Characterization of Available (Marketed) Coals from Illinois Mines

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Final Report (revised) to the Coal Research Board
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ILLINOIS STATE GEOLOGICAL SURVEY
Morris W. Leighton, Chief

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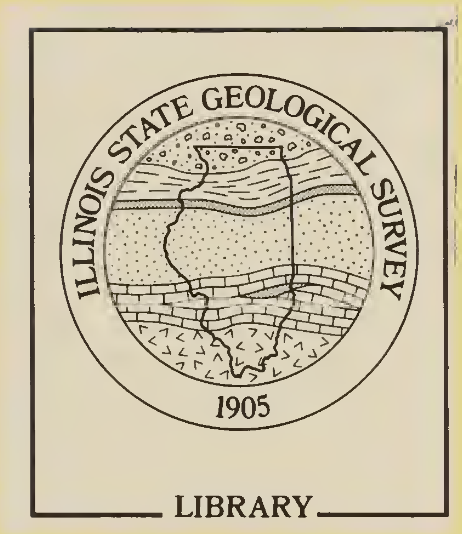

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Abstract

A unique set of samples was collected from cleaned coal output belts or storage piles at one mine and 33 preparation plants active in Illinois during the fall of 1992. The samples represent Illinois Basin coals marketed by coal mining companies in the state.

Concentrations of trace, minor, and major elements, as well as ash content and heating value, were determined for the 34 samples. The results were compared on a regional basis. The analytical data on the cleaned coal samples were compared with the ISGS data on 222 channel samples that represent coal seams at different locations throughout the Illinois coal field. The comparison indicated that conventional coal cleaning reduced concentrations of most trace elements. Improvements in the performance of preparation plants could result in further reductions in concentrations of mineral-associated trace elements.

Sequential (hot water, dilute ammonia, and dilute sodium hydroxide) extraction of three samples indicated variable reductions in chloride concentrations. Microscopic determination of the pyrite cleanability index showed a large variation in the potential for removal of pyrite from samples, partly because of the variation in cleaning from plant to plant. Froth flotation tests of two or more samples from each region of the state demonstrated that deeper cleaning of all samples was possible.

Viscosities of slurries containing 50% solids at -60 mesh particle size were measured for 15 of the 34 samples. The results identified only one sample that might be a problem if pumped as a slurry through pipelines.

Slagging and fouling indices, calculated from sulfur and ash analyses, showed that most coals have a low to medium potential for slagging and fouling in steam-generating plants. Estimated gasification parameters, calculated from proximate, ultimate, and ash analyses, indicated that modern gasification plants could utilize most Illinois coals with limestone added to modify the behavior of ash and manage slag residue.

Objectives

The overall objective of this research was to generate advanced characterization data on cleaned coal products from mines operating in Illinois. The new data, which will benefit a variety of engineering processes, were obtained by carrying out the following tasks:

1. Compile all analytical data on trace elements in Illinois coals and associated strata, particularly face channels, into a computer-retrievable format. Compare the analyses of channel samples with those of cleaned coals to determine any correlations that would make the data more useful to the coal industry.
2. Obtain a suite of samples of cleaned coal from each preparation plant in Illinois.
3. Perform the following analyses and tests, according to rigorous quality assurance and control procedures, on the cleaned coal samples:

   Concentration of trace, minor, and major elements Focus on the elements of greatest environmental concern (U.S. National Committee for Geochemistry 1980) and those regulated under the amendments to the Clean Air Act (PL101-549, 1990). Radioactivity of the decay products of radioactive elements in the coals can be calculated from uraniaum, thorium, and potassium concentrations (Cahill, ISGS, personal communication 1992).

   Pyrite grain-size distribution and maceral association Using a microscopical procedure (Harvey and DeMaris 1985), evaluate the pyrite cleanability of the coal represented by the samples.

   Froth flotation cleanability Use a "release analysis" method (Dell et al. 1972, Forrest 1990) to determine the flotation yields for 15 samples selected to represent different coal regions and seams.

   Slagging and fouling characteristics Calculate according to procedures used by the electricity-generating utilities.

Chlorine forms and distribution Determine the total chlorine (Cl) content for all samples by means of the standard ASTM procedures. Use special procedures (Chou et al. 1990) to probe the forms and distribution of chlorine in three samples.

Preliminary rheology Determine the viscosity of particle-size blends in at least five samples.

Gasification reactivity Calculate from results of other analyses of the samples.

Introduction

Much of the trace element data on Illinois coals is from the analysis of channel samples. Because of technological advances and renewed concerns about noxious emissions from coal-fired power plants, there is growing need to expand the database to available (cleaned) coals from the mines.

The cleanability of Illinois coals should be evaluated by improved methods such as those used to determine pyrite grain-size distribution (including maceral association of the grains) and froth flotation cleanability. Advanced characterization of chlorine (Cl) and its forms in coal and of the propensities for slagging and fouling can be usefully applied to determine performance of the coal in utility boilers. New methods to estimate performance of various coals in gasification plants and pumpability of coal slurries can also be applied to Illinois coals.

The expanded database and improved characterization techniques should prove useful to both the suppliers and consumers of Illinois coal products.

Background

Trace and Minor Elements

The Clean Air Act Amendments of 1990 (Public Law 101-549) identified several trace elements as "hazardous air pollutants" (HAP; table 1). A similar regulation has been proposed for Illinois (Illinois Pollution Control Board 1990). Electric utilities are not now required to meet the standards for HAP emissions. This exempt status is likely to change, however, after the U.S. Environmental Protection Agency (USEPA) completes its risk analyses and sets new emission standards in 2 to 10 years.

HAP elements are present in all coals, not just those from Illinois (Gluskoter et al. 1977, Harvey et al. 1983), although their concentrations vary considerably. Consequently, a database of trace element concentrations in the coals used by power plants could be critical for defining and resolving the emissions problem for electricity-generating utilities.

Swaine (1989) reviewed the environmental aspects of trace elements in coal. Trace elements that "escape" during combustion are attached to ultrafine fly ash particles or emitted as gas. Modern electrostatic precipitation systems can trap up to 99% of fly ash generated during coal combustion. Thus Swaine concluded that, in general, no trace element posed a significant environmental problem. His conclusion is valid if electrostatic precipitators used at power plants are state of the art and coals burned contain no excessively high concentrations of noxious elements that can be emitted in a gas phase.

Deep physical cleaning, a precombustion alternative or supplement to electrostatic precipitators or baghouses, could reduce the levels of HAP elements associated with minerals in the feed coal (Capes et al. 1974, Gluskoter et al. 1977, Cavallaro et al. 1978).

Pyrite Size Distribution

Harvey and DeMaris (1985) described a microscopical procedure to determine the mean diameter of pyrite grains and percentage of grains locked in various types of macerals or as free grains in coals. The results were used to formulate an index of the amounts of pyrite that physical cleaning could easily extract from coal.

Froth Flotation Cleanability

Only 8 of 33 preparation plants in Illinois have flotation circuits, but coal companies are planning to install more circuits to obtain a clean product from finely crushed coal. The flotation process is based on the hydrophobic character of coal surfaces, in contrast to hydrophilic character of mineral surfaces. Coal rank and state of oxidation affect the degree of hydrophobicity and therefore the flotation process (Sun 1954, Ayat 1987). Also critical are the chemical composition of the flotation solution, design of the equipment, and operation of the circuit (Hansen and Klimpel 1986).

Slagging and Fouling Characteristics

The efficiency of fuel engineering practices largely depends upon continuing to develop and expand the data on specific characteristics of feed coals. For example, the causes of slagging and fouling of boilers in coal-fired plants are not well understood. Some slagging and fouling have long been accepted, and boilers have been designed to withstand some of the resulting clogging and corrosion. If the conditions that produce slagging and fouling can be predicted from coal characteristics, then a strategy to prevent clogging, deposition, corrosion, and reduction of heat exchange can be devised.

Chlorine Forms and Distribution

Recent research (Demir et al. 1990, Chou 1991) indicates that there are two forms of Cl in coal: Cl^- as Na^+Cl^- dissolved in the pore waters of coal, and Cl^- adsorbed on the inner surfaces of micropores in macerals. This view partly agrees with a study of British coals (Daybell and Pringle 1958), which suggested that Cl might be attached to an amino group in coal. Given (1984) also suggested that the portion of Cl associated with the organic matter occurs as the hydrochloride of pyridine bases. Data on lithotype samples from the Herrin Coal showed a positive correlation between Cl and N when the concentrations of both were normalized by organic carbon (Chou 1991). If the major form of Cl is Na^+Cl^- dissolved in the pore water, then most Cl (perhaps all) can be removed through extraction during fine coal cleaning processes. If the major form of Cl is organically associated, as an organic amino chloride, for example, then physical removal will not be feasible.

Rheology

Extensive studies that characterized rheological properties of coal–water mixtures were carried out by Turian (1985), who established correlations between suspension microstructure and yield stress, stress/shear rate, and suspension stability. Turian's work made it possible to use viscosity data to evaluate the pumpability of coal–water mixtures, optimized for various particle-size blends of coal. The data are needed to decide whether converting Illinois coal to a slurry and pumping it through pipelines will be practical.

Gasification

Research on coal gasification in the 1980s centered on technical aspects of oxygen consumption and temperature dependence of equilibrium constants for carbon gasification reactions (Kuo 1984). Equations were developed to use the data from proximate, ultimate, and ash analyses to predict the gasification performance of coals. The calculations would permit comparison of the gasification properties of different Illinois coals.

Experimental Procedures

Sampling and Sample Regions

In the fall of 1992, 36 mines were feeding 33 preparation plants in Illinois, and we collected 34 unique samples. Samples of cleaned coal were obtained from the main

output belt or stock pile at each preparation plant. At most plants, company staff helped us collect an 80-pound sample, which normally was a split from the automatic sampler on the output circuit of the plant. Multiple cuts were taken across the coarse output belt for at least 4 hours, but usually 8 to 24 hours, of preparation plant operation. The multiple cuts or subsamples were composited into a single sample at the plant. At some mines, ISGS staff collected samples from a stock pile. A sampling shovel was used to take 15 to 20 increments of the coal from widely spaced locations, and the subsamples were combined into a single sample on site.

After being sealed in 5 mil plastic bags or 5 gallon plastic buckets, the samples were transported or mailed to the ISGS preparation laboratory within 2 days. They were homogenized, riffled, crushed, and packaged (fig. 1) within 1 week of their arrival at our laboratory.

All 34 samples collected for this project were analyzed for chemical composition; pyrite size distribution; froth flotation cleanability; and slagging, fouling, rheology, and gasification characteristics. Confidentiality of results was maintained by dividing the Illinois coal field into four regions, each encompassing four to 14 counties (fig. 2), and by identifying only the regions from which the samples were obtained.

Analyses for Trace, Minor, and Major Elements

The 34 composite samples of cleaned coal were analyzed for 29 trace and minor elements. Other standard analyses were also performed. The elements, methods of analysis, and levels of precision and accuracy are shown in table 2.

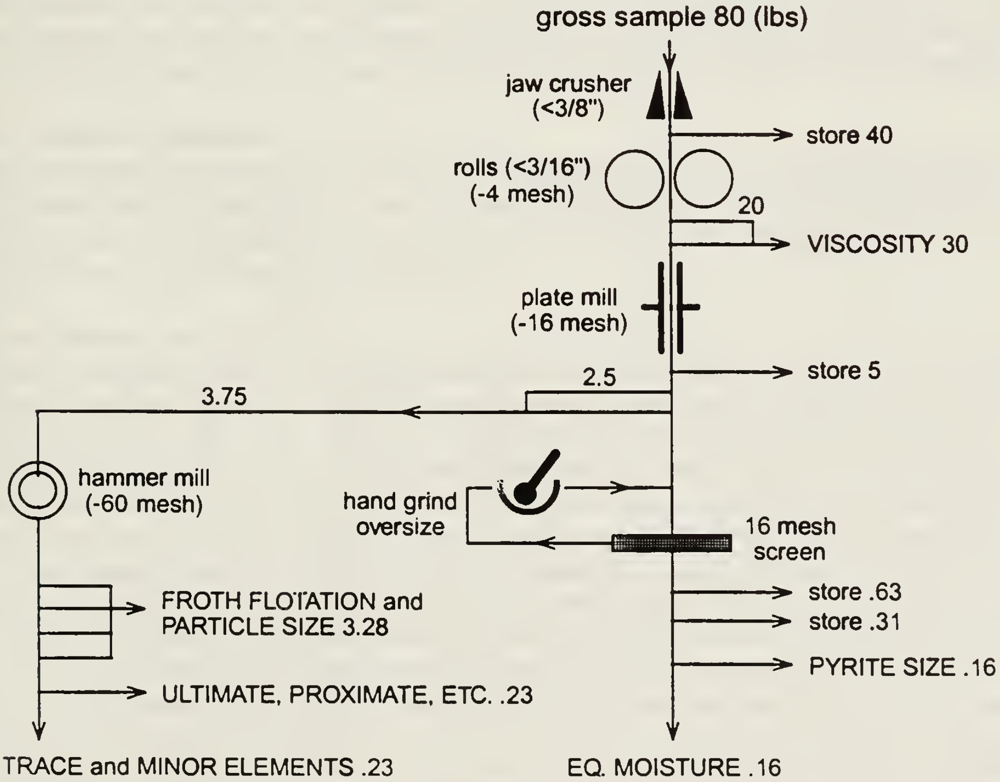

Figure 1 Flow chart for sample preparation. The weight of the laboratory sample is given after the indicated test.

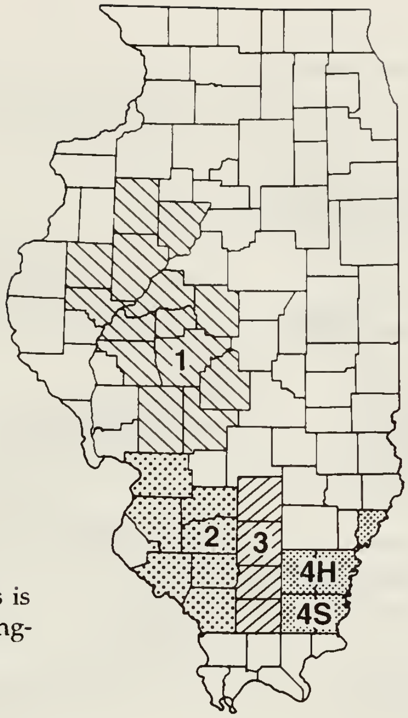

Figure 2 Sample regions. Southeastern Illinois is subdivided by seam into Herrin (4H) and Springfield (4S) coals.

Pyrite Size Distribution and Association

The coal samples were ground to -20 mesh size, embedded in epoxy, then polished for microscopical determination of the size distribution of pyrite grains and their association with different types of macerals. Pyrite sizes are expressed as a percentage of the linear diameter so that the proportion of large grains is weighted in proportion to their mass. Maceral associations were determined visually by estimating the percentage of pyrite and other common minerals attached to the particle of coal under observation.

Froth Flotation Cleanability

Fifteen samples were selected for froth flotation cleanability tests. The feed samples were ground in a Holmes mill, which reduced the particle size to 90% -100 mesh and 100% -60 mesh. Froth flotation tests were conducted using a "release analysis" procedure (Dell et al. 1972, Forrest 1990) (fig. 3).

Chlorine Forms and Distribution

The three samples selected for special analyses of Cl had low (0.15%), medium (0.24%), and high (0.34%) contents of Cl. They were ground to -60 mesh size and sequentially extracted at 93°C with water (15 g of coal with 80 ml water for 35 minutes), then ammonium hydroxide (10 g of water-extracted residue with 70 ml of 0.5 molar ammonium hydroxide for 40 minutes), and finally sodium hydroxide (5 g of residue from ammonia extraction with 45 ml of 0.1 molar sodium hydroxide for 30 minutes). Residues were washed with 1,000 to 2,000 ml of deionized water after each extraction. The high-Cl (0.34%) sample was also dry-ground to -400 mesh size and extracted as above.

Each feed coal and residue obtained from the extractions was pyrolyzed under nitrogen. The resulting off-gasses were analyzed for HCl evolution by two methods: (1) the pyrolysis quadrupole gas analyzer (PY/QGA) technique, and (2) the thermogravimetric analysis–Fourier transform infrared (TGA–FTIR) technique. Chlorine in the feed and residue was also determined by standard ASTM method. The PY/QGA results of Cl (calculated from HCl evolution) compared well with the ASTM results. Each feed coal was also analyzed for sodium (Na) and potassium (K) contents, and for N_2-adsorption surface area and porosity.

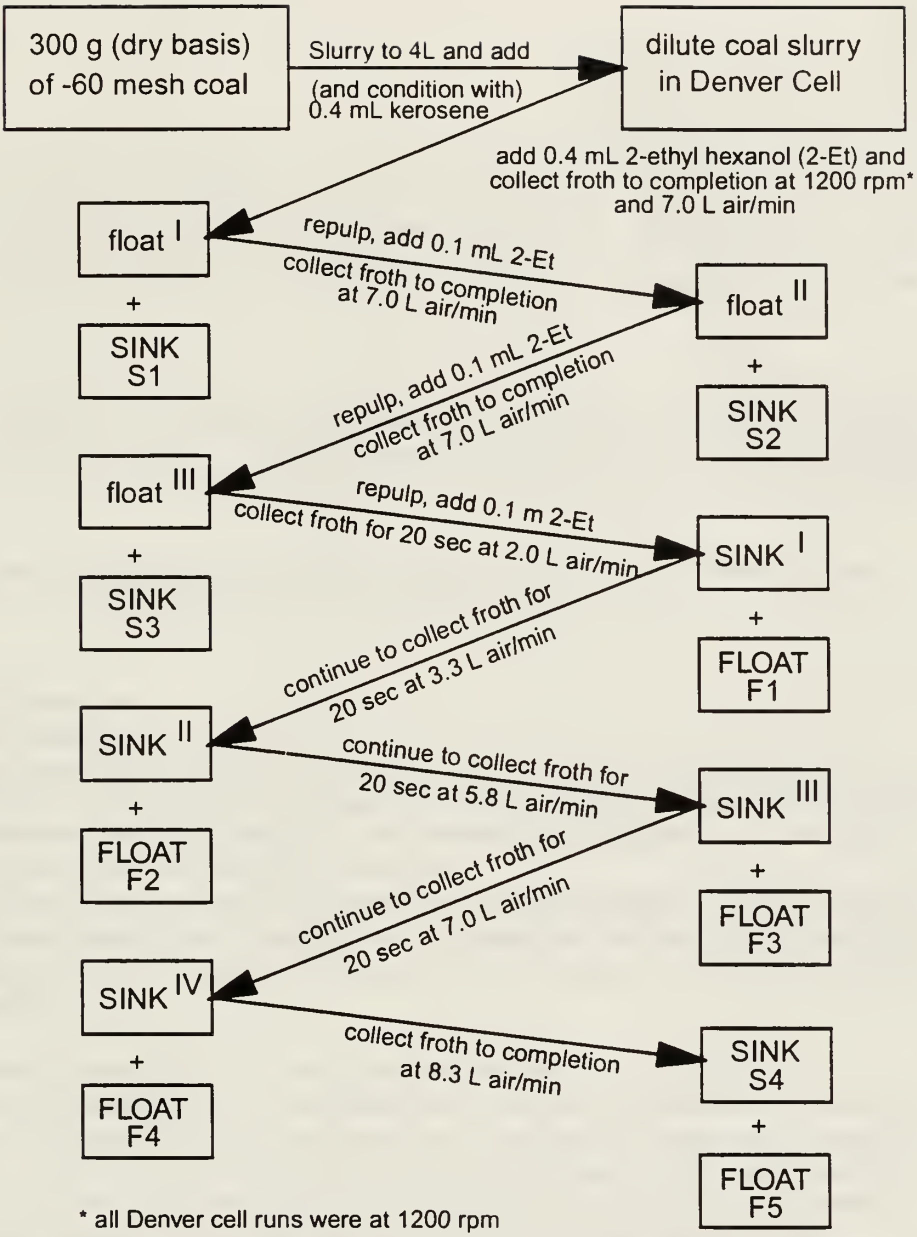

Figure 3 Froth flotation and release analysis approach.

Rheology

A Brookfield Model RV-100 viscosity meter was used for this task. Two viscosity liquids, 100 cps and 500 cps, and a known sample from Black Mesa Pipeline, Inc., with test loop data ranging from 24 cps to 112 cps (graphed as a function of percent solids), were tested to ensure accurate viscosity readings. Slurries of varying percent solids were then tested to select a standard test procedure:

- samples to be tested should be ground to -60 mesh (250 µm) particle size;
- slurries should be 50% solids;
- each viscosity test should be 3 minutes;
- the slurry should be stirred between tests;
- temperature of the slurry during the test should be maintained at a standard value.

The reported viscosity is the average of three separate tests of the given sample.

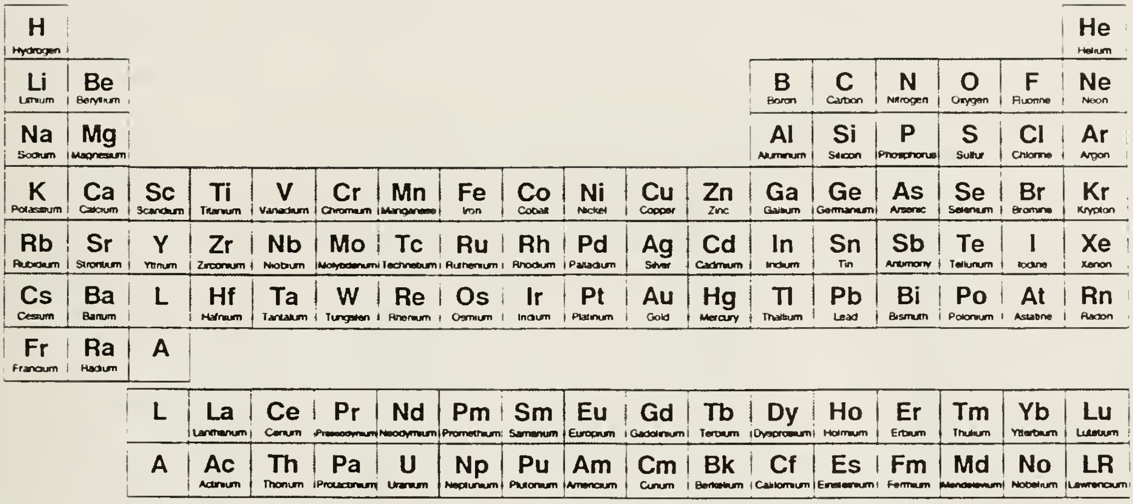

Figure 4 Analytical results on these 60 elements or their compounds are available for many sample records in the ISGS database on trace elements in coal.

Results and Discussion

Trace Element Database

Trace element data of coal samples from Illinois and other states were added to the ISGS computerized database (table 3). Figure 4 identifies 60 elements for which concentrations are available for many samples. Data retrievals and comparison of analytical results can be made with the database (see below).

The most useful data are for 222 channel or equivalent samples, which represent coal in-place before mining and cleaning. For such samples, the averages for the critical environmental elements vary widely (table 4, fig. 5) from region to region, as well as within each region.

Characterization of Available Coals—34 Cleaned Samples

Trace elements and radioactivity Concentrations of most environmentally critical trace elements in the 34 cleaned coals (table 5) vary less than those in the channel samples (compare figs. 5 and 6). Comparison of the data from channel samples with that from cleaned coals indicates that, as a result of conventional coal cleaning, mean concentrations of the trace elements in the latter are lower than in the former (fig. 7); the exceptions are uranium (U) and vanadium (V). The reduction in elemental concentrations at preparation plants results from reduction of mineral matter and leaching by the process water. Because the channel samples were analyzed for fluorine (F) by an old technique, which underestimated F in many samples, the F data from channel samples and cleaned coals were not compared in this study.

As these comparisons indicate, trace elements associated with mineral matter could be reduced further in nearly all samples, if more advanced physical cleaning techniques were applied.

The natural radioactivity of coal is due to decay of thorium-232 (Th-232), uranium-238 (U-238), uranium-235 (U-235), and potassium-40 (K-40). The radioactive isotopes of U and Th decay into a complex secular equilibrium system of mixed radioactive isotopes; whereas K has a single decay product. Radioactivity can be calculated from the observed masses (weights) of U, Th, and K. Calculated radioactivity results for coals agree with measured radioactivity values (Coles et al. 1978). Radiation from K is 19% to 85% of the total in cleaned Illinois coals (table 6).

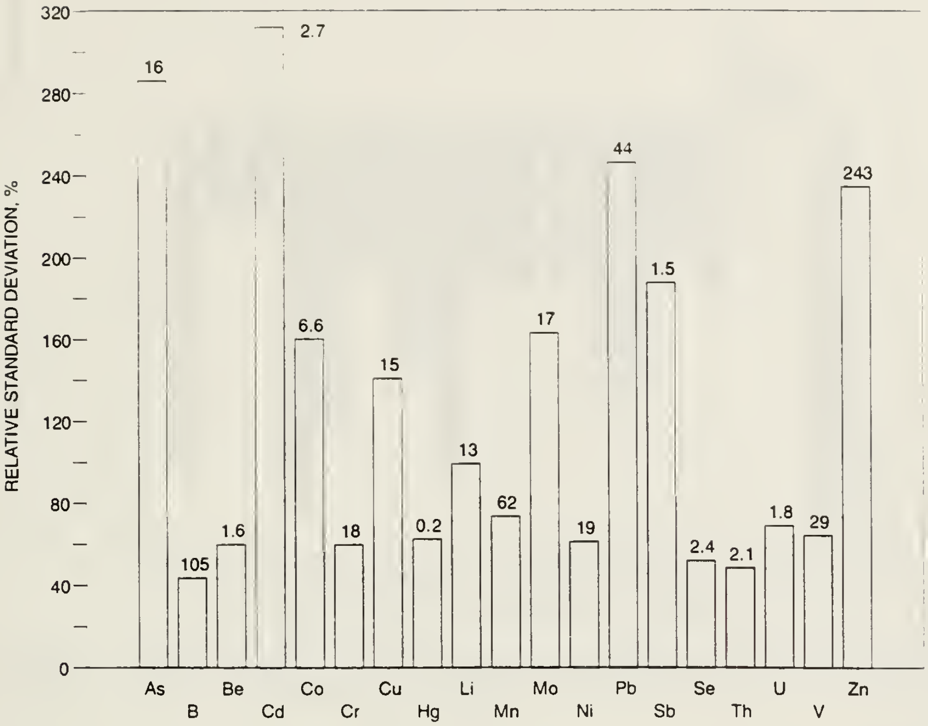

Figure 5 Variability of trace element concentrations in the 222 channel samples of Illinois coals from all regions. Numbers over the bars are mean concentrations.

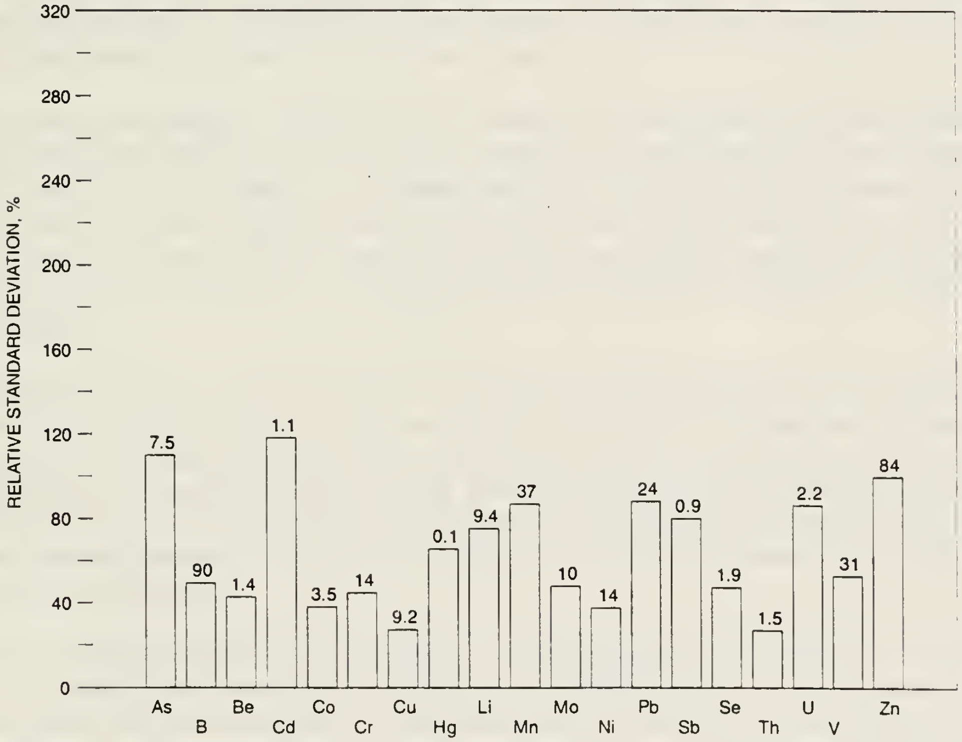

Figure 6 Variability of trace element concentrations in the 34 cleaned coal samples from all regions. Numbers over the bars are mean concentrations.

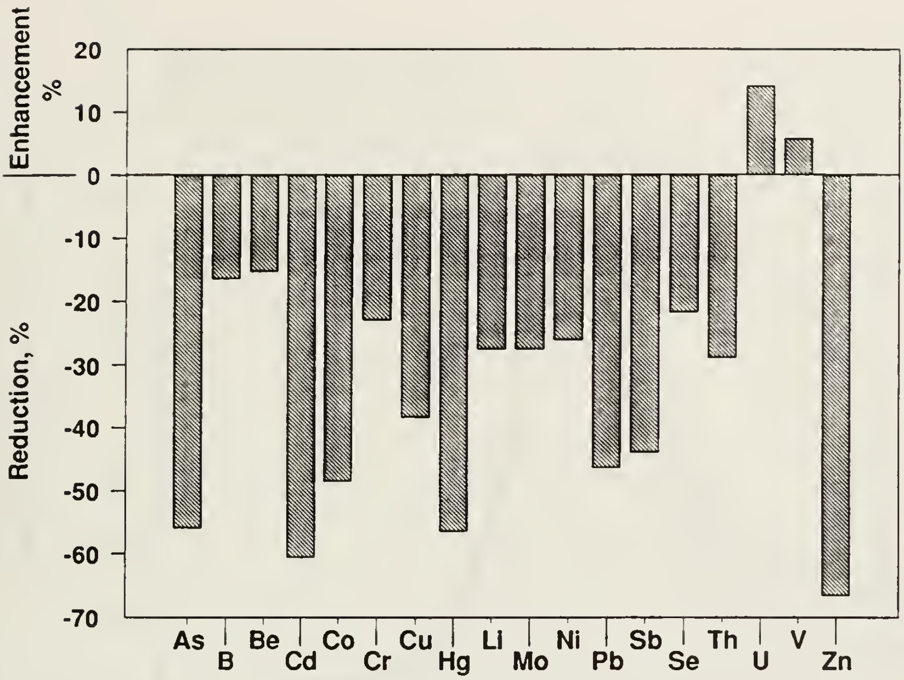

Figure 7 Change in average trace element concentrations in the 34 cleaned coal samples relative to those in the 222 channel samples.

Pyrite size distribution and maceral association The pyrite cleanability index of the samples varies widely, partly because the amount of cleaning varies from one mine to another. Preparation plants vary in average rejects from zero (crushing and no cleaning) to 53% (Illinois Department of Mines and Minerals 1992). Samples from the Springfield Coal in the southeastern region (4S) tend to have the lowest index (table 7), which suggests that, on average, removing pyrite from region 4S cleaned coals would be more difficult than removing it from other cleaned coals.

Froth flotation cleanability Weights of the cumulative froth flotation concentrates and tailings for 15 of the 34 samples are listed in table 8. Recovery (yield) for the samples ranged from 74% to 93%, and it was greater than 80% for all but two samples from region 1. Trace element concentrations in clean flotation products are expected to be notably less than those in the feed samples. This is based on the assumption that trace elements are hosted primarily in the mineral matter and that the tailings are mostly mineral matter.

Slagging and fouling Slagging and fouling indexes were calculated by procedures standard to the utility industry (Attig and Duzy 1969). These formulas use the sulfur content of the coal (table 9) and the ash composition (table 10). Calculated values (table 11) indicated that the slagging and fouling indexes for most of the coal samples range from low to medium. Two samples from region 1 are in the severe type range for slagging; several samples from region 1 and one from region 2 register at the high end of the index for fouling.

Chlorine forms and distribution Examples of pyrolysis results for the high Cl sample (C32662, Cl=0.34%) are shown in figures 8 and 9. Analytical results for the three -60 mesh samples and their extracted residues are given in table 12. A variable portion of Cl in the coals was extracted by the three solutions (hot water, ammonium hydroxide, and sodium hydroxide); 20% to 83% of the initial Cl in the coals remained in the residues. The amount of Cl extracted appears not to relate to the amount of extracted Na or K, the amount of N in the feed coal, or even the N_2-BET surface area or pore

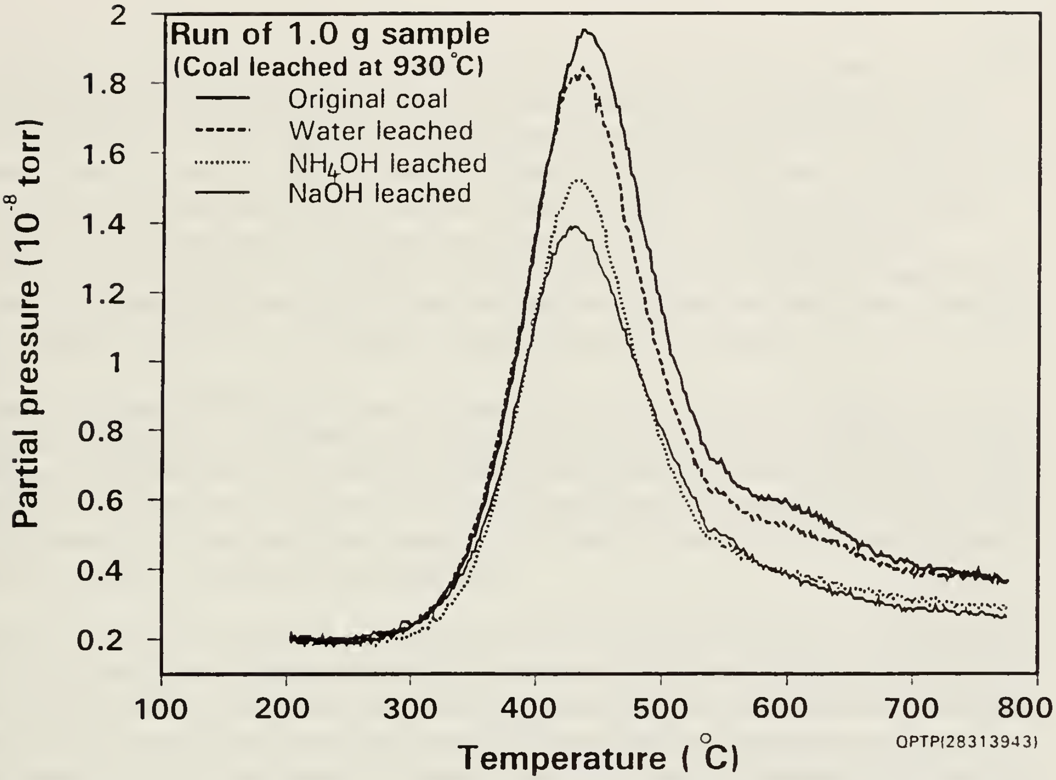

Figure 8 HCl gas evolution profiles during pyrolysis of the coal sample C32662 (0.34% Cl) and its leached products, as measured with PY/QGA.

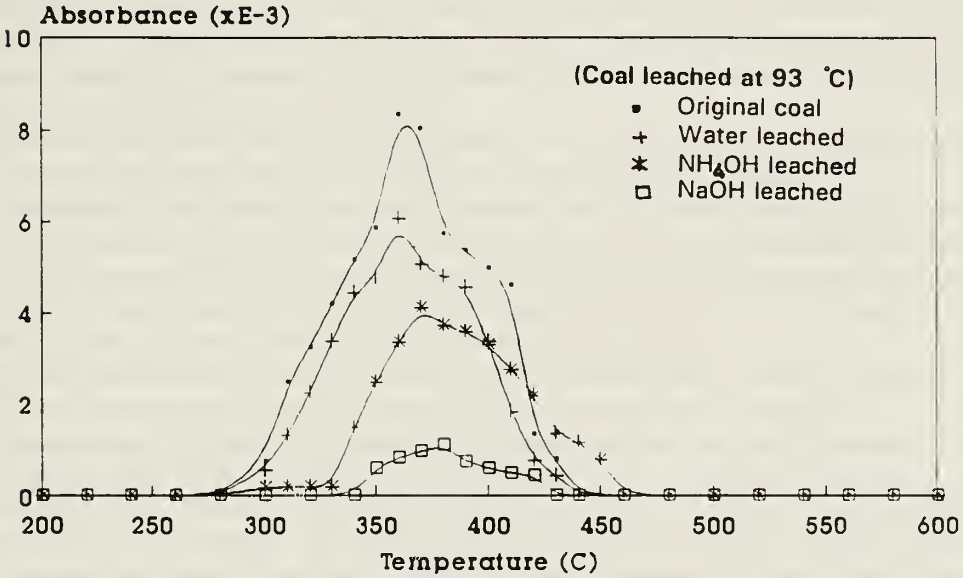

Figure 9 HCl gas evolution profiles during pyrolysis of the coal sample C32662 (0.34% Cl) and its leached products, as measured with TGA/FTIR.

volume of the feed coal. In the tested coals, macroporosity (>500 Å) varies less than microporosity (<20 Å) and mesoporosity (20-500 Å) (table 12). Comparison of Cl data from PY/QGA with those from TGA/FTIR is fair. During PY/QGA analysis, each coal and leached product exhibited one HCl peak at about 430°C (fig. 8); however, the TGA/FTIR analysis showed broad, somewhat bimodal peaks at 360° and 400°C (fig. 9).

Comparison of data for chloride extraction from sample C32662 (0.34% Cl) at -60 mesh (250µm) and -400 mesh (37µm) particle sizes indicated that, regardless of the particle size, the same reductions (about 32%) occurred for the duration of the extraction tests. The extraction results for samples C32662 and C32772 do not approach the higher reductions possible through wet ball milling to -19µm, by which up to 64% to 74% of the chloride was extracted from some coal samples (Chou et al. 1990).

Sodium and K were more readily extracted than Cl from the coals. Water extraction removed most of the Na and K from the feed coals. Ammonia extraction removed only a small amount of Na and K from the water-extracted residues.

Rheology Slurries of 50% solids were made from 15 of the available coals and tested for viscosity. Measured viscosities varied from 62.0 to 139.7 cps; the average was 94.9 cps (table 13). All but one of the viscosity values fall within the desired range for pumping coal in a water slurry (<130 cps) with the typical solid content (50%) and particle size (-60 mesh). The exception from region 3 is so close to the limit that a small change in the solid content would make it pumpable.

Gasification For each region of the state, gasification parameters were calculated (table 14) from the mean values of proximate and other analyses of the cleaned coal (table 9) and from the results of oxide analysis of the ash (table 10). It can be inferred from the data in table 14 that Illinois coals can be used for gasification. Gasification characteristics of coals do not, on average, vary much from one region to another. However, the coals from all regions except region 1 (northwest) are likely to require the addition of pulverized limestone to reduce slagging during gasification.

Summary and Conclusions

Sample types, locations, seams, concentrations of approximately 60 elements, and other data for 764 samples of Illinois coal are now easily retrievable as a result of updating the computerized ISGS database. For comparison, records of 136 samples of coals from other states are included in the database.

Advanced characterization data on cleaned coal products from mines operating in Illinois were generated during this project and added to the database:

- Analyses of channel samples that represent coal in place before mining were compared with those of 34 available (i.e. marketed) cleaned coals collected for this project from preparation plants throughout the state. Results indicate that mean concentrations of all trace elements studied, except U and V, were lower in the cleaned coals (products of conventional cleaning) than in the channel samples.
- Froth flotation test data on a selected set of cleaned coal samples strongly indicate that they could be further cleaned by physical fine coal cleaning.
- The amount of chlorine extracted from three samples by water, ammonia, and sodium hydroxide varied, but under the test conditions, a substantial fraction of Cl remained in the coal. Results also indicate that the samples contain a variable amount of nonextractable Cl. It is likely associated with the micropore matrix and not accessible under the test conditions. Chou et al. (1990) showed that more Cl can be extracted by wet-grinding coal to a finer particle size; even so, a significant fraction of Cl remains in the coal.
- Characterization of pyrite size distribution and maceral association in the samples provided useful data on pyrite in cleaned coals. The pyrite cleanability index varied greatly, partly because the degree of cleaning varied from one preparation plant to another.
- Viscosity measurements for 15 cleaned coal samples suggested that all coals except one can be pumped through a pipeline at a -60 mesh particle size and in a 50%

solid slurry form. The exception, one of the coals from region 3, is so close to the limit that a small adjustment in the solid content would make it also pumpable.

- The potential of most cleaned Illinois coals for slagging and fouling in steam-generating plants ranges from low to medium, as shown by the indices calculated from sulfur and ash analyses of all 34 samples. Some samples from the northwestern part of the coal field tested in the high and severe end of both ranges.
- Estimated gasification parameters, calculated from proximate, ultimate, and ash analyses, indicated that most Illinois coals can be utilized in gasification plants. Net power yields and heating rates are, on average, about the same for coals from the five regions of the Illinois coal field. The results also show that, during gasification, limestone should be added to coals from all regions except the northwestern part of the coal field. Adding limestone modifies the behavior of ash and promotes effective management of slag residue.

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Table 1. Elements analyzed in project samples

Elements regulated* and analyzed	Symbol	Other elements analyzed	Symbol
Antimony	Sb	Aluminum	Al
Arsenic	As	Boron	B
Beryllium	Be	Calcium	Ca
Cadmium	Cd	Carbon	C
Chlorine	Cl	Copper	Cu
Chromium	Cr	Hydrogen	H
Cobalt	Co	Iron	Fe
Fluorine	F	Lithium	Li
Lead	Pb	Molybdenum	Mo
Manganese	Mn	Nitrogen	N
Mercury	Hg	Oxygen	O
Nickel	Ni	Phosphorus	P
Polonium**	Po	Potassium	K
Radium**	Ra	Silicon	Si
Radon**	Rn	Sodium	Na
Selenium	Se	Sulfur	S
Thorium	Th	Titanium	Ti
Uranium	U	Vanadium	V
		Zinc	Zn

* Regulated by U.S. Public Law 101-549, 1990.

** Radioactive isotopes of these elements were calculated from the analytical concentrations of Th and U.

Table 2. Relative precision and methods for analyses of coal samples

Element	Relative precision %		Average detection limit		Methods*				
					WDXRF	AAS	INAA	OEP	PyroIC
Major and minor oxides									
Al_2O_3	ash	3	0.1	%	X				
CaO	ash	3	0.02	%	X				
Fe_2O_3	ash	3	0.01	%	X				
MgO	ash	5	0.1	%	X				
MnO	ash	5	0.01	%	X				
P_2O_5	ash	5	0.02	%	X				
K_2O	ash	2	0.01	%	X				
SiO_2	ash	1	0.1	%	X				
Na_2O	ash	5	0.05	%	X				
Na_2O	coal	5	0.003	%			X		
TiO_2	ash	3	0.01	%	X				
Trace elements									
As	coal	7	1.0	ppm			X		
B	coal	15	10.0	ppm				X	
Be	ash	5	0.5	ppm				X	
Cd	ash	10	2.5	ppm		X			
Co	coal	5	0.3	ppm			X		
Cr	ash	2	7.0	ppm			X		
Cu	ash	5	2.5	ppm		X			
F	coal	10	20.0	ppm					X
Hg	coal	15	0.01	ppm		X**			
Li	ash	12	5.0	ppm		X			
Mo	coal	10	10.0	ppm				X	
Ni	ash	10	15.0	ppm		X			
Pb	ash	20	25.0	ppm		X		X	
Sb	coal	10	0.2	ppm			X		
Se	coal	10	2.0	ppm			X		
Th	coal	5	0.4	ppm			X		
U	coal	15	3.0	ppm			X		
V	ash	3	8.0	ppm				X	
Zn	ash	7	1.5	ppm		X			

Constituent	Absolute precision (%)	Accuracy (%)	ASTM method
Moisture	0.02	0.3	D5142-90
Ash	0.10	0.5	D5142-90
Volatile matter	0.24	1.4	D5142-90
Carbon	0.04	0.40	D3178-89
Hydrogen	0.02	0.10	D3178-89
Nitrogen	0.03	0.05	D3189-89
Total sulfur	0.05	0.20	D5016-89
Sulfatic sulfur	0.04	0.20	D2492-90
Pyritic sulfur	0.1	0.2	D2492-90
Organic sulfur	≤0.19	≤0.6	D2492-90
Total chlorine	0.05	0.20	D4208-88
Calorific value	50 Btu/lb	100 Btu/lb	D2015-91

* WDXRF = wavelength-dispersive x-ray fluorescence spectrometry
AAS = atomic absorption spectrometry
INAA = instrumental neutron activation analysis
OEP = optical emission (photographic) spectrometry
PyroIC = pyrohydrolysis and ion chromatography
** Hg by cold vapor atomic absorption spectrometry

Table 3. Summary of sample types and seams in the ISGS database on trace elements in coal

	From Illinois	Other states	Total no.
Sample Types			
Channel and equivalent	222	67	289
Bench (partial seam)	158	11	169
Float-sink fractions	77	20	97
Run-of-mine	20	17	37
As-shipped	47	8	55
Shales and coal-assoc. rock	240	13	253
All types	764	136	900
Seams			
Herrin (Illinois No. 6)	473	4	477
Springfield (Illinois No. 5)	166	20	186
Colchester (Illinois No. 2)	50	5	55
Other seams and rocks	75	107	182

Table 4. Trace element composition of the 222 channel samples in the database; dry basis

	Region	As ppm	B ppm	Be ppm	Cd ppm	Co ppm	Cr ppm	Cu ppm	F ppm	Hg ppm	Li ppm	Mn ppm	Mo ppm	Ni ppm	Pb ppm	Sb ppm	Se ppm	Th ppm	U ppm	V ppm	Zn ppm
Mean	1	29.2	135.5	2.2	8.9	9.8	16.8	22.2	53.7	0.2	9.9	66.4	10.3	23.6	90.2	2.1	2.4	1.9	1.7	27.5	521.4
St dev		94.2	33.7	1.5	17.7	21.4	8.1	38.3	18.5	0.1	10.5	40.5	7.1	18.6	225.9	3.2	1.4	1.2	0.9	13.1	1129.9
Mean	2	5.5	142.3	1.2	0.8	4.8	18.8	10.6	70.8	0.1	10.5	51.7	18.1	16.0	14.0	0.7	2.5	2.2	1.8	24.3	138.9
St dev		10.2	41.1	0.3	0.6	2.6	7.9	3.0	23.1	0.1	7.6	22.1	34.0	6.8	10.8	0.8	0.8	0.8	1.0	10.6	124.4
Mean	3	13.5	91.7	1.5	1.2	6.4	19.7	16.3	59.9	0.1	18.6	61.8	17.2	17.8	31.1	2.1	2.5	2.2	1.4	30.1	123.9
St dev		15.9	25.8	0.8	1.2	2.7	16.8	18.4	19.7	0.1	21.2	40.7	23.6	7.0	21.4	4.5	1.6	1.4	1.2	23.6	128.9
Mean	4H	6.0	73.6	1.7	0.5	5.4	17.2	11.3	77.1	0.1	13.4	63.4	20.1	14.5	30.4	0.5	2.2	2.1	2.9	28.5	260.3
St dev		5.0	28.7	0.6	0.3	2.4	4.1	3.0	38.4	0.0	4.3	49.0	8.8	8.9	18.1	0.2	0.7	0.6	1.9	9.9	435.6
Mean	4S	25.2	55.3	1.3	1.6	5.6	14.0	10.8	62.8	0.2	9.4	72.9	22.4	18.0	51.1	1.8	2.3	1.7	1.3	36.9	214.8
St dev		20.3	22.9	0.4	1.5	2.3	5.9	6.7	24.6	0.1	5.5	74.9	43.2	7.1	38.5	1.7	1.4	0.4	0.9	27.3	219.0
Mean	ALL	16.3	105.0	1.6	2.7	6.6	17.6	14.8	63.0	0.2	12.7	62.2	17.1	18.5	43.5	1.5	2.4	2.1	1.8	29.0	243.0
St dev		46.8	45.9	0.9	8.3	10.5	10.6	20.9	23.8	0.1	12.6	45.9	27.9	11.4	107.3	2.9	1.3	1.0	1.3	18.7	570.9

Table 5. Trace element composition, dry basis

Lab no.	Region	As ppm	B ppm	Be ppm	Cd ppm	Co ppm	Cr ppm	Cu ppm	F ppm	Hg ppm	Li ppm
C32773	1	1.3	135	1	<0.3	2.3	12	7.4	90	0.13	3.9
C32774	1	20	116	4	<0.3	3.1	5.8	13.6	68	0.22	5.8
C32777	1	5.1	119	1.2	5.1	1.5	11	8	78	0.05	2.3
C32778	1	10	202	2.2	0.6	4.6	12	15.4	70	0.04	9.6
C32782	1	2.4	106	<1	0.4	1.6	14	6.2	78	0.07	2.8
C32783	1	2.2	155	1.4	<0.3	2.7	11	7.7	81	0.07	3.4
C32785	1	2.3	178	1.5	0.4	2.6	17	8.8	115	0.07	3.8
C32797	1	4	147	1.2	1.3	3	13	10	116	0.04	4.7
C32814	1	6.4	83	2	1	2.5	5.7	8.8	63	0.07	0.9
Mean A*		**6.0**	**138**	**1.8**	**<1.5**	**2.7**	**11**	**9.5**	**84**	**0.08**	**4.1**
St dev A*		**5.9**	**37**	**1.0**	**1.8**	**0.9**	**4**	**3.0**	**19**	**0.06**	**2.5**
Mean G†		**4.2**	**133**	**1.8**	**-**	**2.5**	**11**	**9.2**	**83**	**0.07**	**3.5**
C32779	2	1.7	114	<1	0.4	2	17	10.3	91	0.05	4.7
C32794	2	2.3	128	1.1	<0.1	2.8	12	7.2	95	0.08	7.5
C32798	2	2.2	128	<1	0.4	3.3	23	10.6	134	0.05	6
C32800	2	2	137	<1	<0.2	2.8	23	9.6	150	0.06	6.7
C32813	2	2.4	127	1.4	1.1	3.5	42	14	263	0.06	10.1
C32815	2	3	126	<1	<0.2	2.7	14	8.5	88	0.06	8.4
Mean A		**2.3**	**127**	**1.3**	**<0.6**	**2.9**	**22**	**10.0**	**137**	**0.06**	**7.2**
St dev A		**0.4**	**7**	**0.2**	**0.4**	**0.5**	**11**	**2.3**	**67**	**0.01**	**1.9**
Mean G		**2.2**	**126**	**-**	**-**	**2.8**	**20**	**9.8**	**126**	**0.06**	**7.0**
C32784	3	18	74	1.8	<0.3	4.2	11	7.7	67	0.11	15.6
C32795	3	3.6	57	1	<0.1	4.8	8.6	7.1	53	0.03	8.6
C32796	3	9.8	49	1	0.9	8.5	19	15.6	123	0.06	41.6
C32799	3	17	58	1	<0.2	4.4	12	10.4	127	0.02	13.2
C32801	3	10	64	1	<0.1	4.4	12	7.8	76	0.04	12.3
C32802	3	3.1	78	<1	<0.1	2.5	12	6.5	88	0.04	8.6
C32803	3	4.1	78	1.2	<0.1	2.7	12	11	94	0.04	13.6
Mean A		**9.4**	**65**	**1.2**	**<0.3**	**4.5**	**12**	**9.4**	**90**	**0.05**	**16.2**
St dev A		**6.2**	**11**	**0.3**	**-**	**2.0**	**3**	**3.2**	**28**	**0.03**	**11.5**
Mean G		**7.5**	**65**	**-**	**-**	**4.2**	**12**	**9.0**	**86**	**0.04**	**14.0**
C32661	4H	3.4	47	1.6	<0.3	3.9	16	9.2	81	0.07	7.6
C32664	4H	5.4	41	1.4	<0.3	4.4	13	8.6	87	0.19	20.1
C32665	4H	4.4	60	1.2	<0.3	3.6	13	8.2	84	0.17	13.7
C32771	4H	3.7	58	1.1	<0.5	4.1	14	9.3	131	0.14	12.5
C32776	4H	2.7	76	1.5	<0.3	3.6	15	8.3	74	0.07	5.3
Mean A		**3.9**	**56**	**1.4**	**<0.3**	**3.9**	**14**	**8.7**	**91**	**0.13**	**11.8**
St dev A		**1.0**	**14**	**0.2**	**-**	**0.3**	**1**	**0.5**	**23**	**0.06**	**5.8**
Mean G		**3.8**	**55**	**1.3**	**-**	**3.9**	**14**	**8.7**	**89**	**0.12**	**10.7**
C32662	4S	14	40	1.4	<0.3	4.4	10	11.5	83	0.08	10.3
C32663	4S	34	45	1.1	<0.3	4.1	11	8.6	78	0.25	12.6
C32772	4S	8	40	1	<0.2	3.9	9.2	5.2	75	0.17	10.7
C32775	4S	4.9	38	1.8	1.1	4.7	14	8.8	97	0.21	7.9
C32780	4S	3.1	64	<1	<0.6	1.9	12	6.1	75	0.07	6.3
C32781	4S	4.3	24	<1	0.5	2.7	12	6.3	104	0.11	8.1
C32793	4S	33	82	1.2	<0.2	5.5	13	10.1	124	0.13	11.5
Mean A		**14.5**	**48**	**1.3**	**<0.8**	**3.9**	**12**	**8.1**	**91**	**0.15**	**9.6**
St dev A		**13.5**	**19**	**0.3**	**<0.4**	**1.2**	**2**	**2.3**	**18**	**0.07**	**2.3**
Mean G		**9.7**	**44**	**-**	**-**	**3.7**	**11**	**7.8**	**89**	**0.13**	**9.4**
All mean A		7.5	90	<1.4	<1.1	3.5	14	9.2	97	0.09	9.4
All st dev A		8.2	45	<0.6	<1.3	1.3	6	2.5	37	0.06	7.1
All mean G		5.0	80	-	-	3.3	13	8.9	92	0.08	7.6

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* The calculation of the arithmetic mean (mean A) and standard deviation (st dev A) do not include the < data.

† Geometric mean

continued on next page

Table 5. Trace element composition *continued*

Lab no.	Region	Mn ppm	Mo ppm	Ni ppm	Pb ppm	Sb ppm	Se ppm	Th ppm	U ppm	V ppm	Zn ppm
C32773	1	38.5	<6	11	<6	0.2	1.9	1.2	1.7	16	32.9
C32774	1	18.0	<5	15	102	1.2	1.2	0.8	<0.8	11	70.8
C32777	1	205.0	<6	7	36	1.1	1.6	1.1	1.1	18	447
C32778	1	38.0	<5.7	31	13.5	2.2	1.5	1.5	0.9	25	105
C32782	1	55.0	11	7	<6	0.5	1.9	1.1	1.3	23	42.2
C32783	1	36.5	9.7	8	<5.5	0.1	1.3	1.3	1.1	17	54.1
C32785	1	38.5	10.3	17.5	<5.3	0.4	3.9	1.3	1.8	29	59.9
C32797	1	31.5	12	16	8.5	0.6	1.4	1.5	1.9	27	105
C32814	1	29.5	15	12	23	1.9	1.3	0.6	8	16	67.9
Mean A*		**54.5**	**<11.6**	**14**	**<37**	**0.9**	**1.8**	**1.2**	**2.2**	**20**	**109**
St dev A		**57.2**	**<2.1**	**8**	**<38**	**0.7**	**0.8**	**0.3**	**2.4**	**6**	**129**
Mean G		**41.8**	**-**	**12**	**-**	**0.6**	**1.7**	**1.1**	**-**	**19**	**78**
C32779	2	28.5	19	11	7	0.4	2.3	1.3	3.1	41	77.9
C32794	2	39.5	11.7	14	14.5	0.3	1.9	1.4	2	23	120
C32798	2	53.5	10.3	18	12	0.3	3.2	1.7	2.7	46	78
C32800	2	30.0	9	15.5	8	0.4	2.8	1.6	2.9	30	68.5
C32813	2	40.0	14.3	24	12.5	0.7	5.4	2.1	3.7	65	141
C32815	2	61.0	9	10	12.3	0.6	2.1	1.7	1.9	27	101
Mean A		**42.1**	**12.2**	**15**	**11.1**	**0.5**	**3.0**	**1.6**	**2.7**	**39**	**98**
St dev A		**12.9**	**3.9**	**5**	**2.9**	**0.2**	**1.3**	**0.3**	**0.7**	**16**	**28**
Mean G		**40.5**	**11.8**	**15**	**10.7**	**0.4**	**2.8**	**1.6**	**2.6**	**36**	**95**
C32784	3	17.0	<5	15	39.5	1.1	1.4	1.4	1	18	28.8
C32795	3	11.2	<5	18	16	1.1	1.1	1.2	0.6	15	39.9
C32796	3	41.0	<6	23.5	31.3	1	2	3	1	39	322.5
C32799	3	63.5	<5	14.5	63.7	3.6	1.3	1.6	0.7	28	120.5
C32801	3	20.5	<5	14	22	0.6	1.5	1.5	1	21	34.5
C32802	3	22.5	<5	7	7	0.3	1.5	1.4	1.2	32	32.1
C32803	3	27.5	5.5	13	12.5	0.4	1.5	1.6	1.1	34	25.4
Mean A		**29.0**	**<5.5**	**15**	**27.4**	**1.2**	**1.5**	**1.7**	**0.9**	**27**	**86.2**
St dev A		**17.9**	**-**	**5**	**19.5**	**1.1**	**0.3**	**0.6**	**0.2**	**9**	**109.4**
Mean G		**25.1**	**-**	**14**	**21.9**	**0.8**	**1.5**	**1.6**	**0.9**	**25**	**53.5**
C32661	4H	20.0	21.3	13.5	19	0.5	2	1.5	7.5	33	68.2
C32664	4H	19.5	<8.3	11	32.5	0.5	1.6	1.7	2.2	22	38.7
C32665	4H	25.0	15.3	11	18.5	0.4	1.7	1.6	5.7	35	23.5
C32771	4H	36.0	12.3	10	21.5	0.3	1.4	1.8	2.2	26	104
C32776	4H	37.5	14.7	12	10	0.6	1.7	1.4	1.8	45	32
Mean A		**27.6**	**<16**	**12**	**20**	**0.5**	**1.7**	**1.6**	**3.9**	**32**	**53**
St dev A		**8.6**	**<4**	**1**	**8**	**0.1**	**0.2**	**0.2**	**2.6**	**9**	**33**
Mean G		**26.5**	**-**	**11**	**19**	**0.4**	**1.7**	**1.6**	**3.3**	**31**	**46**
C32662	4S	15.0	<7.3	17	22.5	1	1.3	1.9	1.9	27	28.4
C32663	4S	16.5	<7.5	13	69.5	1.4	1.5	1.4	0.9	23	61.8
C32772	4S	38.5	<5	13	27	0.7	1.3	1.3	<1	19	39.8
C32775	4S	15.5	19.7	17.5	45.3	1.2	3.6	1.3	6.8	29	109
C32780	4S	24.0	11.3	7.5	11.7	1.4	2.3	1.2	2	64	35.7
C32781	4S	36.5	12	11	46	1.4	2.5	1.2	2	91	62.4
C32793	4S	39.0	<5.5	22	35.5	1.2	1.1	1.8	0.8	32	91.3
Mean A		**26.4**	**<14.3**	**14**	**36.8**	**1.2**	**1.9**	**1.4**	**2.4**	**41**	**61.2**
St dev A		**11.3**	**4.7**	**5**	**19.0**	**0.3**	**0.9**	**0.3**	**2.2**	**27**	**29.9**
Mean G		**24.3**	**-**	**14**	**32.3**	**1.2**	**1.8**	**1.4**	**-**	**35**	**55.1**
All mean A		**37.3**	**<12.8**	**14.1**	**27**	**0.9**	**1.9**	**1.5**	**2.3**	**31**	**84.4**
All st dev A		**32.3**	**4.0**	**5.3**	**22**	**0.7**	**0.9**	**0.4**	**2.0**	**16**	**84.2**
All mean G		**31.3**	**-**	**13.3**	**-**	**0.7**	**1.8**	**1.4**	**-**	**28**	**64.3**

* See footnote on the previous page of this table.

Table 6. Natural radioactivity

Sample	Region	Th ppm	Th-232 series * Bq/kg††	U ppm	U-238 series** Bq/kg††	U-235 series† Bq/kg††	K ppm	K-40 Bq/kg††
C32773	1	1.2	4.9	1.7	21.1	0.51	1498	46.5
C32774	1	0.8	3.4	0.8	9.9	0.24	921	28.6
C32777	1	1.1	4.5	1.1	13.6	0.33	1880	58.3
C32778	1	1.5	6.1	0.9	11.2	0.27	1831	56.7
C32782	1	1.1	4.5	1.3	16.1	0.39	1575	48.8
C32783	1	1.3	5.3	1.1	13.6	0.33	2327	72.1
C32785	1	1.3	5.3	1.8	22.3	0.54	1870	58.0
C32797	1	1.5	6.1	1.9	23.6	0.57	1862	57.7
C32814	1	0.6	2.5	8.0	99.2	2.39	782	24.2
Mean	1	1.2	4.7	2.1	25.6	0.62	1616	50.1
St dev	1	0.3	1.1	2.1	26.4	0.64	464	14.4
C32779	2	1.3	5.3	3.1	38.4	0.93	1663	51.5
C32794	2	1.4	5.7	2.0	24.8	0.60	1651	51.2
C32798	2	1.7	6.9	2.7	33.5	0.81	527	16.3
C32800	2	1.6	6.5	2.9	36.0	0.87	2014	62.4
C32813	2	2.1	8.5	3.7	45.9	1.11	3063	95.0
C32815	2	1.7	6.9	1.9	23.6	0.57	1738	53.9
Mean	2	1.6	6.6	2.7	33.7	0.81	1776	55.1
St dev	2	0.3	1.0	0.6	7.7	0.19	742	23.0
C32784	3	1.4	5.7	1.0	12.4	0.30	1593	49.4
C32795	3	1.2	4.9	0.6	7.4	0.18	1152	35.7
C32796	3	3.0	12.2	1.0	12.4	0.30	3448	106.9
C32799	3	1.6	6.5	0.7	8.7	0.21	2531	78.5
C32801	3	1.5	6.1	1.0	12.4	0.30	1575	48.8
C32802	3	1.4	5.7	1.2	14.9	0.36	1741	54.0
C32803	3	1.6	6.5	1.1	13.6	0.33	1839	57.0
Mean	3	1.7	6.8	0.9	11.7	0.28	1983	61.5
St dev	3	0.6	2.3	0.2	2.5	0.06	711	22.0
C32661	4H	1.5	6.1	7.5	93.0	2.24	1628	50.5
C32664	4H	1.7	6.9	2.2	27.3	0.66	1704	52.8
C32665	4H	1.6	6.5	5.7	70.7	1.70	1941	60.2
C32771	4H	1.8	7.3	2.2	27.3	0.66	2598	80.5
C32776	4H	1.4	5.7	1.8	22.3	0.54	1655	51.3
Mean	4H	1.6	6.5	3.9	48.1	1.16	1905	59.1
St dev	4H	0.1	0.6	2.3	28.5	0.69	364	11.3
C32662	4S	1.9	7.7	1.9	23.6	0.57	1726	53.5
C32663	4S	1.4	5.7	0.9	11.2	0.27	1807	56.0
C32772	4S	1.3	5.3	1.0	12.4	0.30	1665	51.6
C32775	4S	1.3	5.3	6.8	84.3	2.03	1490	46.2
C32780	4S	1.2	4.9	2.0	24.8	0.60	1986	61.6
C32781	4S	1.2	4.9	2.0	24.8	0.60	1806	56.0
C32793	4S	1.8	7.3	0.8	9.9	0.24	3381	104.8
Mean	4S	1.4	5.9	2.2	27.3	0.66	1980	61.4
St dev	4S	0.3	1.1	1.9	24.1	0.58	589	18.2
All mean		1.5	6.0	2.2	27.8	0.67	1837	57.0
All St dev		0.4	1.6	2.0	25.3	0.61	606	18.8

* Th-232, Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208

** U-238, Th-234, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210

† U-235, Th-231, Pa,231, Ac-227, Th-227, Ra-223, Pb-211, Bi-211

†† Becquerel/kg = number of disintegration per second per kg of coal

Table 7. Pyrite size distribution and maceral association

			Percentage pyrite diameter by particle type*					
Lab no.	Region	Mean diameter µm	Free pyrite	Pyritic coal	Carbominerite	Inertite	Macerite	Pyrite cleanability index†
C32773	1	3	34	12	3	0	49	1.04
C32774	1	5	16	27	2	2	51	0.94
C32777	1	4	16	24	10	0	47	1.10
C32778	1	4	26	22	4	1	44	1.22
C32782	1	5	25	10	4	5	54	0.82
C32783	1	4	25	10	0	1	61	0.63
C32785	1	9	16	27	20	2	33	1.97
C32797	1	6	36	7	17	6	32	2.07
C32814	1	6	26	24	2	1	46	1.17
Mean		**5**	**24**	**18**	**7**	**2**	**46**	**1.22**
St dev		**2**	**7**	**8**	**7**	**2**	**9**	**0.49**
C32779	2	3	27	12	1	1	57	0.75
C32794	2	7	25	6	38	0	29	2.35
C32798	2	5	25	6	17	2	47	1.11
C32800	2	7	20	14	25	4	35	1.83
C32813	2	5	12	33	2	2	49	1.01
C32815	2	5	27	10	0	3	57	0.74
Mean		**5**	**23**	**14**	**14**	**2**	**46**	**1.30**
St dev		**2**	**6**	**10**	**16**	**1**	**12**	**0.65**
C32784	3	7	32	10	13	4	39	1.53
C32795	3	4	31	0	12	2	53	0.88
C32796	3	4	29	0	34	4	30	2.28
C32799	3	4	37	0	21	8	31	2.13
C32801	3	3	22	3	1	6	66	0.50
C32802	3	2	27	6	7	1	56	0.76
C32803	3	6	21	11	9	2	54	0.84
Mean		**4**	**28**	**4**	**14**	**4**	**47**	**1.27**
St dev		**2**	**6**	**5**	**11**	**2**	**14**	**0.71**
C32661	4H	6	18	21	0	11	48	1.05
C32664	4H	4	29	19	1	3	45	1.19
C32665	4H	4	25	16	2	3	53	0.89
C32771	4H	5	13	14	6	11	53	0.86
C32776	4H	4	26	17	2	1	51	0.93
Mean		**5**	**22**	**17**	**2**	**6**	**50**	**0.98**
St dev		**1**	**7**	**3**	**2**	**5**	**3**	**0.14**
C32662	4S	3	32	11	0	0	54	0.83
C32663	4S	4	22	14	3	1	56	0.77
C32772	4S	4	25	6	4	2	61	0.64
C32775	4S	6	14	41	1	0	40	1.44
C32780	4S	5	20	22	1	1	54	0.85
C32781	4S	5	12	11	1	1	73	0.36
C32793	4S	5	17	4	26	3	48	1.06
Mean		**5**	**20**	**16**	**5**	**1**	**55**	**0.85**
St dev		**1**	**7**	**13**	**9**	**1**	**10**	**0.34**
All mean		**5**	**24**	**14**	**9**	**3**	**49**	**1.13**
All st dev		**1**	**6**	**10**	**10**	**2**	**10**	**0.51**

* Percentage of the summed diameters of all grains observed within the given particle type; a measure proportional to the mass of pyrite that occurs in those particles.

† See text for explanation.

Table 8. Summary of flotation test results

Sample	Region	Weight (gm) Concentrate*	Weight (gm) Tailings**	Recovery(%)
C32774	1	256.43	45.47	85
C32777	1	255.22	46.15	85
C32778	1	251.50	86.54	74
C32782	1	252.58	66.03	79
C32779	2	271.76	40.32	87
C32815	2	268.35	52.89	84
C32795	3	269.74	49.85	84
C32799	3	267.51	35.09	88
C32801	3	276.55	27.49	91
C32665	4H	286.65	20.70	93
C32771	4H	262.34	31.31	89
C32776	4H	286.42	26.14	92
C32793	4S	252.51	39.66	86
C32780	4S	282.06	22.31	93
C32775	4S	291.07	27.77	91

* combined weight of five concentrate fractions in grams.
** combined weight of four tailing fractions in grams.

Table 9. Proximate and other standard analyses*

Lab no.	Region	EQMoist %	Ash %	Vol %	FxC %	C %	H %	N %	O %	S %	SuS %	PyS %	OrS %	Cl %	Btu/lb	FSI
C32773	1	13.94	8.72	41.22	50.06	71.47	5.04	1.21	9.41	4.14	0.14	0.97	3.03	0.10	12808	3.5
C32774	1	13.36	7.07	40.87	52.06	74.58	5.38	1.31	8.09	3.58	0.56	1.46	1.56	0.03	13273	2.5
C32777	1	14.38	14.52	38.60	46.88	69.44	5.04	1.22	6.63	3.14	0.08	1.01	2.05	0.12	12451	3.5
C32778	1	13.95	9.80	36.68	53.53	71.95	5.16	1.42	10.08	1.60	0.07	0.54	0.98	0.07	12709	2.5
C32782	1	14.29	11.62	38.98	49.40	69.45	5.17	1.25	8.61	3.90	0.20	1.25	2.45	0.15	12503	3.0
C32783	1	14.24	12.86	43.90	42.24	69.85	5.37	1.25	6.26	4.41	0.12	1.33	2.96	0.16	12653	3.5
C32785	1	13.47	9.75	41.43	48.81	70.22	5.34	1.30	9.22	4.17	0.12	1.05	3.00	0.12	12741	4.0
C32797	1	13.95	10.29	40.27	49.45	71.11	5.06	1.23	8.68	3.62	0.18	0.99	2.45	0.09	12728	4.0
C32814	1	11.34	6.00	45.68	48.31	76.20	5.49	1.28	7.35	3.68	0.18	1.09	2.41	0.01	13841	3.0
Mean		**13.66**	**10.07**	**40.85**	**48.97**	**71.59**	**5.23**	**1.27**	**8.26**	**3.58**	**0.18**	**1.08**	**2.32**	**0.09**	**12856**	**3.3**
St dev		**0.94**	**2.68**	**2.72**	**3.20**	**2.36**	**0.17**	**0.06**	**1.29**	**0.84**	**0.15**	**0.26**	**0.69**	**0.05**	**437**	**0.6**
C32779	2	12.31	9.63	39.39	50.98	71.19	5.13	1.24	8.62	4.20	0.09	1.04	3.07	0.08	12753	4.0
C32794	2	10.06	10.52	38.49	51.00	71.22	4.92	1.31	8.37	3.67	0.14	1.24	2.29	0.04	12685	4.0
C32798	2	11.05	13.16	38.31	48.53	68.84	4.97	1.27	8.28	3.48	0.15	1.20	2.13	0.08	12285	3.0
C32800	2	9.50	11.39	38.42	50.19	70.45	4.94	1.20	8.39	3.63	0.22	0.92	2.49	0.08	12599	4.0
C32813	2	10.19	14.70	36.49	48.80	67.69	4.72	1.26	8.16	3.47	0.05	1.45	1.97	0.05	12086	4.0
C32815	2	10.99	12.03	37.16	50.82	69.42	4.93	1.41	8.48	3.73	0.12	1.41	2.19	0.02	12422	3.5
Mean		**10.68**	**11.91**	**38.04**	**49.87**	**69.80**	**4.94**	**1.28**	**8.38**	**3.70**	**0.13**	**1.21**	**2.36**	**0.06**	**12472**	**3.8**
St dev		**0.99**	**1.83**	**1.04**	**1.14**	**1.41**	**0.13**	**0.07**	**0.16**	**0.27**	**0.06**	**0.21**	**0.39**	**0.03**	**256**	**0.4**
C32784	3	9.31	8.13	35.62	56.24	74.81	5.22	1.57	8.48	1.79	0.13	0.74	0.92	0.39	13329	4.5
C32795	3	9.76	5.76	35.25	58.99	78.02	5.11	1.63	8.75	0.73	0.02	0.17	0.55	0.45	13779	4.5
C32796	3	9.06	16.10	32.00	51.90	69.01	4.64	1.49	7.71	1.05	0.10	0.42	0.53	0.38	12120	2.0
C32799	3	9.70	11.42	34.40	54.18	72.42	4.82	1.94	8.62	0.76	0.03	0.21	0.52	0.01	12728	3.0
C32801	3	8.45	8.36	35.93	55.71	75.08	5.19	1.57	7.82	1.98	0.17	0.70	1.11	0.35	13280	4.0
C32802	3	7.11	9.36	38.34	52.30	73.74	5.11	1.41	7.25	3.12	0.23	0.88	2.01	0.29	13094	4.5
C32803	3	8.22	9.19	36.62	54.19	74.10	5.11	1.46	7.59	2.54	0.19	0.79	1.56	0.32	13145	4.0
Mean		**8.80**	**9.76**	**35.45**	**53.53**	**73.88**	**5.03**	**1.58**	**8.03**	**1.71**	**0.12**	**0.56**	**1.03**	**0.31**	**13068**	**3.8**
St dev		**0.95**	**3.27**	**1.96**	**1.77**	**2.75**	**0.21**	**0.17**	**0.58**	**0.92**	**0.08**	**0.29**	**0.58**	**0.14**	**523**	**1.0**
C32661	4H	7.60	8.17	36.60	55.23	74.99	5.11	1.48	7.36	2.89	0.14	0.99	1.76	0.26	13238	5.0
C32664	4H	5.80	9.87	36.67	53.45	73.80	4.99	1.41	7.06	2.87	0.05	1.18	1.64	0.09	13148	6.5
C32665	4H	6.80	9.39	36.31	54.30	74.17	5.05	1.44	7.23	2.73	0.07	1.05	1.61	0.13	13151	5.0
C32771	4H	6.50	12.57	35.06	52.37	71.65	4.75	1.34	6.75	2.93	0.12	1.22	1.59	0.09	12616	5.0
C32776	4H	9.28	9.27	37.92	52.81	72.98	5.14	1.44	8.05	3.13	0.10	1.13	1.90	0.15	13182	4.0
Mean		**7.20**	**9.85**	**36.51**	**53.63**	**73.52**	**5.01**	**1.42**	**7.29**	**2.91**	**0.10**	**1.11**	**1.70**	**0.14**	**13067**	**5.1**
St dev		**1.33**	**1.64**	**1.02**	**1.15**	**1.27**	**0.16**	**0.05**	**0.48**	**0.14**	**0.04**	**0.09**	**0.13**	**0.07**	**255**	**0.9**
C32662	4S	8.20	7.00	34.88	58.12	77.02	5.12	1.59	7.75	1.51	0.08	0.59	0.85	0.35	13525	4.5
C32663	4S	6.70	8.96	35.39	55.65	75.05	5.07	1.59	7.15	2.18	0.15	1.01	1.02	0.21	13102	5.0
C32772	4S	5.26	9.33	35.44	55.23	75.10	5.08	1.58	6.53	2.38	0.10	0.99	1.29	0.24	13274	5.0
C32775	4S	2.93	7.67	35.88	56.45	77.09	5.11	1.40	5.76	2.98	0.04	1.16	1.78	0.17	13779	8.0
C32780	4S	6.11	9.57	37.75	52.68	73.46	5.03	1.44	7.17	3.32	0.21	1.05	2.07	0.21	13123	4.5
C32781	4S	2.64	9.71	34.44	55.84	75.69	5.30	1.60	4.68	3.02	0.12	1.10	1.80	0.19	13773	8.0
C32793	4S	10.75	14.14	33.52	52.35	70.37	4.86	1.49	7.50	1.64	0.04	0.92	0.69	0.20	12402	4.5
Mean		**6.08**	**9.48**	**35.33**	**55.19**	**74.83**	**5.08**	**1.53**	**6.65**	**2.43**	**0.11**	**0.97**	**1.36**	**0.22**	**13283**	**5.6**
St dev		**2.86**	**2.29**	**1.32**	**2.05**	**2.33**	**0.13**	**0.08**	**1.09**	**0.70**	**0.06**	**0.19**	**0.53**	**0.06**	**479**	**1.6**
All mean		**9.62**	**10.18**	**37.47**	**51.96**	**72.70**	**5.07**	**1.41**	**7.76**	**2.88**	**0.13**	**0.98**	**1.77**	**0.17**	**12951**	**4.2**
All st dev		**3.25**	**2.49**	**2.87**	**3.35**	**2.73**	**0.19**	**0.16**	**1.08**	**1.01**	**0.09**	**0.31**	**0.74**	**0.12**	**478**	**1.3**

* Dry basis, except for moisture

EQMoist: equilibrium moisture
Vol: volatile matter
FxC: fixed carbon
SuS: sulfate S
PyS: pyritic S
OrS: organic S
Btu/lb: unit of heating value
FSI: free swelling index

Table 10. Major oxides in the high temperature (750°C) ash

Lab no.	Region	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	K_2O %	Na_2O %	TiO_2 %	P_2O_5 %	SO_3 %
C32773	1	48.80	18.48	18.48	4.35	0.87	2.07	1.52	0.98	0.11	3.66
C32774	1	34.57	14.43	43.14	2.14	0.57	1.57	0.29	0.71	0.29	1.83
C32777	1	41.09	11.47	11.92	17.48	0.78	1.56	0.45	0.67	0.11	13.78
C32778	1	52.36	21.21	11.48	5.02	1.02	2.25	1.64	1.13	0.20	3.13
C32782	1	50.39	13.91	18.45	6.09	0.77	1.63	1.29	0.77	0.17	6.12
C32783	1	45.63	18.50	22.97	3.01	0.94	2.18	2.08	0.94	0.10	2.93
C32785	1	49.70	18.51	17.71	3.62	1.01	2.31	1.71	0.91	0.30	3.33
C32797	1	49.16	19.09	16.91	4.25	0.99	2.18	1.48	0.99	0.20	3.77
C32814	1	37.24	12.59	31.47	8.57	0.70	1.57	0.17	0.70	0.06	6.31
Mean		**45.44**	**16.46**	**21.39**	**6.06**	**0.85**	**1.93**	**1.18**	**0.87**	**0.17**	**4.98**
St dev		**6.32**	**3.40**	**10.10**	**4.67**	**0.16**	**0.33**	**0.70**	**0.16**	**0.08**	**3.61**
C32779	2	49.38	19.02	17.57	4.47	0.94	2.08	1.46	0.94	0.10	3.55
C32794	2	47.59	18.89	20.68	4.15	0.85	1.89	0.47	0.94	0.09	3.60
C32798	2	47.41	18.30	15.21	7.03	1.08	2.01	1.08	0.85	0.15	6.15
C32800	2	50.27	19.63	16.34	4.09	0.98	2.13	1.15	0.98	0.18	3.62
C32813	2	51.66	19.89	15.14	3.67	1.22	2.51	0.81	0.95	0.48	3.11
C32815	2	45.82	18.56	17.98	7.04	0.99	1.74	0.41	0.91	0.08	5.90
Mean		**48.69**	**19.05**	**17.15**	**5.07**	**1.01**	**2.06**	**0.90**	**0.93**	**0.18**	**4.32**
St dev		**2.14**	**0.61**	**2.09**	**1.54**	**0.13**	**0.26**	**0.41**	**0.04**	**0.15**	**1.33**
C32784	3	49.13	23.57	17.74	1.36	0.99	2.36	1.49	1.24	0.12	1.33
C32795	3	55.34	26.03	6.90	1.72	1.03	2.41	2.41	1.38	0.17	1.52
C32796	3	58.00	25.03	6.33	2.09	1.11	2.58	1.05	1.23	0.12	2.14
C32799	3	48.54	25.99	4.39	9.12	1.03	2.67	0.60	0.95	0.86	5.16
C32801	3	48.92	22.47	17.37	2.61	0.91	2.27	1.25	1.25	0.11	2.60
C32802	3	47.54	20.30	18.16	4.27	0.85	2.24	0.85	0.96	0.11	4.14
C32803	3	48.36	21.99	16.85	3.06	0.88	2.41	1.20	1.09	0.11	3.40
Mean	**3**	**50.83**	**23.63**	**12.53**	**3.46**	**0.97**	**2.42**	**1.27**	**1.16**	**0.23**	**2.90**
St dev		**4.09**	**2.18**	**6.29**	**2.67**	**0.09**	**0.16**	**0.58**	**0.16**	**0.28**	**1.41**
C32661	4H	48.20	20.98	19.66	2.28	0.96	2.40	0.84	1.08	0.12	2.83
C32664	4H	50.99	21.13	19.35	1.98	0.89	2.08	0.40	1.29	0.40	1.67
C32665	4H	50.62	21.83	17.98	2.08	0.94	2.49	0.42	1.04	0.10	2.05
C32771	4H	50.86	20.53	16.17	3.42	0.93	2.49	0.47	1.01	0.08	3.67
C32776	4H	46.13	19.46	19.25	5.16	0.86	2.15	0.97	0.97	0.11	4.38
Mean		**49.36**	**20.79**	**18.48**	**2.98**	**0.92**	**2.32**	**0.62**	**1.08**	**0.16**	**2.92**
St dev		**2.14**	**0.88**	**1.44**	**1.35**	**0.04**	**0.19**	**0.27**	**0.13**	**0.13**	**1.12**
C32662	4S	48.94	24.61	15.13	1.84	1.13	2.97	1.13	1.27	0.57	1.73
C32663	4S	50.44	23.34	17.81	1.77	0.88	2.43	0.33	1.00	0.11	1.75
C32772	4S	48.93	19.04	17.81	4.61	0.92	2.15	0.51	1.02	0.20	4.37
C32775	4S	45.45	20.52	24.55	1.82	0.91	2.34	0.26	1.04	0.13	2.28
C32780	4S	46.67	18.96	19.38	4.79	0.83	2.50	0.63	1.04	0.10	4.69
C32781	4S	51.01	18.14	19.21	2.88	1.49	2.24	0.32	0.96	0.11	3.37
C32793	4S	54.55	21.74	12.20	2.88	1.14	2.88	1.06	1.06	0.30	1.97
Mean		**49.43**	**20.91**	**18.01**	**2.94**	**1.04**	**2.50**	**0.61**	**1.06**	**0.22**	**2.88**
St dev		**2.99**	**2.43**	**3.83**	**1.29**	**0.23**	**0.31**	**0.36**	**0.10**	**0.17**	**1.26**
All mean		**48.52**	**19.95**	**17.70**	**4.26**	**0.95**	**2.23**	**0.95**	**1.01**	**0.19**	**3.70**
All st dev		**4.43**	**3.39**	**6.71**	**3.04**	**0.16**	**0.34**	**0.56**	**0.17**	**0.17**	**2.26**

Table 11. Slag characteristics

Lab no.	Region	Silica %	Visc/2600 p*	Tcv °F†	T250p °F*	Base/acid ‡	Slag index‡	Slag type‡	Foul index‡	Foul type‡
C32773	1	67	110	2470	2500	0.40	1.65	medium	0.61	high
C32774	1	43	4	2150	**	0.96	3.44	severe	0.27	medium
C32777	1	58	29	3700	**	0.60	1.90	medium	0.27	medium
C32778	1	75	385	2450	2650	0.29	0.46	low	0.47	medium
C32782	1	67	110	3840	**	0.43	1.69	medium	0.56	high
C32783	1	63	60	2310	2360	0.48	2.11	high	1.00	high
C32785	1	69	150	2520	2520	0.38	1.59	medium	0.65	high
C32797	1	69	150	2440	2520	0.37	1.35	medium	0.55	high
C32814	1	48	8	2630	**	0.84	3.09	severe	0.15	low
Mean		**62**	**112**	**2723**	**2510**	**0.53**	**1.92**		**0.50**	
St dev		**11**	**117**	**609**	**103**	**0.23**	**0.89**		**0.25**	
C32779	2	68	140	2450	2500	0.38	1.61	medium	0.56	high
C32794	2	65	80	2360	2410	0.42	1.53	medium	0.20	medium
C32798	2	67	105	2440	2460	0.40	1.38	medium	0.43	medium
C32800	2	70	170	2450	2530	0.35	1.26	medium	0.40	medium
C32813	2	72	240	2490	2590	0.32	1.12	medium	0.26	medium
C32815	2	64	78	2330	2380	0.43	1.61	medium	0.18	low
Mean		**68**	**136**	**2420**	**2478**	**0.38**	**1.42**		**0.34**	
St dev		**3**	**62**	**61**	**78**	**0.04**	**0.20**		**0.15**	
C32784	3	71	200	2290	2570	0.32	0.58	low	0.48	medium
C32795	3	85	1500	2490	2820	0.18	0.13	low	0.42	medium
C32796	3	86	1600	2530	2830	0.16	0.16	low	0.16	low
C32799	3	77	580	2410	2710	0.24	0.18	low	0.14	low
C32801	3	70	170	2290	2530	0.34	0.67	medium	0.42	medium
C32802	3	67	110	2300	2460	0.38	1.20	medium	0.33	medium
C32803	3	70	170	2300	2530	0.34	0.87	medium	0.41	medium
Mean		**75**	**619**	**2373**	**2636**	**0.28**	**0.54**		**0.34**	
St dev		**8**	**655**	**103**	**150**	**0.09**	**0.41**		**0.13**	
C32661	4H	68	140	2290	2500	0.37	1.08	medium	0.31	medium
C32664	4H	70	170	2350	2530	0.34	0.97	medium	0.13	low
C32665	4H	71	200	2330	2570	0.33	0.89	medium	0.14	low
C32771	4H	71	200	2410	2570	0.32	0.95	medium	0.15	low
C32776	4H	65	80	2290	2410	0.43	1.33	medium	0.41	medium
Mean		**69**	**158**	**2334**	**2516**	**0.36**	**1.04**		**0.23**	
St dev		**3**	**50**	**50**	**66**	**0.04**	**0.18**		**0.13**	
C32662	4S	73	290	2320	2620	0.30	0.45	low	0.34	medium
C32663	4S	71	200	2290	2570	0.31	0.68	medium	0.10	low
C32772	4S	68	140	2420	2500	0.38	0.90	medium	0.19	low
C32775	4S	63	60	2210	2360	0.45	1.33	medium	0.12	low
C32780	4S	65	80	2330	2420	0.42	1.40	medium	0.26	medium
C32781	4S	68	140	2620	**	0.37	1.13	medium	0.12	low
C32793	4S	77	580	2500	2710	0.26	0.43	low	0.28	medium
Mean		**69**	**213**	**2384**	**2530**	**0.36**	**0.90**		**0.20**	
St dev		**5**	**179**	**139**	**130**	**0.07**	**0.40**		**0.09**	
All mean		**68**	**248**	**2471**	**2539**	**0.39**	**1.21**		**0.34**	
All st dev		**8**	**355**	**347**	**120**	**0.15**	**0.73**		**0.20**	

* Corey (1964)

Silica % = $100SiO_2/(SiO_2 + Fe_2O_3 + CaO + MgO)$

Viscosity @ 2600 (°F) by graphical correlation

T@250poise in °F by graphical correlation

** The predicted temperature is below the temperature of critical viscosity (Tcv) and thus the graphical correlation is not applicable.

† Hazard (1980); Hoy et al. (1964)

$Tcv, {}^{\circ}C = 2990 - 1470(s/a) + 360(s/a)^2 - 14.7(f) + 0.15(f)^2$

where s/a is SiO_2/Al_2O_3 and f is $Fe_2O_3 + CaO + MgO$ and the result is converted to °F

‡ Attig and Duzy (1969)

Base/Acid = oxides of (Fe + Ca + Mg + Na + K) / (Si + Al + Ti)

Slagging Index = Base/acid($\%S_{coal}$)

Fouling Index = Base/acid($\%Na_2O_{ash}$)

Table 12. Characterization of extracted coals for chlorine

	Samples		
	C32662	C32772	C32782
Cl in feed coal(%)	0.34	0.24	0.15
Cl in H_2O-extd coal(%)	0.32	0.21	0.06
Cl in H_2O/NH_4OH-extd residue(%)	0.26	0.21	0.04
Cl in $H_2O/NH_4OH/NaOH$-extd residue(%)	0.23	0.20	0.03
Na/K in feed coal(%)	0.84 /2.05	0.38/1.78	0.96 /1.12
Na/K in H_2O-extd coal(%)	0.027/0.16	-	0.029/0.15
Na/K in H_2O/NH_4OH-extd residue(%)	0.025/0.15	-	0.021/0.14
Pore volume in feed coal (cc/g)			
Total	0.147	0.015	0.024
Macro	0.009	0.006	0.006
Meso	0.097	0.007	0.011
Micro	0.041	0.002	0.007
Surface area, multi-point BET(m^2/g)	74.0	3.1	7.6

Table 13. Viscosities of slurried samples, -60 mesh particle size, 50% solids

Sample no.	Region	Viscosity cp
C32774	1	106.5
C32777	1	108.8
C32778	1	110.6
C32782	1	93.1
C32815	1	76.7
C32779	2	95.6
C32795	3	102.8
C32799	3	88.8
C32801	3	139.7
C32665	4H	96.8
C32771	4H	87.5
C32776	4H	88.0
C32780	4S	78.0
C32775	4S	62.0
C32793	4S	88.1

Table 14. Regional means of gasification characteristics*

Estimated performance	Region 1	2	3	4H	4S
Coal					
Dry, tpd	2250	2318	2149	2161	2117
As received, tpd	2647	2628	2383	2333	2270
Limestone, tpd	0.0	26.7	42.5	24.4	24.8
Oxygen required (95%), tpd	2224	2263	2136	2182	2156
Slag product, tpd	283	344	278	258	253
Syngas properties					
Dry composition, vol %					
H_2	32.7	31.8	31.4	31.3	31.3
CO	49.0	49.7	51.2	51.3	51.5
CO_2	14.0	14.1	12.7	12.8	12.5
CH_4	1.5	1.5	1.8	1.8	1.9
Ar + N_2	2.8	2.8	2.9	2.9	2.9
Molecular weight	20.6	20.8	20.7	20.7	20.7
High heating value (HHV), Btu/scf (Dry basis)	278.2	277.5	284.0	283.5	285.2
Net power, Mw	272.4	271.1	269.5	268.9	268.6
Heat rate (HHV), Btu/kwhr	8856	8888	8685	8752	8710

* Based on a proprietary gasification process.