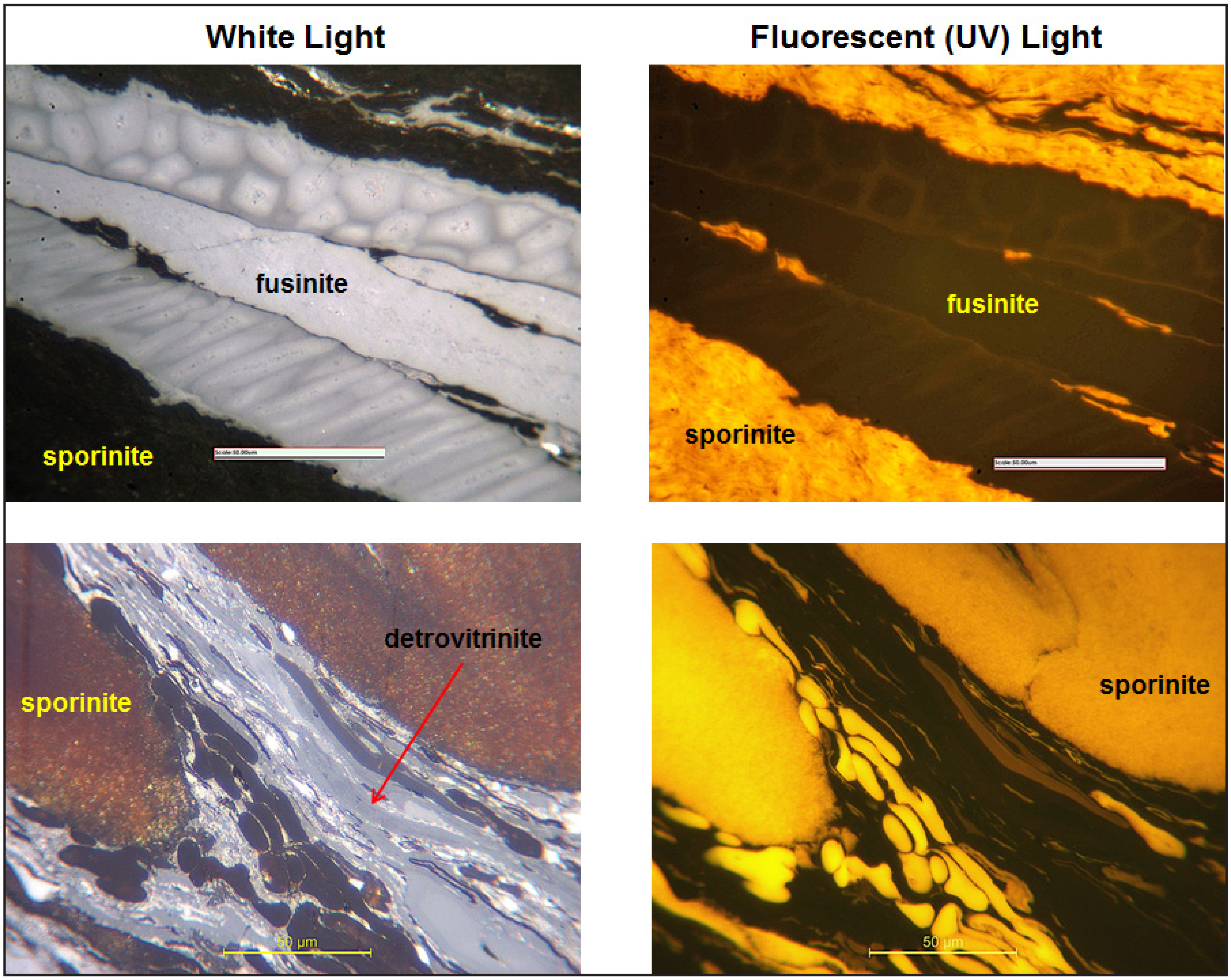


Figure 23. Examples of macerals in eastern Kentucky coal (3 of 4). The scale bar in each photo is 50 µ.

and Schapiro and Gray (1964) has been followed. In this method, a composition balance index is calculated, with the ideal CBI being 1.0. Coals with a CBI greater than 1.0 are oversaturated with respect to inert components, and coals with a CBI less than 1.0 are undersaturated in inert components (Bustin and others, 1983). A second index, referred to as strength or rank index, is also determined. This index is a sum of the strength factors for each vitrinite class (V-type), related to the amount of inert components in the coal. Both of these indices are based on the analysis of literally hundreds of coal and coke samples for U.S. Steel Corp. The two indices are expressed as follows:

1. $CBI = \text{total inerts}/(R_1/M_1 + R_2/M_2 \ldots R_n/M_n)$

where R_1, R_2, R_n = volume percent of reactive components in V-types and M_1, M_2, M_n = the optimal ratio of reactives to inerts in V-types

2. $SI = (K_1 \times P_1) + (K_2 \times P_2) \ldots (K_n \times P_n)/\text{total reactives}$

where K_1, K_2, K_n = strength indices of reactive V-types and P_1, P_2, P_n = volume percent of total reactives.

Results indicate an average CBI of 0.72 (range, 0.23 to 1.11) and average SI of 3.4 (range, 3.0 to 3.8). These two indices can then be used to predict a coke strength after reaction value. The area of optimum metallurgical coke properties is a relatively small part of the total with limited SI and CBI ranges. This is one reason why blending coals for coke production is a common practice, since very few

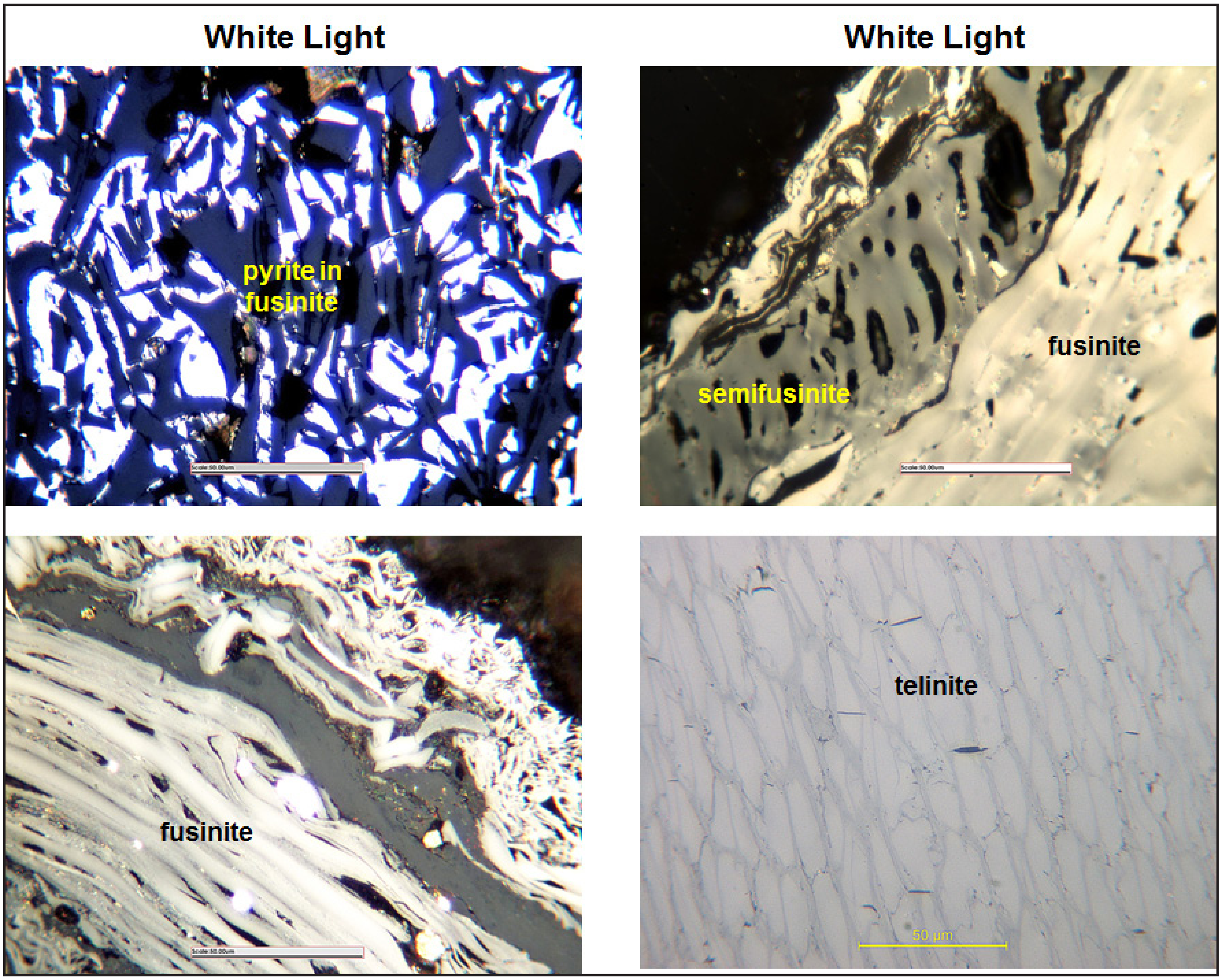


Figure 24. Examples of macerals in eastern Kentucky coal (4 of 4). The scale bar in each photo is 50 µ.

Table 11. Summary of coal petrographic (maceral) parameters. Reported values are in percent, on a mineral-matter-free basis.

Parameter	*Average*	*Maximum*	*Minimum*
Vitrinite	72.0	93.2	27.6
Telovitrinite	53.3	74.8	7.2
Detrovitrinite + gelovitrinite	18.7	30.0	8.0
Telovitrinite/ (detrovitrinite + gelovitrinite)	3.1	7.5	0.4
Liptinite	12.1	30.4	5.2
Inertinite	15.9	42.0	1.6
Ro maximum	0.87	0.98	0.77

coals fit into this narrow area by themselves. Coals analyzed in this study had an average predicted coke strength after reaction of 40.1 (range, 18 to 51).

Metallurgical Coal Applicability

No single characteristic qualifies or disqualifies a coal as being metallurgical grade. A general ratings chart for high-volatile bituminous coal was obtained from Coal Tech Petrographic Associates Inc., the company that performed Gieseler plasticity and Audibert-Arnu dilatation analyses on selected samples for this study. With reference to that chart (Table 12), Table 13 shows observations for 20 samples that had Geiseler plasticity and Audibert-Arnu dilatation analyses performed, in addition to other analyses.

Comparison of the range of values obtained with acceptable limits indicates that many of the tested coals have several favorable parameters for metallurgical coal application, but occur on the

Table 12. General quality ratings for high-volatile coking coals. The values should be regarded as approximate, and may vary somewhat depending on individual coke-producing equipment and coal requirements. From Coal Tech Petrographic Associates Inc. (2011).

Property	*Poor/ Marginal*	*Fair/Good*	*Very Good/ Excellent*
VM daf	≥40	>34 to ≤39.9	31–34
Ash	≥8	6 to 7.9	<6
Sulfur	≥1.3	>0.8 to <1.3	≤0.8
Oxidation test	<87	87 to 94	≥94
Free-swelling index	≤6	≥6.5 to <8	≥8
Fluidity	< 5,000	≥5,000 to <20,000	≥20,000
Plastic range	≤75	>75 to <95	≥95
Dilatation	<100	≥100 to <180	≥180
Sole oven	<–12	–12 to –20	>–20
HGI	<42	≥42 to <55	≥55 to <80
Ash fusion (st.)	≤2,250°F	>2,250 to ≤ 2,575°F	≥2,580°F
Ash A/B ratio	<3.5	3.5 to 5.9	≥6.0
P_2O_5 % in ash	≥1.2	>0.5 to <1.2	≤0.5
Reflectance	≤0.82	>0.82 to ≤0.98	>0.98
Inert content	>35 and <15	15 to 20, 30 to 35	>20 to <30
CSR potential	<45	≥45 to 56	>56

lower end of the acceptable rank range (average Ro max = 0.89). Most eastern Kentucky coals do not achieve sufficient rank to be considered as coking coals individually, but can probably serve well in a blend with higher-rank coals. Collectively, low-ash, low-sulfur coal with the highest rank possible probably has the best potential for metallurgical application in this regard.

Although the composition-balance indices generated from this study indicate that the organic compositions (balance of reactive and inert components) of eastern Kentucky coals are generally favorable for metallurgical applications, the results also show that sulfur variability will probably be the critical factor for mining companies looking to sell coal on the metallurgical market. Analysis

Table 13. Summary of coking-coal parameters for 20 selected samples.

Parameter	*Average*	*Maximum*	*Minimum*
Volatile matter (%, dry, ash-free)	39.9	42.3	36.3
Ash yield (dry)	6.6	11.4	1.2
Total sulfur content (dry)	1.1	2.0	0.7
Free swelling index	5.2	8.0	2.0
Fluidity (dial divisions per minute)	6,803	30,000	4.0
Plastic range	69	93	40
Dilatation	67	194	2
Ash acid/base ratio	5.7	12.3	1.9
P_2O_5 in ash	0.21	0.91	0.11
Vitrinite reflectance (Ro max)	0.89	0.98	0.81
Inert content	20.3	28.3	8.2
CSR potential	40.3	51	18

from this study indicates a wide variation in sulfur content; personal communication with coal company personnel reinforces this finding. Sulfur contents often vary from less than 1 percent to greater than 2 percent across areas covered by individual mines. Perhaps more problematic is that much of the sulfur occurs as very small grains (less than 10 μ) of pyrite, which are randomly disseminated throughout the organic matrix. This type of distribution makes sulfur reduction through coal beneficiation extremely difficult.

Pulverized Coal Injection Coal

Declining supply of quality coking coal and escalating prices of coke have led iron and steel manufacturers to seek other carbon-based products to reduce the consumption of the more expensive coal to produce coke. One solution is the technology of injecting pulverized coal into a blast furnace as an auxiliary fuel to reduce the amount of coke consumed, thereby reducing operating costs in the production of pig iron and crude steel. Coal used for this purpose is termed pulverized coal injection coal. The technology injects very fine particles of coal at high rates into the chamber of the blast furnace as a fuel. Most modern furnaces are equipped with a coal-grinding and coal-injection system. Typically, 1.0 ton of PCI coal can replace up to 1.5 tons of more expensive coking coal.

The specifications of PCI coal are similar to those of high-Btu compliance steam coal, of which eastern Kentucky is a major supplier. The major limiting factor with using eastern Kentucky coal for PCI applications is principally the same as that for using eastern Kentucky coal as a metallurgical coal/coal blend: sulfur content and variability.

Summary

Coal is used by the metallurgical industry to produce coke. Coke, a very carbon-dense material, serves principally as a reducing agent when heated with iron ore to produce steel. This contrasts with steam coal, which is burned to produce electricity. Metallurgical coal has more narrow operating parameters than steam coal. The coal must be low in ash (less than 10 percent) and sulfur (less than 1.0 percent), and should have a volatile-matter content between 22 and 31 percent (dry, ash-free basis). The organic components of the coal should also have an acceptable mixture of reactive and inert components; a mixture of 70 to 80 percent reactives and 20 to 30 percent inerts is preferable. Furthermore, the rank (level of coal metamorphism) of the coal should be greater than or equal to 0.82 Ro max, with higher reflectance values (greater than or equal to 0.95 Ro max) being preferred. Metallurgical coals in the high-volatile bituminous rank range should exhibit broad ranges of plasticity (greater than or equal to 75) and dilatation (greater than or equal to 100). Ash acid/base ratios should exceed 3.5, and the phosphorus content of the ash should be minimal (less than or equal to 0.06 percent). Predicted coal strength after reaction values should be greater than or equal to 45.

Many eastern Kentucky coals examined during the course of this study (n=87) were found to be low in ash yield (average, 9.8 percent; range, 1.2 to 41.6 percent, dry basis); many were also low in sulfur content (average, 1.4 percent; range, 0.3 to 5.2 percent, dry basis). In higher-sulfur coal samples, much of the sulfur was found to exist as very small (less than 10 μ), highly disseminated pyrite grains. These are not easily removed by coal-preparation techniques, making the identification of low-sulfur mining resources prior to extraction very important. Volatile-matter contents of the eastern Kentucky coal samples analyzed ranged between 35.8 and 47.0 percent (average, 40.0 percent, dry, ash-free basis), which exceeds the preferred upper limit of 31 percent.

The average plastic range of 20 selected samples was 69 (range, 40 to 94), with an average dilatation of 67 (range, 2 to 194). Both of these average values fall below the acceptable lower limits of 75 and 100, respectively. Average ash acid/base ratios were 5.7 (range, 1.9 to 12.3); average phosphorus contents were 0.05 (range, 0.02 to 0.2). Both of these average values are within acceptable limits (greater than 3.5 and less than 0.06, respectively) for these parameters. The average reflectance of coal samples was 0.89 Ro max, with an observed range between 0.81 and 0.98. Most of the samples had reflectance values greater than 0.82 Ro max, the lower practical limit, but only a few were greater than or equal to 0.95 Ro max. Reactive components in the 20 selected samples averaged 79.7 percent (range, 71.7 to 91.8 percent), and inert components averaged 20.3 percent (range, 8.2 to 28.3 percent). Therefore, the petrographic composition of the coal samples is within acceptable limits (inerts content between 15 and 35 percent). Predicted coke strength after reaction values averaged 40.3, and ranged from 18 to 51, which is below the accepted limit of 45.

Although many parameters (on an average basis) for the analyzed coals fall outside limitations proposed for coking-coal consideration, no single parameter qualifies or disqualifies a coal from metallurgical consideration. Results indicate that many eastern Kentucky coals can be used as metallurgical feedstock, though primarily through blending with other (mainly low-volatile bituminous) coals. Furthermore, low-ash, low-sulfur eastern Kentucky coal appears to be of prime consideration as pulverized coal injection coal. Because PCI coal is primarily used as a heat source, the fact that many samples analyzed during the course of this study had calorific values in excess of 14,000 Btu/lb (average, 13,617; range, 11,236 to 15,001, dry basis), indicates that many eastern Kentucky coals have application to the PCI coal market.

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Appendix 1: Sample Information

Sample ID	*2975*	*2976*	*2977*	*2978*	*2979*	*2980*	*2988*
Coal bed	Lower Elkhorn	Lower Elkhorn	Lower Elkhorn	Lower Elkhorn	Lower Elkhorn	Lower Elkhorn	Van Lear
Sample type	full channel, 52.8 in.	preparation plant stoker	preparation plant composite	preparation plant coarse	preparation plant medium	preparation plant fine	full channel, 51.6”
Sample area	mine	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	mine
Latitude	37.591467	37.593697	37.593697	37.593697	37.593697	37.593697	37.706636
Longitude	–82.492935	–82.487711	–82.487711	–82.487711	–82.487711	–82.487711	–82.510917
County	Pike	Pike	Pike	Pike	Pike	Pike	Martin
Quadrangle	Meta	Meta	Meta	Meta	Meta	Meta	Thomas
Company	Alliance	Alliance	Alliance	Alliance	Alliance	Alliance	Alliance
Sample ID	*2989*	*2990*	*2992*	*2993*	*3003*	*3004*	*3005*
Coal bed	Van Lear	Van Lear	Van Lear	Van Lear	Fire Clay	Fire Clay	Fire Clay
Sample type	preparation plant stoker	preparation plant composite	preparation plant medium	preparation plant fine	full channel, 40.2 in.	preparation plant coarse	preparation plant medium
Sample area	preparation plant	preparation plant	preparation plant	preparation plant	mine	preparation plant	preparation plant
Latitude	37.765381	37.765381	37.765381	37.765381	36.978961	36.978961	36.978961
Longitude	–82.485239	–82.485239	–82.485239	–82.485239	–83.406839	–83.406839	–83.406839
County	Martin	Martin	Martin	Martin	Leslie	Leslie	Leslie
Quadrangle	Kermit	Kermit	Kermit	Kermit	Helton	Helton	Helton
Company	Alliance	Alliance	Alliance	Alliance	James River	James River	James River
Sample ID	*3006*	*3007*	*3023*	*3024*	*3025*	*3026*	*3027*
Coal bed	Fire Clay	Fire Clay	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3
Sample type	preparation plant fine	Pp composite	run of mine	preparation plant composite	run of mine	preparation plant coarse	preparation plant composite
Sample area	preparation plant	preparation plant	mine	preparation plant	mine	preparation plant	preparation plant
Latitude	36.978961	36.978961	37.207894	37.110175	37.026658	37.063708	37.063708
Longitude	–83.406839	–83.406839	–82.974292	–82.933475	–83.128292	–83.128292	–83.128292
County	Leslie	Leslie	Knott	Letcher	Perry	Perry	Perry
Quadrangle	Helton	Helton	Blackey	Roxana	Leatherwood	Leatherwood	Leatherwood
Company	James River	James River	James River	James River	James River	James River	James River

Sample ID	3028	3029	3030	3031	3032	3033	3034
Coal bed	Fire Clay	Amburgy	Upper Elkhorn No. 3	Amburgy	Upper Elkhorn No. 3 + Hazard No. 5a	Jellico	Jellico
Sample type	preparation plant composite	run of mine	run of mine	preparation plant composite	preparation plant composite	bench 1, 26.4 in.	parting, 16.7 in.
Sample area	preparation plant	mine	mine	preparation plant	preparation plant	mine	mine
Latitude	37.063708	37.221469	37.221469	37.226036	37.226036	36.602700	36.602700
Longitude	–83.128292	–83.152522	–83.152522	–83.186283	–83.186283	83.790000	83.790000
County	Perry	Perry	Perry	Perry	Perry	Bell	Bell
Quadrangle	Leatherwood	Hazard South	Hazard South	Hazard South	Hazard South	Fork Ridge	Fork Ridge
Company	James River	Teco	Teco	Teco	Teco	James River	James River
Sample ID	3035	3036	3037	3038	3039	3040	3041
Coal bed	Jellico	Jellico	Jellico	Jellico	Pond Creek leader	Pond Creek leader	Lower Elkhorn
Sample type	bench 2, 18.9 in.	rider bench, 34 in.	preparation plant coarse	preparation plant fine	top bench, 31 in.	bottom bench, 4 in.	full channel, 56.5 in.
Sample area	mine	mine	preparation plant	preparation plant	outcrop	outcrop	outcrop
Latitude	36.602700	36.602700	36.614133	36.614133	37.139633	37.139633	37.595233
Longitude	83.790000	83.790000	83.794622	83.794622	–82.276378	–82.276378	–82.280739
County	Bell	Bell	Bell	Bell	Pike	Pike	Pike
Quadrangle	Fork Ridge	Fork Ridge	Fork Ridge	Fork Ridge	Williamson	Williamson	Belfry
Company	James River	James River	James River	James River			
Sample ID	3042	3043	3044	3045	3046	3050	3051
Coal bed	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3 bench 1	Upper Elkhorn No. 3 bench 2
Sample type	full channel, 42.7 in.	bench 1, 17.7 in.	bench 2, 6.3 in.	bench 3, 8.1 in.	bench 4, 10.6 in.	bench 1, 27.6 in.	bench 2, 8.3 in.
Sample area	outcrop	outcrop	outcrop	outcrop	outcrop	outcrop	outcrop
Latitude	37.605892	37.605892	37.605892	37.605892	37.605892	37.605892	37.619217
Longitude	–82.313989	–82.313989	–82.313989	–82.313989	–82.313989	–82.313989	–82.347525
County	Pike	Pike	Pike	Pike	Pike	Pike	Pike
Quadrangle	Belfry	Belfry	Belfry	Belfry	Belfry	Belfry	Belfry
Company							

Sample ID	3052	3053	3054	3055	3056	3057	3058
Coal bed	Upper Elkhorn No. 3 bench 3	Upper Elkhorn No. 3 bench 4	Upper Elkhorn No. 3 bench 1a	Upper Elkhorn No. 3 bench 1b	Upper Elkhorn No. 3 bench 1c	Jellico cannel	Fire Clay
Sample type	bench 3, 8.1 in.	bench 4, 7.6 in.	bench 1a, 16.4 in.	bench 1b, 11.6”	parting 1c, 1.6 in.	1.8 in.	full channel, 48.4 in.
Sample area	outcrop	outcrop	outcrop	outcrop	outcrop	outcrop	outcrop
Latitude	37.619217	37.619217	37.619217	37.619217	37.619217	36.602700	37.24355
Longitude	–82.347525	–82.347525	–82.347525	–82.347525	–82.347525	83.790000	–83.184558
County	Pike	Pike	Pike	Pike	Pike	Bell	Perry
Quadrangle	Belfry	Belfry	Belfry	Belfry	Belfry	Fork Ridge	Hazard South
Company							
Sample ID	3059	3060	3061	3062	3063	3064	3065
Coal bed	Manchester	Blue Gem	Alma	Alma	Alma	Alma	Alma
Sample type	full channel, 24.8 in.	full channel, 23.4 in.	bench 1, 28.7 in.	bench 2, 12.1”	bench 3, 25.2 in.	preparation plant stoker	preparation plant medium
Sample area	outcrop	outcrop	mine	mine	mine	preparation plant	preparation plant
Latitude	37.139633	36.786931	37.736178	37.736178	37.736178	37.736178	37.736178
Longitude	–83.767467	–84.169958	–82.650133	–82.650133	–82.650133	–82.616800	–82.616800
County	Clay	Whitley	Johnson	Johnson	Johnson	Martin	Martin
Quadrangle	Manchester	Wofford	Lancer	Lancer	Lancer	Thomas	Thomas
Company			Czar Coal	Czar Coal	Czar Coal	Czar Coal	Czar Coal
Sample ID	3066	3067	3068	3069	3070	3071	3072
Coal bed	Alma	Alma	Williamson + Fire Clay rider	PCK + Williamson + Fire Clay rider	Williamson + Cedar Grove	Fire Clay rider + Coalburg	Glamorgan + Upper Elkhorn No. 3
Sample type	preparation plant fine	preparation plant coarse 1	preparation plant composite	preparation plant composite	preparation plant composite	preparation plant composite	preparation plant composite
Sample area	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant
Latitude	37.736178	37.736178	37.624167	37.624167	37.624167	37.624167	37.554817
Longitude	–82.616800	–82.616800	–82.361233	–82.361233	–82.361233	–82.361233	–82.414633
County	Martin	Martin	Pike	Pike	Pike	Pike	Pike
Quadrangle	Thomas	Thomas	Belfry	Belfry	Belfry	Belfry	Meta
Company	Czar Coal	Czar Coal	Sydney Coal	Sydney Coal	Sydney Coal	Sydney Coal	James River

Sample ID	*3073*	*3074*	*3075*	*3076*	*3077*	*3078*	*3079*
Coal bed	Glamorgan + Upper Elkhorn No. 3	Glamorgan + Upper Elkhorn No. 2	Upper Elkhorn No. 2	Upper Elkhorn No. 3	Glamorgan	Glamorgan	Glamorgan
Sample type	preparation plant stoker	preparation plant composite	run of mine	run of mine	run of mine	run of mine	preparation plant composite
Sample area	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant
Latitude	37.554817	37.554817	37.554817	37.554817	37.554817	37.344233	37.344233
Longitude	–82.414633	–82.414633	–82.414633	–82.414633	–82.414633	–82.544228	–82.544228
County	Pike	Pike	Pike	Pike	Pike	Pike	Pike
Quadrangle	Meta	Meta	Meta	Meta	Meta	Dorton	Dorton
Company	James River	James River	James River	James River	James River	CAM Mining	CAM Mining
Sample ID	*3080*	*3081*	*3082*	*3083*	*3084*	*3085*	*3086*
Coal bed	Jellico	Jellico	Blue Gem	Blue Gem	Rich Mountain	Rich Mountain	Alma
Sample type	run of mine	preparation plant composite	run of mine	preparation plant composite	run of mine	preparation plant composite	PP 2X 0 in.
Sample area	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant	preparation plant
Latitude	36.678297	36.678297	36.678297	36.678297	36.678297	36.678297	37.736178
Longitude	–84.017706	–84.017706	–84.017706	–84.017706	–84.017706	–84.017706	–82.616800
County	Whitley	Whitley	Whitley	Whitley	Whitley	Whitley	Martin
Quadrangle	Saxton	Saxton	Saxton	Saxton	Saxton	Saxton	Thomas
Company	Alden Resources	Alden Resources	Alden Resources	Alden Resources	Alden Resources	Alden Resources	Czar Coal
Sample ID	*3087*	*3088*	*3089*	*3090*	*3091*	*3092*	*3093*
Coal bed	Cedar Grove	Lower Elkhorn	Fire Clay rider	Williamson	Coalburg	Upper Elkhorn No. 3	Upper Elkhorn No. 3
Sample type	run of mine	run of mine	run of mine	run of mine	run of mine	core	core
Sample area						bench 1, 26 in.	parting 1, 3.1 in.
Latitude	37.624167	37.624167	37.624167	37.624167	37.624167	36.999440	36.999440
Longitude	–82.361233	–82.361233	–82.361233	–82.361233	–82.361233	–82.337559	–83.337559
County	Pike	Pike	Pike	Pike	Pike	Leslie	Leslie
Quadrangle	Belfry	Belfry	Belfry	Belfry	Belfry	Bledsoe	Bledsoe
Company	Sydney Coal	Sydney Coal	Sydney Coal	Sydney Coal	Sydney Coal	James River	James River

Sample ID	3094	3095	3096	3097	3097A	3098	3099
Coal bed	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3
Sample type	core	core	core	core	core	core	core
Sample area	bench 2, 5.9 in.	parting 2, 1.8 in.	bench 3, 15.9 in.	bench 1, 14 in.	parting 1, 0.4 in.	bench 2, 6.5 in.	parting 2, 2.2 in.
Latitude	36.999440	36.999440	36.999440	36.970332	36.970332	36.970332	36.970332
Longitude	–83.337559	–83.337559	–83.337559	–83.447318	–83.447318	–83.447318	–83.447318
County	Leslie	Leslie	Leslie	Leslie	Leslie	Leslie	Leslie
Quadrangle	Bledsoe	Bledsoe	Bledsoe	Helton	Helton	Helton	Helton
Company	James River	James River	James River	James River	James River	James River	James River
Sample ID	3100	3101	3102	3103	3104	3105	3115
Coal bed	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3	Upper Elkhorn No. 3A
Sample type	core	core	core	core	core	core	outcrop
Sample area	bench 3, 6.5 in.	bench 1, 16.5 in.	parting 1, 2.2 in.	bench 2, 5.3 in.	parting 2, 1.2 in.	bench 3, 15.4 in.	bench 1, 7.1 in.
Latitude	36.970332	37.002982	37.002982	37.002982	37.002982	37.002982	37.560628
Longitude	–83.447318	–83.314038	–83.314038	–83.314038	–83.314038	–83.314038	–82.424611
County	Leslie	Leslie	Leslie	Leslie	Leslie	Leslie	Pike
Quadrangle	Helton	Cutshin	Cutshin	Cutshin	Cutshin	Cutshin	Meta
Company	James River	James River	James River	James River	James River	James River	
Sample ID	3116	3117	3118	3119	3120		
Coal bed	Upper Elkhorn No. 3A	Upper Elkhorn No. 3A	Upper Elkhorn No. 3A	Upper Elkhorn No. 3A	Upper Elkhorn No. 3A		
Sample type	outcrop	outcrop	outcrop	outcrop	outcrop		
Sample area	bench 2, 16.1 in.	parting, 3.9 in.	bench 1, 7.5 in.	bench 2, 16.9 in.	parting, 0.2 in.		
Latitude							
Longitude	37.560628	37.560628	37.514283	37.514283	37.514283		
County	–82.424611	–82.424611	–82.478253	–82.478253	–82.478253		
Quadrangle	Pike	Pike	Pike	Pike	Pike		
Company	Meta	Meta	Meta	Meta	Meta		

Appendix 2: Analytical Data

Sample ID	*2975*	*2976*	*2977*	*2978*	*2979*	*2980*	*2988*	*2989*	*2990*	*2992*	*2993*	*3003*	*3004*	*3005*
telinite	8.40	8.00	10.00	7.20	8.40	9.20	17.20	4.00	8.80	2.80	6.00	4.00	7.20	2.00
collotelinite	40.00	43.20	52.40	46.40	44.80	49.20	42.40	43.60	36.00	48.80	62.40	42.40	35.20	49.20
collodetrinite	9.20	21.60	14.40	14.00	14.00	16.00	5.20	11.60	18.40	21.20	9.60	23.20	22.80	20.00
vitrodetrinite														
corpogelinite	3.20		1.20	2.00		0.80	1.20	2.00	2.00	1.20	0.80	0.40	0.80	2.00
gelinite	4.40	0.80	1.20	0.80	2.00		10.00	11.60	3.60	2.40	1.60	2.40	2.40	1.60
total vitrinite	**65.20**	**73.60**	**79.20**	**70.40**	**69.20**	**75.20**	**76.00**	**72.80**	**68.80**	**76.40**	**80.40**	**72.40**	**68.40**	**74.80**
telovitrinite	48.40	51.20	62.40	53.60	53.20	58.40	59.60	47.60	44.80	51.60	68.40	46.40	42.40	51.20
detrovitrinite + gelovitrinite	16.80	22.40	16.80	16.80	16.00	16.80	16.40	25.20	24.00	24.80	12.00	26.00	26.00	23.60
telovitrinite/detrovitrinite + gelovitrinite	2.88	2.29	3.71	3.19	3.33	3.48	3.63	1.89	1.87	2.08	5.70	1.78	1.63	2.17
sporinite	13.60	11.60	9.60	12.00	10.80	5.20	11.60	13.20	13.60	11.20	6.40	8.80	11.60	10.80
cutinite			0.80	0.40	0.40		0.40			0.40				
resinite				0.80		0.40	0.40	0.40				0.40	0.40	0.40
exsudatinite							0.40							
liptodetrinite		2.00	0.40	1.20	0.80	0.80	0.40	0.40	0.40			1.20	0.40	1.20
total liptinite	**13.60**	**13.60**	**10.80**	**14.40**	**12.00**	**6.40**	**13.20**	**14.00**	**14.00**	**11.60**	**6.40**	**10.40**	**12.40**	**12.40**
fusinite	7.60	2.40	3.60	6.00	7.60	10.80	7.60	6.80	8.40	5.60	8.80	9.20	8.40	4.40
semifusinite	8.40	3.60	2.00	4.80	6.80	4.00	0.80	2.40	4.80	3.20	2.00	4.80	4.80	3.20
macrinite	0.40	1.20									0.40			
micrinite	4.00	3.20	3.20	3.60	4.40	3.20	2.40	3.20	3.20	3.20	1.60	2.00	5.60	4.40
secretinite								0.80						
funginite														
inertodetrinite	0.80	2.40	1.20	0.80		0.40			0.80		0.40	1.20	0.40	0.80
total inertinite	**21.20**	**12.80**	**10.00**	**15.20**	**18.80**	**18.40**	**10.80**	**13.20**	**17.20**	**12.00**	**13.20**	**17.20**	**19.20**	**12.80**
average Ro random	0.86	0.85	0.85	0.84	0.85	0.84	0.78	0.77	0.77	0.76	0.78	0.83	0.83	0.82
maximum Ro random	0.93	0.91	0.90	0.94	0.92	0.93	0.85	0.83	0.84	0.83	0.85	0.89	0.88	0.89
minimum Ro random	0.77	0.78	0.76	0.76	0.75	0.76	0.70	0.71	0.69	0.68	0.71	0.78	0.79	0.73
standard deviation	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.03	0.04	0.04	0.04	0.03	0.02	0.04
calculated Ro max	0.92	0.91	0.90	0.90	0.90	0.89	0.83	0.81	0.81	0.81	0.82	0.89	0.88	0.87
(Ro random × 1.066)														

Sample ID	*3006*	*3007*	*3023*	*3024*	*3025*	*3026*	*3027*	*3028*	*3029*	*3030*	*3031*	*3032*	*3033*	*3035*
telinite	4.40	4.80	4.40	3.20	1.20	2.40	4.00	6.40	4.80	3.20	3.20	6.40	2.80	6.00
collotelinite	57.60	51.60	61.60	49.20	51.60	48.00	40.40	48.40	31.60	46.40	42.80	40.00	47.20	51.60
collodetrinite	11.20	18.80	6.80	6.00	8.40	6.80	23.20	15.60	12.00	8.80	12.40	8.40	15.20	14.00
vitrodetrinite			1.20	0.80	4.80	0.00	0.80	0.00	0.80	3.20	0.00	0.00	0.00	0.00
corpogelinite	0.80	1.60	0.80	1.20	0.80	2.00	1.60	0.00	1.20	0.40	0.40	0.40	0.80	0.40
gelinite	6.40	2.80	3.20	8.80	2.40	5.20	2.40	5.20	1.60	3.60	5.60	4.40	2.40	5.20
total vitrinite	**80.40**	**79.60**	**78.00**	**69.20**	**69.20**	**64.40**	**72.40**	**75.60**	**52.00**	**65.60**	**64.40**	**59.60**	**68.40**	**77.20**
telovitrinite	62.00	56.40	66.00	52.40	52.80	50.40	44.40	54.80	36.40	49.60	46.00	46.40	50.00	57.60
detrovitrinite + gelovitrinite	18.40	23.20	12.00	16.80	16.40	14.00	28.00	20.80	15.60	16.00	18.40	13.20	18.40	19.60
telovitrinite/detrovitrinite + gelovitrinite	3.37	2.43	5.50	3.12	3.22	3.60	1.59	2.63	2.33	3.10	2.50	3.52	2.72	2.94
sporinite	6.80	7.60	9.60	11.20	14.40	8.80	11.20	9.60	12.00	20.40	13.20	16.00	11.20	8.00
cutinite									0.40	0.40			0.00	0.40
resinite	0.40	0.40	1.20			0.80	0.40			0.40	0.40		0.40	1.20
exsudatinite													0.00	0.00
liptodetrinite		0.80	0.80		1.60	0.80	0.80	1.20		0.80	1.20	0.40	0.80	0.00
total liptinite	**7.20**	**8.80**	**11.60**	**11.20**	**16.00**	**10.40**	**12.40**	**10.80**	**12.40**	**22.00**	**14.80**	**16.40**	**12.40**	**9.60**
fusinite	5.60	4.80	4.40	10.00	7.60	15.20	6.40	5.60	22.40	7.60	12.80	11.60	5.20	2.40
semifusinite	3.60	3.60	1.60	4.40	2.00	4.40	6.40	4.00	6.00	3.20	3.60	6.80	8.40	4.00
macrinite				0.40	0.40	0.40					0.40	0.40	0.40	0.00
micrinite	2.80	2.80	2.40	4.40	2.80	4.40	2.00	4.00	5.20		3.60	4.00	4.40	5.60
secretinite						0.40						0.40	0.00	0.40
funginite													0.00	0.00
inertodetrinite	0.40	0.40	2.00	0.40	2.00	0.40	0.40		2.00	1.60	0.40	0.80	0.80	0.80
total inertinite	**12.40**	**11.60**	**10.40**	**19.60**	**14.80**	**25.20**	**15.20**	**13.60**	**35.60**	**12.40**	**20.80**	**24.00**	**19.20**	**13.20**
average Ro random	0.82	0.83	0.84	0.83	0.83	0.83	0.82	0.81	0.81	0.82	0.82	0.82	0.89	0.88
maximum Ro random	0.92	0.91	0.89	0.86	0.89	0.89	0.88	0.88	0.85	0.92	0.90	0.89	0.95	0.97
minimum Ro random	0.79	0.77	0.78	0.79	0.75	0.75	0.77	0.76	0.77	0.71	0.74	0.74	0.82	0.81
standard deviation	0.03	0.04	0.04	0.02	0.03	0.03	0.03	0.03	0.02	0.04	0.04	0.04	0.04	0.04
calculated Ro max	0.87	0.89	0.90	0.88	0.88	0.88	0.87	0.87	0.86	0.88	0.87	0.88	0.95	0.94
(Ro random × 1.066)														

Sample ID	*3036*	*3037*	*3038*	*3039*	*3040*	*3041*	*3042*	*3043*	*3044*	*3045*	*3046*	*3050*	*3051*	*3052*
telinite	6.00	6.40	2.80	2.80		3.20	8.40	10.80	0.80	7.20	16.00	1.60	10.00	7.20
collotelinite	38.00	43.20	60.40	39.20	7.20	52.00	57.20	48.00	60.00	67.60	52.40	43.60	56.80	58.40
collodetrinite	24.00	13.60	10.80	10.00	9.60	12.40	9.60	13.60	8.00	4.40	10.40	10.80	9.60	6.40
vitrodetrinite	0.00	0.00	0.00									0.40		
corpogelinite	1.20	0.40	0.00	1.60	0.40		0.40	0.80	1.60	0.80	0.40	0.80	1.60	0.40
gelinite	2.00	2.00	1.60	3.60	10.40	3.60	4.00	5.60	8.80	4.80	4.00	9.60	6.00	5.20
total vitrinite	**71.20**	**65.60**	**75.60**	**57.20**	**27.60**	**71.20**	**79.60**	**78.80**	**79.20**	**84.80**	**83.20**	**66.80**	**84.00**	**77.60**
telovitrinite	44.00	49.60	63.20	42.00	7.20	55.20	65.60	58.80	60.80	74.80	68.40	45.20	66.80	65.60
detrovitrinite + gelovitrinite	27.20	16.00	12.40	15.20	20.40	16.00	14.00	20.00	18.40	10.00	14.80	21.60	17.20	12.00
telovitrinite/detrovitrinite + gelovitrinite	1.62	3.10	5.10	2.76	0.35	3.45	4.69	2.94	3.30	7.48	4.62	2.09	3.88	5.47
sporinite	8.00	12.40	12.40	17.60	28.40	11.20	10.40	7.20	11.20	7.60	6.80	13.60	7.60	12.80
cutinite	0.40	0.40	0.40	0.80									0.40	
resinite	0.00	0.00	0.00	0.40		1.20			0.40	0.40	0.80		1.20	0.80
exsudatinite	0.40	0.00	0.00											
liptodetrinite	0.00	0.00	0.00		2.00			0.80			0.40		0.40	
total liptinite	**8.80**	**12.80**	**12.80**	**18.80**	**30.40**	**12.40**	**10.40**	**8.00**	**11.60**	**8.00**	**8.00**	**13.60**	**9.60**	**13.60**
fusinite	11.20	10.80	3.60	10.80	18.80	9.20	4.80	4.00	3.60	3.20	2.00	10.40	2.80	2.80
semifusinite	5.60	6.00	3.20	6.40	14.00	3.60	2.80	5.20	1.60	1.60	2.00	3.20	0.80	0.80
macrinite	0.40	0.40	0.40		2.40				0.40	0.40	0.40	0.40		
micrinite	1.60	3.20	3.20	4.00	5.60	2.00	2.40	3.20	3.20	2.00	2.80	4.40	2.40	4.80
secretinite	0.40	1.20	1.20			1.20		0.80						
funginite	0.00	0.00	0.00											
inertodetrinite	0.80	0.00	0.00	2.80	1.20	0.40			0.40		1.60	1.20	0.40	0.40
total inertinite	**20.00**	**21.60**	**11.60**	**24.00**	**42.00**	**16.40**	**10.00**	**13.20**	**9.20**	**7.20**	**8.80**	**19.60**	**6.40**	**8.80**
average Ro random	0.88	0.88	0.90	0.90		0.92	0.85		0.85			0.84	0.83	
maximum Ro random	1.01	0.96	0.96	0.97		1.00	0.92		0.92			0.89	0.86	
minimum Ro random	0.80	0.80	0.84	0.85		0.84	0.77		0.77			0.78	0.79	
standard deviation	0.04	0.03	0.04	0.03		0.04	0.03		0.03			0.04	0.02	
calculated Ro max	0.94	0.94	0.96	0.96		0.98	0.91		0.91			0.90	0.88	
(Ro random × 1.066)														

Sample ID	*3053*	*3054*	*3055*	*3057*	*3058*	*3059*	*3060*	*3061*	*3062*	*3063*	*3064*	*3065*	*3066*	*3067*
telinite	1.20	4.00	2.00	0.80	1.20	4.00	4.40	11.20	14.40	4.00	5.60	3.60	6.80	4.00
collotelinite	52.00	58.00	58.80	14.00	25.20	52.80	64.40	36.40	56.00	64.40	54.40	48.40	44.00	41.20
collodetrinite	4.00	8.40	2.40	2.00	15.20	9.60	9.20	11.60	2.80	6.40	8.80	14.40	10.80	14.40
vitrodetrinite			10.80	2.40		0.80		1.20	6.40		0.80	0.40	0.40	
corpogelinite	1.60	1.60	4.00	0.80	0.80	0.40	0.40	1.20	0.40	2.40	0.40	2.00	2.80	1.20
gelinite	2.40	3.60	6.40	3.20	4.40	3.60	3.20	7.60	4.40	3.20	7.20	8.80	1.60	5.20
total vitrinite	**61.20**	**75.60**	**84.40**	**23.20**	**46.80**	**71.20**	**81.60**	**69.20**	**84.40**	**80.40**	**77.20**	**77.60**	**66.40**	**66.00**
telovitrinite	53.20	62.00	60.80	14.80	26.40	56.80	68.80	47.60	70.40	68.40	60.00	52.00	50.80	45.20
detrovitrinite + gelovitrinite	8.00	13.60	23.60	8.40	20.40	14.40	12.80	21.60	14.00	12.00	17.20	25.60	15.60	20.80
telovitrinite/detrovitrinite + gelovitrinite	6.65	4.56	2.58	1.76	1.29	3.94	5.38	2.20	5.03	5.70	3.49	2.03	3.26	2.17
sporinite	12.80	8.00	10.80	20.00	12.40	13.20	7.20	11.60	8.80	6.00	11.20	8.40	9.60	12.40
cutinite						0.80	0.40	0.80	0.40			0.40		0.40
resinite		0.80	0.40	0.80	0.40		0.40	0.80		0.40	0.40		0.40	0.80
exsudatinite														
liptodetrinite		0.40	1.20	3.20	0.40	0.40		2.00	0.40		0.80		0.80	
total liptinite	**12.80**	**9.20**	**12.40**	**24.00**	**13.20**	**14.40**	**8.00**	**15.20**	**9.60**	**6.40**	**12.40**	**8.80**	**10.80**	**13.60**
fusinite	16.00	7.60	2.00	30.00	24.80	4.40	4.40	7.20	2.00	6.00	4.40	7.20	16.40	9.60
semifusinite	5.60	3.20		10.00	7.60	3.60	1.20	4.40	2.80	4.80	3.60	0.40	3.20	4.80
macrinite	1.20	0.80		1.60	1.20	0.40		0.40						
micrinite	2.80	3.60		1.20	6.00	4.00	4.80	3.20	1.20	2.40	2.40	4.80	2.80	3.60
secretinite	0.40			0.40								0.40		2.40
funginite														
inertodetrinite			1.20	9.60	0.40	2.00		0.40				0.80	0.40	
total inertinite	**26.00**	**15.20**	**3.20**	**52.80**	**40.00**	**14.40**	**10.40**	**15.60**	**6.00**	**13.20**	**10.40**	**13.60**	**22.80**	**20.40**
average Ro random					0.82	0.78	0.76	0.75	0.76	0.75	0.73	0.72	0.73	0.73
maximum Ro random					0.88	0.85	0.83	0.83	0.80	0.80	0.77	0.77	0.77	0.76
minimum Ro random					0.74	0.74	0.71	0.69	0.72	0.70	0.68	0.67	0.68	0.68
standard deviation					0.03	0.03	0.04	0.03	0.02	0.03	0.03	0.03	0.02	0.02
calculated Ro max					0.87	0.83	0.81	0.80	0.81	0.80	0.78	0.77	0.77	0.77
(Ro random × 1.066)														

Sample ID	*3068*	*3069*	*3070*	*3071*	*3072*	*3073*	*3074*	*3075*	*3076*	*3077*	*3078*	*3079*	*3080*
telinite	14.00	5.20	7.60	8.00	3.20	5.20	9.20	3.60	2.00	0.40	4.40	3.60	4.80
collotelinite	44.80	49.20	43.20	42.80	43.20	36.40	55.60	59.60	50.80	36.40	57.20	53.60	45.60
collodetrinite	13.20	11.60	14.40	12.00	16.00	24.00	11.20	13.20	8.00	17.20	7.20	15.60	12.00
vitrodetrinite					0.80	0.40			1.60		2.80		
corpogelinite	2.00	0.40	0.40	0.80	1.20	1.20	1.20	0.40	2.00	2.00	3.20	0.80	2.40
gelinite	8.40	6.80	4.00	10.80	4.80	4.40	4.80	4.00	3.60	5.60	5.60	3.20	8.80
total vitrinite	**82.40**	**73.20**	**69.60**	**74.40**	**69.20**	**71.60**	**82.00**	**80.80**	**68.00**	**61.60**	**80.40**	**76.80**	**73.60**
telovitrinite	58.80	54.40	50.80	50.80	46.40	41.60	64.80	63.20	52.80	36.80	61.60	57.20	50.40
detrovitrinite + gelovitrinite	23.60	18.80	18.80	23.60	22.80	30.00	17.20	17.60	15.20	24.80	18.80	19.60	23.20
telovitrinite/detrovitrinite + gelovitrinite	2.49	2.89	2.70	2.15	2.04	1.39	3.77	3.59	3.47	1.48	3.28	2.92	2.17
sporinite	9.20	10.80	15.20	12.40	16.40	10.40	9.20	10.00	19.60	13.60	10.40	5.60	9.20
cutinite	0.40		0.80		0.40		0.40	0.40		0.40		1.20	
resinite		0.40			0.40	0.80			0.80	0.80	1.60	0.80	0.80
exsudatinite													
liptodetrinite		1.20	0.40	0.80	1.20	0.40				0.40			0.40
total liptinite	**9.60**	**12.40**	**16.40**	**13.20**	**18.40**	**11.60**	**9.60**	**10.40**	**20.40**	**15.20**	**12.00**	**7.60**	**10.40**
fusinite	4.00	5.20	8.00	7.60	6.00	8.40	4.40	4.80	6.80	7.20	2.40	10.80	9.20
semifusinite	1.20	5.20	2.80	2.40	2.40	2.80	1.60		1.60	6.80	0.80	2.00	2.80
macrinite	0.40	1.20	0.40										
micrinite	1.60	2.40	2.40	1.60	2.40	4.40	2.00	2.80	2.40	5.60	4.40	2.40	2.40
secretinite						0.40							0.40
funginite													
inertodetrinite	0.80	0.40	0.40	0.80	1.60	0.80	0.40	1.20	0.80	3.60		0.40	1.20
total inertinite	**8.00**	**14.40**	**14.00**	**12.40**	**12.40**	**16.80**	**8.40**	**8.80**	**11.60**	**23.20**	**7.60**	**15.60**	**16.00**
average Ro random	0.78	0.85	0.80	0.80	0.88	0.83	0.84	0.73	0.77	0.81	0.89	0.92	0.84
maximum Ro random	0.83	0.98	0.88	0.89	0.95	0.92	0.91	0.79	0.83	0.86	0.97	0.97	0.90
minimum Ro random	0.70	0.65	0.74	0.71	0.78	0.73	0.77	0.69	0.73	0.77	0.84	0.85	0.77
standard deviation	0.03	0.07	0.03	0.05	0.05	0.05	0.04	0.03	0.03	0.03	0.04	0.04	0.04
calculated Ro max	0.83	0.91	0.85	0.85	0.94	0.88	0.89	0.78	0.82	0.86	0.95	0.98	0.89
(Ro random × 1.066)													

Sample ID	*3081*	*3082*	*3083*	*3084*	*3085*	*3086*	*3087*	*3088*	*3089*	*3090*	*3091*	*3092*	*3093*	*3094*
telinite	3.20	3.20	6.00	7.60	5.20	11.60	2.80					3.60	1.20	9.60
collotelinite	51.20	62.40	55.20	52.40	56.00	44.80	48.80					47.20	56.40	47.20
collodetrinite	12.40	8.40	15.20	12.40	15.20	11.20	11.20					14.80	2.00	12.40
vitrodetrinite		0.80					0.40						24.40	0.80
corpogelinite	2.40	1.20	0.40	2.80		1.20						2.40	1.20	0.80
gelinite	7.60	7.60	6.80	6.00	7.60	5.20	2.40					4.00	4.80	3.20
total vitrinite	**76.80**	**83.60**	**83.60**	**81.20**	**84.00**	**74.00**	**65.60**					**72.00**	**90.00**	**74.00**
telovitrinite	54.40	65.60	61.20	60.00	61.20	56.40	51.60					50.80	57.60	56.80
detrovitrinite + gelovitrinite	22.40	18.00	22.40	21.20	22.80	17.60	14.00					21.20	32.40	17.20
telovitrinite/detrovitrinite + gelovitrinite	2.43	3.64	2.73	2.83	2.68	3.20	3.69					2.40	1.78	3.30
sporinite	8.80	9.60	9.60	11.60	7.20	8.40	12.00					9.20	4.80	11.60
cutinite														
resinite	0.40	1.20		0.80			0.40						0.40	0.80
exsudatinite														
liptodetrinite		0.40			0.80								2.40	
total liptinite	**9.20**	**11.20**	**9.60**	**12.40**	**8.00**	**8.40**	**12.40**					**9.20**	**7.60**	**12.40**
fusinite	6.40	2.00	2.00	4.00	2.80	11.20	12.40					7.20	1.20	5.60
semifusinite	3.20		0.40	0.40	2.40	4.40	4.80					2.80		5.60
macrinite	0.40					0.40	0.80							
micrinite	3.60	3.20	4.00	2.00	2.80	1.20	3.20					6.80	0.40	1.20
secretinite							0.40					0.80		
funginite														
inertodetrinite	0.40		0.40			0.40	0.40					1.20	0.80	1.20
total inertinite	**14.00**	**5.20**	**6.80**	**6.40**	**8.00**	**17.60**	**22.00**					**18.80**	**2.40**	**13.60**
average Ro random	0.83	0.83	0.84	0.86	0.85	0.77								0.82
maximum Ro random	0.89	0.89	0.91	0.90	0.90	0.83								0.90
minimum Ro random	0.77	0.77	0.78	0.78	0.80	0.73								0.75
standard deviation	0.04	0.04	0.03	0.03	0.03	0.03								0.04
calculated Ro max	0.89	0.89	0.89	0.91	0.91	0.82								0.88
(Ro random × 1.066)														

Sample ID	*3095*	*3096*	*3097*	*3097A*	*3098*	*3099*	*3100*	*3101*	*3102*	*3103*	*3104*	*3105*	*3115*	*3116*
telinite	2.00	6.40	5.20	0.40	4.00	0.80	1.60	6.00	0.80	4.40	0.80	0.80	6.00	3.20
collotelinite	58.80	56.40	39.20	25.20	50.40	67.20	42.00	49.60	55.20	58.40	66.80	27.60	54.80	33.60
collodetrinite	4.40	8.40	12.80	6.80	14.80	0.80	10.40	12.80	6.40	9.60	10.00	15.20	6.80	10.40
vitrodetrinite	19.60	0.40		2.80		22.80			16.40	1.60	6.80		0.80	
corpogelinite		1.20	1.60	0.40	1.20	0.40	0.80	1.20	1.20	1.60	2.40	0.80	2.40	2.80
gelinite	2.80	6.40	4.40	4.80	6.00	1.60	6.40	4.00	4.40	1.60	6.40	1.60	2.80	8.40
total vitrinite	**87.60**	**79.20**	**63.20**	**40.40**	**76.40**	**93.60**	**61.20**	**73.60**	**84.40**	**77.20**	**93.20**	**46.00**	**73.60**	**58.40**
telovitrinite	60.80	62.80	44.40	25.60	54.40	68.00	43.60	55.60	56.00	62.80	67.60	28.40	60.80	36.80
detrovitrinite + gelovitrinite	26.80	16.40	18.80	14.80	22.00	25.60	17.60	18.00	28.40	14.40	25.60	17.60	12.80	21.60
telovitrinite/detrovitrinite + gelovitrinite	2.27	3.83	2.36	1.73	2.47	2.66	2.48	3.09	1.97	4.36	2.64	1.61	4.75	1.70
sporinite	7.20	12.80	13.60	22.40	9.60	4.00	12.00	14.40	11.20	7.20	3.20	17.60	10.80	14.00
cutinite								0.40						0.40
resinite	1.20			0.40	0.40					0.40	0.40		0.40	
exsudatinite														
liptodetrinite	1.20	0.40		0.40		0.80	0.40		1.20	0.40	1.60	0.40	1.20	
total liptinite	**9.60**	**13.20**	**13.60**	**23.20**	**10.00**	**4.80**	**12.40**	**14.80**	**12.40**	**8.00**	**5.20**	**18.00**	**12.40**	**14.40**
fusinite	1.20	2.80	8.80	20.80	6.40	0.40	20.00	5.20	2.80	8.80		14.80	6.40	12.40
semifusinite	0.40		6.80	8.40	3.60	0.40	2.40	1.60	0.40	2.80		14.00	3.20	8.40
macrinite			0.40	1.20			0.40			0.40		1.20		
micrinite	0.80	3.60	5.60	2.80	3.20	0.40	2.40	4.40		2.40		4.40	4.00	6.00
secretinite				0.80										
funginite														
inertodetrinite	0.40	1.20	1.60	2.40	0.40	0.40	1.20	0.40		0.40	1.60	1.60	0.40	0.40
total inertinite	**2.80**	**7.60**	**23.20**	**36.40**	**13.60**	**1.60**	**26.40**	**11.60**	**3.20**	**14.80**	**1.60**	**36.00**	**14.00**	**27.20**
average Ro random	0.82	0.82	0.82										0.81	0.80
maximum Ro random	0.88	0.89	0.90										0.86	0.86
minimum Ro random	0.76	0.77	0.73										0.74	0.76
standard deviation	0.04	0.03	0.05										0.04	0.03
calculated Ro max	0.88	0.87	0.88										0.86	0.85
(Ro random × 1.066)														

Sample ID	**3117**	**3118**	**3119**	**3120**
telinite	9.60	6.40	4.00	0.80
collotelinite	20.00	48.40	60.00	43.60
collodetrinite	2.00	8.00	6.40	0.40
vitrodetrinite	12.00			24.80
corpogelinite	1.60	2.80	1.20	1.20
gelinite	3.20	6.00	7.60	3.60
total vitrinite	**48.40**	**71.60**	**79.20**	**74.40**
telovitrinite	29.60	54.80	64.00	44.40
detrovitrinite + gelovitrinite	18.80	16.80	15.20	30.00
telovitrinite/detrovitrinite + gelovitrinite	1.57	3.26	4.21	1.48
sporinite	30.00	16.80	9.60	16.40
cutinite				
resinite	0.80	0.80	0.40	
exsudatinite				
liptodetrinite	2.40			2.80
total liptinite	**33.20**	**17.60**	**10.00**	**19.20**
fusinite	12.00	5.60	6.80	3.20
semifusinite	2.40	0.40	0.40	1.20
macrinite	0.80	1.20	0.40	0.80
micrinite		3.20	3.20	
secretinite		0.40		
funginite				
inertodetrinite	3.20			1.20
total inertinite	**18.40**	**10.80**	**10.80**	**6.40**
average Ro random		0.80	0.80	
maximum Ro random		0.85	0.84	
minimum Ro random		0.75	0.75	
standard deviation		0.03	0.02	
calculated Ro max		0.85	0.85	
(Ro random × 1.066)				

Appendix 3: Analytical Geochemical Data

Sample ID	*2975*	*2976*	*2977*	*2978*	*2979*	*2980*	*2988*	*2989*	*2990*	*2992*
Proximate Analysis										
% ash (dry basis)	13.11	8.64	8.87	12.75	8.66	11.27	6.68	6.72	5.98	6.47
% fixed carbon (dry basis)	54.74	56.81	58.04	54.11	57.89	57.03	57.34	56.21	56.37	56.46
% moisture	2.97	3.14	4.12	3.07	3.43	7.66	3.87	3.50	3.55	3.63
% volatile matter (dry basis)	32.15	34.55	33.10	33.15	33.45	31.70	35.99	37.07	37.65	37.07
decimal % organic matter	0.87	0.91	0.91	0.87	0.91	0.89	0.93	0.93	0.94	0.94
% volatile matter (dry, ash-free basis)	37.00	37.82	36.32	37.99	36.62	35.73	38.57	39.74	40.04	39.63
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	75.40	76.80	77.80	73.40	77.90	74.60	77.80	78.60	78.40	78.40
calorific value, Btu (dry basis)	13,022.00	13,754.00	13,622.00	12,847.00	13,575.00	13,087.00	13,887.00	13,925.00	13,000.00	13,835.00
total chlorine in coal (dry basis)	2,495.00	2,932.00	2,783.00	2,521.00	2,979.00	3,043.00	3,975.00	2,963.00	3,012.00	2,965.00
total sulfur (dry basis)	1.48	0.65	0.73	1.09	0.92	0.67	1.97	1.36	1.31	1.25
Sample ID	*2993*	*3003*	*3004*	*3005*	*3006*	*3007*	*3023*	*3024*	*3025*	*3026*
Proximate Analysis										
% ash (dry basis)	7.36	5.98	6.47	7.36	8.51	7.97	41.18	11.02	32.87	4.36
% fixed carbon (dry basis)	58.98	56.37	56.46	58.98	57.22	57.40	32.79	53.96	39.82	59.59
% moisture	3.10	3.55	3.63	3.10	1.92	2.97		1.55	1.50	1.81
% volatile matter (dry basis)	33.66	37.65	37.07	33.66	36.85	34.64	26.03	37.66	29.37	38.76
decimal % organic matter	0.93	0.94	0.94	0.93	0.91	0.92	0.59	0.89	0.67	0.96
% volatile matter (dry, ash-free basis)	36.33	40.04	39.63	36.33	40.28	37.64	44.25	42.32	43.75	40.53
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	76.30	78.40	78.40	76.30	78.50	76.10	47.74	90.60	47.74	87.40
calorific value, Btu (dry basis)	13,531.00	11,000.00	13,835.00	13,531.00	13,614.00	13,773.00		13,365.00		14,489.00
total chlorine in coal (dry basis)	2,787.00	3,012.00	2,965.00	2,787.00	1,570.00	1,919.00	792.00	1,466.00	792.00	2,066.00
total sulfur (dry basis)	1.08	1.31	1.25	1.08	1.52	1.30	2.12	2.72	1.93	1.47

Sample ID	*3027*	*3028*	*3029*	*3030*	*3031*	*3032*	*3033*	*3035*	*3036*	*3037*
Proximate Analysis										
% ash (dry basis)	21.06	7.42	22.66	47.29	7.16	7.33	3.96	5.17	10.42	2.33
% fixed carbon (dry basis)	49.19	58.10	47.17	30.27	57.65	57.61	61.83	58.75	56.80	61.38
% moisture	2.20	2.15	2.12	1.65	2.13	2.52	1.92	1.69	1.89	1.64
% volatile matter (dry basis)	31.98	37.08	32.44	24.14	37.84	37.69	36.80	38.80	35.25	39.03
decimal % organic matter	0.79	0.93	0.77	0.53	0.93	0.93	0.96	0.95	0.90	0.98
% volatile matter (dry, ash-free basis)	40.51	40.05	41.94	45.80	40.76	40.67	38.32	40.92	39.35	39.96
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)										
calorific value, Btu (dry basis)	67.70	80.90	58.78	43.68	81.40	81.30	85.90	84.20	77.50	86.50
total chlorine in coal (dry basis)	11,511.00	13,869.00			13,998.00	13,894.00	14,690.00	14,458.00	13,333.00	15,001.00
total sulfur (dry basis)	1,277.00	1,877.00	1,508.00	1,367.00	2,268.00	2,653.00	39.00	47.00	40.00	41.00
	0.78	0.84	0.69	0.92	0.69	0.90	0.86	0.95	1.23	0.72
Sample ID	*3038*	*3039*	*3040*	*3041*	*3042*	*3043*	*3044*	*3045*	*3046*	*3050*
Proximate Analysis										
% ash (dry basis)	4.10	6.37	41.55	8.37	3.88	4.25	4.95	6.22	2.59	4.71
% fixed carbon (dry basis)	60.79	60.90	36.47	58.49	58.78	60.27	56.19	56.02	60.32	57.63
% moisture	1.87	3.56	1.56							
% volatile matter (dry basis)	37.76	35.19	23.63	33.14	37.34	35.48	38.86	37.76	37.09	37.66
decimal % organic matter	0.96	0.94	0.58	0.92	0.96	0.96	0.95	0.94	0.97	0.95
% volatile matter (dry, ash-free basis)	39.37	37.58	40.43	36.17	38.85	37.05	40.88	40.26	38.08	39.52
				100.00	100.00	100.00	100.00	100.00	100.00	100.00
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	85.60	78.11	48.83	77.17	77.20	80.01	79.29	77.88	81.40	78.80
calorific value, Btu (dry basis)	14,723.00									
total chlorine in coal (dry basis)	44.00	1,485.00	790.00	1,371.00	1,614.00	1,388.00	1,537.00	1,460.00	1,699.00	1,395.00
total sulfur (dry basis)	0.73	0.54	0.31	0.52	0.82	0.77	0.96	1.04	0.80	0.78

Sample ID	*3051*	*3052*	*3053*	*3054*	*3055*	*3057*	*3058*	*3059*	*3060*	*3061*
Proximate Analysis										
% ash (dry basis)	3.45	2.29	7.67	3.37	3.07	47.70	4.60	5.12	1.53	22.66
% fixed carbon (dry basis)	54.88	57.69	56.41	59.45	54.72	33.57	61.80	58.14	63.62	45.83
% moisture						1.46	3.87	2.85	5.53	2.71
% volatile matter (dry basis)	41.67	40.02	35.92	37.18	42.21	18.73	36.13	39.51	37.48	32.71
decimal % organic matter	0.97	0.98	0.92	0.97	0.97	0.52	0.95	0.95	0.98	0.77
% volatile matter (dry, ash-free basis)	43.16	40.96	38.90	38.48	43.55	35.81	37.87	41.64	38.06	42.29
	100.00	100.00	100.00	100.00	100.00					
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	80.34	81.81	75.55	79.99	77.83					62.23
calorific value, Btu (dry basis)										11,236.00
total chlorine in coal (dry basis)	1,770.00	1,748.00	1,338.00	1,368.00	1,364.00					2,112.00
total sulfur (dry basis)	1.49	0.81	0.72	0.77	0.99	0.76	0.61	1.75	0.63	1.61
Sample ID	*3062*	*3063*	*3064*	*3065*	*3066*	*3067*	*3068*	*3069*	*3070*	*3071*
Proximate Analysis										
% ash (dry basis)	53.43	13.58	7.38	8.93	12.03	9.14	9.88	9.55	9.69	11.43
% fixed carbon (dry basis)	25.25	51.54	54.14	52.23	52.16	53.71	54.92	55.99	54.23	53.85
% moisture		2.91	2.51	3.10	3.24	2.91	2.95	3.79	2.98	4.99
% volatile matter (dry basis)	21.32	36.20	39.93	38.84	35.82	38.56	36.54	35.77	37.45	36.04
decimal % organic matter	0.47	0.86	0.93	0.91	0.88	0.91	0.90	0.90	0.90	0.89
% volatile matter (dry, ash-free basis)	45.78	41.89	43.11	42.65	40.72	42.44	40.55	39.55	41.47	40.69
	100.00									
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	35.69	73.44	77.76	73.87	72.30	76.27	76.99	78.04	77.53	76.12
calorific value, Btu (dry basis)		12,824.00	13,682.00	13,344.00	12,886.00	13,367.00	13,495.00	13,451.00	13,491.00	13,030.00
total chlorine in coal (dry basis)	1,457.00	2,990.00	2,715.00	2,671.00	2,702.00	2,467.00	1,575.00	2,034.00	1,789.00	779.00
total sulfur (dry basis)	0.76	1.82	1.98	1.97	1.66	2.03	1.88	0.95	1.24	0.87

Sample ID	*3072*	*3073*	*3074*	*3075*	*3076*	*3077*	*3078*	*3079*	*3080*	*3081*
Proximate Analysis										
% ash (dry basis)	6.81	6.06	8.84	6.19	28.41	8.70	48.37	6.43	27.72	2.22
% fixed carbon (dry basis)	57.06	55.83	54.04	49.28	39.73	53.29	29.55	59.63	43.32	62.01
% moisture	2.97	2.87	3.92					2.73		3.55
% volatile matter (dry basis)	37.50	39.56	38.53	44.53	31.86	38.01	22.08	35.23	28.96	37.13
decimal % organic matter	0.93	0.94	0.91	0.94	0.72	0.91	0.52	0.94	0.72	0.98
% volatile matter (dry, ash-free basis)	40.24	42.11	42.27	47.47	44.50	41.63	42.77	37.65	40.07	37.97
				100.00	100.00	100.00	100.00		100.00	
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	79.46	79.03	76.12	76.44	58.07	76.11	40.58	81.40	58.68	83.56
calorific value, Btu (dry basis)	14,018.00	13,789.00	13,462.00					14,208.00		14,624.00
total chlorine in coal (dry basis)	2,151.00	1,814.00	1,511.00	1,708.00	1,342.00	2,036.00	1,108.00	2,312.00	1,885.00	2,969.00
total sulfur (dry basis)	1.11	1.18	1.87	3.52	0.95	0.73	0.68	1.05	0.72	0.93
Sample ID	*3082*	*3083*	*3084*	*3085*	*3086*	*3087*	*3088*	*3089*	*3090*	*3091*
Proximate Analysis										
% ash (dry basis)	8.58	1.15	4.39	2.04	10.50	7.08	54.33	46.34	53.90	52.74
% fixed carbon (dry basis)	53.60	61.10	56.60	60.94	53.01	50.68	26.16	27.72	23.49	26.05
% moisture		4.42		3.43	4.18					
% volatile matter (dry basis)	37.82	39.17	39.01	38.42	37.89	42.24	19.51	25.94	22.61	21.21
decimal % organic matter	0.91	0.99	0.96	0.98	0.90	0.93	0.46	0.54	0.46	0.47
% volatile matter (dry, ash-free basis)	41.37	39.63	40.80	39.22	42.34	45.46	42.72	48.34	49.05	44.88
	100.00									
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	75.70	85.14	78.77	83.10	76.08	76.58	35.60	41.46	35.59	36.77
calorific value, Btu (dry basis)		14,870.00		14,672.00	13,168.00					
total chlorine in coal (dry basis)	2,573.00	3,256.00	171.00	970.00	2,507.00	1,965.00	641.00	438.00	298.00	354.00
total sulfur (dry basis)	0.67	0.77	0.68	0.91	1.99	1.86	0.24	1.75	2.40	0.60

Sample ID	*3092*	*3093*	*3094*	*3095*	*3096*	*3097*	*3097A*	*3098*	*3099*	*3100*
Proximate Analysis										
% ash (dry basis)	4.82	67.35	7.43	55.39	5.20	4.50	39.46	6.92	63.92	8.99
% fixed carbon (dry basis)	55.69	16.61	53.95	25.07	54.24	53.97	31.94	52.95	18.66	51.77
% moisture		2.05		2.13			1.57		1.75	
% volatile matter (dry basis)	39.49	16.05	38.62	19.54	40.56	41.53	28.60	40.13	17.42	39.25
decimal % organic matter	0.95	0.33	0.93	0.45	0.95	0.96	0.61	0.93	0.36	0.91
% volatile matter (dry, ash-free basis)	41.49	49.16	41.72	43.80	42.78	43.49	47.24	43.11	48.28	43.13
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	78.61		75.84		77.50	80.25		76.30		73.92
calorific value, Btu (dry basis)										
total chlorine in coal (dry basis)	1,723.00		2,002.00		1,604.00	1,971.00		2,072.00		1,987.00
total sulfur (dry basis)	0.80	0.64	2.18	1.59	3.45	1.85	2.56	2.76	2.40	5.02
Sample ID	*3101*	*3102*	*3103*	*3104*	*3105*	*3115*	*3116*	*3117*	*3118*	*3119*
Proximate Analysis										
% ash (dry basis)	7.61	64.07	16.38	40.26	5.38	7.64	7.86	56.38	5.15	4.89
% fixed carbon (dry basis)	52.79	18.81	49.11	35.25	55.35	55.00	54.95	23.98	55.66	57.25
% moisture		1.82		1.72						
% volatile matter (dry basis)	39.60	17.12	34.51	24.49	39.27	37.41	37.19	19.64	39.19	37.86
decimal % organic matter	0.92	0.36	0.84	0.60	0.95	0.92	0.92	0.44	0.95	0.95
% volatile matter (dry, ash-free basis)	42.86	47.65	41.27	40.99	41.50	40.50	40.36	45.03	41.32	39.81
Carbon/Sulfur/Btu/Chlorine										
% carbon (dry basis)	74.54		68.28		79.61	76.95	76.52	33.93	77.98	79.24
calorific value, Btu (dry basis)										
total chlorine in coal (dry basis)	1,815.00		1,625.00		1,798.00	1,356.00	1,530.00	336.00	1,420.00	1,452.00
total sulfur (dry basis)	5.16	1.36	2.70	1.64	1.81	0.79	0.84	0.39	0.96	0.84

Sample ID	*3120*
Proximate Analysis	
% ash (dry basis)	66.28
% fixed carbon (dry basis)	16.97
% moisture	
% volatile matter (dry basis)	16.75
decimal % organic matter	0.34
% volatile matter (dry, ash-free basis)	49.67
Carbon/Sulfur/Btu/Chlorine	
% carbon (dry basis)	25.10
calorific value, Btu (dry basis)	
total chlorine in coal (dry basis)	232.00
total sulfur (dry basis)	0.36

Appendix 4: Analytical Ash Geochemistry Data

Sample ID	*2975*	*2976*	*2977*	*2978*	*2979*	*2980*	*2988*	*2989*	*2990*	*2992*	*2993*	*3003*
X-ray Fluorescence (%, ash basis)												
Aluminum oxide (Al_2O_3)	24.26	31.76	27.56	29.78	29.29	23.19	17.80	27.99	28.33	28.41	22.44	28.33
Barium oxide (BaO)	0.08	0.11	0.12	0.09	0.12	0.11	0.09	0.12	0.14	0.13	0.14	0.14
Calcium oxide (CaO)	4.45	1.17	2.77	1.30	2.37	3.50	5.84	2.34	2.55	2.44	4.84	2.55
Ferric oxide (Fe_2O_3)	11.03	5.65	6.98	7.79	7.08	5.95	32.95	11.75	11.49	10.18	9.81	11.49
Magnesium oxide (MgO)	0.77	0.72	0.85	0.74	0.79	1.00	1.09	0.80	0.91	0.96	1.32	0.91
Phosphorus pentoxide (P_2O_5)	0.10	0.11	0.11	0.10	0.10	0.10	0.12	0.11	0.11	0.11	0.13	0.11
Potassium oxide (K_2O)	2.07	2.12	2.26	2.50	2.25	2.71	1.88	2.60	2.65	2.88	2.74	2.65
Silicon dioxide (SiO_2)	48.13	52.42	51.17	51.90	50.88	55.09	29.04	48.33	46.51	48.13	47.34	46.51
Sodium oxide (Na_2O)	0.51	0.50	0.50	0.40	0.46	0.50	0.70	0.49	0.54	0.56	0.59	0.54
Strontium oxide (SrO)	0.10	0.12	0.13	0.07	0.14	0.11	0.13	0.14	0.17	0.14	0.15	0.17
Sulfur trioxide (SO_3)	4.83	1.08	2.73	1.38	2.60	3.15	6.10	2.08	2.15	2.25	5.52	2.15
Titanium dioxide (TiO_2)	1.48	1.87	1.77	1.76	1.78	1.50	0.71	1.48	1.44	1.38	1.79	1.44
TOTAL	97.80	97.60	97.00	97.80	97.90	96.90	96.70	98.30	97.00	97.60	96.90	97.00
Acid/base ratio	3.92	8.47	6.03	6.55	6.33	5.84	1.12	4.33	4.21	4.58	3.71	4.21
P in ash	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02
X-ray Fluorescence (ppm, ash basis)												
Barium (Ba)	846.00	1,142.00	1,141.00	949.00	1,097.00	977.00	864.00	1,191.00	1,248.00	1,247.00	1,228.00	1,248.00
Cerium (Ce)	174.00	186.00	179.00	175.00	178.00	152.00	212.00	278.00	264.00	249.00	211.00	264.00
Chromium (Cr)	140.00	207.00	196.00	190.00	193.00	178.00	123.00	207.00	234.00	231.00	234.00	234.00
Cobalt (Co)	101.00	162.00	141.00	117.00	173.00	105.00	199.00	229.00	229.00	210.00	176.00	229.00
Copper (Cu)	110.00	222.00	200.00	170.00	178.00	158.00	122.00	270.00	278.00	273.00	370.00	278.00
Gallium (Ga)	42.00	62.00	58.00	53.00	56.00	47.00	39.00	83.00	85.00	86.00	71.00	85.00
Lanthanum (La)	104.00	143.00	120.00	117.00	127.00	99.00	83.00	116.00	115.00	119.00	121.00	115.00
Lead (Pb)	61.00	104.00	107.00	89.00	89.00	117.00	40.00	74.00	79.00	77.00	188.00	79.00
Nickel (Ni)	145.00	216.00	205.00	147.00	211.00	172.00	186.00	289.00	311.00	300.00	320.00	311.00
Niobium (Nb)	27.00	39.00	38.00	36.00	34.00	33.00	18.00	34.00	33.00	34.00	37.00	33.00
Rubidium (Ru)	96.00	120.00	111.00	140.00	119.00	133.00	45.00	99.00	106.00	116.00	103.00	106.00
Strontium (Sr)	1,036.00	1,593.00	1,584.00	914.00	1,511.00	1,243.00	711.00	1,396.00	1,449.00	1,487.00	1,535.00	1,449.00
Thorium (Th)	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	523.00	< 5
Uranium (U)	51.00	18.00	93.00	18.00	18.00	18.00	18.00	103.00	84.00	150.00	43.00	84.00
Vanadium (V)	188.00	272.00	274.00	251.00	265.00	234.00	214.00	379.00	466.00	452.00	564.00	466.00
Yttrium (Y)	89.00	143.00	132.00	126.00	121.00	111.00	112.00	207.00	202.00	204.00	173.00	202.00
Zinc (Zn)	91.00	93.00	127.00	68.00	127.00	168.00	145.00	119.00	177.00	171.00	300.00	177.00
Zirconium (Zr)	354.00	427.00	415.00	346.00	391.00	381.00	130.00	315.00	303.00	318.00	341.00	303.00

Sample ID	*3004*	*3005*	*3006*	*3007*	*3023*	*3024*	*3025*	*3026*	*3027*	*3028*	*3029*	*3030*
X-ray Fluorescence (%, ash basis)												
Aluminum oxide (Al_2O_3)	28.41	22.44	26.33	26.61		28.95		23.61	26.60	29.04		
Barium oxide (BaO)	0.13	0.14	0.10	0.12		0.14		0.18	0.08	0.11		
Calcium oxide (CaO)	2.44	4.84	0.93	1.17		1.89		3.23	0.86	1.08		
Ferric oxide (Fe_2O_3)	10.18	9.81	10.06	8.46		14.31		21.81	3.88	4.10		
Magnesium oxide (MgO)	0.96	1.32	0.79	0.94		0.86		0.88	1.00	0.66		
Phosphorus pentoxide (P_2O_5)	0.11	0.13	0.14	0.15		0.56		0.28	0.14	0.16		
Potassium oxide (K_2O)	2.88	2.74	2.27	2.53		2.68		1.46	2.65	1.71		
Silicon dioxide (SiO_2)	48.13	47.34	52.57	53.31		44.41		40.89	58.17	56.77		
Sodium oxide (Na_2O)	0.56	0.59	0.42	0.47		0.61		0.65	0.46	0.55		
Strontium oxide (SrO)	0.14	0.15	0.10	0.11		0.29		0.32	0.05	0.11		
Sulfur trioxide (SO_3)	2.25	5.52	0.73	0.60		1.74		3.52	0.45	0.64		
Titanium dioxide (TiO_2)	1.38	1.79	1.37	1.81		1.28		1.54	1.40	1.63		
TOTAL	97.60	96.90	95.83	96.30		97.73		98.42	95.76	96.57		
Acid/base ratio	4.58	3.71	5.55	6.02		3.67		2.36	9.74	10.80		
P in ash	0.02	0.03	0.03	0.03		0.12		0.06	0.03	0.03		
X-ray Fluorescence (ppm, ash basis)												
Barium (Ba)	1,247.00	1,228.00	1,022.00	1,141.00		1,464.00		1,875.00	848.00	1,105.00		
Cerium (Ce)	249.00	211.00	382.00	547.00		263.00		186.00	267.00	449.00		
Chromium (Cr)	231.00	234.00	184.00	224.00		206.00		206.00	133.00	179.00		
Cobalt (Co)	210.00	176.00	76.00	113.00		71.00		110.00	52.00	87.00		
Copper (Cu)	273.00	370.00	157.00	219.00		148.00		165.00	98.00	148.00		
Gallium (Ga)	86.00	71.00	72.00	100.00		53.00		58.00	59.00	80.00		
Lanthanum (La)	119.00	121.00	169.00	320.00		95.00		87.00	129.00	231.00		
Lead (Pb)	77.00	188.00	78.00	129.00		65.00		54.00	65.00	82.00		
Nickel (Ni)	300.00	320.00	206.00	275.00		161.00		263.00	112.00	188.00		
Niobium (Nb)	34.00	37.00	57.00	71.00		30.00		36.00	52.00	75.00		
Rubidium (Ru)	116.00	103.00	95.00	120.00		88.00		39.00	127.00	92.00		
Strontium (Sr)	1,487.00	1,535.00	1,055.00	1,306.00		3,064.00		2,705.00	689.00	1,565.00		
Thorium (Th)	< 5	523.00	59.00	1,956.00		26.00		16.00	57.00	89.00		
Uranium (U)	150.00	43.00	79.00	321.00		22.00		< 10	157.00	187.00		
Vanadium (V)	452.00	564.00	424.00	568.00		377.00		405.00	228.00	311.00		
Yttrium (Y)	204.00	173.00	205.00	318.00		78.00		81.00	162.00	360.00		
Zinc (Zn)	171.00	300.00	274.00	300.00		153.00		153.00	185.00	182.00		
Zirconium (Zr)	318.00	341.00	591.00	881.00		406.00		404.00	594.00	869.00		

Sample ID	*3031*	*3032*	*3033*	*3035*	*3036*	*3037*	*3038*	*3039*	*3040*	*3041*	*3042*
X-ray Fluorescence (%, ash basis)											
Aluminum oxide (Al_2O_3)	33.31	31.63	29.07	12.39	34.47	29.43	25.60				
Barium oxide (BaO)	0.11	0.11	0.13	0.05	0.07	0.18	0.12				
Calcium oxide (CaO)	1.23	1.72	1.48	4.31	0.77	2.60	1.77				
Ferric oxide (Fe_2O_3)	3.03	6.27	10.20	48.52	8.67	12.08	9.99				
Magnesium oxide (MgO)	0.62	0.71	1.16	2.52	0.89	1.03	1.22				
Phosphorus pentoxide (P_2O_5)	0.14	0.14	0.55	0.21	0.27	0.91	0.36				
Potassium oxide (K_2O)	1.79	1.88	2.64	0.75	1.79	1.39	2.45				
Silicon dioxide (SiO_2)	54.01	51.78	49.85	22.53	49.07	45.92	51.85				
Sodium oxide (Na_2O)	0.59	0.39	0.46	0.68	0.16	0.82	0.65				
Strontium oxide (SrO)	0.11	0.13	0.11	0.04	0.04	0.16	0.07				
Sulfur trioxide (SO_3)	0.98	1.65	0.55	4.63	0.26	1.62	0.98				
Titanium dioxide (TiO_2)	1.71	1.54	1.50	0.48	2.12	1.71	1.47				
TOTAL	97.64	97.96	97.73	97.41	98.60	97.90	96.57				
Acid/base ratio	12.26	7.74	5.05	0.62	6.98	4.30	4.91				
P in ash	0.03	0.03	0.12	0.05	0.06	0.20	0.08				
X-ray Fluorescence (ppm, ash basis)											
Barium (Ba)	1,157.00	1,058.00	1,367.00	627.00	758.00	1,843.00	1,133.00				
Cerium (Ce)	220.00	191.00	291.00	143.00	227.00	344.00	216.00				
Chromium (Cr)	175.00	203.00	217.00	146.00	214.00	264.00	239.00				
Cobalt (Co)	78.00	91.00	86.00	59.00	31.00	13.00	79.00				
Copper (Cu)	180.00	170.00	179.00	31.00	128.00	178.00	160.00				
Gallium (Ga)	73.00	68.00	57.00	24.00	53.00	66.00	64.00				
Lanthanum (La)	99.00	83.00	132.00	65.00	108.00	161.00	92.00				
Lead (Pb)	80.00	89.00	60.00	11.00	63.00	61.00	55.00				
Nickel (Ni)	197.00	232.00	493.00	100.00	91.00	648.00	511.00				
Niobium (Nb)	56.00	49.00	50.00	19.00	49.00	60.00	58.00				
Rubidium (Ru)	98.00	82.00	97.00	12.00	66.00	48.00	85.00				
Strontium (Sr)	1,638.00	1,647.00	1,163.00	142.00	355.00	1,690.00	614.00				
Thorium (Th)	31.00	29.00	25.00	< 10	42.00	27.00	16.00				
Uranium (U)	< 10	122.00	< 10	< 10	72.00	< 10	44.00				
Vanadium (V)	315.00	396.00	360.00	150.00	320.00	426.00	454.00				
Yttrium (Y)	188.00	127.00	158.00	53.00	80.00	235.00	157.00				
Zinc (Zn)	98.00	158.00	222.00	31.00	48.00	161.00	219.00				
Zirconium (Zr)	499.00	430.00	362.00	90.00	338.0	432.00	391.00				

Sample ID	*3059*	*3060*	*3061*	*3062*	*3063*	*3064*	*3065*	*3066*	*3067*	*3068*	*3069*	*3070*
X-ray Fluorescence (%, ash basis)												
Aluminum oxide (Al_2O_3)			29.12		30.47	30.87	30.25	24.70	30.41	26.92	29.06	29.17
Barium oxide (BaO)			0.08		0.09	0.11	0.10	0.08	0.11	0.10	0.09	0.14
Calcium oxide (CaO)			1.59		1.46	2.86	2.62	3.28	2.69	1.75	1.83	2.75
Ferric oxide (Fe_2O_3)			6.61		11.18	17.40	14.69	10.20	14.61	12.75	6.08	7.04
Magnesium oxide (MgO)			0.94		0.94	0.68	0.86	1.12	0.83	0.75	0.84	0.93
Phosphorus pentoxide (P_2O_5)			0.12		0.30	0.19	0.19	0.17	0.18	0.11	0.11	0.28
Potassium oxide (K_2O)			3.14		3.37	1.60	2.43	2.76	2.36	2.04	2.25	2.31
Silicon dioxide (SiO_2)			52.06		47.17	40.84	43.58	49.42	43.13	50.26	53.84	51.07
Sodium oxide (Na_2O)			0.62		0.70	0.51	0.46	0.65	0.56	0.37	0.41	0.45
Strontium oxide (SrO)			0.06		0.10	0.18	0.14	0.10	0.14	0.13	0.10	0.21
Sulfur trioxide (SO_3)			1.17		1.00	2.51	2.68	2.96	2.53	1.32	1.45	2.33
Titanium dioxide (TiO_2)			1.57		0.92	0.81	1.04	1.25	1.02	1.49	1.59	1.50
TOTAL			97.63		97.71	98.58	99.06	96.72	98.59	98.01	97.66	98.20
Acid/base ratio			6.46		4.45	3.15	3.56	4.18	3.54	4.45	7.40	6.06
P in ash			0.03		0.07	0.04	0.04	0.04	0.04	0.02	0.02	0.06
X-ray Fluorescence (ppm, ash basis)												
Barium (Ba)			773.00		910.00	1,161.00	1,008.00	863.00	1,106.00	1,001.00	855.00	1,356.00
Cerium (Ce)			231.00		376.00	338.00	290.00	231.00	291.00	264.00	266.00	282.00
Chromium (Cr)			154.00		155.00	218.00	260.00	214.00	252.00	210.00	200.00	220.00
Cobalt (Co)			12.00		69.00	85.00	81.00	67.00	81.00	88.00	104.00	96.00
Copper (Cu)			77.00		141.00	156.00	158.00	154.00	156.00	138.00	156.00	166.00
Gallium (Ga)			46.00		51.00	64.00	57.00	53.00	60.00	56.00	63.00	65.00
Lanthanum (La)			113.00		119.00	134.00	105.00	79.00	126.00	121.00	119.00	120.00
Lead (Pb)			37.00		45.00	53.00	102.00	104.00	66.00	51.00	65.00	79.00
Nickel (Ni)			65.00		153.00	192.00	194.00	175.00	192.00	169.00	248.00	219.00
Niobium (Nb)			35.00		25.00	28.00	31.00	34.00	31.00	34.00	41.00	40.00
Rubidium (Ru)			136.00		127.00	51.00	87.00	108.00	78.00	76.00	108.00	93.00
Strontium (Sr)			639.00		1,101.00	1,586.00	1,260.00	1,062.00	1,295.00	1,279.00	1,240.00	2,622.00
Thorium (Th)			< 10		< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Uranium (U)			< 10		< 10	< 10	< 10	52.00	< 10	17.00	111.00	104.00
Vanadium (V)			215.00		266.00	387.00	439.00	418.00	451.00	309.00	288.00	375.00
Yttrium (Y)			76.00		111.00	110.00	97.00	89.00	97.00	97.00	126.00	121.00
Zinc (Zn)			38.00		159.00	166.00	189.00	206.00	190.00	139.00	170.00	174.00
Zirconium (Zr)			317.00		225.00	265.00	258.00	313.00	260.00	328.00	383.00	446.00

Sample ID	*3071*	*3072*	*3073*	*3074*	*3075*	*3076*	*3077*	*3078*	*3079*	*3080*	*3080*	*3081*
X-ray Fluorescence (%, ash basis)												
Aluminum oxide (Al_2O_3)	30.90	29.82	31.06	27.62					25.90			31.11
Barium oxide (BaO)	0.06	0.16	0.22	0.18					0.14			0.18
Calcium oxide (CaO)	0.96	2.51	2.20	2.01					2.23			3.67
Ferric oxide (Fe_2O_3)	4.15	8.07	9.22	14.88					9.71			8.73
Magnesium oxide (MgO)	0.83	0.97	0.84	0.99					1.04			0.85
Phosphorus pentoxide (P_2O_5)	0.18	0.14	0.27	0.14					0.14			0.18
Potassium oxide (K_2O)	2.33	2.30	1.84	2.83					2.58			1.20
Silicon dioxide (SiO_2)	55.83	50.22	48.05	46.34					51.73			46.51
Sodium oxide (Na_2O)	0.22	0.57	0.42	0.42					0.95			0.79
Strontium oxide (SrO)	0.06	0.23	0.34	0.23					0.17			0.32
Sulfur trioxide (SO_3)	0.35	2.36	2.10	1.79					1.85			2.83
Titanium dioxide (TiO_2)	1.62	1.33	1.35	1.26					1.26			1.90
TOTAL	97.50	98.70	97.93	98.71					97.73			98.28
Acid/base ratio	10.41	5.64	5.54	3.56					4.78			5.22
P in ash	0.04	0.03	0.06	0.03					0.03			0.04
X-ray Fluorescence (ppm, ash basis)												
Barium (Ba)	685.00	1,670.00	2,251.00	1,719.00					1,417.00			1,795.00
Cerium (Ce)	277.00	312.00	481.00	330.00					233.00			309.00
Chromium (Cr)	228.00	212.00	173.00	204.00					187.00			321.00
Cobalt (Co)	92.00	95.00	100.00	94.00					96.00			< 10
Copper (Cu)	152.00	177.00	177.00	153.00					139.00			52.00
Gallium (Ga)	65.00	68.00	73.00	60.00					66.00			64.00
Lanthanum (La)	123.00	119.00	219.00	135.00					89.00			114.00
Lead (Pb)	77.00	53.00	61.00	49.00					43.00			70.00
Nickel (Ni)	220.00	235.00	273.00	224.00					262.00			968.00
Niobium (Nb)	44.00	40.00	41.00	33.00					37.00			76.00
Rubidium (Ru)	117.00	99.00	75.00	95.00					106.00			40.00
Strontium (Sr)	778.00	2,959.00	4,447.00	2,214.00					1,793.00			4,127.00
Thorium (Th)	< 10	< 10	< 10	< 10					< 10			< 10
Uranium (U)	149.00	89.00	100.00	10.00					66.00			93.00
Vanadium (V)	347.00	386.00	340.00	406.00					359.00			683.00
Yttrium (Y)	122.00	148.00	198.00	115.00					118.00			253.00
Zinc (Zn)	166.00	196.00	246.00	218.00					250.00			223.00
Zirconium (Zr)	362.00	447.00	563.00	351.00					363.00			791.00

Sample ID	*3043*	*3044*	*3045*	*3046*	*3050*	*3051*	*3052*	*3053*	*3054*	*3055*	*3057*	*3058*
X-ray Fluorescence (%, ash basis)												
Aluminum oxide (Al_2O_3)												
Barium oxide (BaO)												
Calcium oxide (CaO)												
Ferric oxide (Fe_2O_3)												
Magnesium oxide (MgO)												
Phosphorus pentoxide (P_2O_5)												
Potassium oxide (K_2O)												
Silicon dioxide (SiO_2)												
Sodium oxide (Na_2O)												
Strontium oxide (SrO)												
Sulfur trioxide (SO_3)												
Titanium dioxide (TiO_2)												
TOTAL												
Acid/base ratio												
P in ash												
X-ray Fluorescence (ppm, ash basis)												
Barium (Ba)												
Cerium (Ce)												
Chromium (Cr)												
Cobalt (Co)												
Copper (Cu)												
Gallium (Ga)												
Lanthanum (La)												
Lead (Pb)												
Nickel (Ni)												
Niobium (Nb)												
Rubidium (Ru)												
Strontium (Sr)												
Thorium (Th)												
Uranium (U)												
Vanadium (V)												
Yttrium (Y)												
Zinc (Zn)												
Zirconium (Zr)												

Sample ID	*3082*	*3083*	*3084*	*3085*	*3086*
X-ray Fluorescence (%, ash basis)					
Aluminum oxide (Al_2O_3)		24.60		28.46	27.72
Barium oxide (BaO)		0.39		0.18	0.09
Calcium oxide (CaO)		8.10		4.12	2.49
Ferric oxide (Fe_2O_3)		16.16		15.19	13.15
Magnesium oxide (MgO)		1.76		1.17	0.91
Phosphorus pentoxide (P_2O_5)		0.26		0.23	0.19
Potassium oxide (K_2O)		1.40		1.78	2.37
Silicon dioxide (SiO_2)		31.45		42.04	47.79
Sodium oxide (Na_2O)		2.15		0.61	0.54
Strontium oxide (SrO)		0.82		0.25	0.12
Sulfur trioxide (SO_3)		8.76		3.03	2.01
Titanium dioxide (TiO_2)		1.22		1.21	1.05
TOTAL		97.11		98.30	98.46
Acid/base ratio		1.94		3.14	3.93
P in ash		0.06		0.05	0.04
X-ray Fluorescence (ppm, ash basis)					
Barium (Ba)		3,579.00		1,859.00	911.00
Cerium (Ce)		290.00		357.00	263.00
Chromium (Cr)		401.00		349.00	207.00
Cobalt (Co)		< 10		< 10	77.00
Copper (Cu)		89.00		118.00	148.00
Gallium (Ga)		76.00		75.00	58.00
Lanthanum (La)		103.00		128.00	117.00
Lead (Pb)		53.00		57.00	60.00
Nickel (Ni)		1,193.00		841.00	192.00
Niobium (Nb)		52.00		50.00	29.00
Rubidium (Ru)		39.00		59.00	81.00
Strontium (Sr)		9,121.00		2,351.00	1,149.00
Thorium (Th)		< 10		< 10	< 10
Uranium (U)		< 10		< 10	16.00
Vanadium (V)		657.00		559.00	357.00
Yttrium (Y)		208.00		205.00	92.00
Zinc (Zn)		320.00		315.00	179.00
Zirconium (Zr)		811.00		450.00	274.00

Appendix 5: Metallurgical Parameters

Sample ID	*2977*	*2990*	*3004*	*3026*	*3028*	*3031*	*3032*	*3037*	*3038*	*3068*	*3069*	*3070*
Proximate/sulfur/free swelling index												
% volatile matter (dry, ash free)	36.32	40.04	39.63	40.53	40.05	40.76	40.67	39.96	39.37	40.55	39.55	41.47
% ash (dry basis)	8.87	5.98	6.47	4.36	7.42	7.16	7.33	2.33	4.10	9.88	9.55	9.69
total sulfur (dry basis)	0.73	1.31	1.25	1.47	0.84	0.69	0.90	0.72	0.73	1.88	0.95	1.24
free swelling index	2.00	3.00	5.50	6.50	5.50	6.50	5.50	7.50	7.50	6.50	4.00	4.50
Gieseler plasticity												
maximum fluidity (dial divisions per minute)	4.00	8.00	430.00	30,000.00	1,334.00	1,622.00	461.00	30,000.00	30,000.00	4,004.00	317.00	773.00
maximum fluidity temperature (°C)	426.00	425.00	432.00	430.00	428.00	440.00	434.00	418.00	424.00	426.00	434.00	427.00
softening temperature (°C)	406.00	396.00	393.00	390.00	389.00	405.00	398.00	388.00	382.00	383.00	398.00	393.00
solidification temperature (°C)	446.00	446.00	461.00	467.00	459.00	470.00	464.00	470.00	471.00	460.00	461.00	458.00
plastic range	40.00	50.00	68.00	77.00	70.00	65.00	66.00	82.00	89.00	77.00	63.00	65.00
Arnu dilatation												
maximum contraction (%)	–28.00	–29.00	–27.00	–25.00	–27.00	–23.00	–25.00	–26.00	–28.00	–25.00	–24.00	–24.00
maximum dilatation (%)	ND	ND	+15	+79	+50	+17	+8	+160	+154	+31	–9	+4
initial softening temperature (°C)	380.00	366.00	354.00	344.00	353.00	359.00	361.00	338.00	343.00	347.00	368.00	357.00
initial dilatation temperature (°C)	440.00	441.00	411.00	399.00	403.00	414.00	411.00	401.00	399.00	401.00	419.00	413.00
maximum dilatation temperature (°C)	NA	NA	450.00	448.00	445.00	449.00	451.00	458.00	460.00	443.00	450.00	442.00
ASTM % dilatation (2.5 g, air dry)	ND	ND	26.00	101.00	62.00	33.00	19.00	194.00	181.00	41.00	–2.00	17.00
acid/base ratio	6.03	4.21	4.58	2.36	10.80	12.26	7.74	4.30	4.91	4.45	7.40	6.06
% P_2O_5 in ash	0.11	0.11	0.11	0.28	0.16	0.14	0.14	0.91	0.36	0.11	0.11	0.28
Coal petrography												
total reactives (mmf)	90.67	84.40	82.40	76.27	87.73	80.40	78.26	80.40	89.47	92.40	87.33	86.93
total reactives (volume %)	81.62	78.34	76.07	72.06	80.30	73.88	71.68	78.06	85.14	81.58	77.87	77.24
total organic inerts (volume %)	8.40	14.48	16.25	22.43	11.23	18.01	19.91	19.03	10.03	6.71	11.30	11.61
mineral matter (volume %)	9.98	7.18	7.68	5.52	8.48	8.11	8.41	2.91	4.83	11.70	10.84	11.15
total inerts (volume %)	18.38	21.66	23.93	27.94	19.70	26;12	28.32	21.94	14.86	18.42	22.13	22.76
calculated Ro max (Ro random × 1.066)	0.90	0.81	0.88	0.88	0.87	0.87	0.88	0.94	0.96	0.83	0.91	0.85
composition balance index	0.59	0.80	0.85	1.05	0.69	0.99	1.11	0.73	0.45	0.63	0.74	0.80
strength index	3.50	3.00	3.60	3.60	3.30	3.60	3.60	3.70	3.60	3.00	3.60	3.30
coal strength after reaction potential	42.00	34.00	49.00	48.00	40.00	48.00	47.00	49.00	42.00	32.00	46.00	40.00

Sample ID	*3071*	*3072*	*3074*	*3079*	*3081*	*3083*	*3085*	*3086*
Proximate/sulfur/free swelling index								
% volatile matter (dry, ash free)	40.69	40.24	42.27	37.65	37.97	39.63	39.22	42.34
% ash (dry basis)	11.43	6.81	8.84	6.43	2.22	1.15	2.04	10.50
total sulfur (dry basis)	0.87	1.11	1.87	1.05	0.93	0.77	0.91	1.99
free swelling index	3.00	6.00	4.00	8.00	4.50	4.00	5.00	4.50
Gieseler plasticity								
maximum fluidity (dial divisions per minute)	28.00	2,661.00	1,521.00	29,905.00	671.00	1,710.00	457.00	145.00
maximum fluidity temperature (°C)	432.00	427.00	428.00	423.00	432.00	431.00	429.00	426.00
softening temperature (°C)	396.00	385.00	389.00	385.00	395.00	392.00	387.00	385.00
solidification temperature (°C)	447.00	460.00	459.00	478.00	463.00	464.00	455.00	451.00
plastic range	51.00	75.00	70.00	93.00	68.00	72.00	68.00	66.00
Arnu dilatation								
maximum contraction (%)	–24.00	–25.00	–24.00	–29.00	–28.00	–20.00	–21.00	–23.00
maximum dilatation (%)	ND	+55	+29	+158	+34	+50	+20	-4
initial softening temperature (°C)	360.00	353.00	352.00	349.00	367.00	351.00	357.00	358.00
initial dilatation temperature (°C)	423.00	399.00	408.00	394.00	408.00	407.00	409.00	408.00
maximum dilatation temperature (°C)	NA	444.00	447.00	457.00	446.00	443.00	444.00	451.00
ASTM % dilatation (2.5 g, air dry)	ND	73.00	41.00	176.00	47.00	76.00	41.00	4.00
acid/base ratio	10.41	5.64	3.56	4.78	5.22	1.94	3.14	3.93
% P_2O_5 in ash	0.14	0.14	0.14	0.18	0.26	0.23	0.19	
Coal petrography								
total reactives (mmf)	88.40	88.40	92.13	85.07	87.07	93.33	92.80	83.87
total reactives (volume %)	77.06	81.36	82.39	78.67	84.53	91.78	90.29	73.44
total organic inerts (volume %)	10.11	10.68	7.04	13.81	12.56	6.56	7.01	14.13
mineral matter (volume %)	12.82	7.97	10.58	7.52	2.91	1.67	2.70	12.43
total inerts (volume %)	22.94	18.64	17.61	21.33	15.47	8.22	9.71	26.56
calculated Ro max (Ro random × 1.066)	0.85	0.94	0.89	0.98	0.89	0.89	0.91	0.82
composition balance index	0.80	0.57	0.56	0.68	0.48	0.23	0.28	1.01
strength index	3.30	3.60	3.40	3.80	3.40	3.10	3.20	3.00
coal strength after reaction potential	40.00	44.00	40.00	51.00	38.00	18.00	24.00	34.00