Indiana Coals
and the Steel Industry

Special Report 64

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INDIANA COALS AND THE STEEL INDUSTRY

By Hardarshan S. Valia and Maria Mastalerz

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ABSTRACT

This report discusses the characteristics of Indiana coals with regard to their application in the steel industry. We examine the coal characteristics that are favorable for the application of coal in coking blends and those that are suitable for application in pulverized coal injection. We demonstrate that selected Brazil Formation coals have superior coking properties and could be successfully used in coking blends. They possess high fluidity, high fluid range, and an unusually high amount of contraction for such a low-rank coal. In addition to their higher fluid properties, some of these coals, when compared, for example, with similar ranked Illinois coals, are characterized by lower sulfur, lower alkalies, and lower chlorine contents. The higher fluidity coupled with lower sulfur contents and a lower alkali index of some of the Brazil Block coals result in high predicted and actual coke strength after reaction. Replacement ratio is an important parameter in the evaluation of coal for pulverized coal injection applications. Because of their higher hydrogen content, some Indiana coals, particularly Brazil Formation coals, have a moderate predicted replacement ratio, which makes these coals attractive for use in blast furnace pulverized coal injection. The locations of coals having adequate replacement ratios are listed.

INTRODUCTION

Background

Indiana coal was first used to make coke for the production of iron in the state's blast furnaces in the latter part of the nineteenth century. In the mid-1870s, coal from the Brazil Formation was used to make coke in 20 beehive ovens located around Brazil, Indiana (Warren, 2001). By 1886 there were about 45,000 coke ovens in the United States; fewer than 200 of these were slot ovens (Hogan, 1971). The state of the coking and steel industry in Indiana during the late 1800s is described in a report by Weeks (1885):

> "In 1876, about 15 coking coal seams were recognized in Indiana, some of which 7-8 ft thickness were found in 14 counties, producing coke yield from 52-64.50%. However, coke production was meager, about 1000 tons in that year. This coke was charged into blast furnace replacing coke made from good coking Cannellsville coal of Pennsylvania with satisfactory results. Professor Cox of Indiana Geological Survey did carbonization tests of Brazil Block under pressure (slot oven carbonization) and concluded that it made remarkable strong and dense coke. The most detailed use of Indiana coal usage was in North Chicago Rolling Mill Company in 1882 which possessed a series of slot ovens. 100% of Indiana coal, Coal Creek from Fountain County, was initially used but the coke quality was inferior. However, when mixed with 10-15% Cannellsville of Pennsylvania, fairly good results were obtained."

Beehive cokemaking was the principal mode of coke production and was gradually replaced by slot-oven coke production from about 1900 to 1920. Slot-oven production increased from 60 percent in 1920 to 94.2 percent in 1930 (Hogan, 1971).

In the 1800s, interest in Indiana coals for use in cokemaking was high. There were attempts to lower the use of costly coking coal from Pennsylvania by substituting it with less expensive local coals, especially those from the Brazil Formation. Today, however, no Indiana coal is used in coal blends for cokemaking. In order to lower the cost of coke plant operations while maintaining high coke quality, various steel companies around the world use low-value carbon materials, such as noncoking coals. Iwakiri (1990) described a mechanism for using 15 percent noncoking coal (0.65 percent reflectance). Valia and Hooper (1994) detailed two months of plant-scale coke production that used 16 percent of Brazil Formation coals (0.58 percent vitrinite reflectance); thereafter, the producers increased the amount to 23 percent.

The challenge to today's coke producers is to design a blend that will consistently produce low-cost, high-quality coke that has a safe coke charge pushing from the ovens. A higher contraction of coke mass from the oven walls aids in pushing the coke charge, an important factor in prolonging the

useful lifetime of a battery. One way to answer this challenge is to design a coal blend that includes relatively inexpensive carbon materials that do not compromise the quality of the resultant coke. Indiana coal meets these requirements.

Indiana Coal Production

Figure 1 shows coal production trends in Indiana since 1879, including both coking and noncoking coals. From the middle of the nineteenth century, production from underground mines increased steadily until 1910. Around 1910, demand for coal decreased, which together with the declining marketability of Illinois Basin coal resulted in a drop in coal production from underground operations. Low heating values and high sulfur contents as compared to eastern coals, as well as high salaries paid to unionized miners in Indiana and Illinois, were among the factors that limited the development of underground mining in Indiana (Harper, 1981).

Indiana, along with Illinois, Ohio, and western Pennsylvania, was the part of so-called "Central Competitive Field" that accounted for almost 40 percent of total U.S. coal production at the turn of the century. The operators and union representatives of these states met periodically to adjust wages and settle questions of labor policy. In the period before World War I, this organization evidently helped shield the midwestern operators from competition elsewhere. This organization, however, ceased to exist during the war (Harper, 1981).

The events of World War I resulted in a brief doubling of Indiana production, but it was short-lived. After 1923, newer non-union coal fields (for example, those in West Virginia) attracted consumers in Chicago as well as in Indiana and Illinois, causing a dramatic decline in Indiana underground coal production to levels far below those that occurred just prior to the war. In addition, control of underground mining was consolidating in the hands of a few large companies whose operations needed thick coal seams to be economically viable. By the 1960s, limited resources of thick and laterally extensive coals precluded the development of underground mining in Indiana. At the same time, the development of less expensive surface mining proved to be a viable alternative. Since that time, surface mining has dominated the industry. In recent years, approximately 30 to 40 surface mines have been active in Indiana, in comparison with three to five underground mines.

Figure 2 shows the locations of active surface and underground mines in Indiana on the framework of mined-out areas. This map, as well as the Directory of Coal Mines in Indiana (Eaton and Gerteisen, 2000), is available from the Indiana Geological Survey.

Steel Industry in Indiana

The beginning of the steel industry in Indiana dates back to 1901, when the region's first steel manufacturing company (later named the Inland Steel Corporation and now known as Ispat Inland) began operations in East Chicago. The first ingots were poured from the new open hearth steel mill in July 1902 (Moore, 1959). In 1906, the U.S. Steel Corporation began construction of its mills along the lakefront farther

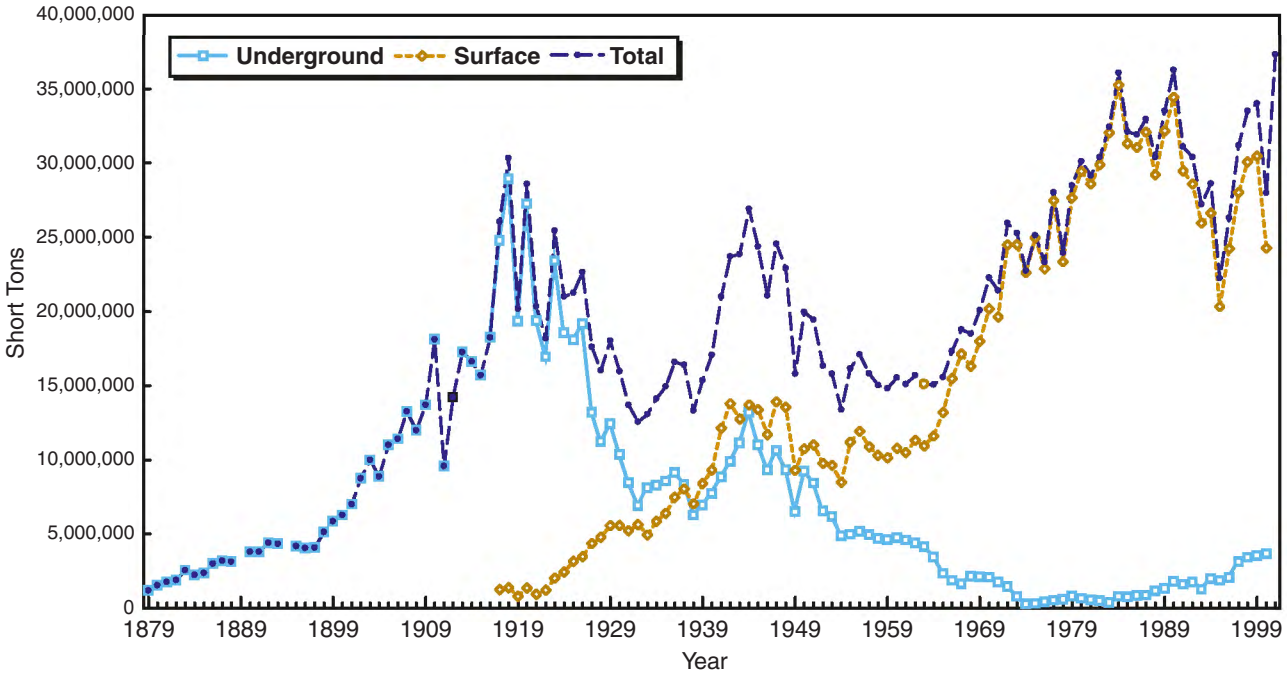


Figure 1. Graph showing coal production in Indiana (in short tons) (sources: U.S. Geological Survey, U.S. Bureau of Mines, and Indiana Bureau of Mines and Mining Safety).

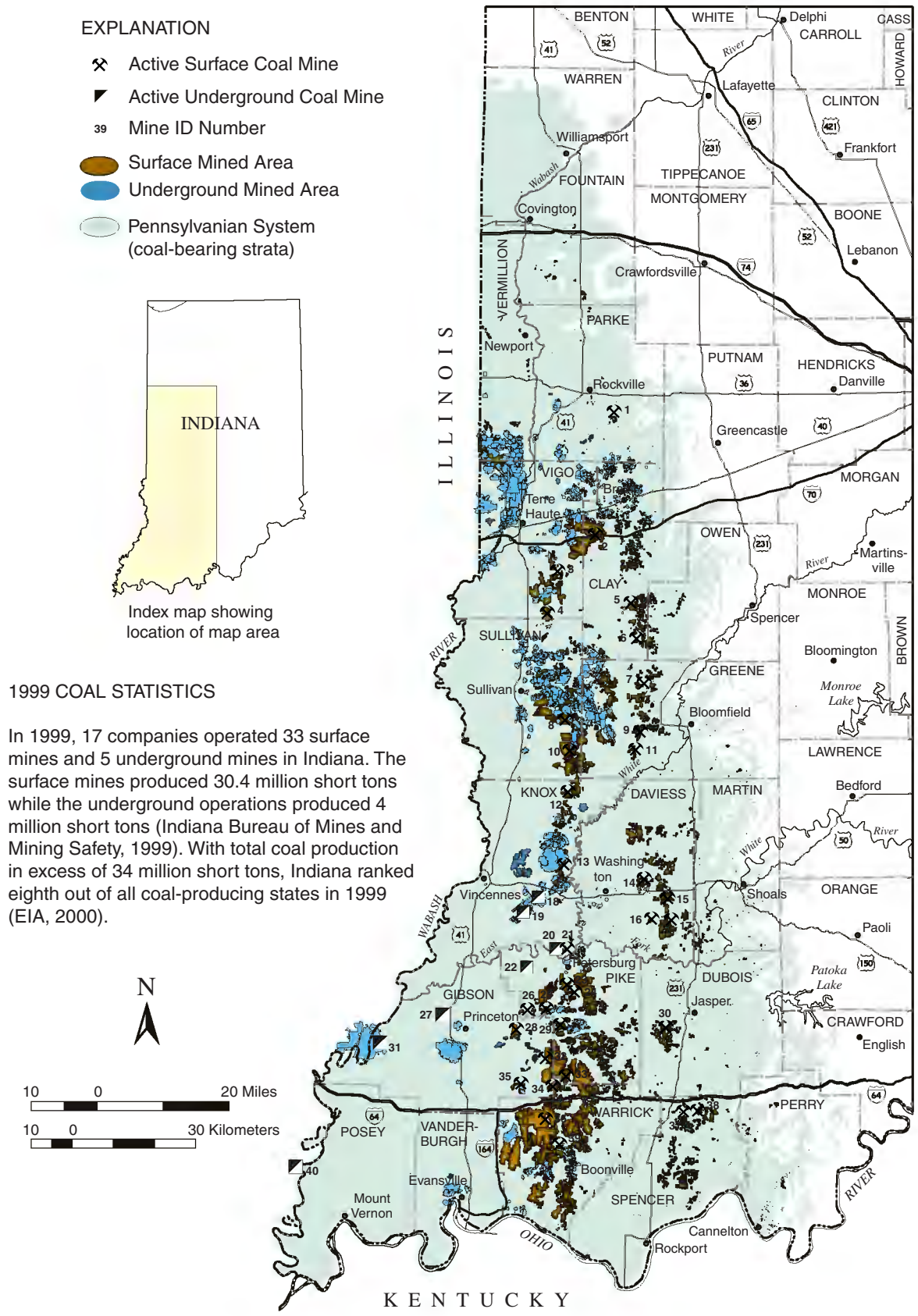


Figure 2. Map showing active and abandoned coal mines in Indiana (after Eaton, 2000).

east. The city of Gary was built nearby on the Grand Calumet River to accommodate the steelworkers and the plant became known as the Gary plant (Romano, 1976). The Gary plant had a similar design to Inland Steel's East Chicago plant, but on a much larger scale. It went into operation in 1909 (Reshkin and others, 1991) and by 1910, steel and finished metal processing were the leading industries in the Calumet area.

In 1916, American Sheet and Tube Company started its steel plant directly across from Inland Steel on the Indiana Harbor. The Youngstown Sheet and Tube Company purchased the American Sheet and Tube Company in 1929 (Moore, 1959). Other steel companies operating in the area included the American Steel Foundries and Gary Sheet and Tin Mill. Subsequently, two other steel companies entered the Portage-Burns Harbor region of northwest Indiana; National Steel Company's Midwest Division opened in 1959 and, just a few years later, Bethlehem Steel opened their mills at Burns Harbor.

By 1919, the majority of steel mills were using open hearth techniques that consumed more scrap metal than earlier Bessemer furnaces (Golten, 1985). By 1929, the Youngstown Sheet and Tube Company was producing 1.7 million tons of steel using 16 open hearth furnaces and three blast furnaces. By 1943, Inland Steel was producing over 3.5 million ingot tons of steel annually from eight blast furnaces, six coke batteries, and 36 open hearth furnaces (Reshkin and others, 1991). At that time, U.S. Steel's production was estimated at 5 million ingot tons. Clearly, it was a dramatic increase compared with the early years (1880), when the state's total iron production was only 95,468 net tons (Hogan, 1971). Steel production trends over the last two decades (Table 1) show Indiana replacing Pennsylvania as the leading producer of steel in the nation. The development of new midwestern markets, Indiana's proximity to iron ore reserves, and lower production costs all contributed to this change (Hogan, 1971).

The steel industry has experienced rapid changes in recent years. As a result of new investments and reorganization, the industry has decreased production costs and prices for their products. Four integrated mills are currently operating in Indiana: Bethlehem Steel Corporation located in Burns Harbor, Ispat Inland, Inc. (formerly Inland Steel Company) in East Chicago, International Steel Group in East Chicago (formerly LTV/Youngstown Sheet and Tube Company), and U.S. Steel Corporation in Gary. In addition, several rolling mills and steel processing plants are operating in Indiana.

Table 1. Raw steel production in Pennsylvania and Indiana (in net tons) (AISI, 2002)

	1980	1990	2000
Penn.	23,517,000	21,231,000	7,926,000
Indiana	19,820,000	12,049,000	25,667,000
Total in U.S.	111,835,000	98,906,000	112,242,000

One of the most significant changes in the American steel industry was the development of the electric arc furnace (EAF), also known as the "minimill," which converts scrap from many sources (for example, bridges, automobiles, and refrigerators) to steel, thus bypassing the labor- and cost-intensive blast furnace technique. The term "minimill" derives from the mill's relatively small size compared to traditional integrated mills. Since the 1980s, minimills have accounted for an important portion of steel production in the United States. Recycling scrap in highly efficient electric furnaces and continuously installing new capacity, minimills now produce approximately 46 percent of U.S. steel. They are profitable and their share is expected to continue to grow, partly at the expense of integrated mills.

Indiana has a leading role in the minimill industry. Nucor, located in Crawfordsville, is one of the largest minimills in the nation. It pioneered thin slab casting more than a decade ago, and recently has ventured into direct strip casting of carbon steels. Its annual capacity is 1,800,000 tons of hot-rolled, cold-rolled and galvanized products (Nucor Sheet Mill Group, 2002). The recent decline in steel prices is closely related to the decline in scrap prices, as well as to the much faster decline in total production costs; these price declines make the minimills more profitable, despite the decrease in the prices of their products.

The newest minimill in northwest Indiana is the Butler minimill, of Iron Dynamics, Inc. Its production commenced in 1996; current production is about 2.2 million tons per year for flat material with a capacity of 2.4 million tons per year in the plant's two casters (Steel Technology, 2002). This plant is of special interest to the coal industry because it has the ability to combine ore fines and coal into pellets.

Coke Manufacturing in Indiana

Because coke is a critical raw material for ironmaking, the history of coke production is strongly linked to the development of the steel industry. In 1988, world coke demand was about 346 million metric tons; it is expected to rise to about 393 million metric tons by 2005 (IISI, 1997). However, cokemaking capacity in the United States has been declining. According to Hogan and Koelble (1996), U.S. cokemaking capacity in mid-1979 was 57.1 million net tons (51.78 million metric tons); in mid-1988, 28.6 million net tons (25.94 million metric tons); and in 1996, 22.7 million net tons (20.59 million metric tons). Coke production and consumption in the United States is shown in Table 2.

Table 2. United States coke production data (in thousand net tons) (Marcus, 2002)

Production	1995	2000	2001	2005 forecast
Coke required by blast furnace (AISI)	24,469	21,181	18,999	15,200
Coke required by foundry/other	1,376	2,061	1,294	1,800
Total coke consumption (DOE)	25,845	23,242	20,293	17,000
Domestic coke practical capacity	20,820	19,540	17,750	12,000
U.S. coke production (DOE)	23,749	20,808	18,949	11,500
Imports (DOE)	3,820	3,781	2,340	5,500
Pulverized coal injection usage	1,851	4,751	4,177	4,800

The decline in cokemaking capacity was dramatic during the 1980s; thereafter, it has declined rather steadily. Cokemaking capacity in the U.S. for the year 2000 was about 19.54 million net tons (21.89 million metric tons). The decline in cokemaking capacity is due to the following reasons: 1) a reduction in the number of blast furnaces utilizing coke, 2) the higher cost of operation because of aging batteries, and 3) a reduction in the coke volume for blast furnaces. A dramatic drop in ironmaking production by blast furnace can be summarized as follows: in 1979, 79.9 million net tons; in 1985, 50.4 million net tons; in 1995, 56.1 million net tons; and in 2000, 52.79 million net tons (data compiled from AISI, 2002). A decline in cokemaking capacity causes a decline in the demand for coking coal (fig. 3).

Indiana is an important producer of coke and fulfills about 30 percent of U.S. coke capacity. The following Indiana coke plants were producing coke by blast furnace in the year 2000: Bethlehem Burns Harbor, 1.8 million tons; U.S. Steel Gary Works, 2.7 million tons; SUN Indiana Harbor Coke Company, 1.3 million tons; Citizens Gas & Coke, 0.25 million tons.

Similar to the national trend, however, there has been a general decline in the consumption of coking coal in Indiana (fig. 4). In 1989, coking coal consumption in Indiana was about 10 million short tons, whereas in 1997 it was about 6 million short tons. Coking coal for cokemaking in Indiana has come from West Virginia, Virginia, Kentucky, Pennsylvania, Alabama, and western Canada. It should be noted that, except during the nineteenth century, no significant amount of Indiana coal has been used for metallurgical cokemaking.

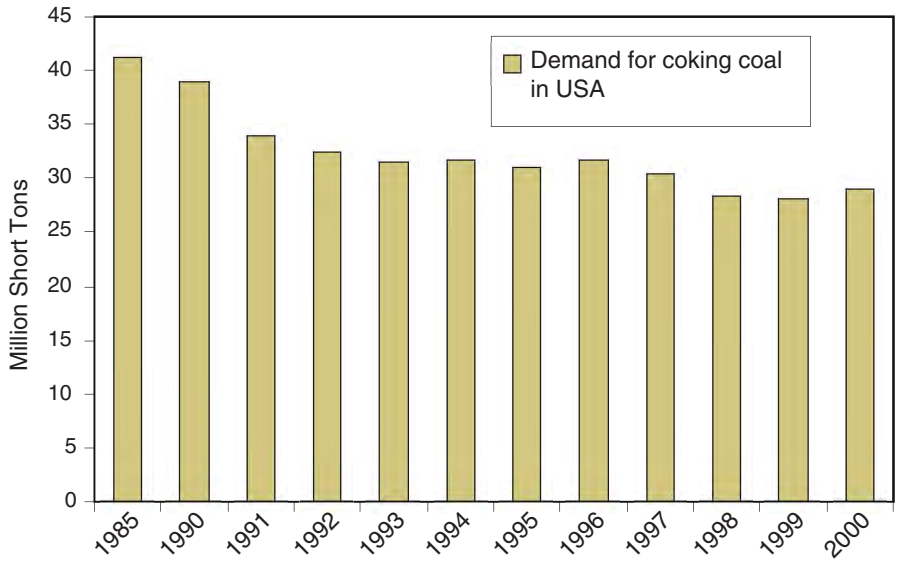


Figure 3. Graph showing the demand for coking coal in the United States (EIA, 2000).

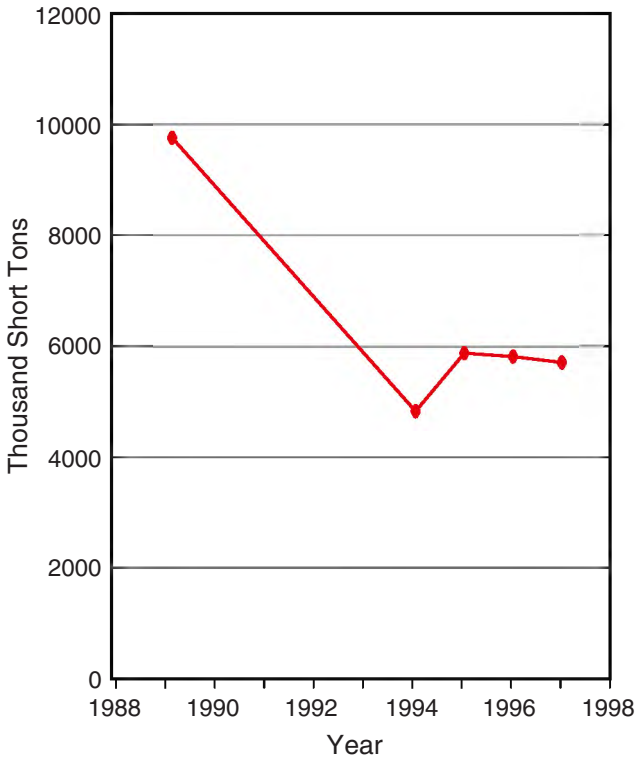


Figure 4. Graph showing the demand for coking coal in Indiana (EIA, 2000).

GEOLOGY OF INDIANA COAL

Stratigraphy

The coal-bearing Pennsylvanian strata of Indiana include three major stratigraphic units: the Raccoon Creek Group, the Carbondale Group, and the McLeansboro Group. Figure 5 presents the stratigraphy of coal seams in Indiana and correlations with the coal seams of western Kentucky and Illinois. This correlation is based on the compilation of Mastalerz and Harper (1998), with an addition of a recent shift of the position of the Seelyville Coal Member into the Carbondale Group by the Tri-State Correlation Committee (2001).

The Raccoon Creek Group extends from the base of the Pennsylvanian System (below the French Lick Coal Member) to the base of the Seelyville Coal Member. This group consists of three formations: the Mansfield Formation (50 to more than 800 feet thick), the Brazil Formation, 30 to 90 feet thick (Hutchison, 1960), and the Staunton Formation, which ranges in thickness from 75 to 150 feet (Shaver and others, 1986). Several coal beds of the Raccoon Creek Group—the Blue Creek, Mariah Hill, Lower Block, Upper Block, and Minshall/Buffaloville Coal Members—are of economic interest to Indiana because locally they contain low-sulfur coal. The Raccoon Creek Group coals, and those of the Brazil Formation in particular, are of interest for coke manufacturing, because of their favorable coking behavior (Valia and Hooper, 1994).

Coal beds of the Carbondale Group account for most of the large-scale mining operations in Indiana because of the thick and laterally extensive Springfield and Danville Coal Members. The Carbondale Group comprises three formations: the Linton Formation, the Petersburg Formation, and the Dugger Formation (fig. 5). The Linton Formation extends from the base of the Seelyville Coal Member to the top of the Survant Coal Member. The thickness of this formation ranges from 43 to 162 feet (Shaver and others, 1986). The Petersburg Formation has its upper boundary at the top of the Springfield Coal Member and ranges in thickness from 70 to 190 feet (Wier, unpub. data, 1965). The Dugger Formation overlies the Petersburg Formation and extends to the top of the Danville Coal Member; its thickness ranges from 73 to 185 feet. The sulfur contents of the coal beds of the Carbondale Group are generally higher than that of the coals of the Raccoon Creek Group, although some coals, the Danville coal, in particular, has relatively large low- and medium-sulfur coal resources.

The McLeansboro Group includes the Pennsylvanian strata above the Danville coal. This is a sequence that has no thick, extensive, or low-sulfur coals, and consequently has not been extensively mined.

Depositional Environments

Pennsylvanian rocks in Indiana are part of the Pennsylvanian System of the Illinois Basin. The Illinois Basin is a broad, shallow, troughlike structural depression. The sediment was transported into the basin from the northeast and the northwest in western Illinois (Potter, 1962, 1963). The source of sediment is generally thought to have been the southern part of the Canadian Shield and possibly the highlands of the Northern Appalachians. For many decades, the depositional environment of the Pennsylvanian Period in Indiana was considered a dominantly fluvial-deltaic setting with short-term marine transgressions and regressions. Such an interpretation was the basis for the so-called "cyclothem" concept, developed for the Pennsylvanian System in the Illinois Basin by H. R. Wanless and numerous co-workers (Wanless and others, 1969; Wanless and Wright, 1978). More recently, a tidally dominated coastal setting has been proposed for various Pennsylvanian intervals in Indiana (Kvale and Archer, 1990, 1991; Archer and Kvale, 1993). Arguments in support of various models continue.

Sources of Data on Quality of Indiana Coals

The best source of publicly available information on the quality of Indiana's coals is the Indiana Coal Analysis Database (ICAD) (Hasenmueller and Miller, 1992). Information on

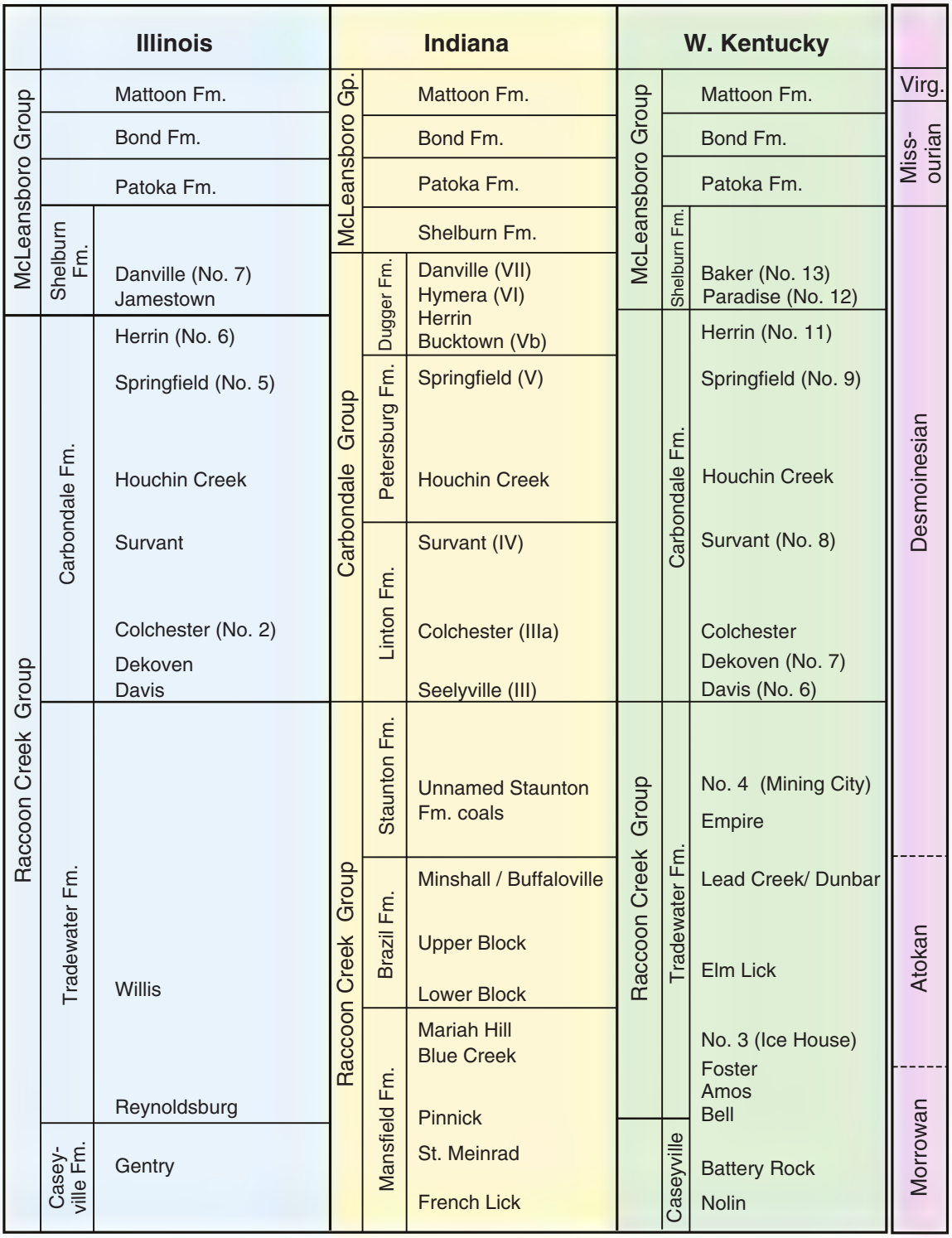


Figure 5. Chart showing the lithostratigraphy of coal-bearing strata in Indiana, Illinois, and western Kentucky (after Mastalerz and Harper, 1998; Tri-State Committee, 2001, and references within).

coal quality and other physical and chemical parameters of Indiana coals, including trace elements, is also included in the U.S. Geological Survey (USGS) Coal Quality (COALQUAL) Database (USGS, 1997). Limited data on the quality of Indiana coal is included in the Pennsylvania State University (Penn State) Coal Database. Descriptions of these databases can be found in Mastalerz and Harper (1998).

General Characteristics of Indiana Coals

The bituminous coal beds of Indiana are of high-volatile C to A rank (Mastalerz and Harper, 1998). On an as-received basis, fixed carbon ranges from 39 to 44 percent (namely, for mean values of individual coal beds), volatile matter ranges from 33 to 38 percent, and calorific value is typically between 10,500 and 12,000 Btu/lb, but is as much as 14,000 Btu/lb in places. Moisture content is commonly within the range of 5 to 15 percent, ash content within 5 to 20 percent, and sulfur content usually within the range of 0.5 to 5 percent. The petrographic composition of the coal varies; coal beds dominated by bright coal are common in the Petersburg and Dugger Formations, whereas duller coal dominates many of the Brazil Formation coal beds.

PROPERTIES OF INDIANA COALS WITH REGARD TO COKING

Coking Coal Characteristics

Table 3 shows ratings of coals for coking, and Table 4 presents coke quality specifications for blast furnaces. Indiana coal, which is mainly high-volatile bituminous C rank (lower than that presented in Table 3), cannot be classified based solely on these criteria because of its low rank. However, with regard to characteristics such as sulfur, ash, and ash chemistry, a significant percentage of Indiana's coal resources could be used in coking.

Two parameters, referred to as the coke cold-strength parameter (coke stability) and coke hot-strength property (coke strength after reaction with CO_2 or "CSR"), are generally used to characterize coke strength. Coke stability is predicted using the U.S. Steel prediction method (Schapiro and others, 1961). It is based on petrographic parameters: coal rank (strength index/rank indicator) and maceral composition (compositional balance index/ inert indicator). Stability for a coal blend is not linearly additive, meaning that the stability of a coal blend cannot be predicted by simply adding the stabilities of the individual components of the blend.

In recent years, larger-volume blast furnaces have come into use and the requirements for coke strength have become increasingly rigorous. However, dissections of Nippon Steel Corporation's (NSC) blast furnaces having inner volumes ranging from 646 to 1,407 m^3 have revealed considerable changes in coke properties in the lower furnace regions (Kojima and others, 1977; Kanbara and others, 1977; Nakamura and others, 1978). As the coke descends inside a blast furnace, it is reduced in size. This degradation may be explained in terms of gasification by CO_2, thermal and mechanical stresses, or the effects of alkalies. Therefore, tests indicating coke strength under high-temperature gaseous environments are increasingly used for coke quality evaluation. The benefits of high CSR for blast furnace productivity and stability are described in numerous papers (for example, Ishikawa and others, 1983; Valia and others, 1989; and Grosspietsch and others, 2000).

Table 3. Rating of coal for coking (based on Gray and others, 1978)

	COAL CLASSIFICATION								
	High-Volatile A			Medium-Volatile			Low-Volatile		
	Rating			Rating			Rating		
Property	*Good*	*Medium*	*Poor*	*Good*	*Medium*	*Poor*	*Good*	*Medium*	*Poor*
Volatile Matter (%)	31.0–33.0	33.0–36.0	>36	21–24	24.0–27.0	27.0–31.0	18.0–21.0	15.0–18.0	<15
R_o* (%)	0.92–1.10	0.85–0.92	0.68–0.85	1.40–1.50	1.20–1.40	1.10–1.20	1.51–1.70	1.70–1.85	>1.85
Fluidity, ddpm†	>20.000	5,000–20,000	<5,000	500–8,000	300–20,000	<300–>20,000	100–300	30–1,000	<30–>1,000
Free Swelling Index	9	6 to 8	<6	9	7 to 8	<7	9	7 to 8	<7
H.G.‡ Index	48–75		32–70	80–135		60–90	90–120		85–105
CBI§	0.40–0.80	0.80–1.40	>1.40	1.00–1.50	1.50–2.00	>2.00	2.00–3.50	3.50–5.00	>5.00
Rank Index	3.4–4.3	3.0–3.4	2.2–3.0	6.0–6.5	4.3–5.5	<4.3	>6.8	6.0–7.5	<7.5

* vitrinite reflectance
† dial divisions per minute
‡ Hardgrove grindability
§ Compositional Balance Index

Table 4. Coke quality specifications (Valia, 2002)

Physical (measured at the blast furnace)	Mean	Range
Average coke size (mm)	52.0	45–60
Size > 4" (% by weight)	1.0	4 max
Size < 1" (% by weight)	8.0	11 max
Coke stability	60.0	58 min
CSR	65.0	61 min
Physical (% by weight)		
Ash	8.0	9.0 max
Moisture	2.5	5.0 max
Sulfur	0.65	0.82 max
Volatile matter	0.5	1.5 max
Alkali (K_2O+Na_2O)	0.25	0.40 max
Phosphorus	0.02	0.33 max

Coke strength after reaction (by the NSC method) is determined on the basis of a reaction between a coke sample and CO_2 at 1100°C for two hours, after cooling the coke with N_2 gas (for this test procedure, see Valia, 1989). Coke strength after reaction (CSR) is a linearly additive property, meaning that the CSR of coke produced from blended coals can be predicted from individual coal characteristics through the application of the additivity law (Valia, 1989). Several factors have been documented to influence CSR, primarily coal rank, inert content (Hara and others, 1980), dilatation (Wilkinson, 1984), and fluidity (Kitamura and others, 1982). An increase in maximum fluidity results in an increase in CSR (Kitamura and others, 1982; Goscinski and others, 1985a, b; Valia and others, 1989) and decrease in reactivity (Marsh, 1982; Wilkinson, 1984). Also, mineral matter in coal appears to be a very important factor that influences CSR. Alkalies can act as catalysts in CO_2 gasification thereby adversely affecting CSR (Chiu, 1982). The size and form of mineral matter also seems to be of importance (Gill and others, 1985).

A few prediction methods have been developed for CSR. Nippon Steel Corporation used reflectance and the inertinite content of coal in their prediction model (Hara and others, 1980). Reflectance and inertinite-based methods of predicting CSR generally give better results for coals having low fluidity. Kobe Steel developed a CSR prediction method based on maximum fluidity, reflectance, and alkali content (Goscinski and others, 1985a, b). Based on extensive studies of the relationship between CSR and petrographic, dilatometric, and plasticity, as well as other parameters, the most significant relationship was found between CSR and the plastic range of coal (Valia, 1989). The predictive equation developed for CSR at Ispat Inland Steel is as follows:

CSR = 28.91 + 0.63 plastic range – catalytic index.

Catalytic index (CI) is calculated as follows:

CI = 9.64 x alkali index + 14.04 x sulfur,

where alkali index (Al) = Ash (%) x $(CaO+MgO+Fe_2O_3+Na_2O+K_2O)(SiO_2+A_2O_3)$.

Plastic range is determined by Gieseler plastometry as a difference between softening temperature and solidification temperature. In a large number of samples predicted in this manner, CSR compared very well with the actual value of CSR, following the equation:

PREDICTED = 8.98 + 0.9 ACTUAL.

This prediction model has been tested for Carboniferous coals and may not be equally valid for other coals. For Australian coals, for example, Coin and Broome (1997) have identified coal rank as the major factor of statistical importance for coke quality and that no other parameters are of relevance.

Coking Properties of Indiana Coals

Some Indiana coals have better coking properties than would be expected from a typical coal of high-volatile bituminous rank. While low-sulfur coals from Indiana were used at the power generating stations of Inland Steel, it was noted that some Indiana coals from the Brazil Formation possessed superior rheological properties (Valia and Hooper, 1994). This led to the question of whether Indiana coals possess the characteristics of coking coal. Ispat Inland has a long history of using noncoking Illinois coal from the Carbondale Group in its coke batteries, but because of poor CSR and the lower contraction properties of Illinois coal, the contribution of this coal in the coke blends was decreased to 10 to 20 percent. The comparison of Indiana coal from the power generating station and the Illinois coal from the coke battery reveals significant differences, including various parameters related to rheological properties (Table 5).

It is clearly evident that low-rank Indiana coal (reflectance of 0.58 percent) possesses high fluidity and a high fluid range (48 ddpm; 64°C) and unusually high contraction (minus 10 percent). On the other hand, similarly ranked Illinois coal possessed negligible or no fluidity, a low fluid range (3 ddpm; 41°C), very low contraction and, at times, it exerts expansion (-2 percent contraction to +2 percent expansion). The increase in fluidity, fluid range, and contraction is attributed to greater amounts of liptinite macerals in the Indiana

Table 5. Differences between Illinois coal and Indiana coal from the Brazil Formation

	Illinois Coal	Indiana Upper Block Coal
Reflectance (% R_o)	0.65	0.58
Liptinite (%)	4.2	12.8
FSI	2.0	1.5
Max. fluidity (ddpm)	3.0	48.0
Fluid range (deg. C.)	41.0	64.0
SHO contraction (%)*	-2 to +2	-10.0
Alkali index	1.33	0.78
Sulfur (%, db)	1.04	0.78
Predicted CSR†	27.0 (actual 27)	50.0 (actual 48)

*Contraction is measured via sole-heated oven; data represented at 52 bulk density and 2 percent moisture.
†Actual CSR measured on coke obtained via carbonization in a pilot oven.

coal (about 13 percent) (Table 5), compared to the smaller amount in the Illinois coal (about 4 percent). Since CSR is highly dependent upon fluid range and, to some extent, on alkali index and sulfur content, Indiana coal has a very high predicted and actual CSR. Coke quality, therefore, could be dramatically increased by the addition of Indiana coal. The higher contraction of Indiana coal also will assist in pushing the coke charge, thus prolonging the life of coke battery. This is especially important for the slot-oven coke batteries in Indiana, not to speak of the rest of the U.S., as most of these batteries are reaching the end of their useful life (in North America, about 28 years) (Hofherr, 2000).

Because of these promising coking characteristics, Ispat Inland decided to find more Brazil Formation coals and characterize their properties. Table 6 shows coal properties for nine Brazil Upper and Lower Block reserves. For comparison, the properties of the Illinois coal supplied to Inland Steel are also included.

Table 6. Analytical data on Brazil Formation coals from selected mines in Indiana. (Each number represents a different mine; Illinois coal was included for comparison.)

	Illinois	1	2	3	4	5	6	7	8	9
Petrography										
Total inerts (%)	10.22	14.99	32.43	15.80	25.84	16.14	21.22	18.58	18.91	23.38
Reflectance (%)	0.65	0.56	0.60	0.51	0.60	0.58	0.56	0.51	0.58	0.55
Liptinite (%)	4.20	4.6	15.0	13.0	9.4	6.8	6.6	11.0	12.80	8.0
Inert index	0.37	0.64	1.68	0.71	1.21	0.68	0.97	0.87	0.84	1.11
Rank index	2.52	2.52	2.05	2.48	2.40	2.55	2.50	2.47	2.54	2.43
Pred. stability	25.0	12.0	0.05	11.0	2.0	13.0	9.0	10.0	12.0	4.0
Chemistry										
VM (db, %)	35.80	35.1	38.8	nd	37.5	37.4	37.2	38.6	37.5	36.3
FC (db, %)	58.40	49.9	55.8	nd	53.6	52.3	52.7	51.5	55.6	54.9
Ash (db, %)	5.8	5.1	5.4	9.03	8.9	10.3	10.1	9.9	7.0	8.8
Sulfur (db, %)	1.04	0.75	0.52	1.51	1.04	1.05	1.01	1.25	0.82	0.75
FSI	2.0	3.5	1.0	nd	2.0	4.0	2.0	6.0	1.5	1.0
Alkali index	1.33	1.02	0.37	1.61	1.53	1.48	1.80	1.70	0.78	0.85
Phosphorus (%)	0.009	0.18	0.015	nd	0.02	0.021	0.019	0.009	0.043	0.037
Rheology										
F. range (°C)	41.0	76.0	57.0	91.0	67.0	77.0	73.0	71.0	64.0	52.0
M. fluid. (ddpm)	3.0	12.0	18.0	4449.0	18.0	72.0	60.0	552.0	48.0	30.0
Pred. CSR	27.0	56.0	54.0	50.0	42.0	48.0	43.0	40.0	50.0	43.0

Note: nd = no data

All nine Brazil Formation coals exhibited a higher predicted CSR than the Illinois coal (Table 6). Samples 3 and 7 are characterized by very high fluidity (4449 ddpm and 552 ddpm) which, besides high liptinite, may be related specifically to the presence of the maceral exsudatinite, undetectable under white polarized light. It should be noted that samples 3 and 7, besides having high fluid ranges, also show some decline in CSR values owing to higher sulfur and alkali index values, which affect CSR negatively.

Table 7 shows the petrographic, chemical, and rheological properties for some of the Lower Block and Upper Block coals from selected active mines in Clay and Greene Counties in Indiana. In addition, predicted coke stability and carbon strength after reaction have been calculated. Most of the coals have high CSR values. In most cases, the coals having predicted high CSRs also have low sulfur contents, suggesting that they are desirable for coking. Vitrinite reflectance of all these coals is relatively close, ranging from 0.49 to 0.6 percent.

Some of the pilot oven carbonization results of single coals and blends are shown in Tables 8 and 9. Table 8 contains carbonization results of the Brazil Formation Upper Block coal from Indiana versus those from Illinois (No. 5 and No. 6 coals), and a coal of similar rank from Columbia (EC). It should be noted that coal from the Brazil Formation in Indiana produced a coke having a CSR of 48; the charge produced a contraction of -10 percent. However, the Illinois coals (No. 5 and No. 6 coals) had either low contraction (-2.0 percent), or showed expansion (+1.5 percent) and produced lower CSR (27–22). Similar low CSR values were also obtained from

Table 7. Petrographic, chemical, and rheological data of the Brazil Formation coals from Clay and Greene Counties, Indiana

	Clay County			Greene County				
	E1UB	***E2UB***	***E3UB***	***LBV***	***LB1***	***LB2***	***UB1***	***MC Pr***
Petrography								
Total inerts (%)	16.6	11.0	14.4	25.84	17.2	12.1	20.3	17.2
Tot. reactive (%)	83.4	88.9	85.6	nd	82.7	87.8	79.6	82.7
Vitrinite (%)	64.5	73.7	66.8	nd	53.0	60.0	64.1	57.0
Liptinite (%)	19.0	17.0	19.4	9.4	28.0	28.0	15.6	27.0
Reflectance (%)	0.57	0.56	0.58	0.6	0.56	0.57	0.59	0.56
Inert index (CBI)	0.74	0.46	0.62	1.21	0.7	0.5	0.9	0.73
Rank index	2.6	2.58	2.6	2.4	2.7	2.68	2.77	2.71
Pred. stability	22.0	12.0	20.0	2.0	25.0	15.0	29.0	28.0
Chemistry								
V.M. (db,%)	39.49	38.17	40.39	37.5	40.03	40.04	38.12	40.41
F.C. (db,%)	55.18	55.45	53.99	53.6	54.66	54.88	49.88	53.65
Ash (%)	5.33	6.38	5.62	8.9	5.34	5.08	11.94	5.94
Sulfur (%)	1.12	0.68	1.2	1.04	1.68	1.19	2.15	1.06
FSI	2.0	3.5	2.0	2.0	3.0	3.5	2.5	3.5
Alkali index	1.78	1.13	1.13	1.53	1.7	1.2	3.4	nd
Phosphorus	nd	nd	nd	0.02	nd	nd	nd	nd
Rheology								
Fluid. range (°C)	60.0	56.0	59.0	67.0	68.0	60.0	t63.0	58.0
Max. fluid (ddpm)	170.0	85.0	73.0	18.0	442.0	87.0	114.0	233.0
Pred. CSR	33.85	43.78	38.35	42.0	32.0	38.8	5.6	nd

Note: nd = no data

Table 8. Carbonization tests of Indiana coals and comparison with other coals of similar rank

	TC 1957	TC2003	TC 1967	TC 1588	TC 1737
	*100% Ind**	*100% Ind #7*†	*100% ILL (#5)*	*100% ILL (#6)*	*100% EC*‡
Moisture (%)	9.5	11.2	7.42	8.8	6.5
Grind (%, -3.35mm)	77.4	85.4	89.2	80.0	64.7
Dry oven blk	724.00	739.0	776.0	827.0	820.0
Max. oven wall	2.07	2.96	5.44	6.54	2.55
Coking time (h)	18.6	20.15	18.62	20.0	26.0
Stability	33.0	33.0	31.0	39.0	nd
CSR	48.0	30.0	27.0	22.0	16.0
CRI	40.0	nd	59.0	67.0	nd
Hardness	54.0	69.0	70.0	72.0	nd
Coke size (mm)	53.4	55.1	48.5	56.6	17.02
Coke yield (%)	67.9	67.0	67.9	65.6	nd
SHO contr	-10.0	nd	-2.0	1.5	nd

* Brazil Formation coal
† Danville coal
‡ Coal from Columbia
nd = no data

Table 9. Carbonization pilot oven test results of Indiana and Illinois coals in blends

	TC 1931	TC 1933	TC 1935	TC 1940	TC 1941	TC 1951	TC 1952	TC 1953	TC 1954
	30% Ill*	30% Ind†	80% Ind	45% Ind	45% Ind	30% Ind	30% Ill	20% Ind	20% III
	30% EHV‡	30% EHV	20% Pet. Coke	15% EHV	15% EHV	30% EHV	30% EHV	10% Pet. Coke	10% Pet. Coke
	40% EMV**	40% EMV		40% EMV	40% WCMV§	40% WCMV	40% WCMV	30% EHV 40% WCMV	30% EHV 40% WCMV
Moisture (%)	2.94	nd	2.5	4.98	5.15	4.48	4.03	3.29	3.24
Grind (%, -3.35 mm)	97.1	93.3	87.6	90.7	91.1	91.9	92.7	94.6	96.9
Dry oven bulk density (kg/m^3)	792.0	816.0	754.0	801.0	788.0	801.0	804.0	804.0	805.0
Maximum oven wall pressure (kPa)	5.65	6.27	2.55	4.62	nd	3.45	4.07	4.07	3.58
Coking time (h)	16.87	16.37	16.05	17.13	17.03	17.05	17.0	16.6	16.1
Stability	61.0	60.0	42.0	58.0	63.0	57.0	61.1	60.5	60.7
CSR	61.0	68.0	24.0	57.0	65.0	65.0	70.0	72.0	71.0
CRI	30.0	22.0	44.0	32.0	24.0	nd	21.0	20.0	nd
Hardness	70.0	70.0	51.3	70.0	68.0	70.0	70.0	69.0	68.0
Coke size (mm)	61.73	65.53	70.9	70.74	69.3	62.8	59.0	61.3	64.2
Coke yield (%)	73.58	70.15	69.6	73.39	74.6	74.9	76.3	78.0	76.9
SHO contraction (%)	-7.99	-9.57	-11.94	-11.13	-10.14	-12.82	-7.93	-10.59	-12.93
Coke sulfur (%)	nd	nd	nd	nd	nd	0.66	nd	0.93	nd
Coke ash (%)	nd	nd	nd	nd	nd	11.1	nd	8.9	nd

* Illinois coal
† Indiana Brazil Formation coal
‡ Eastern high-volatile coal
§ Western Canadian medium-volatile coal
** Eastern medium-volatile coal
nd = no data

Indiana Danville coal. The coal from Columbia, with a reflectance value of 0.63 percent (coal VM, db = 40.2 percent), produced an extremely unfavorable CSR value (16). Table 9 provides carbonization results on blends using Indiana Brazil Formation coals varying in proportions from 20 percent to 80 percent. All these blends show high contraction. All except TC 1935 have high CSR and high stability values. The run TC 1935 contains 80 percent of Indiana coal with 20 percent of petroleum coke; petroleum coke is devoid of fluidity, resulting in the deterioration of coking properties.

Realizing the coking potential of Indiana coals and their positive effect on charge contraction, Ispat Inland adopted a blend containing 16 percent of Brazil Formation coal from Indiana (with CSR of 48), replacing Illinois No. 6 coal for use in all of the four wet-charged batteries (Valia and Hooper, 1994). After two months of successful and high-quality coke production (CSR and stability of 65 and 61, Table 10), the proportion of Indiana coal was increased to 25 percent at the expense of the Eastern high volatile (EHV) coal. This blend produced excellent quality coke. The high contraction of the Indiana coal blend, as observed through sole heated oven testing, was also noted at the coke batteries, and resulted in aiding coke-charge pushing. When comparing these results with some of the pilot oven test results (Table 10), it is evident that with proper blend design, Indiana coal could be successfully incorporated in amounts up to 45 percent of the coal blend.

It should be noted that for a long time Illinois No. 5 and No. 6 coals have been used in coke blends in varying proportions. With proper blend design, they can be safely used at about 30 percent (see TC 1931, Table 9). Substituting Brazil Formation coals results in better CSR values and higher charge contraction, which is of particular importance for older ovens. As can be seen in Table 8, the Danville coal from Indiana (Coal VII) can also be used for cokemaking. However, because of lower CSR values and lower contraction properties, the Danville coal, as well as the Illinois coals, should be used as a "filler coal," with the main purpose of reducing costs, thereby, lowering dependence on more costly coking coals.

Reasons for the Superior Coking Behavior of the Brazil Formation Coals

Our data demonstrate that Brazil Formation coals can be successfully incorporated into coking blends in significant proportions. The reasons for the very unique rheological properties of the Brazil Formation coals are not well understood and are the subject of a detailed study that is currently underway (Walker and Mastalerz, in press). High-volatile bituminous coals, like those in Indiana, have always been regarded as "noncoking," and the superior coking behavior of Brazil Formation coals is unusual. Valia and Hooper (1994) suggested that the presence of liptinite macerals—exsudatinite, sporinite, and cutinite—contributes to higher fluid properties owing to the higher hydrogen contents of these macerals.

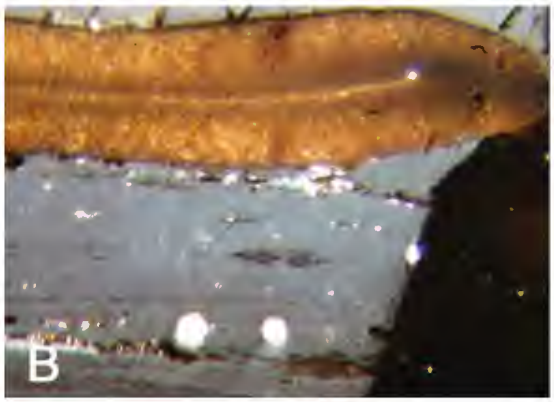
The study of Walker and others (2001) compared the Lower Block coal to the Danville Coal Member petrographically and chemically. At comparable values of vitrinite reflectance (R_o 0.56 to 0.58 percent), the Lower Block has a higher carbon content and a lower O/C ratio. In addition, its organic sulfur content correlates positively with the plastic range, suggesting that organic sulfur is a parameter that promotes good coking behavior in Brazil Formation coals. Supporting Valia and Hooper's (1994) suggestion of the importance of liptinite macerals, a study by Walker and others (2001) shows the liptinite content in the Lower Block is at least twice as high as in the Danville. In addition, the inertinite content is also higher in the Lower Block, contributing to a more favorable reactive/inert ratio.

Table 10. Commercial and pilot-scale carbonization of Indiana coals blended with high-volatile and medium-volatile bituminous coals (data from Valia and Hooper, 1994).

	I	II	III	IV
	16% Ind*	25% Ind	45% Ind	40% Ind
	44% EHV†	35% EHV	15% EHV	40% EHV
	40% EMV‡	40% EMV	40% EMV	20% EMV
CSR	65.0	66.0	57.0	75.0
Stability	61.0	60.0	58.0	57.0
Coke sulfur (%, dry)	0.77	0.75	nd	0.53
Coke ash (%, dry)	8.84	7.9	nd	9.30

Note: I = Commercial results; II, III, IV = Pilot oven results.
* Brazil Formation coals
† Eastern high-volatile coal
‡ Eastern medium-volatile coal


A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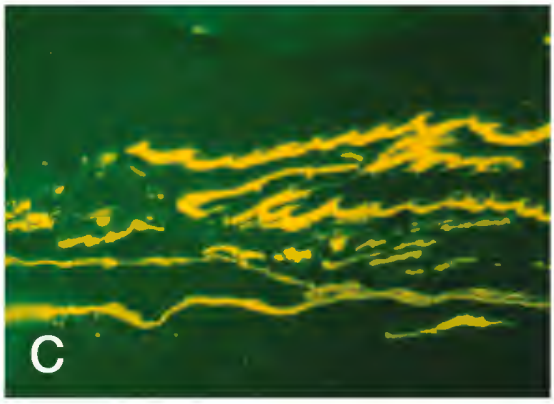
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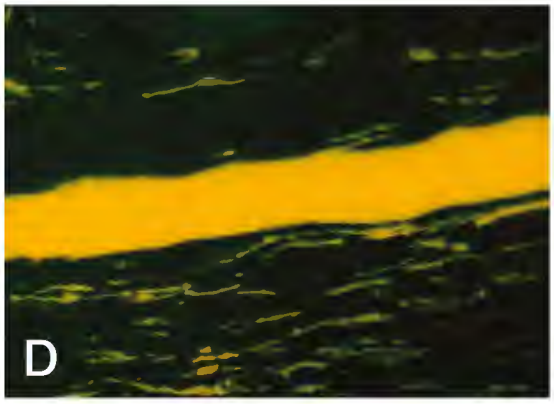
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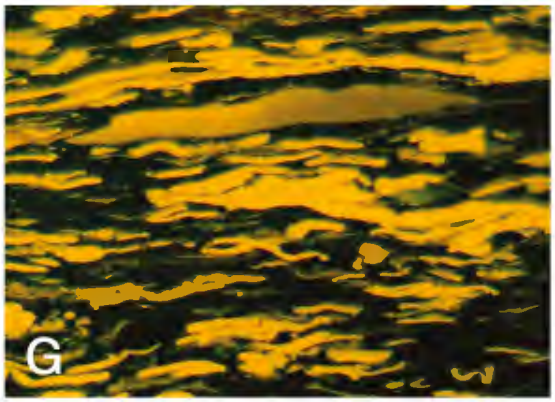
E


F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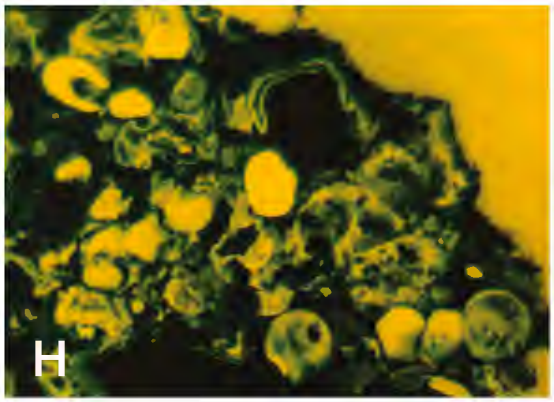
H

Figure 6 compares macerals of the Lower Block coal and the Danville coal. The Danville coal contains more vitrinite, often as telocollinite (fig. 6A, B), than the Lower Block, which is significantly richer in liptinite and lower in vitrinite, represented dominantly by desmocollinite (fig. 6E, F). Fluorescent light emphasizes the greater abundance of liptinite macerals in the Lower Block (fig. 6G, H) than in the Danville (fig. 6C, D). Recent data from Clay, Daviess, and Greene Counties (Mastalerz and Padgett, 1999) demonstrate that very good rheological properties are not only found locally, but are characteristic of the Lower Block coal in general and that substantial resources having excellent coking properties are available in Indiana.

The maps in Figures 7 and 8 show active and abandoned mines in the Brazil Formation in Indiana. The areas of active and future mining of the Brazil Formation coals should be the main focus of any search for Indiana coal to be used successfully in cokemaking.

INDIANA COALS AND PULVERIZED COAL INJECTION (PCI)

Criteria for PCI Application

Pulverized coal injection (PCI) into blast furnaces gained importance because it replaced costly coke with cheaper coal. It was an attractive investment in those steel mills where there was a coke shortage because of aging batteries that were plagued with environmental problems. Pulverized coal injection into blast furnaces gained popularity in the United States after successful application in Japan and Europe and has been a common practice in almost all steel plants since the 1990s. Some plants use semipulverized or granular coal to replace coke.

For this application, high-, medium-, or low-volatile coals can be used. Low-volatile bituminous coal has more carbon and can replace more coke. High-volatile bituminous coal is usually harder than low-volatile bituminous coal and, therefore, more energy is needed to pulverize it. However, high-volatile bituminous coals burn faster than low-volatile coals, allowing more injection without affecting the blast furnace burden permeability. For a coal to be considered for use in a blast furnace, it must have high combustibility and a high replacement ratio. The replacement ratio is defined as the ratio of mass of coke saved to the mass of coal needed to replace it.

In order to achieve a high PCI rate, coal should combust in the raceway of the blast furnace. Takeda and others (1990) reported that the maximum injection rates for perfect combustibility increase with the increasing volatile matter content of coal. In actual plant trials at the Kawasaki Steel plant, it was shown that, using four coals that varied in rank from low-volatile matter (VM = 16.4 percent) to high-volatile matter (VM = 34.1 percent), maximum PCI rates were obtained using high-volatile matter coals of no fluidity. Takeda and others (1990) and Koen and others (1994) indicated that at a higher PCI rate (200 Kg/net ton of hot metal [NTHM]), 85 to 95 percent of the coal is combusted near the tuyere; however, at even higher PCI rates, unburnt coal seems to increase up to 20 percent at 300 Kg/NTHM for coal having high-volatile matter content, and even 35 percent for the coal having low-volatile matter content (Koen and others, 1994).

Since replacement ratio increases with rank, coals having a lower-volatile matter content should have a higher replacement ratio (Fitzgerald, 1985). However, this does not take into consideration the benefits associated with coal hydrogen content, which decreases with increasing coal rank. According to Bocong and others (1986), bituminous coal, because of its higher calorific value and a higher hydrogen content, produces higher replacement ratios than those produced by injecting anthracite; the difference is about 10 percent.

Besides combustibility and replacement ratios, other coal parameters that play a role are grindability, hardness, ash, moisture, sulfur, ash fusion temperature, and coal ash chemistry. It should be noted that low-rank coals, such as Indiana coals, are characterized by high moisture (about 16 percent). Higher moisture results in a decrease in plant capacity and an increase in operating costs. However, because of higher hydrogen content, some Indiana coals have a moderate replacement ratio; such coals have excellent combustibility. The cost-benefit of certain Indiana coals may necessitate a need for blending them with low-moisture Eastern high-volatile coals, which will result in an overall decrease of coal cost. In summary, the economics of coal injection depends primarily upon coal price, and therefore, a balance must be made between coal replacement ratio, combustibility, ease of grinding, and ease of injection.

Potential Indiana Coals for PCI

Since Indiana coals have high combustibility, in this report we decided to rank coals by potential replacement ratio and sulfur

Figure 6 (facing page). Photomicrographs of Indiana coals. Longer axis of each photo is 240µm (oil immersion technique). Photomicrographs A through D are from the Danville Coal Member. A) Vitrinite-rich coal (gray) with rare spores (brown) and inertinite (white), reflected white light; B) Megaspore (brown) in vitrinite, reflected white light; C) Cutinite (yellow) in vitrinite-rich coal, fluorescent light; D) Megaspore (orange) in vitrinite-rich coal, fluorescent light. Photomicrographs E through H are from the Lower Block Coal Member. E) Abundance of spores (dark gray bodies) in vitrinite groundmass, reflected white light; F) Thick cutinite (dark gray) surrounded by vitrinite and sporinite, reflected white light; G) Abundance of sporinite (spores fluorescing orange) in the coal, fluorescent light; H) Abundance of sporinite (pollen fluorescing yellow) in the coal, fluorescent light.

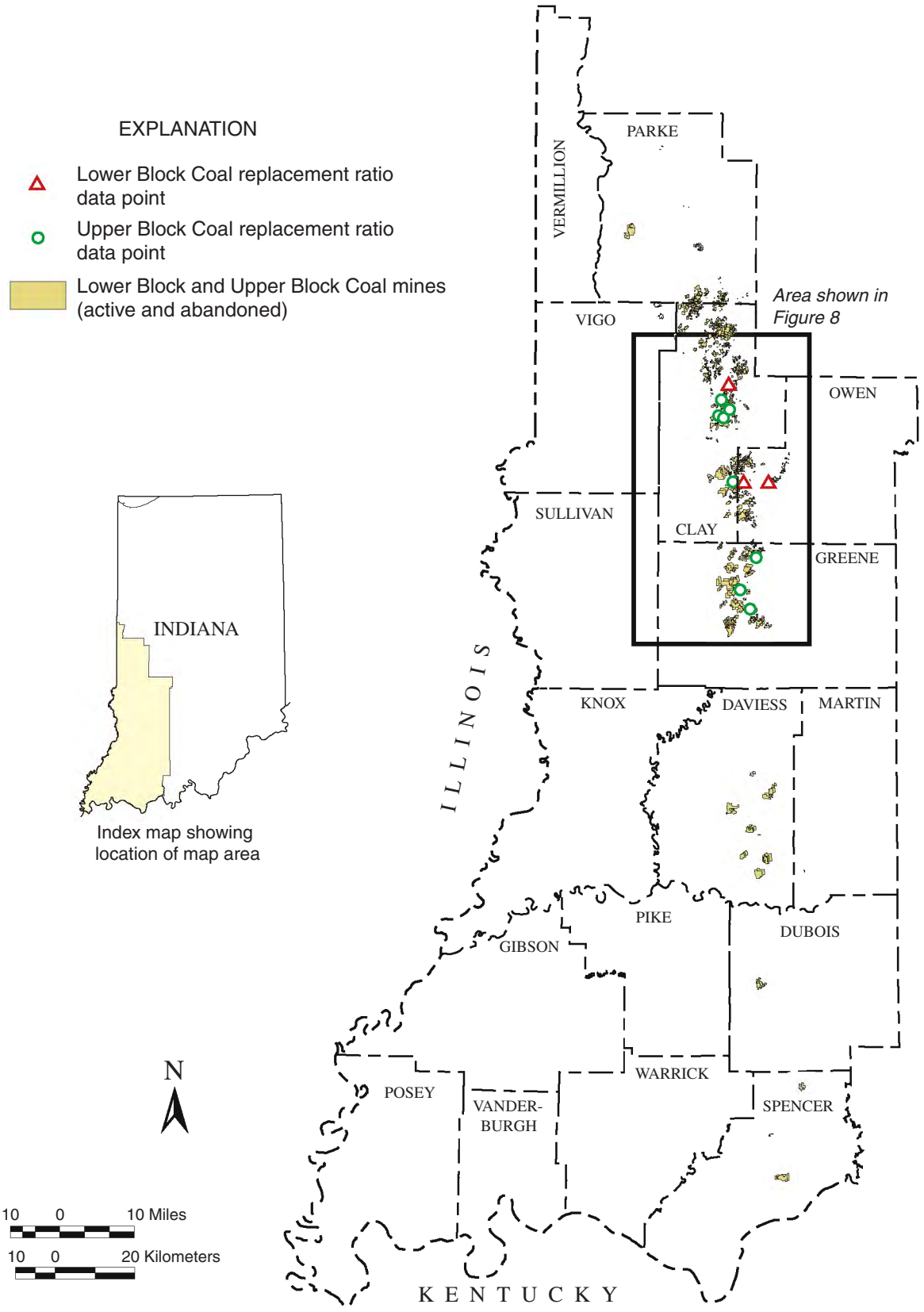

Figure 7. Map of southwestern Indiana showing the active and abandoned mines of the Lower Block and Upper Block Coal Members and the locations of coal samples that show good potential for pulverized coal injection (replacement ratio >0.8, and S<1 percent).

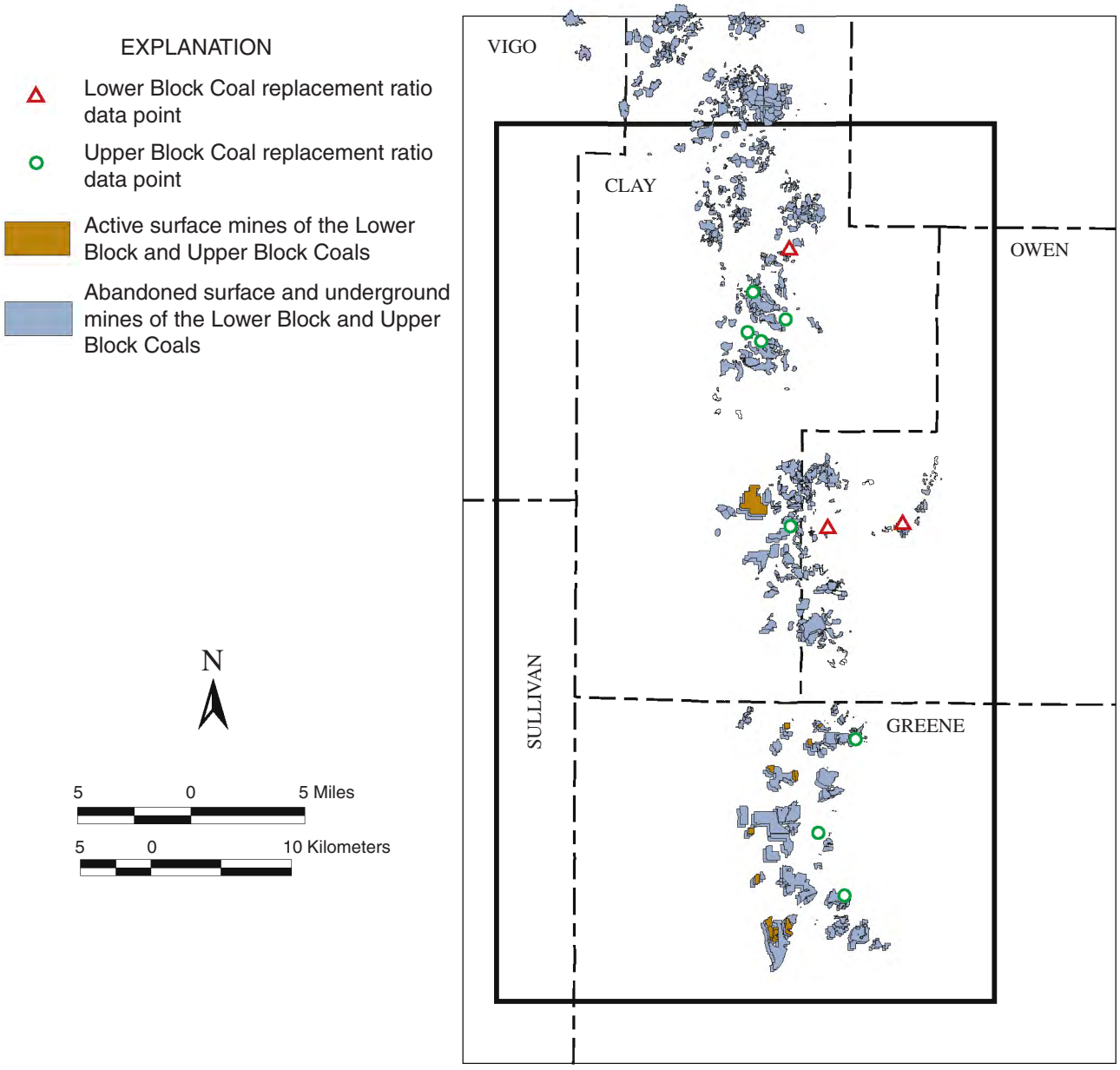

Figure 8. Inset map from Figure 7 showing more detailed locations of the mines (active and abandoned) of the Upper Block and Lower Block Coal Members and locations of coal samples that show good potential for pulverized coal injection.

Table 11. Locations of coal having replacement ratios (RR) above 0.8 and sulfur contents less than 1 percent (dry basis) in Indiana

Coal bed	Latitude	Longitude	Utme	Utmn	County	S dry	RR
Danville							
	38.727000	-87.484800	457861	4286387	Knox	0.9	0.83
	38.655100	-87.520200	454736	4278423	Knox	0.9	0.82
	39.040100	-87.305100	473593	4321062	Sullivan	0.5	0.82
	39.097000	-87.336600	470889	4327383	Sullivan	0.6	0.83
	39.063700	-87.340000	470587	4323687	Sullivan	0.4	0.86
	39.333500	-87.376000	467590	4353640	Vigo	0.5	0.83
Hymera							
	39.071400	-87.272900	476391	4324524	Sullivan	0.8	0.82
	38.393900	-87.322300	471854	4249362	Pike	0.7	0.81
Springfield							
	38.322600	-87.582900	449047	4241558	Gibson	0.9	0.81
	38.408600	-87.222300	480595	4250974	Pike	0.8	0.83
	38.371700	-87.223700	480458	4246871	Pike	0.8	0.86
	39.089200	-87.376900	467405	4326531	Sullivan	0.7	0.88
	39.544900	-87.457200	460716	4377139	Vigo	0.9	0.83
	38.102700	-87.218600	480831	4217031	Warrick	0.9	0.81
	38.096100	-87.227400	480059	4216302	Warrick	0.9	0.88
	38.096600	-87.2277	480033	4216349	Warrick	0.8	0.83
	38.095200	-87.245200	478502	4216197	Warrick	0.9	0.87
Colchester							
	39.549900	-87.279700	475966	4377625	Vigo	0.9	0.88
Upper Block							
	39.410100	-87.071900	493812	4362080	Clay	0.4	0.81
	39.401800	-87.103400	491098	4361163	Clay	0.8	0.90
	39.394100	-87.089800	492264	4360306	Clay	0.5	0.82
	39.401800	-87.103000	491132	4361160	Clay	0.6	0.90
	39.423400	-87.097000	491647	4363564	Clay	0.9	0.91
	39.277600	-87.068000	494133	4347382	Clay	0.6	0.88
	39.141300	-87.010440	499105	4332247	Greene	0.1	0.87
	39.043400	-87.022300	498070	4321387	Greene	0.8	0.87
	39.083200	-87.046300	495997	4325797	Greene	0.8	0.88
Lower Block							
	39.450300	-87.068800	494084	4366547	Clay	0.8	0.86
	39.449800	-87.069500	494017	4366486	Clay	0.9	0.88
	39.277600	-87.068000	494133	4347382	Clay	0.7	0.85
	39.276000	-87.035000	496981	4347200	Owen	0.8	0.85
	39.275700	-87.035100	496974	4347165	Owen	0.6	0.85
	39.275400	-87.035600	496928	4347132	Owen	0.7	0.84
	39.278800	-86.975600	502103	4347506	Owen	0.8	0.88
Unnamed Mansfield							
	38.5991	-86.871	511232	4272085	Martin	0.9	0.90

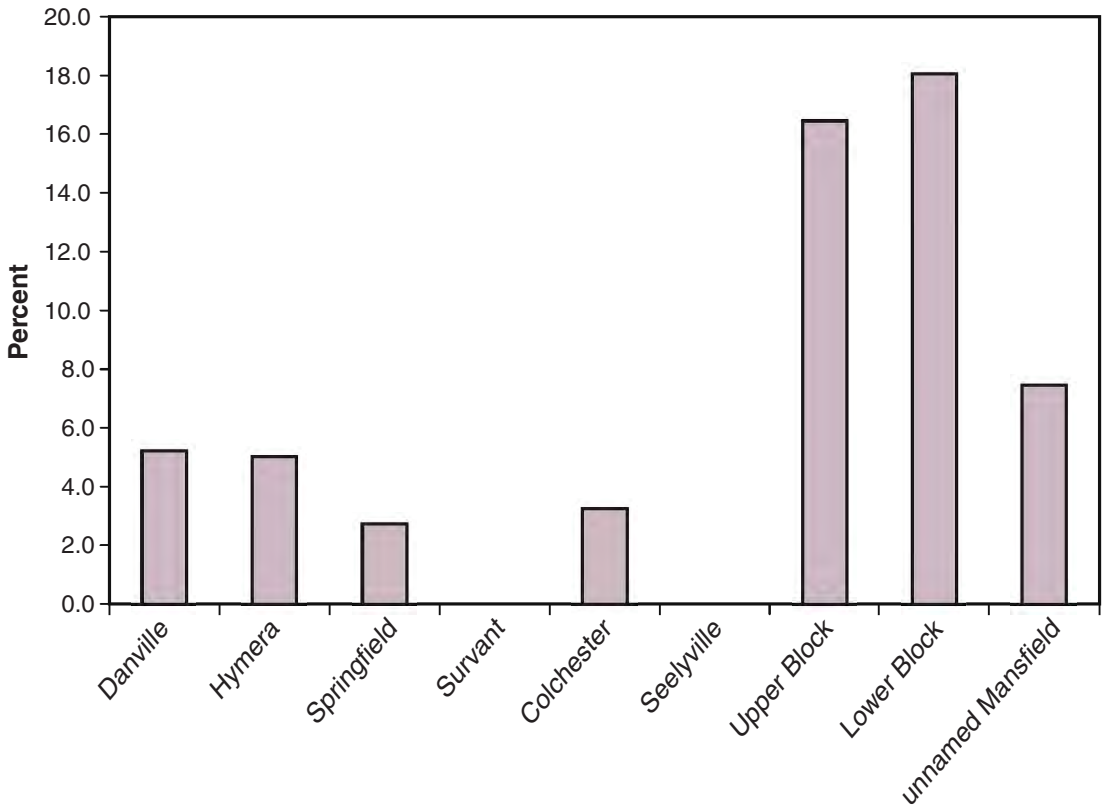

Figure 9. Graph showing the proportion (percentage of all the data in the database) of data that satisfy the requirement of sulfur contents less than 1 percent (S <1%) and replacement ratio above 0.8 (RR = >0.8) for individual seams.

content. Replacement ratios can be calculated from elemental analyses of coal and coke. In this report, we calculate the replacement ratio according to the following equation (van der Vliet, pers. comm., 2002):

$$RR = 0.9 \times C_{coal}\ (\%, db) + 2H\ (\%, db)/C_{coke}\ (\%, db),$$

where
C_{coke} used = 90 percent.

Low sulfur content is an important coal property for PCI, because sulfur increases the use of flux, causes brittleness, and negatively influences other properties of the iron (Schapiro and Gray, 1964).

In this report, data for the calculation of replacement ratios and sulfur contents were obtained from the Indiana coal quality database (Hasenmueller and Miller, 1992). Coals having replacement ratios (RR) greater than 0.8 and sulfur contents less than 1 percent (db) have been identified as adequate for PCI applications. Table 11 lists those locations from the Indiana coal quality database that fulfill these two requirements, arranged by coal bed. This table indicates that significant resources of the Danville, Springfield, Upper Block, and the Lower Block coals may be suitable for PCI. It should be noted that Table 11 presents data on raw coals. The majority of coals in Indiana are washed before utilization and, consequently, the availability of coal having sulfur contents below 1 percent will be significantly greater. Also, since the database was compiled, new data have been acquired that show additional potential resources.

Figure 9 shows the proportion of all data in the Indiana coal quality database that satisfy the requirements of sulfur being less than 1 percent and a replacement ratio above 0.8 for individual seams. Because of the uneven geographic distribution of the data, these numbers do not reflect the real proportion of coal resources that could be used for PCI; they only present a very rough estimate. Locations of coal having low sulfur contents and high replacement ratios are shown in Figures 7 and 8 for the Lower Block and the Upper Block Coal, Figures 10 and 11 for the Springfield, and Figures 12 and 13 for the Danville coal. In addition, we include locations of active coals mines of particular coal beds in these figures to show mines that should be targeted in a search for coal suitable for PCI.

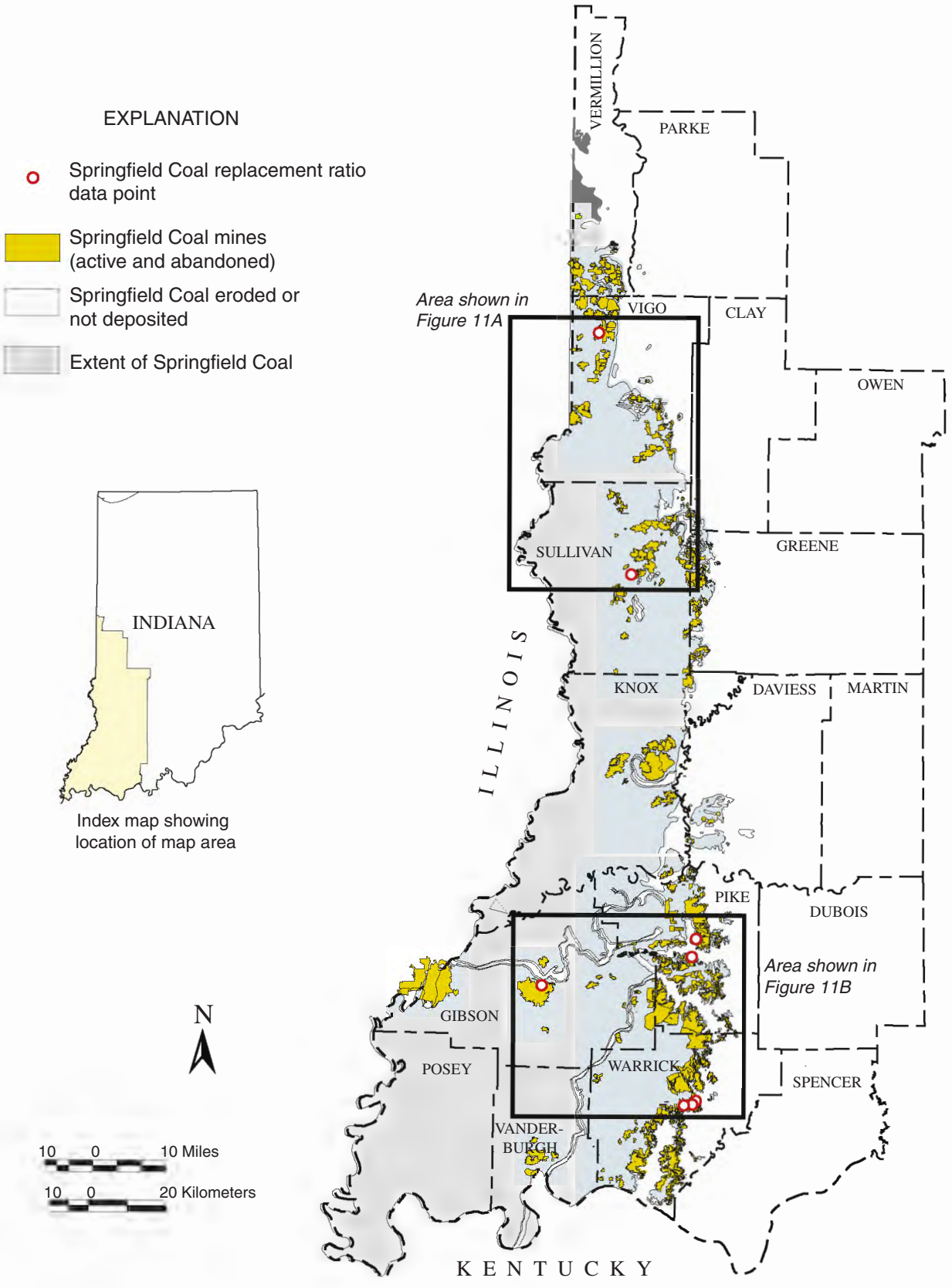

Figure 10. Map of southwestern Indiana showing the active and abandoned mines of the Springfield Coal Member and locations of coal samples that show good potential for pulverized coal injection (RR >0.8, and S <1 percent).

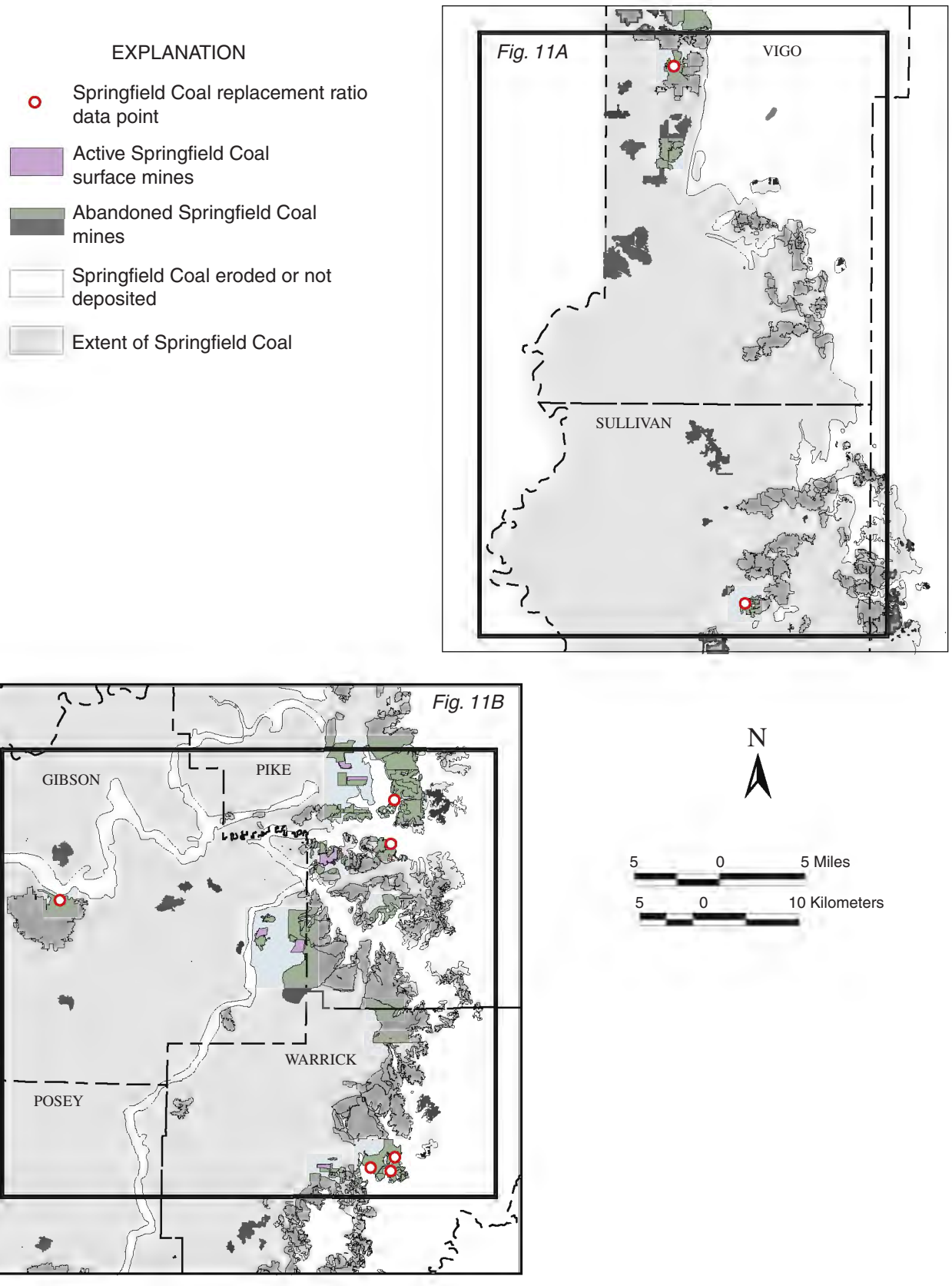

Figure 11. Inset map from Figure 10 showing more detailed locations of the mines (active and abandoned) of the Springfield Coal Member and locations of coal samples that show good potential for pulverized coal injection.

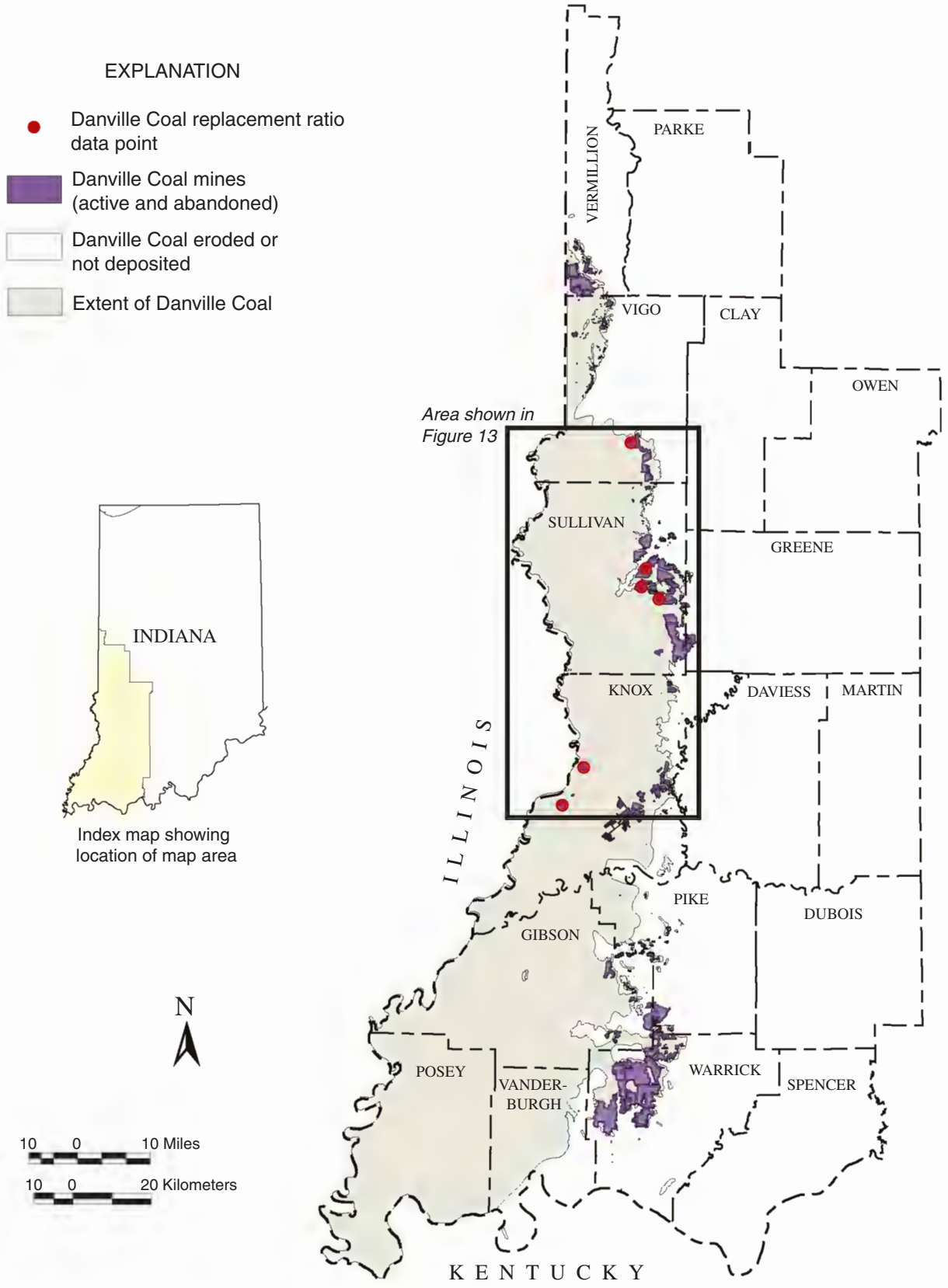

Figure 12. Map of southwestern Indiana showing the active and abandoned mines of the Danville Coal Member and locations of coal samples that show good potential for pulverized coal injection (RR >0.8, and S <1 percent).

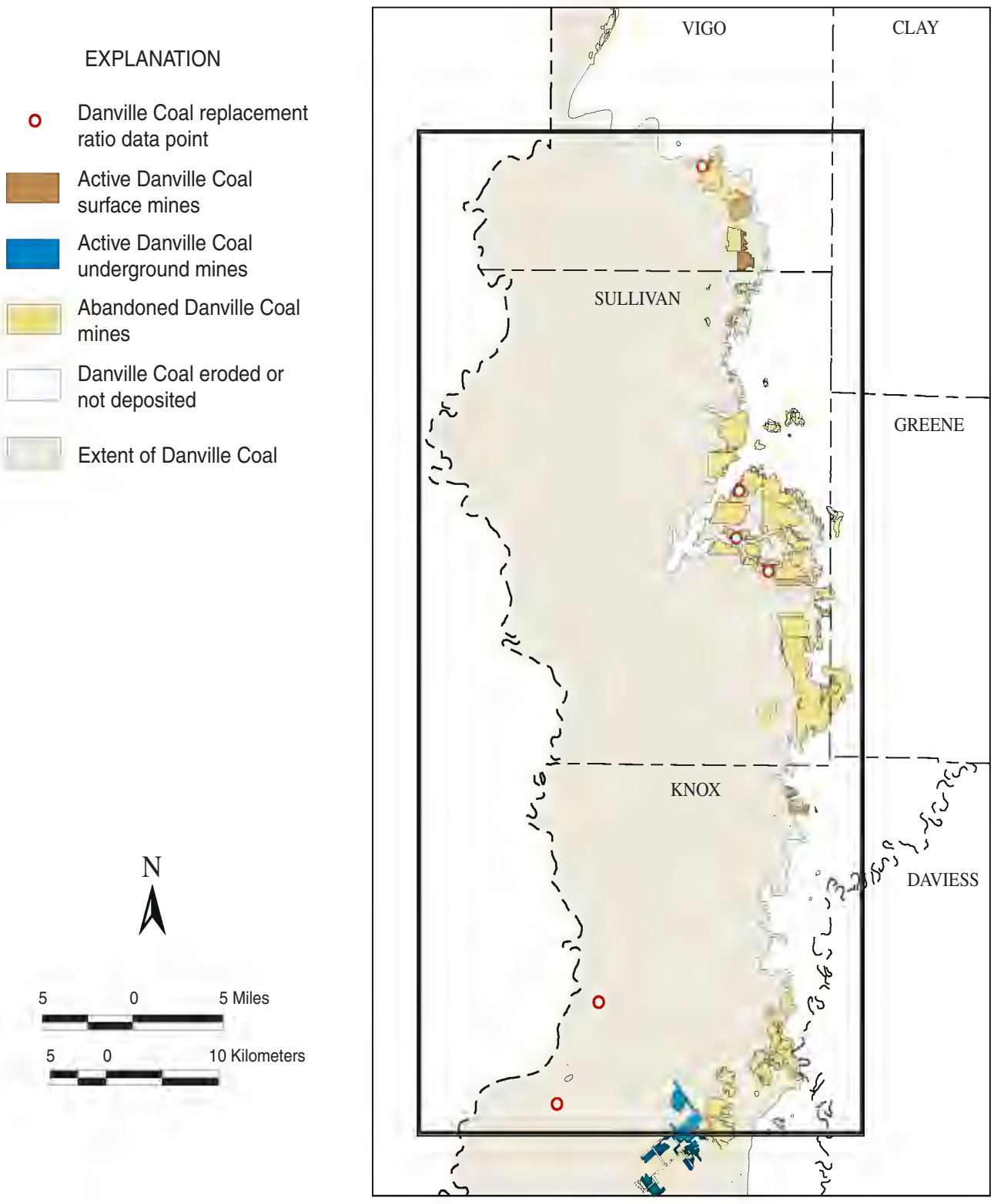

Figure 13. Inset map from Figure 12 showing more detailed locations of the mines (active and abandoned) of the Danville Coal Member and locations of coal samples that show good potential for pulverized coal injection.

CONCLUSIONS

- Indiana coal, especially that from the Brazil Formation, was used for coke production and in regional steel mills during the mid-1870s.

- Today, no Indiana coal is used in the steel industry, either in cokemaking or for blast furnace pulverized coal injection (PCI).

- The challenge of today's integrated steel mills to produce low-cost hot metal necessitates a fresh look at the use of particular low-cost Indiana coals.

- Our research indicates that Brazil Formation coals from Indiana possess high fluidity, a high fluid range, and an unusually high amount of contraction for such a low-rank coal. On the other hand, Illinois coals of similar rank possess negligible to no fluidity, a low fluid range, and very low contraction, and some at times show expansion. Besides having higher fluid properties, some Indiana coals, when compared with similar ranked Illinois coals, are characterized by lower sulfur, lower alkali, and lower chlorine contents.

- The higher fluidity, coupled with lower sulfur content and lower alkali index, result in high predicted and actual CSR values for some of the Brazil Formation coals. High CSR is desired by many ironmakers for improvements in blast furnace productivity and stability.

- The higher contraction of some of the Brazil Formation coals assists in pushing the coke charge from the ovens, an important factor for prolonging the useful lifetime of a coke battery. This is a critical consideration for the region's slot oven batteries, as most of them are reaching their maximum useful life expectancy.

- Other Indiana coals having lower coking properties, such as the Danville, could be used as filler coal to reduce cost and to lower dependence on much costlier coking coals.

- Replacement ratio is an important parameter in the evaluation of coal for application in PCI. Because of their higher hydrogen contents, some of the Indiana coals (especially Brazil Formation coals) have moderate predicted replacement ratios. These coals are, therefore, attractive for use in blast furnace pulverized coal injection application.

- The higher moisture content of Indiana coals results in a decrease in plant capacity and an increase in operating costs. For PCI, they could be blended, however, with higher-cost, low-moisture coals that are currently being used in many North American blast furnaces.

- Locations of coals having high CSR values and adequate replacement ratios, together with other coal quality parameters, are available from the IGS coal quality database. These data are easily accessible in a variety of paper and digital formats.

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GLOSSARY OF SELECTED TERMS RELATED TO COKEMAKING

ash fusion analysis: Method to determine fusibility of ash; measurements done in both oxidizing and reducing environments.

beehive oven (nonrecovery/heat recovery oven) cokemaking: Coal is heated in large, wide oven chambers under negative pressure in partially reducing environment. In such an oven, the air for combustion enters through the ports on doors resulting in burning of all combustibles. In nonrecovery/heat recovery, unlike beehive cokemaking, the partially combusted gases pass through the sole flue allowing the conduction of heat through the sole floor. In heat recovery cokemaking, the waste heat is used for the generation of power.

bituminous coal/coking coal: Coal that undergoes softening and solidification during carbonization giving rise to an agglomerated residue called coke. Bituminous coals are classified into three groups, as follows:

	Volatile Matter / Mean Vitrinite Reflectance
1) High-volatile bituminous	40–30% / 0.5–1.1%
2) Medium-volatile bituminous	30–23% / 1.1–1.40%
3) Low-volatile bituminous	23–14% / 1.40–1.80%

blast furnace: A large reactor for making iron using iron ore (lump or pellet), coke, and limestone or fluxed pellets.

blast furnace pulverized coal injection (PCI): Injection of pulverized coal into a blast furnace in order to replace costly coke with cheaper coal. PCI rate is expressed as kilogram of coal injected per net tons of hot metal produced.

blow-pipe: A pipe through which pulverized coal is injected. This pipe directs the coal into a tuyere of a blast furnace.

byproduct cokemaking (slot oven): Coal is heated from side walls in slot ovens under a positive pressure and reducing environment. Each oven shares a common heating flue with the adjacent oven. The off-gas is collected and sent to the byproduct plant where various byproducts are recovered.

carbonization: Heating of coal under an oxygen-deficient environment (as opposed to combustion that takes place in the presence of oxygen).

coalification/rank: Represents stages of transformation of plant to peat to lignite to sub-bituminous to bituminous to anthracite coal.

coke: A strong solid mass resulting from agglomeration of plastic coal material after carbonization.

coke battery: A series of coke ovens.

coke oven: An oven for carbonization of coal.

coke hardness: Cold strength property of coke representing abrasion resistance.

coke reactivity index (CRI): Reactivity of coke as it undergoes gasification with CO_2 at high temperature. It is measured by the Nippon Steel Test.

coke stability: Cold strength property of coke representing impact resistance.

coke strength after reaction (CSR): Hot strength property of coke represents breakage of coke as it travels from top to the bottom of a blast furnace. It is measured by the Nippon Steel Test.

coke strength after reaction (CSR) prediction model: Prediction of CSR from coal analysis. One example is the Inland Steel Method which utilizes fluid range (via Giesler Plastometery), alkali index (base to acid ratio from ash analyses), and sulfur content.

coke yield: Amount of coke produced from a given amount of coal.

cold strength coke properties: Impacts- and abrasion-resistant properties measured in tumbler drum under ambient conditions.

expansion (dilatation)/contraction: Expansion (dilatation) or contraction of coal during carbonization measured by Audibert-Arnu dilatometer.

free swelling index: Measure of the caking power of coal during heating.

Hardgrove grindability: Procedure to determine grindability of coal.

hot strength properties: Coke strength properties measured after coke is treated to reaction under high temperatures in a gaseous environment.

inerts: Macerals that remain "inert" during carbonization forming part of the cell wall component of coke, for example, the macerals fusinite, semifusinite, and funginite.

integrated steel mills: Steelmaking using coke–blast furnace–basic oxygen furnace route.

maceral: Organic entities in coal identified via polarized light microscopy. Macerals are divided into three groups—vitrinite, liptinite, and inertinite.

minimills: Steelmaking by smelting in electric furnaces, thus eliminating coke–blast furnace–basic oxygen furnace route.

pilot oven: Oven used to simulate conditions of a plant oven in the laboratory; some have moveable oven walls, whereby wall pressure exerted by coal expansion can be measured.

plasticity (fluidity) and plastic (fluid) range: Degree of plasticity (fluidity) of coal during heating and the temperature interval between softening and solidification (plastic/fluid range) during heating as measured via Gieseler Plastometer.

proximate analysis: Method to determine moisture, volatile matter, fixed carbon (by difference), and ash.

raceway of blast furnace: A cavity created by the hot blast in front of a tuyere.

reactives: Macerals that undergo softening, devolatilization, plasticization forming coke cell wall material, for example, vitrinite, sporinite, cutinite, resinite, and exudatinite.

replacement ratio: The ratio of mass of coke saved to the mass of coal needed to replace it via blast furnace pulverized coal injection.

sole-heated oven test: Contraction/expansion of coal/coke mass during carbonization as measured using a sole heated oven.

stability prediction method: Prediction of coke stability using petrographic analyses of coal. One example is the U.S. Steel model, which utilizes the "strength index" (coke strength of the reactive macerals) and the "composition balance index" (inert content indicator).

tuyere: Lower part of a blast furnace through which a hot blast, as an energy source, is injected to the furnace.

vitrinite reflectance: A parameter to measure coal rank. It is measured using a photometry system on a polished surface of coal.

wall pressure: Pressure exerted by expanding coal mass and gases during carbonization. High wall pressure leads to slot oven wall damage.


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