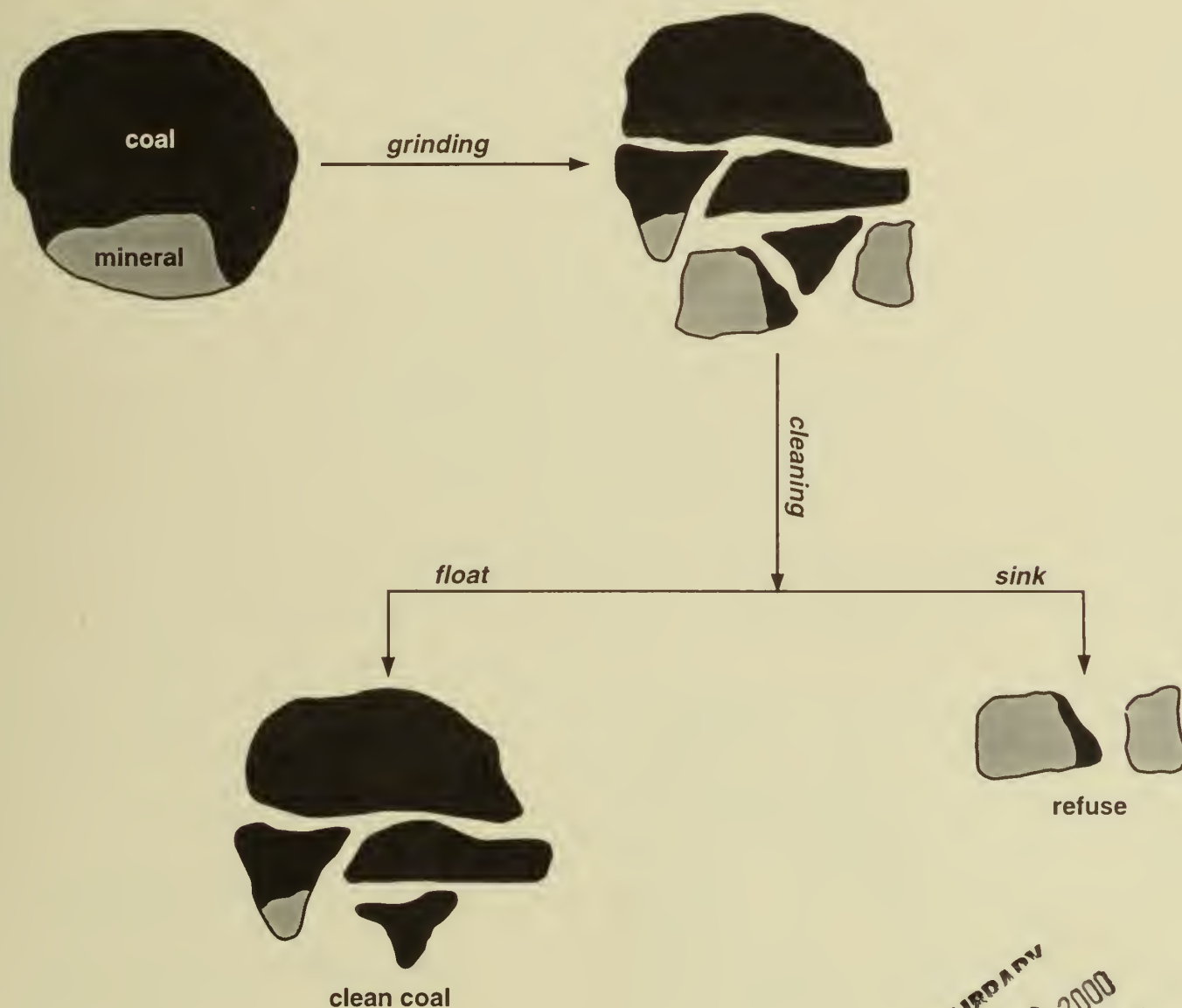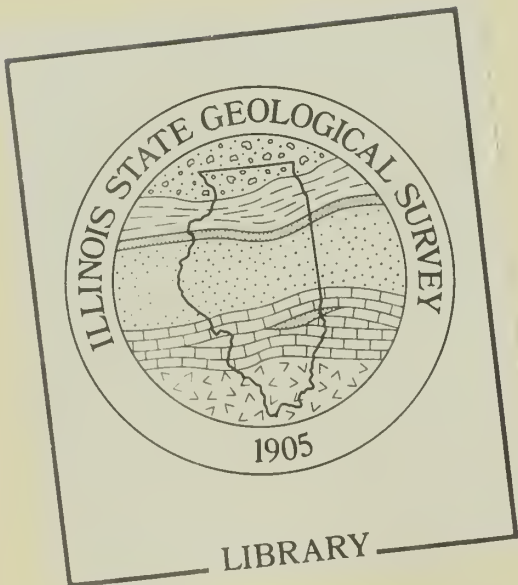# Assessing the Removal of Air Toxics in Marketed Illinois Coals by Gravity-Based Cleaning

Ilham Demir, Rodney R. Ruch, John M. Lytle,
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CONTENTS

Glossary

channel sample sample representing the full thickness of a coal seam, excluding mineral bands, partings, or nodules thicker than 1 cm. It is taken by cutting a channel with a pick from the top to the bottom of the coal seam.

compliance coal coal that meets the standards set by environmental regulations.

conventional cleaning commercial cleaning methods currently used in coal preparation plants. It is usually used for cleaning mostly coarse-size (~1 cm) coal, and occasionally for fine-size (<0.6 mm) fractions.

run-of-mine coal mined coal that has not undergone cleaning or preparation.

particle sizes (in mesh and millimeter) used in this publication

mesh	mm
4	4.769
14	1.410
100	0.150
200	0.074
270	0.053
325	0.044
400	0.037
500	0.025

particle size definitions used in this publication:

coarse coal	coal crushed to particle size greater than 0.6 mm
fine coal	coal ground to particle sizes less than 0.6 mm
ultrafine coal	coal ground to particle sizes less than 0.074 mm

washability the degree of coal cleaning that can be achieved by using wet methods. It is generally considered the ultimate cleanability achieved under laboratory conditions.

ABSTRACT

Advanced gravity-based cleaning of finely ground Illinois coals can potentially reduce their contents of ash and air toxics, including sulfur (S) and trace elements of environmental concern, to levels predicted by laboratory float-sink (F-S) tests. To estimate the response of marketed Illinois coals to advanced gravity separation, we generated F-S washability data for ash, S, and 15 trace and minor elements (As, Be, Cd, Co, Cr, F, Hg, Mn, Ni, P, Pb, Sb, Se, Th, U)—all identified as hazardous air pollutants (HAPs) by the Clean Air Act Amendments of 1990. Samples of marketed coal products from 29 coal preparation plants operating in Illinois during 1995 were ground to reduce their particle size to <0.150 mm (–100 mesh). Each ground sample was separated, using a centrifugal F-S method, into specific-gravity fractions of <1.3, 1.3 to 1.4, 1.4 to 1.6, and >1.6. In addition, representative splits of 10 of the 29 samples were ground to <0.074 mm (–200 mesh) and subjected to similar F-S tests. Using ash, moisture, and yield data on the F-S fractions, we prepared a clean composite sample of 80%-combustibles recovery for each F-S test.

The ash content of the <0.150-mm composite samples was 37% to 75% ($\bar{x}$ 53% ± 9%) less than the ash content of the parent coals. Average reductions for the concentrations of S and other elements were:

As	63% ± 10%	P	58% ± 25%
Cd	73% ± 23%	Pb	45% ± 25%
Co	33% ± 16%	S	27% ± 8%
Cr	19% ± 12%	Sb	18% ± 14%
F	35% ± 19%	Se	38% ± 12%
Hg	70% ± 10%	Th	28% ± 10%
Mn	70% ± 8%	U	12% ± 23%
Ni	30% ± 12%		

The average concentration of Be in the clean composite samples was about twice as much as that in the parent coals. The additional environmental risk from Be-enrichment during fine-coal cleaning would be insignificant, however, because this element occurs in very small concentrations in Illinois coals and is not very mobile during coal combustion. Grinding the samples to <0.074 mm generally did not improve the F-S separation of ash, S, and HAPs substantially beyond the separations obtained at <0.150 mm. The F-S data of this study showed that

- the ultimate cleanability of Illinois coals is considerably greater than the cleanability indicated by release-analysis data of a previous study.

- advanced fine-coal cleaning can potentially reduce the contents of ash and air toxics in these coals to levels significantly lower than those obtained through conventional cleaning.

INTRODUCTION

Run-of-mine coal generally has an ash content of 5% to 40% and a sulfur (S) content of 0.3% to 8%, depending on the geologic conditions and mining technique used. Coal cleaning is normally required, therefore, to remove excessive impurities that interfere with efficient and environmentally safe utilization of coal. The ultimate level of cleanability of coal, as determined by laboratory tests, cannot be achieved through conventional cleaning, which is generally applied to relatively coarse coal. A substantial amount of fine and ultrafine coal produced during mining and preparation is not cleaned by conventional methods and thus ends up in waste ponds.

This study was prompted by the idea that advanced gravity separators or technologies that combine gravity separation with column flotation can potentially achieve the same level of coal-cleaning as can be achieved in the laboratory through float-sink (F-S) separation. Therefore, we studied the F-S washability characteristics of conventionally cleaned marketed Illinois coals to estimate how their further beneficiation through advanced gravity cleaning would reduce their ash and air

toxics contents. Most marketed coals are currently ground so that 70% of the coal has particle sizes of <0.074 mm for utilization in pulverized coal (PC) boilers; this is the form used by more than 90% of the combustion boilers used in Illinois (Honaker et al. 1995). Because the coal is already ground, an advanced cleaning strategy to produce compliance coal from high-S Illinois coals might be economical if the cleaning is done at PC plants; if the coal were to be ground and cleaned elsewhere, however, the difficulty of transporting fine coal to power plants will have to be resolved for the cleaning to be economical.

The objectives of this study were

- to generate fine-coal washability data to evaluate the effectiveness of gravity-based advanced cleaning techniques for reducing the content of ash, S, and HAP elements in coal shipped from Illinois mines, and

- to compare the results from gravity-based techniques with froth-flotation cleanability data previously obtained on the same coals.

The results reported here are significant for evaluating noxious emissions, fouling, and slagging at power-generating plants, and for matching specific coals with prospective uses such as advanced gasification processing, making activated carbons, and producing synthetic organic chemicals.

BACKGROUND

The National Committee for Geochemistry (National Research Council 1980), concerned with the effects of coal utilization on the environment, identified three categories of elements:

1. Those of greatest concern: As, B, Cd, Pb, Hg, Mo, and Se

2. Those of moderate concern: V, Cr, Ni, Cu, Zn, and F

3. Those of minor concern: Li, Na, Sr, Ba, Mn, Co, Ge, Cl, Br, Ra, Po, Rn, Th, and U

These categories were based on known toxicity, levels of occurrence of each element in coal, and anticipated mobility upon combustion or disposal of ash.

The 1990 Clean Air Act Amendments (U.S. Public Law 101-549 1990) not only regulated the sulfur dioxide (SO_2) emissions from coal-fired power plants but also targeted 16 other elements that occur in coal and are among 189 hazardous air pollutants (HAPs). These HAP elements are As, Be, Cd, Cl, Cr, Co, F, Hg, Mn, Ni, P, Pb, Sb, Se, Th, and U. Radioactive isotopes derived from U and Th, such as Po, Ra, and Rn, were also implicated as HAPs. Although present in all coals, the concentrations and modes of occurrence of these HAP elements can vary considerably from one coal to another (Gluskoter et al. 1977, Swanson et al. 1976, Zubovic et al. 1979 and 1980, Cahill et al. 1982, Harvey et al. 1983, Finkelman 1994a, Huffman et al. 1994, Galbreath and Brekke 1994, Demir et al. 1998). Phase I of the 1990 Amendments, which restricts SO_2 emissions, took effect on January 1, 1995; Phase II, which requires further reductions in SO_2 emissions, will take effect in 2000. A decision about whether to regulate HAP emissions from coal-fired power plants is expected in the near future, after the U.S. Environmental Protection Agency completes its risk assessment.

The U.S. Geological Survey (USGS) has a large amount of data on HAPs in channel samples of coals from various regions of the United States (Finkelman 1994b). The channel samples represent in-place coal and contain more impurities than washed coals. Most midwestern and eastern U.S. coals are washed to reduce their mineral matter contents (Demir et al. 1994, Fiscor and Fisher 1998); therefore, the channel-sample data overestimate the emission of HAPs from the combustion of coal, especially from midwestern and eastern coals.

Coal Cleaning

Employment of an economical coal-cleaning technique is an attractive alternative to costly post-combustion control of SO_2 and HAP emissions from power plants. Current commercial coal-cleaning methods are invariably based on physical separation; chemical and biological methods tend to be too expensive. Typically, gravity (density) separation is used to clean coarse coal, whereas surface-property-based methods are preferred for fine-coal cleaning.

In gravity-based processes, coal particles are added to a liquid medium, which is then subjected to gravity or centrifugal forces to separate the organic-rich (float) phase from the mineral-rich (sink) phase. Gravity-based separation, the most common coal-cleaning method, is commercially accomplished by the use of jigs, mineral spirals, concentrating tables, hydrocyclones, and heavy-media separators. In surface-property-based processes, finely ground coal is mixed with water, and a small amount of collector reagent is added to the mixture to increase the hydrophobicity of coal surfaces. Subsequently, air bubbles are introduced in the presence of a frother to carry the coal particles to the top of the slurry and separate them from the hydrophilic mineral particles. Commercial surface-property-based cleaning is accomplished through the use of froth or column flotation equipment.

Progress in the removal of trace elements by coal cleaning has been reviewed and summarized by Mezey (1977), the National Research Council (1979, 1980), Wheelock and Markuszewski (1981, 1984), Streeter (1986), Kaiser Engineers (1989), Jacobsen et al. (1992), Norton et al. (1986, 1992), Norton and Markuszewski (1989), and Couch (1995). In general, these reviews point out that coal cleaning can be effective for reducing the content of most HAPs and S prior to combustion. Those trace elements associated with macerals (that is, elements chemically bonded to the organic matter or occurring in fine-grained minerals disseminated within organic matter) are difficult or impossible to remove by physical cleaning. In some cases, their concentration may actually increase in the cleaned coal. Studies indicate chemical means provide good removal of trace elements. The cost of chemical cleaning, however, would be quite high (Norton et al. 1986).

The concentration of some trace and minor elements in run-of-mine coal is reduced through conventional coal cleaning; however, the coarse particle size (~1 cm) used in conventional cleaning generally limits the amount of mineral matter liberated and, accordingly, the reduction in elemental concentrations. Float-sink studies on the 0.6-mm × 1-cm (28-mesh × 3/8-in.) fraction of Illinois coals (Gluskoter et al. 1977, Fiene et al. 1979, Harvey et al. 1983) indicated that many elements (As, Ba, Ca, Cd, Fe, Mn, Mo, Pb, Tl, and Zn) have a strong inorganic association and can be removed to a significant degree (~50% or greater). Other elements (B, Be, Ge, Ni, Sb, U, and V) are associated with organic matter and, therefore, generally not removed during physical coal cleaning.

Demir et al. (1994, 1998) showed that on average the concentration of trace elements, except for U and V, was lower in the conventionally cleaned coals than in the channel samples. Release-analysis data on 34 conventionally cleaned Illinois coals indicated that froth or column flotation would remove additional ash, S, and HAP elements from the coals beyond conventional cleaning (Demir et al. 1995). At 80%-combustibles recovery, the release-analysis procedure removed up to 69%, 76%, and 83% of the ash-forming material from the <0.150-mm, <0.074-mm, and <0.037-mm coals, respectively. The average reduction for most HAP elements was less than that for ash; reductions for some elements in individual samples, however, approached or exceeded reductions for ash. The elements that were not removed as efficiently as ash tended to be concentrated in finely disseminated minerals trapped in the release-analysis concentrates. Both the feed coals (washed products of conventional cleaning) and their release-analysis products contained significantly fewer HAP elements than did channel samples that represent coal in place. In the <0.074-mm release-analysis products with 80%-combustibles recovery, for example, average concentrations of As, Hg, and Se were reduced by 73%, 75%, and 46%, respectively, relative to their average concentrations in channel samples.

Theoretically, the efficiency of physical cleaning should increase as particle size decreases because of the improved liberation of mineral matter from the coal matrix. Recent research on advanced coal cleaning thus has focused on improving fine-coal cleaning. Advanced gravity separators, developed mainly for the metal mining industry, were recently shown to have a good potential for improving the cleaning of finely ground coal (Paul and Honaker 1994, Honaker and Wang 1995, Honaker et al. 1998). Similarly, column flotation devices developed since the 1980s can efficiently clean finely ground coal (Yang 1990, Yoon et al. 1990, Kenedy 1990).

Development and Utilization of Laboratory Float-Sink Methods

The performance of gravity-based cleaning circuits is estimated by using laboratory float-sink (F-S) tests. It has been generally recognized that conventional, static F-S procedures are not applicable to fine coal. Franzidis and Harris (1986), Cavallaro and Killmeyer (1988), Ho and Warchol (1988), Bosold and Glessner (1988), Dumm and Hogg (1988), and Suardini (1993) reported on various centrifugal F-S methods for use with coal crushed to <1.2 mm (−14 mesh). These methods differed slightly in centrifugal conditions, equipment, particle size of the feed, and reagents used. An extensive interlaboratory comparison program involving eight laboratories studied the variables in various procedures in an attempt to develop a standard centrifugal F-S procedure (Killmeyer et al. 1992).

Harrison (1986) reported that centrifugal F-S procedures could successfully predict cleaning performance for coal particle sizes <0.6 mm (−28 mesh). Cavallaro and Killmeyer (1988) observed that the centrifugal F-S technique yielded greater ash rejection than did the static technique for a Kittanning bituminous coal ground to <0.150 mm (−100 mesh). Suardini (1993) reported on centrifuge testing of a <0.150-mm Illinois Herrin (No. 6) coal by using a calcium nitrate solution. Crelling and Hippo (1992) used density gradient centrifugation and thermal gravimetric analysis to describe the separation of fine and ultrafine coal into various specific-gravity fractions. Vassalo et al. (1990) reported on a technique that utilized diffuse-reflectance Fourier transform infrared (FTIR) spectroscopy to generate washability data. Lin et al. (1991) applied x-ray-computed tomography for constructing coal washability curves.

Flotation Cleanability and Comparison with Float-Sink Washability

Release analysis has been used to estimate the state of release or ultimate cleanability of a sample by standard froth-flotation or column-flotation methods (Dell 1964, Dell et al. 1972, Forrest 1990, Honaker and Paul 1994, Demir et al. 1995) that take advantage of the differences between the surface properties of the mineral matter and organic portions of coal. Straszheim and Markuszewski (1989) compared the efficiency of a gravity-based process with that of a surface-property-based process for cleaning a <0.044-mm sample of Upper Freeport coal. They found that the density-based process produced significantly greater ash rejection than the surface-property-based process. This increase may have resulted in part from decreasing selectivity of flotation with decreasing particle size (Vanangamudi et al. 1988) or the inefficiency of the surface-property-based process in treating mixed-phase (coal-ash) particles.

METHODS AND MATERIALS

Samples and Sample Preparation

Demir et al. (1994) collected samples of washed (marketed) coal products from 34 coal preparation plants that processed mine outputs from different regions of Illinois (fig. 1). Because of the confidential nature of the data produced by this study, the names and locations of the individual mines that provided the coal samples were not revealed. Data on individual mines were identified only by laboratory numbers and by the multi-county coal region where the samples were collected. Details of the collection, preparation, and storage of the samples under nitrogen were described previously (Demir et al. 1994). All 34 samples were stored under nitrogen and are <4.76 mm (−4 mesh) in particle size. Twenty-nine of the preparation plants were still in operation in 1995, and samples from these plants were used for this study.

A representative split of each of the 29 coal samples was dry-ground to <0.150 mm in a hammer mill and saved under nitrogen gas. Previous analysis of particle size distribution (Demir et al. 1995) indicated that this grinding procedure reduced particle size to 90% <0.150 mm.

Ten samples, two from each region of the Illinois coal field, were selected from the 29 samples for grinding to <0.074 mm. About 700 g of each of the ten coals was mixed with 700 mL of tap water and ground in a rod mill for 30 minutes. The coal slurry was filtered, air-dried, and saved under nitrogen. Previous analysis of particle size distribution (Demir et al. 1995) indicated that this grinding procedure reduced the particle size to 90% <0.074 to <0.053 mm.

Washability Tests

A centrifugal float-sink (F-S) method based on the procedures reported in Ho and Warchol (1988) and Cavallaro and Killmeyer (1988) was used to determine the washabilities of ash, S, and HAPs. We had originally planned to use lithium metatungstate (LMT) salt solutions as the heavy medium because of their easy handling and regeneration. However, initial QA/QC tests that we conducted indicated that a substantial amount of LMT remained in the F-S fractions in spite of rigorous filtering and washing with deionized water. This residual LMT increased the tungsten concentration in the products by several orders of magnitude. Interference from such large tungsten concentrations in coal

Figure 1 Coal regions of Illinois. The southeastern Illinois coal field is divided into Herrin (4H) and Springfield (4S) coal seams.

produces unacceptably large analytical errors in most trace element determinations, particularly those by neutron activation. Thus, for our washability tests, we decided to use coalgrav® liquids (mixtures of perchloroethylene and naphta) as the heavy media. A surface-active reagent, dioctyl sodium sulfosuccinate (Aerosol OT-100), was used to disperse the coal in the heavy media.

There were 12 steps in the F-S test procedure:

1. 100 g of a ground coal sample dried at 40°C overnight was mixed with 2 L of coalgrav® liquid with a 1.3 specific gravity (sg); 0.5 g of Aerosol OT-100 was then added to the mixture.

2. The mixture was agitated first with a mechanical stirrer for 6 to 10 minutes and then in an ultrasonic bath until no agglomeration persisted (usually 2 to 10 minutes).

3. The slurry was poured into 250 mL Teflon centrifuge bottles, and the bottles were tightly capped and placed in a centrifuge.

4. The slurry was centrifuged at 2000 rpm (about 880 g-force for the centrifuge used) for 20 minutes.

5. The float portion of the slurry in the bottles was gently stirred without disturbing the sink portion.

6. Steps 4 and 5 were repeated twice.

7. The float was gently poured out of the bottles onto a filter paper placed in a filter funnel.

8. The filtered float was washed thoroughly (first with 250 mL of ethanol, and then with 1.5 L of deionized water, to remove residues of coalgrav® and Aerosol OT-100), dried overnight at 40°C, and weighed.

9. The >1.3 sg sink from step 8 was mixed with 2 L of 1.4 sg coalgrav®, and steps 2 through 8 were repeated.

10. The >1.4 sg sink from step 9 was mixed with 2 L of 1.6 sg coalgrav®, and steps 2 through 8 were repeated.

11. The >1.6 sg sink was washed, dried, and weighed as in step 8.

12. The <1.3, 1.3 to 1.4, 1.4 to 1.6, and >1.6 sg fractions were submitted for analysis.

Sample Analysis

The 29 marketed coals and their F-S products were analyzed using a combination of different techniques (appendix 1). The data on ash, moisture, and minor and trace elements in the 29 coal samples that had been published by Demir et al. (1994) were incorporated into this study. In this study, the F-S fractions from all the washability tests were analyzed for ash, moisture, and total S. The F-S fractions of one of the samples were also analyzed for trace and minor elements, including 15 HAPs (As, Be, Cd, Co, Cr, F, Hg, Mn, Ni, P, Pb, Sb, Se, Th, and U), to compute mass balances. For each of the remaining 37 washability tests (28 at <0.150 mm and 9 at <0.074 mm), minor and trace element analyses were conducted on a composite sample of 80%-combustibles recovery. Several samples were also analyzed for Cl, which indicated that a small amount of Cl from the heavy medium (perchloroethylene) used in the washability tests may have remained at least in some of the samples, in spite of rigorous washing with ethanol and deionized water followed by complete drying. Such contamination made it difficult to determine the behavior of Cl in coal during the washability tests.

To prepare the composite samples of 80%-combustibles recovery, the combustible materials content of each F-S fraction was calculated by subtracting its ash and moisture contents from 100%. Then a plot of percentage cumulative combustibles recovery versus cumulative weight yield of F-S fractions was constructed for each F-S test. Using these plots, the lightest fraction (<1.3 sg) was combined with a portion of 1.3 to 1.4 sg, and sometimes also of the 1.4 to1.6 sg fraction, in such a way that the composite sample represented 80%-combustibles recovery. For example, to generate the composite sample of the 80%-combustibles recovery for the F-S test on sample C32775 at <0.150-mm particle size (fig. 2), all of the <1.3 sg fraction and 11.7 grams of the 1.3 to 1.4 sg fraction were combined; this step resulted in a 79-gram clean sample that retained 80% of the total combustible material in the feed coal.

RESULTS AND DISCUSSION

Washabilities of Ash and Sulfur

The F-S washability data (fig. 3, appendixes 2 and 3) indicated that ash and S contents of marketed Illinois coals can be reduced substantially, well beyond that achieved by conventional cleaning, through the use of advanced physical fine-coal cleaning.

At 80%-combustibles recovery, clean coals having ash contents of 2.8% to 3.9% were produced from 10 of the 29 samples ground to <0.150 mm (appendix 4). For the remaining clean F-S washability products obtained at <0.150 mm, the ash content ranged from 4.0% to 5.3% for 12 samples and 5.6% to 7.9% for 7 samples. The decrease in the ash content of the 29 samples ground to <0.150 mm represents a 37% to 75% reduction, with an average reduction of 53% (fig. 4, appendix 5).

The S content of the 29 clean F-S products obtained at <0.150 mm varied between 0.6% and 3.5%, representing an 8% to 47% reduction ($\bar{x} = 27\% \pm 8\%$) relative to the parent coals (fig. 4, appendixes 4 and 5). Comparison of the S washability data from this study with the data on S forms in the parent coals reported in Demir et al. (1994) indicated that the S in clean F-S products was predominantly organic S; most of the pyritic and sulfate S was removed during the F-S process.

Washabilities of HAPs

The average concentrations of HAP elements in the 29 samples of marketed Illinois coals (fig. 5) can be divided into four categories:

<1 mg/kg	Hg, Cd, Sb
1 to 10 mg/kg	As, Be, Co, Se, Th, U
10 to 30 mg/kg	Cr, Ni, Pb
30 to 91 mg/kg	F, Mn, P

Knowing the concentrations of HAPs and their combustion behavior is important for addressing the environmental concerns related to HAP emissions at coal-fired power plants. By comparing the analytical data on the marketed coals with the data on their clean F-S products (appendix 4), the reduction of the HAP concentrations in the coals through the use of advanced physical fine-coal cleaning can be estimated. The HAP concentrations (except for Be) in the coals decreased substantially (with a few exceptions) as a result of F-S separation at <0.150 mm (fig. 4, appendix 5). Some of the decreases (or enrichments) in HAP concentrations calculated for some individual samples may have been erroneous if the difference between the concentration in the parent coal and that in its clean F-S product was not greater than the analytical precision for that particular element. Such errors, however, generally cancel each other out when mean values for the entire sample set are computed. On average, Be was enriched in the <0.150-mm washability products by 118% when compared with the parent coals (fig. 4). This enrichment suggests that Be was finely disseminated (perhaps organically associated) within the coal macerals. On a mg/ million Btu basis, the average enrichment value for Be would be somewhat smaller than 118% because the clean F-S products have greater heating value (less ash) than their parent coals (appendix 4). Because the mean Be content of the marketed coals was only 1.3 mg/kg (fig. 5), and because Be tends to remain largely with bottom ash and slag during coal combustion (fig. 6), additional environmental risks arising from the enrichment of this element in advanced coal cleaning products would be small or insignificant.

Data on several samples indicated no change or varying degrees of enrichment of Cl in the F-S products
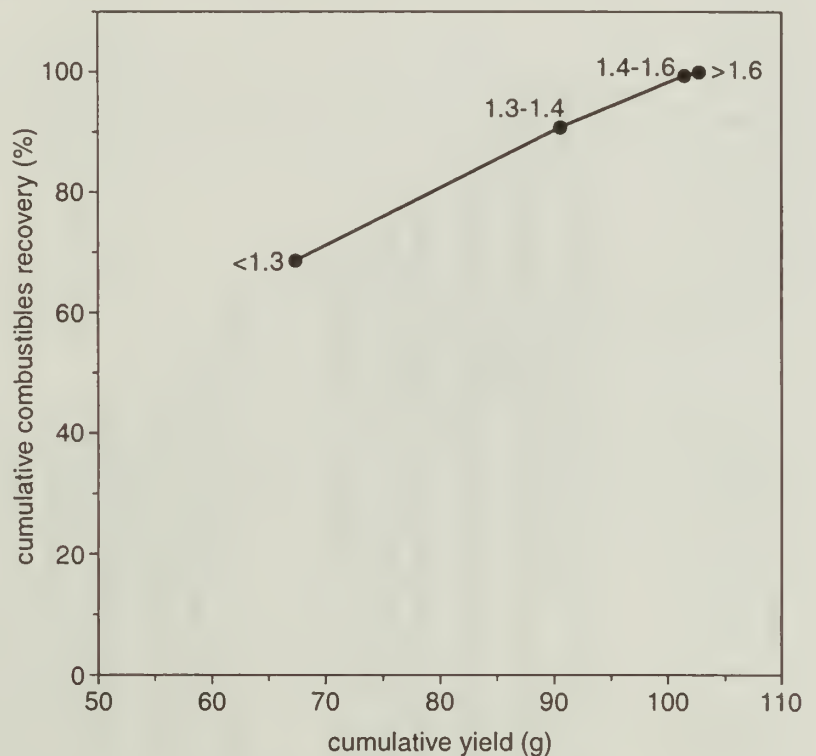
Figure 2   Relationship between combustibles recovery and cumulative weight yield for sample C32775 separated into four F-S fractions of <0.150 mm. Specific gravities of the F-S fractions are given on the plot.

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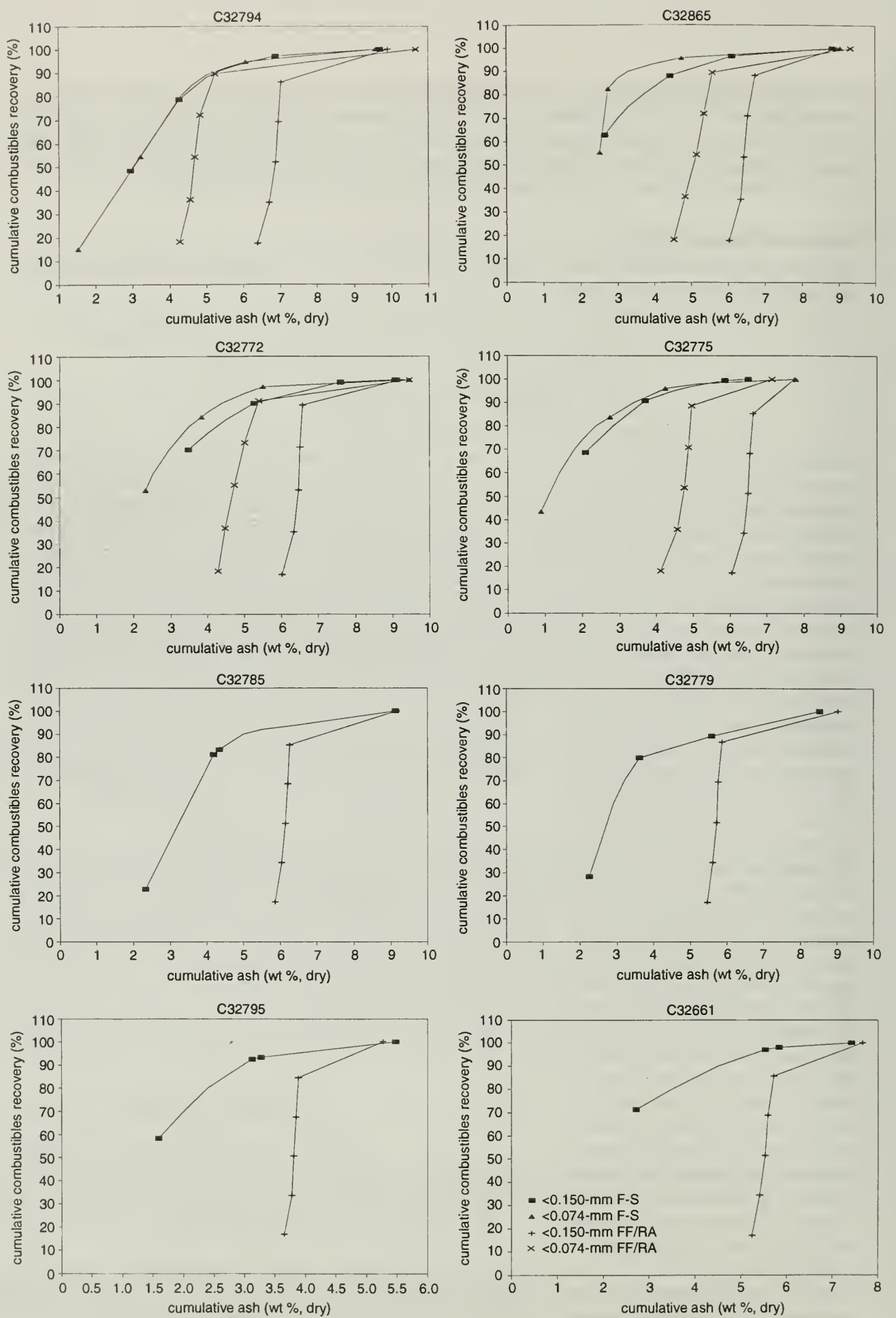
Figure 3 Examples of ash washability (F-S) and froth flotation/release-analysis (FF/RA) curves for marketed Illinois coals ground to <0.150 mm and <0.074 mm. Sample numbers are given above the graphs. The FF/RA data are from Demir et al. (1995).

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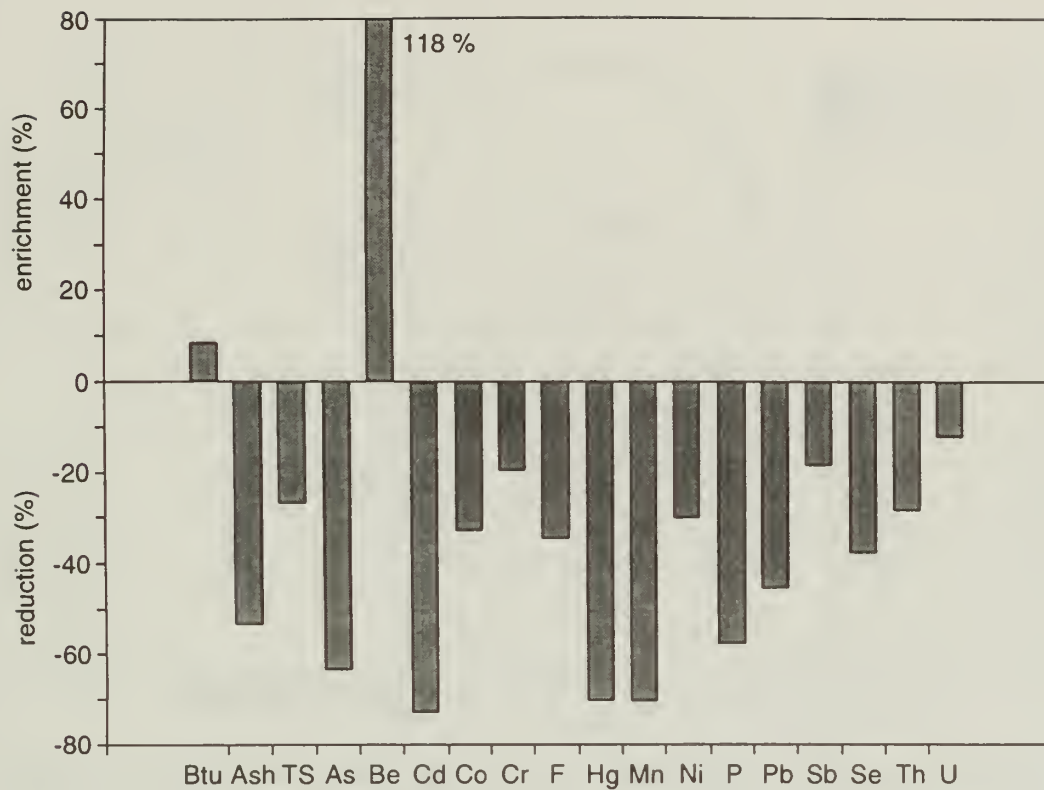
Figure 4 Mean changes in heating value (Btu) and in concentrations of ash, total S (TS), and HAPs in the 29 samples of marketed Illinois coals as a result of float-sink separation at <0.150-mm (–100 mesh). The combustibles recovery was 80%.
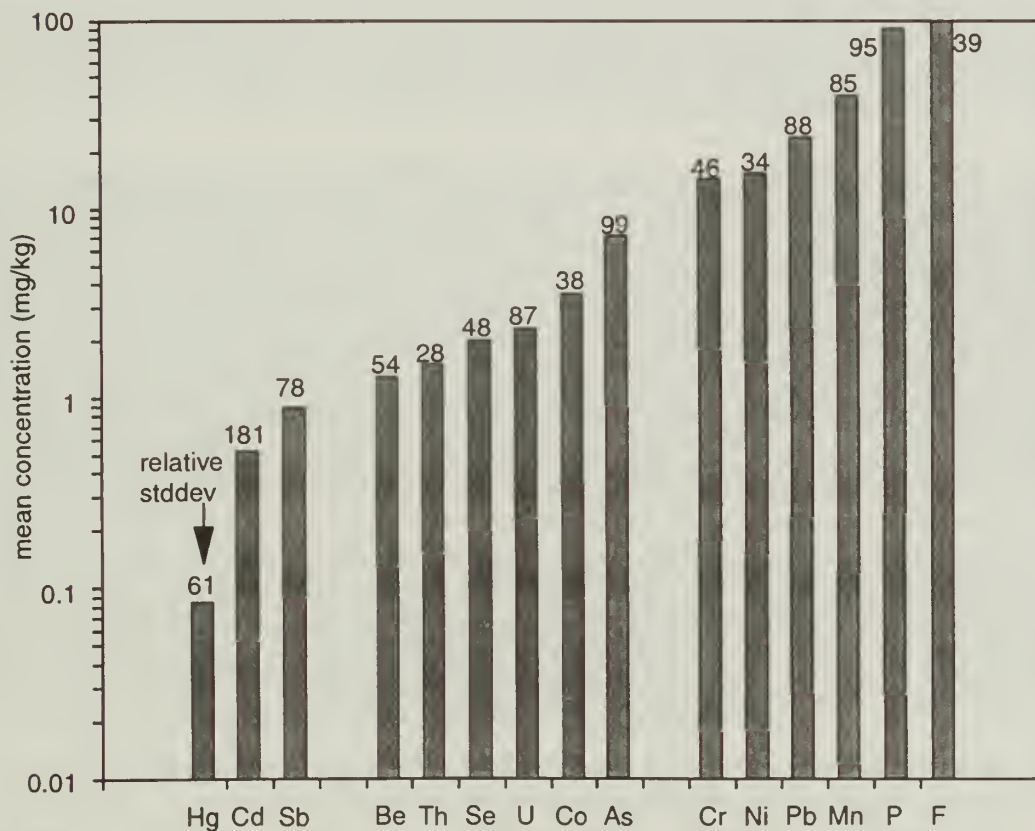
Figure 5 Mean concentrations and variabilities (relative standard deviations in %) of HAPs in 29 samples of marketed Illinois coals.
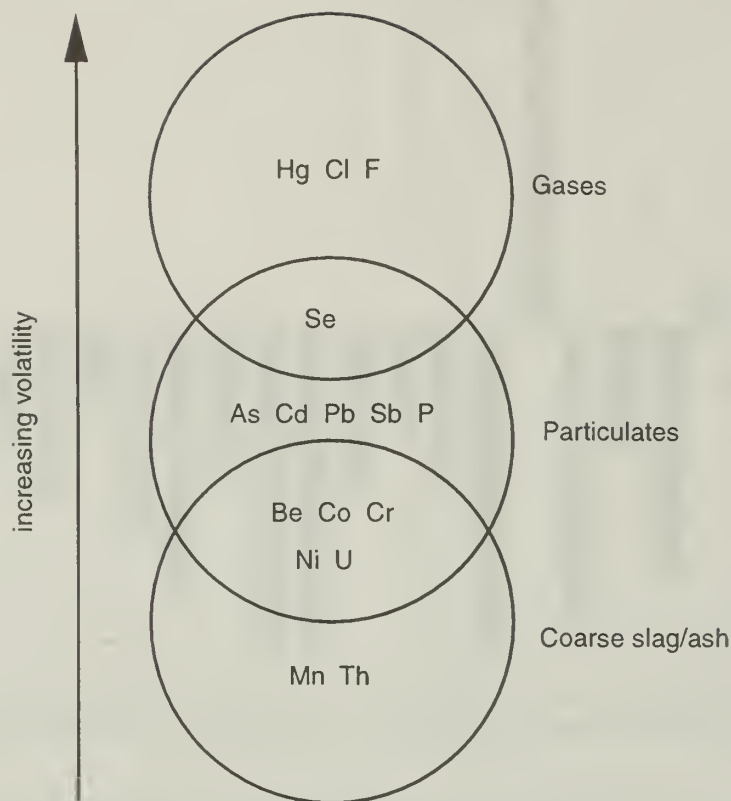
Figure 6 General partitioning of HAPs in different combustion and gasification products (after Clarke and Sloss 1992).

relative to the parent coals, most likely as a result of the contribution of small amounts of Cl from the perchloroethylene used in the washability tests. However, in a commercial cleaning coal plant where water, not perchloroethylene, would be the liquid medium, the Cl level probably would be reduced to some degree through leaching (Demir et al. 1990, Chou 1992).

The average reductions for As, Cd, Hg, Mn, and P resulting from F-S separation at <0.150 mm exceeded the average reduction for ash (fig. 4, appendix 5). This observation suggests that these five elements were somewhat enriched in relatively coarse or heavy mineral grains that were effectively removed during the F-S process. Arsenic was likely associated with pyrite, Cd with sphalerite, Hg with pyrite and other sulfide minerals, Mn with calcite, and P with apatite. Precombustion removal of As, Cd, and Hg from coal is important because of the relatively significant atmospheric mobility of these elements during coal combustion (fig. 6). The average reductions of Pb (45%), F (35%), and Se (38%) (the three other elements with relatively significant atmospheric mobility during coal combustion) were smaller than the average reduction of ash but still significant. The average reductions for Co (33%), Cr (19%), Ni (30%), Sb (18%), Th (28%), and U (12%) were significantly less than the average reduction for ash. Among these six elements, only Sb has a relatively significant atmospheric mobility during coal combustion. However, the relatively small concentrations of Sb (generally <1.5 mg/kg) in marketed Illinois coals limit any environmental risk associated with Sb emission from combustion of these coals. It is likely that the other five elements (Co, Cr, Ni, Th, U) with relatively small F-S washabilities are largely retained in coarse ash and slag rather than emitted into the atmosphere during combustion (fig. 6).

The foregoing discussion of the F-S data suggests that an efficient and perhaps low-cost fine-coal cleaning to improve the quality of currently marketed Illinois coals is possible at <0.150 mm. Such cleaning could reduce not only the atmospheric emissions of SO_2 and HAPs but also the slagging and fouling in coal-fired utility boilers.
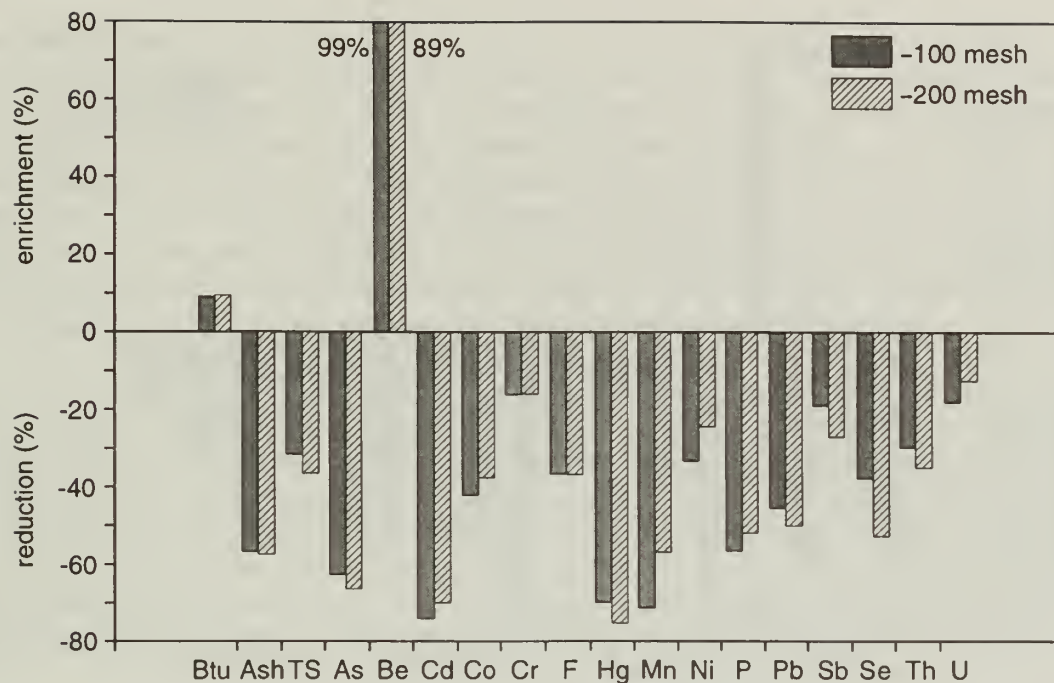
Figure 7 Mean changes in heating value (Btu) and in concentrations of ash, total S, and HAPs in the samples of ten marketed Illinois coals as a result of F-S separation at <0.150 mm (−100 mesh) and <0.074 mm (−200 mesh) sizes. The combustibles recovery was 80%.

Comparison of Float-Sink Washabilities at <0.150-mm and <0.074-mm Particle Sizes

On average, further grinding of 10 of the 29 coal samples from <0.150 mm to <0.074 mm resulted in only small or no improvement in the F-S separation of ash, S, and HAPs compared with the separations obtained for the same coals at <0.150 mm (fig. 7, appendix 6). However, future centrifugation tests at higher speeds and for a longer time may show improved F-S separation efficiency at <0.074 mm.

Float-Sink Washability Versus Froth-Flotation Cleanability

Average reductions of ash and HAP contents of the <0.150-mm coals through the use of F-S separation reported in this study were considerably greater than the average reductions obtained through froth flotation/release analysis (FF/RA) as reported in Demir et al. (1995) (fig. 8). The difference between the F-S washability and FF/RA cleanability was particularly large for some samples (fig. 3). For the <0.074-mm samples, the difference between the F-S washabilities and FF/RA cleanabilities generally was large for As, Cd, Hg, Pb, and Se, and small or even reversed for other elements (fig. 9). Because Be tends to remain largely with the organic matter, it is generally enriched more in the F-S products than in the FF/RA products; the former contained less ash and, accordingly, more organic matter than the latter.

Comparison of the F-S and FF/RA data suggested that, although FF/RA can estimate the performance of standard column or froth flotation circuits, it would likely underestimate, in most cases, the performance of advanced gravity separators and some advanced column flotation devices. Float-sink tests, therefore, appear to be more suitable for estimating the performance of advanced physical cleaning equipment, especially those relying on gravity separation.
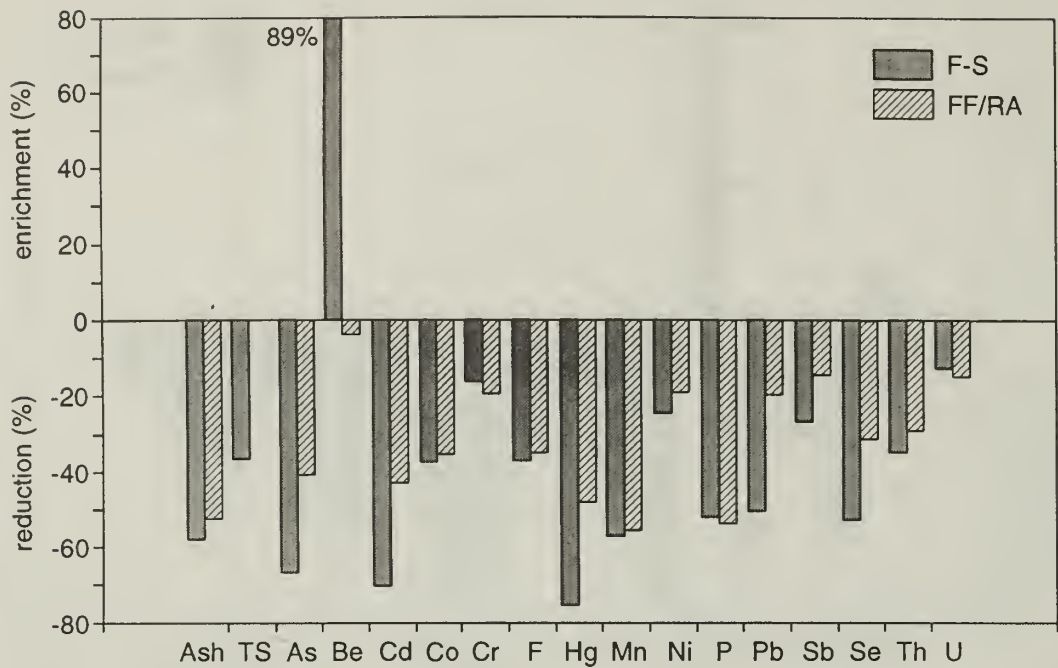
Figure 8 Mean changes in contents of ash, total S, and HAPs in the <0.150-mm (−100 mesh) samples of 29 marketed Illinois coals as a result of F-S and FF/RA separations. The total S value was not available for the FF/RA tests. The combustibles recovery was 80%.
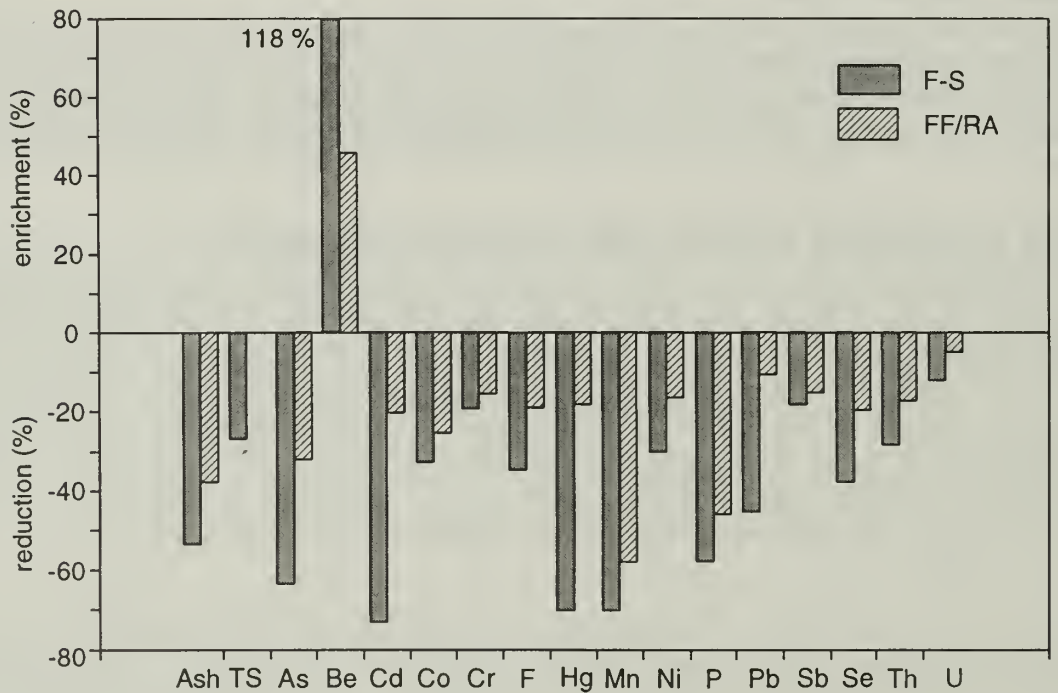
Figure 9 Mean changes in contents of ash, total S, and HAPs in the <0.074-mm (−200 mesh) samples of ten marketed Illinois coals as a result of F-S and FF/RA separations. The total S value was not available for the FF/RA tests. The combustibles recovery was 80%.

Mass Balances

The relative difference between the ash content of the marketed coals and the cumulative ash recovered from their respective F-S fractions (appendixes 2 and 3) was 10% for 33 tests and 10% to 15% for the remaining 6 tests, which indicates that a good mass balance was obtained. The mass balance difference for total S was 10% for 19 tests, 10% to 19% for 18 tests, and 24% and 26% for the remaining 2 tests. The samples with relatively large differences in S mass balance probably contained more elemental S and sulfate S than the other samples. A fraction of the elemental S and sulfate S was probably leached with the heavy media and water, respectively, during the F-S process, accounting for the S mass balance deficiencies for some of the samples.

All four F-S fractions of one of the samples (C32796) were analyzed to determine mass balances for HAPs, as well as for ash and S. Mass balances achieved for the HAPs were generally within analytical errors (table 1). Only Hg recovery at <0.150 mm was somewhat low (67%), which could have been the result of analytical error in this particular case. If the HAPs were leached by the heavy media, the mass balances would have been consistently less for the <0.074-mm sample than for the <0.150-mm sample because leaching would increase with reduced particle size (greater surface area). Because this was not the case (table 1) and because overall mass balances were fairly good, leaching of HAPs, if any, was apparently within analytical errors.

Commercial Potential of Gravity-Based Methods for Fine- or Ultrafine-Coal Cleaning

It has been reported that gravity-based separation can be potentially superior to surface-property-based separation for reducing the pyrite content in fine coal (Adel et al. 1991). Several recent studies (Paul and Honaker 1994, Honaker et al. 1996 and 1998, Honaker and Govindarajan 1998, Mohanty and Honaker 1998) evaluated the application of enhanced gravity separation to pilot and full-scale cleaning of fine and ultrafine coal. Using a heavy medium Falcon gravity separator, the ash yield and pyritic S content of a 0.6 x 0.044 mm size coal collected from a preparation plant treating Illinois Herrin (No. 6) coal were reduced from 17.5% to 3.5% and from 0.55% to 0.15%, respectively, while achieving 87.8% combustibles recovery (Honaker et al. 1998). Comparing the results with advanced flotation washability data, the authors suggested that the heavy medium Falcon separator can potentially outperform the best flotation technology available. Pilot-scale tests with a Falcon separator, a Knelson separator, and an Altair Jig indicated that they were all effective for cleaning a 0.6 x 0.037 mm size sample from the Illinois Springfield (No. 5) coal (Honaker and Govindarajan 1998). Typically, 80% of the ash and 70% of the total S were rejected at 85% combustibles recovery. During full-scale testing with a mass flow rate of 100 t/hr, the Falcon separator efficiently cleaned a refuse pond coal sample (Honaker and Govindarajan 1998). The ash yield was reduced from 22% to 8% for the 0.6 x 0.150 mm fraction and from 32% to 15% for the 0.150 x 0.025 mm fraction, while recovering a little over 80% of the original combustibles. Nearly 90% of the pyritic S was rejected, which reduced the total S content of both fractions from 7.9% to 2.7%.

Cost of Advanced Fine- or Ultrafine-Coal Cleaning

Progress in fine-coal cleaning has been significant, but the dewatering and material handling stages of the process can be difficult and expensive. Therefore, the economic and environmental benefits of the final product must justify the cost. Newman et al. (1994) estimated the cost of advanced cleaning to be $12/t for run-of-mine coals containing 1% to 8% S if 90% pyritic S rejection is to be achieved. It is not clear whether dewatering and fine-particle handling costs were included in these estimates. The total cost of advanced cleaning, including dewatering and pelletization (or briquetting), could be $22 to $27.5/ton (Smouse 1994). One should, however, keep in mind that the product of advanced coal cleaning is a low-ash, low-S, and high heating value fuel. Therefore, some expenses of the advanced coal cleaning can be offset by (1) reduction in transportation cost per unit of heating value of coal, (2) elimination of milling cost at power plants, and (3) reduced maintenance costs for power plants from decreased fouling, slagging, and other wear and tear. Furthermore, pelletization or briquetting costs can be eliminated if the advanced cleaning product is used as a coal-water

Table 1 Mass balances achieved for ash, total S, and HAP elements for the float-sink (F-S) process applied to region 3 sample C32796 at <0.150-mm and <0.074-mm particle sizes (all values are on a dry basis). In the computation of cumulative recoveries, one-half of the detection limit was used for all values below the detection limit.

Particle size (mm)	Feed coal or F-S fractions	Weight (g, ar*)	Ash (wt%)	Tot. S (wt%)	Concentrations of HAP elements (mg/kg)														
					As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
<0.150	feed	328	16.1	1.05	9.8	1.0	0.9	8.5	19	123	0.06	41	24	87	31	0.9	2.0	2.9	0.7
<0.150	<1.3 sg	99.34	2.27	0.70	2.5	2.1	<0.04	3.8	12	18	0.02	4	20	13	8	1.2	0.9	1.0	0.5
<0.150	1.3–1.4 sg	92.52	6.95	0.76	4.9	1.4	<0.1	6.0	14	51	0.01	11	19	35	16	0.8	1.6	1.7	0.8
<0.150	1.4–1.6 sg	87.61	20.21	0.76	7.0	1.3	<0.3	9.1	21	148	0.04	29	18	83	27	0.7	2.0	3.4	0.9
<0.150	>1.6 sg	37.95	53.72	1.91	30	<1	8.50	18.0	37	359	0.17	196	27	262	110	1.0	6.1	7.1	1.9
Cumulative recovery from F-S fractions		317.42	14.80	0.88	7.8	1.5	1.09	7.6	18	105	0.04	36	20	69	28	0.9	2.0	2.6	0.9
% Mass balance**		97	92	84	80	150	121	89	95	85	67	88	83	79	90	100	100	90	129
<0.074	<1.3 sg	67.2	2.73	0.76	1.5	1.8	<0.05	3.6	13	41	0.01	9	20	13	5	1.1	<0.5	1.0	0.8
<0.074	1.3–1.4 sg	106.22	5.82	0.74	2.7	1.2	<0.1	5.7	14	48	0.01	16	20	31	11	0.9	1.3	1.5	0.7
<0.074	1.4–1.6 sg	99.79	15.60	0.76	5.8	1.3	<0.3	10.3	24	137	0.03	42	22	70	17	0.9	1.8	3.2	1.0
<0.074	>1.6 sg	50.3	53.12	2.59	34	<1	4.90	15.5	32	303	0.21	186	36	218	101	1.0	5.4	5.5	1.8
Cumulative recovery from F-S fractions		323.51	15.59	1.04	8.3	1.3	0.84	8.2	20	114	0.05	49	23	69	26	1.0	1.9	2.5	1.0
% Mass balance**		99	97	99	85	130	93	96	105	93	83	120	96	79	84	111	95	86	143

* ar = as-received basis

** % mass balance = (concentration recovered from F-S fractions/concentration in parent coal) x 100

fuel to replace oil in oil-fired boilers. Transporting coal-water fuels through pipelines would further reduce costs. Although advanced fine-coal cleaning is currently in limited use, its widespread commercialization may eventually occur, depending on further improvements in technology, supply and demand for different fuels, and future environmental regulations.

SUMMARY AND CONCLUSIONS

Float-sink washability data on samples of 29 marketed Illinois coals indicated that, at <0.150-mm (–100 mesh) particle size and with an 80% combustibles recovery, the ash content of the coals can potentially be decreased by an average of 53% beyond that achieved by conventional cleaning if advanced physical fine-coal cleaning, especially gravity-based cleaning, were applied to the coals. As a result, some of the clean products would have ash contents of <3%. Decreases in ash content were accompanied by decreases in the levels of S and HAPs, with a few exceptions. The sulfur content of the clean F-S products varied between 0.6% and 3.5%. The sulfur that remained in the clean F-S products was predominantly organic S because most of the pyritic S and sulfate S was removed by the F-S process.

The decreases for the HAP concentrations resulting from the F-S separation at <0.150 mm varied. The average decreases were

As	63%	Cr	19%	Mn	70%	Pb	45%	Th	28%
Cd	73%	F	35%	Ni	30%	Sb	18%	U	12%
Co	33%	Hg	70%	P	58%	Se	38%		

Seven of these elements (As, Cd, F, Hg, Pb, Sb, and Se) have relatively significant atmospheric mobilities during coal combustion. Only Sb, among these seven elements, appeared to have a relatively low washability. However, any environmental risks associated with atmospheric Sb emission could be small because the marketed Illinois coals contain only small amounts of Sb (generally <1.5 mg/kg).

The average Be concentration in the clean F-S products at <0.150 mm was about twice that in the parent coals. The enrichment of Be resulting from fine-coal cleaning, however, would only slightly increase any related environmental risk, if any, because of the small concentration of this element in the coals (generally <1.5 mg/kg) and its relatively small atmospheric mobility during coal combustion. Some of the Cl from the heavy medium used in the washability tests may have remained in the samples in spite of rigorous washing and drying. In a commercial coal preparation plant where water, not perchloroethylene, would be the liquid medium, the Cl level in the coals would probably be reduced to some degree through leaching.

Under the F-S testing conditions used in this study, grinding 10 of the 29 coal samples further to <0.074 mm (–200 mesh) generally did not significantly improve the F-S separation of ash, S, and HAPs beyond that obtained at <0.150 mm (–100 mesh).

The F-S process used in this study was significantly more effective than a froth-flotation/release-analysis process previously used for cleaning marketed Illinois coals. The optimum performance of advanced coal cleaning techniques, therefore, can be estimated best by using F-S tests. The data suggest that through the use of advanced fine-coal cleaning, the content of ash and air toxics in currently marketed (conventionally cleaned) Illinois coals could be reduced further beyond that achieved by conventional cleaning. The commercialization of such advanced cleaning techniques will depend on future environmental regulations, further improvements in the technology, and supply and demand for different types of fuels.

The results of this study are significant for (1) evaluating noxious emissions, fouling, and slagging at power-generating plants and (2) matching specific coals with prospective uses such as advanced gasification processing, making activated carbon, and producing synthetic organic chemicals.

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Appendix 1 Methods commonly used for analyses of coal samples at the ISGS

Element	Relative precision		Detection limit	Methods*				
				WDXRF	AAS	INAA	OEP	PyroIC
Major and minor oxides	basis	%	%					
Al₂O₃	ash	3	0.1	X				
CaO	ash	3	0.02	X				
Fe₂O₃	ash	3	0.0	X				
MgO	ash	5	0.1	X				
MnO	ash	5	0.01	X				
P₂O₅	ash	5	0.02	X				
K₂O	ash	2	0.01	X				
SiO₂	ash	1	0.1	X				
Na₂O	ash	5	0.05	X				
Na₂0	coal	5	0.003			X		
TiO₂	ash	3	0.01	X				
Trace elements	basis	%	mg/kg					
As	coal	7	1.0			X		
B	coal	15	10.0				X	
Be	ash	5	0.03				X	
Cd	ash	10	0.03		X			
Co	coal	5	0.3			X		
Cr	ash	2	7.0			X		
Cu	ash	5	2.5		X			
F	coal	10	20.0					X
Hg	coal	15	0.01		X**			
Li	ash	12	5.0		X			
Mo	coal	10	10.0				X	
Ni	ash	10	0.12		X			
Pb	ash	20	0.2		X		X	
Sb	coal	10	0.2			X		
Se	coal	10	2.0			X		
Th	coal	5	0.4			X		
U	coal	15	3.0			X		
V	ash	3	0.5				X	
Zn	ash	7	1.5		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
 [+]   ASTM, 1992, Petroleum Products, Lubricants, and Fossil Fuels: Volume 05.05, 506 pp.

Appendix 2 Float-sink (F-S) washability data on ash and total S in 19 of the 29 marketed Illinois coals ground to <0.150 mm

Feed coal lab no.	Feed coal region	Specific gravity (g/cm³)	Yield (g, ar*)	Moisture (wt%, ar*)	Ash (wt%, ar*)	Total S (wt%, ar*)	Combustibles (wt%)	Cumulative ash (wt%, dry)	Cumulative total S (wt%, dry)	%Cumulative combustibles recovery
C32777	1	<1.3	13.04	1.83	4.23	2.3	94	4.31	2.34	14.47
		1.3–1.4	79.44	3.53	8.15	2.41	88	7.86	2.48	95.89
		1.4–1.6	1.19	4.67	15.52	2.87	80	7.96	2.48	96.98
		>1.6	8.62	0.53	70.21	7.72	29	13.38	2.94	100.00
C32778	1	<1.3	6	1.63	2.33	1.53	96	2.37	1.56	6.75
		1.3–1.4	60.6	3.24	3.16	1.04	94	3.18	1.12	72.12
		1.4–1.6	27.3	2	15.24	1.37	83	6.81	1.20	98.49
		>1.6	2.9	1.8	53.83	6.03	44	8.26	1.35	100.00
C32782	1	<1.3	3.85	1.83	2.39	2.55	96	2.43	2.72	4.29
		1.3–1.4	46.4	2.45	3.29	2.59	94	3.30	2.93	54.88
		1.4–1.6	40.91	2.04	11.64	2.88	86	7.16	2.96	95.89
		>1.6	7.89	1	54.61	10.15	44	11.03	3.68	100.00
C32785	1	<1.3	21.2	1.96	2.29	3.15	96	2.34	3.21	22.72
		1.3–1.4	56.65	2.52	4.77	3.22	93	4.19	3.28	81.17
		1.4–1.6	2.09	1.33	9.63	3.26	89	4.34	3.28	83.27
		>1.6	20.98	1.99	26.75	5.47	71	9.13	3.76	100.00
C32797	1	<1.3	16.68	1.27	3.58	3.15	95	3.63	3.19	18.01
		1.3–1.4	69.39	1.86	6.53	2.68	92	6.06	2.82	89.70
		1.4–1.6	8.42	0.91	20.19	3.34	79	7.35	2.87	97.27
		>1.6	5.04	0.52	52.05	10.55	47	9.65	3.27	100.00
C32814	1	<1.3	46.95	2.38	2.18	2.7	95	2.23	2.77	47.82
		1.3–1.4	51.61	2.86	5.06	2.87	92	3.79	2.86	98.28
		1.4–1.6	1.46	3.27	28.76	7.55	68	4.16	2.94	99.33
		>1.6	1.91	0	68.1	17.85	32	5.39	3.22	100.00
C32779	2	<1.3	27.42	2.37	2.19	3.38	95	2.24	3.46	28.32
		1.3–1.4	51.12	2.5	4.24	3.4	93	3.61	3.48	79.84
		1.4–1.6	10.95	2.12	19.26	4.01	79	5.58	3.55	89.18
		>1.6	13.92	1.76	26.84	5.62	71	8.53	3.85	100.00
C32798	2	<1.3	13.98	2.81	2.41	2.38	95	2.48	2.45	15.70
		1.3–1.4	44.79	3.06	3.73	2.33	93	3.52	2.41	65.06
		1.4–1.6	29.78	2.97	14.08	2.39	83	7.22	2.43	94.29
		>1.6	9.51	1.78	48.06	6.37	50	11.31	2.83	100.00
C32800	2	<1.3	41.39	2.09	2.71	2.74	95	2.77	2.80	45.32
		1.3–1.4	52.53	2.11	11.79	3	86	7.96	2.95	97.33
		1.4–1.6	1.41	2.72	34.69	5.86	63	8.36	2.99	98.34
		>1.6	3.93	1.3	62.23	14.05	36	10.55	3.44	100.00
C32815	2	<1.3	33.05	2.19	3.01	2.6	95	3.08	2.66	34.61
		1.3–1.4	37.94	2.37	4.97	2.68	93	4.15	2.70	73.38
		1.4–1.6	3.27	3.26	10.26	2.63	86	4.43	2.71	76.47
		>1.6	29.94	2.12	26.8	4.87	71	11.04	3.36	100.00
C32795	3	<1.3	58.76	1.75	1.57	0.6	97	1.60	0.61	58.35
		1.3–1.4	35.89	1.78	5.55	0.65	93	3.13	0.63	92.50
		1.4–1.6	1.12	1.76	15.34	0.77	83	3.28	0.63	93.45
		>1.6	9.03	1.39	28.29	1.51	70	5.48	0.71	100.00

Appendix 2 *continued*

Feed coal lab no.	Feed coal region	Specific gravity (g/cm³)	Yield (g, ar*)	Moisture (wt%, ar*)	Ash (wt%, ar*)	Total S (wt%, ar*)	Combustibles (wt%)	Cumulative ash (wt%, dry)	Cumulative total S (wt%, dry)	%Cumulative combustibles recovery
C32799	3	<1.3	47.26	0.95	2.32	0.69	97	2.34	0.70	48.82
		1.3–1.4	33.05	2.12	4.85	0.7	93	3.41	0.70	81.26
		1.4–1.6	0.6	5.27	6.21	0.66	89	3.43	0.70	81.81
		>1.6	26.03	1.85	32.1	1.04	66	10.54	0.79	100.00
C32801	3	<1.3	66.75	2.04	2.63	1.34	95	2.68	1.37	68.08
		1.3–1.4	34.18	0.43	15.25	2.05	84	7.01	1.60	99.42
		1.4–1.6	0.52	3.15	40.28	9.16	57	7.18	1.64	99.73
		>1.6	0.81	1.16	67.53	17.4	31	7.67	1.77	100.00
C32803	3	<1.3	51.76	0.41	2.35	1.81	97	2.36	1.82	53.92
		1.3–1.4	46.51	1.5	10.12	2.14	88	6.08	1.98	97.48
		1.4–1.6	0.91	1.11	30.56	3.58	68	6.31	2.00	98.14
		>1.6	4.01	1.13	55.24	10.4	44	8.23	2.33	100.00
C32661	4H	<1.3	70.97	1.83	2.66	1.78	96	2.71	1.81	71.41
		1.3–1.4	28.71	2.32	12.27	2.2	85	5.54	1.94	97.11
		1.4–1.6	1.36	2.6	26.56	2.63	71	5.83	1.95	98.12
		>1.6	3.66	1.16	50.44	8.15	48	7.42	2.17	100.00
C32776	4H	<1.3	59.19	2.23	2.59	2.3	95	2.65	2.35	59.08
		1.3–1.4	32.47	2.29	8.14	2.68	90	4.66	2.49	89.57
		1.4–1.6	0.86	2.85	12.85	2.84	84	4.74	2.49	90.32
		>1.6	14.08	1.68	33.15	5.43	65	8.59	2.90	100.00
C32662	4S	<1.3	80.06	1.1	3.24	1.08	96	3.28	1.09	77.24
		1.3–1.4	20.03	1.25	10.95	1.58	88	4.84	1.19	94.95
		1.4–1.6	0.76	3.3	19.62	2.3	77	4.95	1.20	95.53
		>1.6	6.8	2.13	31.97	4.37	66	6.69	1.41	100.00
C32781	4S	<1.3	55.28	0.88	3.28	1.96	96	3.31	1.98	57.94
		1.3–1.4	31.15	1.11	9.66	2.19	89	5.63	2.06	88.27
		1.4–1.6	7.99	1.03	23.33	3.47	76	7.15	2.18	94.87
		>1.6	7.44	1.23	35.51	7.61	63	9.25	2.59	100.00
C32793	4S	<1.3	39.14	1.95	2.22	0.9	96	2.26	0.92	41.36
		1.3–1.4	41	2.11	4.84	0.96	93	3.63	0.95	83.36
		1.4–1.6	12.79	1.78	15.09	1.39	83	5.25	1.01	95.11
		>1.6	12.26	1.1	63.04	3.82	36	12.12	1.35	100.00

* as-received basis

Appendix 3 Float-sink (F-S) washability data on ash and total S in 10 of the 29 marketed Illinois coals ground to both <0.150-mm and <0.074-mm particle sizes

Feed coal lab no.	Feed coal region	Particle size (mm)	Specific gravity (g/cm³)	Yield (g, ar*)	Moisture (wt%, ar*)	Ash (wt%, ar*)	Total S (wt%, ar*)	Combus- tibles (wt%)	Cumulative ash (wt%, dry)	Cumulative total S (wt%, dry)	%Cumulative combustibles recovery
C32773	1	<0.150	<1.3	23.81	2.60	3.08	3.34	94	3.16	3.43	25.2
			1.3–1.4	64.56	6.22	5.86	3.27	88	5.39	3.47	86.5
			1.4–1.6	14.08	2.96	18.85	4.70	78	7.36	3.66	98.8
			>1.6	2.54	1.43	56.26	15.45	42	8.61	3.96	100.0
		<0.074	<1.3	3.70	2.11	2.46	3.38	95	2.51	3.45	3.9
			1.3–1.4	67.35	2.68	3.77	3.18	94	3.80	3.28	72.6
			1.4–1.6	26.27	2.62	13.12	3.30	84	6.41	3.31	96.8
			>1.6	6.56	1.40	54.74	14.70	44	9.55	4.05	100.0
C32774	1	<0.150	<1.3	35.40	2.54	1.77	1.62	96	1.82	1.66	41.0
			1.3–1.4	45.88	4.11	3.38	2.01	93	2.77	1.91	91.5
			1.4–1.6	7.54	0.44	22.02	5.36	78	4.46	2.21	98.7
			>1.6	2.89	0.65	63.00	23.45	36	6.37	2.90	100.0
		<0.074	<1.3	37.56	2.47	1.55	1.52	96	1.59	1.56	36.2
			1.3–1.4	54.28	2.83	3.33	1.70	94	2.67	1.67	87.3
			1.4–1.6	11.72	3.24	9.76	3.05	87	3.51	1.84	97.4
			>1.6	6.31	1.09	59.28	22.75	40	6.80	3.07	100.0
C32794	2	<0.150	<1.3	46.62	1.84	2.89	2.37	95	2.94	2.41	48.6
			1.3–1.4	30.25	2.04	6.16	2.52	92	4.26	2.48	78.9
			1.4–1.6	20.88	3.28	16.09	2.87	81	6.87	2.58	97.0
			>1.6	6.11	1.72	53.63	11.30	45	9.69	3.11	100.0
		<0.074	<1.3	14.37	3.14	1.47	2.22	95	1.52	2.29	15.1
			1.3–1.4	37.74	2.49	3.77	2.40	94	3.22	2.41	54.5
			1.4–1.6	41.24	2.56	9.44	2.58	88	6.08	2.52	94.8
			>1.6	8.81	1.76	45.54	9.13	53	9.58	3.11	100.0
C32813	2	<0.150	<1.3	38.08	3.36	2.34	2.32	94	2.42	2.40	43.1
			1.3–1.4	52.80	5.79	11.61	2.56	83	8.11	2.58	94.1
			1.4–1.6	3.84	2.15	42.74	4.26	55	9.59	2.66	96.7
			>1.6	7.57	1.62	62.82	11.10	36	13.73	3.31	100.0
		<0.074	<1.3	18.32	2.21	2.06	2.16	96	2.11	2.21	21.3
			1.3–1.4	54.33	2.90	5.45	2.20	92	4.72	2.25	81.2
			1.4–1.6	11.04	2.34	15.65	2.22	82	6.22	2.25	92.1
			>1.6	14.42	2.10	52.95	7.34	45	13.29	3.03	100.0
C32784	3	<0.150	<1.3	70.04	5.23	2.48	1.15	92	2.62	1.21	66.6
			1.3–1.4	22.38	2.22	7.71	1.55	90	3.92	1.31	88.0
			1.4–1.6	11.79	2.11	19.81	1.86	78	5.81	1.37	97.8
			>1.6	4.26	1.67	51.02	6.74	47	7.67	1.60	100.0
		<0.074	<1.3	35.68	2.37	1.86	0.89	96	1.91	0.91	34.3
			1.3–1.4	50.08	2.25	4.15	1.12	94	3.27	1.05	81.5
			1.4–1.6	18.15	1.73	13.94	1.57	84	5.19	1.14	97.0
			>1.6	6.66	0.69	54.81	9.94	45	8.24	1.69	100.0
C32796	3	<0.150	<1.3	95.34	2.14	2.27	0.70	96	2.32	0.72	35.2
			1.3–1.4	92.52	2.93	6.95	0.76	90	4.69	0.75	67.1
			1.4–1.6	87.61	2.06	20.21	0.76	78	9.78	0.76	93.3
			>1.6	37.95	1.24	53.72	1.91	45	15.24	0.90	100.0
		<0.074	<1.3	67.20	2.16	2.73	0.76	95	2.79	0.78	24.0
			1.3–1.4	106.22	1.93	5.82	0.74	92	4.72	0.76	61.0
			1.4–1.6	99.79	2.86	15.60	0.76	82	8.84	0.77	91.3
			>1.6	50.30	1.40	53.12	2.59	46	15.90	1.06	100.0

Appendix 3 *continued*

Feed coal lab no.	Feed coal region	Particle size (mm)	Specific gravity (g/cm³)	Yield (g, ar*)	Moisture (wt%, ar*)	Ash (wt%, ar*)	Total S (wt%, ar*)	Combustibles (wt%)	Cumulative ash (wt%, dry)	Cumulative total S (wt%, dry)	%Cumulative combustibles recovery
C32665	4H	<0.150	<1.3	64.10	2.28	2.60	1.78	95	2.66	1.82	62.9
			1.3–1.4	27.20	2.18	8.44	2.20	89	4.44	1.95	88.0
			1.4–1.6	10.60	2.02	20.05	2.63	78	6.11	2.03	96.5
			>1.6	6.70	1.22	49.32	8.15	50	8.84	2.41	100.0
		<0.074	<1.3	59.00	2.32	2.46	1.66	95	2.52	1.70	55.4
			1.3–1.4	28.40	1.14	3.18	1.86	96	2.75	1.76	82.5
			1.4–1.6	16.00	1.43	15.38	2.23	83	4.75	1.84	95.8
			>1.6	9.60	1.42	54.46	11.35	44	9.05	2.66	100.0
C32771	4H	<0.150	<1.3	58.87	2.31	2.90	1.80	95	2.97	1.84	58.4
			1.3–1.4	25.38	2.11	8.25	2.15	90	4.62	1.95	82.3
			1.4–1.6	15.39	1.78	19.89	2.41	78	7.04	2.03	95.0
			>1.6	11.52	1.23	57.89	8.11	41	12.43	2.67	100.0
		<0.074	<1.3	38.65	2.37	2.37	1.71	95	2.43	1.75	39.0
			1.3–1.4	36.15	2.12	6.11	1.86	92	4.27	1.82	74.2
			1.4–1.6	22.26	2.60	13.75	1.99	84	6.52	1.87	93.9
			>1.6	13.47	1.47	56.15	8.57	42	12.72	2.71	100.0
C32772	4S	<0.150	<1.3	65.55	1.73	3.42	1.43	95	3.48	1.46	70.3
			1.3–1.4	19.72	1.16	11.04	1.92	88	5.27	1.57	90.0
			1.4–1.6	10.76	1.08	25.66	3.59	73	7.59	1.80	99.0
			>1.6	2.52	0.19	64.87	7.00	35	9.08	1.94	100.0
		<0.074	<1.3	52.57	1.42	2.29	1.27	96	2.32	1.29	53.0
			1.3–1.4	31.90	1.13	6.25	1.42	93	3.84	1.34	84.1
			1.4–1.6	14.67	1.04	15.02	1.84	84	5.52	1.42	97.1
			>1.6	7.42	0.76	61.56	10.35	38	9.47	2.05	100.0
C32775	4S	<0.150	<1.3	67.35	1.48	2.06	1.81	97	2.09	1.84	68.6
			1.3–1.4	23.19	1.46	8.32	2.42	90	3.72	2.00	90.8
			1.4–1.6	10.87	1.37	23.46	4.43	75	5.87	2.26	99.4
			>1.6	1.30	1.03	55.00	13.45	44	6.50	2.41	100.0
		<0.074	<1.3	44.87	1.12	0.89	1.70	98	0.90	1.72	43.6
			1.3–1.4	42.60	0.58	4.68	1.85	95	2.76	1.79	83.7
			1.4–1.6	14.49	0.81	13.31	2.22	86	4.27	1.85	96.1
			>1.6	8.12	0.52	51.47	11.90	48	7.79	2.60	100.0

* as-received basis

Appendix 4 Chemical analysis data on the samples of 29 marketed Illinois coals (feed) and their clean products from float-sink (F-S) tests that were conducted at <0.150-mm and <0.074-mm sizes with 80% combustibles recovery of the feed coal. Ash and total S values are in wt% and HAPs values are in mg/kg on a dry basis.

Feed coal lab no.	Feed coal region	Feed coal or F-S product particle mesh size (mm)	Heating value, Btu/lb*	Ash	Total S	As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32773	1	feed	12808	8.72	4.14	1.3	1.0	<0.3	2.3	12	90	0.13	39	11	44	<6	0.2	1.9	1.2	1.7
		<0.150	13940	5.01	3.52	0.5	1.0	<.09	2.0	11	67	0.04	13	9	22	4	0.2	1.2	1.0	<1
		<0.074	13954	4.87	3.29	0.6	1.6	<.08	1.8	10	51	0.02	24	11	26	4	0.1	0.9	0.9	<1
C32774	1	feed	13273	7.07	3.58	20	4.0	<0.3	3.1	5.8	68	0.22	18	15	87	102	1.2	1.2	0.8	<0.8
		<0.150	14272	2.77	1.90	9.1	11.0	<.05	0.9	4.4	56	0.08	5	6	52	73	0.8	0.9	0.6	<1
		<0.074	14288	2.65	1.65	7.4	9.0	<.05	1.4	6.5	45	0.05	5	6	52	72	0.9	0.5	0.6	<1
C32777	1	feed	12451	14.52	3.14	5.1	1.2	5.10	1.5	11	78	0.05	205	7	44	36	1.1	1.6	1.1	1.1
		<0.0150	13493	7.87	2.45	1.2	2.2	0.20	1.6	10	83	0.02	35	6	17	18	0.8	1.1	0.9	0.7
C32778	1	feed	12709	9.80	1.60	10	2.2	0.60	4.6	12	70	0.04	38	31	87	14	2.2	1.5	1.5	0.9
		<0.150	13962	4.79	1.19	2.9	4.8	<.08	3.8	9.4	59	0.01	12	29	39	7	2.2	1.0	1.2	1.3
C32782	1	feed	12503	11.62	3.90	2.4	<1.0	0.40	1.6	14	78	0.07	55	7	87	<6	0.5	1.9	1.1	1.3
		<0.150	13797	5.89	2.99	0.9	2.2	<.1	1.2	9.7	63	0.02	15	5	26	3	0.4	1.0	0.9	1.4
C32785	1	feed	12741	9.75	4.17	2.3	1.5	0.40	2.6	17	115	0.07	39	18	131	<5.3	0.4	3.9	1.3	1.8
		<0.150	14029	4.38	3.28	0.7	1.5	0.10	1.8	12	67	0.01	12	14	31	3	0.2	1.9	1.0	1.4
C32797	1	feed	12728	10.29	3.62	4	1.2	1.30	3	13	116	0.04	32	16	87	8.5	0.6	1.4	1.5	1.9
		<0.150	13844	5.59	2.87	1.1	2.9	<.1	2.3	11	89	0.01	12	14	31	4	0.6	1.0	1.1	1.8
C32814	1	feed	13841	6.00	3.68	6.4	2.0	1.00	2.5	5.7	63	0.07	30	12	30	23	1.9	1.3	0.6	8.0
		<0.150	14128	3.36	2.83	2.6	3.1	<.06	1.5	6.2	56	0.04	7	7	13	9	1.5	1.1	0.6	6.8
C32779	2	feed	12753	9.63	4.20	1.7	<1.0	0.40	2	17	91	0.05	29	11	44	7	0.4	2.3	1.3	3.1
		<0.150	14109	3.86	3.48	0.8	2.3	<.07	1.3	13	61	0.02	9	8	17	4	0.3	1.2	0.9	3.1
C32794	2	feed	12685	10.52	3.67	2.3	1.1	<0.1	2.8	12	95	0.08	40	14	44	15	0.3	1.9	1.4	2.0
		<0.150	14038	4.32	2.48	0.8	2.3	<.08	2.1	12	78	0.02	11	10	17	5	0.2	1.1	1.1	1.8
		<0.074	13828	5.69	2.48	1.0	1.7	<.1	1.8	7.9	92	0.04	19	13	26	7	0.2	0.9	0.9	1.6
C32798	2	feed	12285	13.16	3.48	2.2	<1.0	0.40	3.3	23	134	0.05	54	18	87	12	0.3	3.2	1.7	2.7
		<0.150	13764	6.10	2.43	0.8	1.1	<.1	1.9	14	87	0.02	16	11	35	5	0.3	1.3	1.3	2.6
C32800	2	feed	12599	11.39	3.63	2	<1.0	<0.2	2.8	23	150	0.06	30	16	87	8	0.4	2.8	1.6	2.9
		<0.150	13595	7.23	2.90	1.0	1.2	<.1	2.3	17	114	0.01	14	10	35	6	0.4	1.5	1.2	2.3
C32813	2	feed	12086	14.70	3.47	2.4	1.4	1.10	3.5	42	263	0.06	40	24	305	13	0.7	5.4	2.1	3.7
		<0.150	13485	7.88	2.53	1.0	1.4	0.30	2.1	22	150	0.01	16	14	109	7	0.5	2.9	1.5	2.8
		<0.074	13835	5.67	2.25	0.8	2.7	<.1	2.3	21	132	0.03	17	12	96	5	0.6	1.6	1.2	3.2
C32815	2	feed	12422	12.03	3.73	3	<1.0	<0.2	2.7	14	88	0.06	61	10	44	12	0.6	2.1	1.7	1.9
		<0.150	13933	5.01	2.80	0.9	2.1	<.09	1.7	11	69	0.02	18	7	13	7	0.4	1.0	1.2	1.9
C32784	3	feed	13329	8.13	1.79	18	1.8	<0.3	4.2	11	67	0.11	17	15	44	40	1.1	1.4	1.4	1.0
		<0.150	14189	3.32	1.27	9.3	3.5	<.06	2.5	8.9	19	0.06	7	11	31	25	1.0	1.1	0.9	<1
		<0.074	14206	3.21	1.04	6.0	2.4	<.06	2.8	9.0	25	0.04	9	11	35	20	0.9	0.8	0.8	1.0
C32795	3	feed	13799	5.76	0.73	3.6	1.0	<0.1	4.8	8.6	53	0.03	11	18	44	16	1.1	1.1	1.2	0.6
		<0.150	14277	2.79	0.63	2.2	1.0	<.05	4.6	7.0	12	<0.01	4	17	31	10	1.1	0.8	0.8	<.5
C32796	3	feed	12120	16.10	1.05	9.8	1.0	0.90	8.5	19	123	0.06	41	24	87	31	1.0	2.0	3.0	1.0
		<0.150	14277	6.80	0.73	4.2	1.7	0.04	5.5	14	51	0.02	11	19	32	14	1.0	1.3	1.6	0.7
		<0.074	14206	6.80	0.73	4.2	1.7	0.06	5.5	14	66	0.01	11	19	32	14	1.0	1.3	1.6	0.8
C32799	3	feed	12728	11.42	0.76	17	1.0	<0.2	4.4	12	127	0.02	64	15	436	64	3.6	1.3	1.6	0.7
		<0.150	14168	3.48	0.70	1.6	4.0	<.06	4.0	8.6	59	<0.01	5	10	275	8	3.0	0.9	0.9	0.7
C32801	3	feed	13280	8.36	1.98	10	1.0	<0.1	4.4	12	76	0.04	21	14	44	22	0.6	1.5	1.5	1.0
		<0.150	13980	4.71	1.45	4.6	2.0	<.08	3.0	9.9	54	0.01	9	11	31	12	0.6	1.1	1.1	1.0
C32803	3	feed	13148	9.19	2.54	4.1	1.2	<0.1	2.7	12	94	0.04	28	13	44	13	0.4	1.5	1.6	1.1
		<0.150	13900	5.25	1.92	1.8	1.5	<.09	2.1	11	69	0.01	10	6	17	5	0.3	0.9	1.3	1.3

Appendix 4 *continued*

Feed coal lab no.	Feed coal region	Feed coal or F-S product particle mesh size (mm)	Heating value, Btu/lb*	Ash	Total S	As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32661	4H	feed	13238	8.17	2.89	3.4	1.6	<0.3	3.9	16	81	0.07	20	14	44	19	0.5	2	1.5	7.5
		<0.150	14089	4.01	1.86	1.5	2.5	<.07	1.8	13	64	0.02	7	10	17	13	0.3	1.0	1.0	6.3
C32665	4H	feed	13151	9.39	2.73	4.4	1.2	<0.3	3.6	13	84	0.17	25	11	44	19	0.4	1.7	1.6	5.7
		<0.150	14118	3.80	1.90	1.3	1.0	<.07	2.1	12	62	0.04	6	7	13	6	0.3	0.9	1.1	5.6
		<0.074	14169	3.47	1.75	0.9	1.9	0.10	2.3	12	70	0.02	11	8	17	6	0.2	0.8	1.0	5.3
C32771	4H	feed	12616	12.57	2.93	3.7	1.1	<0.5	4.1	14	131	0.14	36	10	44	22	0.3	1.4	1.8	2.2
		<0.150	14045	4.29	1.93	0.9	1.6	<.07	1.9	12	73	0.04	8	7	17	8	0.2	0.8	1.1	2.1
		<0.074	13910	5.17	1.84	1.0	1.8	<.09	2.8	14	85	0.02	20	10	22	7	0.2	0.7	1.2	2.1
C32776	4H	feed	13182	9.27	3.13	2.7	1.5	<0.3	3.6	15	74	0.07	38	12	44	10	0.6	1.7	1.4	1.8
		<0.150	14062	4.16	2.45	1.0	1.4	<.07	2.3˙	13	40	0.03	10	7	17	3	0.5	1.2	0.9	1.9
C32662	4S	feed	13525	7.00	1.51	14	1.4	<0.3	4.4	10	83	0.08	15	17	175	23	1.0	1.3	1.9	1.9
		<0.150	14143	3.67	1.11	5.2	2.7	<.07	2.8	7.8	43	0.02	6	12	74	14	0.8	0.9	1.2	1.6
C32772	4S	feed	13274	9.33	2.38	8.0	1.0	<0.2	3.9	9.2	75	0.17	39	13	87	27	0.7	1.3	1.3	<1.0
		<0.150	14040	4.34	1.51	2.6	1.0	<.07	2.3	8.2	52	0.05	8	9	44	13	0.6	1.0	1.0	<1
		<0.074	14149	3.62	1.34	1.7	1.4	<.06	2.8	9.1	50	0.03	15	11	39	9	0.6	0.7	0.9	<1
C32775	4S	feed	13779	7.67	2.98	4.9	1.8	1.10	4.7	14	97	0.21	16	18	61	45	1.2	3.6	1.3	6.8
		<0.150	14265	2.87	1.92	1.4	11.0	0.05	1.7	13	54	0.04	4	11	13	12	1.0	1.4	0.9	5.6
		<0.074	14314	2.56	1.81	1.3	7.1	0.11	1.6	12	51	0.02	5	11	13	12	0.8	1.2	0.9	5.8
C32781	4S	feed	13773	9.71	3.02	4.3	<1.0	0.50	2.7	12	104	0.11	37	11	44	46	1.4	2.5	1.2	2.0
		<0.150	13915	5.19	2.04	1.4	1.1	<.09	1.7	9.9	67	0.04	10	8	13	19	1.0	1.3	0.9	1.5
C32793	4S	feed	12402	14.14	1.64	33	1.2	<0.2	5.5	13	124	0.13	39	22	175	36	1.2	1.1	1.8	0.8
		<0.150	14151	3.59	0.95	8.4	2.0	<.06	3.7	7.0	38	0.03	8	15	57	14	1.1	0.9	0.8	0.6

*1 Btu/lb = 0.555 kcal/kg

Appendix 5 Changes (%) in heating value and in ash, total S, and HAPs contents of <0.150-mm size samples of 29 marketed Illinois coals as a result of float-sink (F-S) separation with 80% combustibles recovery. Negative values indicate decreases, and positive values indicate enrichments. In the statistical computations, one-half of the detection limit was used for all values below the detection limit.

Feed coal lab no.	Region	Heating value	Ash	Total S	As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32773	1	9	-43	-15	-62	0	-70	-13	-8	-26	-69	-67	-19	-50	33	0	-37	-17	-7
C32774	1	8	-61	-47	-55	175	-83	-71	-24	-18	-64	-72	-61	-40	-28	-33	-25	-25	25
C32777	1	8	-46	-22	-76	83	-98	7	-9	6	-60	-83	-21	-61	-50	-27	-31	-18	-3
C32778	1	10	-51	-26	-71	118	-93	-17	-22	-16	-75	-68	-6	-55	-50	0	-33	-20	44
C32782	1	10	-49	-23	-63	340	-88	-25	-31	-19	-71	-73	-29	-70	0	-20	-47	-18	8
C32785	1	10	-55	-21	-70	0	-75	-31	-29	-42	-86	-69	-22	-76	13	-50	-51	-23	-22
C32797	1	9	-46	-21	-73	142	-96	-23	-15	-23	-75	-63	-13	-64	-53	0	-29	-27	-5
C32814	1	2	-44	-23	-59	55	-97	-40	9	-11	-43	-77	-41	-57	-61	-21	-15	0	-15
C32779	2	11	-60	-17	-53	360	-91	-35	-24	-33	-60	-69	-26	-61	-43	-25	-48	-31	0
C32794	2	11	-59	-32	-65	109	-20	-25	0	-18	-75	-73	-29	-61	-67	-33	-42	-21	-10
C32798	2	12	-54	-30	-64	120	-88	-42	-39	-35	-60	-70	-38	-60	-58	0	-59	-24	-4
C32800	2	8	-37	-20	-50	140	-50	-18	-26	-24	-83	-53	-35	-60	-25	0	-46	-25	-21
C32813	2	12	-46	-27	-58	0	-73	-40	-48	-43	-83	-60	-43	-64	-46	-29	-46	-29	-24
C32815	2	12	-58	-25	-70	320	-55	-37	-21	-22	-67	-70	-34	-70	-42	-33	-52	-29	0
C32784	3	6	-59	-29	-48	94	-80	-40	-19	-72	-45	-62	-27	-30	-38	-9	-21	-36	-50
C32795	3	3	-52	-14	-39	0	-50	-4	-19	-77	-83	-64	-6	-30	-38	0	-27	-33	-58
C32796	3	18	-58	-30	-57	70	-96	-35	-26	-59	-67	-73	-21	-63	-55	0	-35	-47	-30
C32799	3	11	-70	-8	-91	300	-70	-9	-28	-56	-75	-92	-33	-37	-88	-17	-31	-44	0
C32801	3	5	-44	-27	-54	100	-20	-32	-18	-29	-75	-57	-21	-30	-45	0	-27	-27	0
C32803	3	6	-43	-24	-56	25	-10	-22	-8	-27	-75	-64	-54	-61	-62	-25	-40	-19	18
C32661	4H	6	-51	-36	-56	56	-77	-54	-19	-21	-71	-65	-29	-61	-32	-40	-50	-33	-16
C32665	4H	7	-60	-30	-70	-17	-77	-42	-8	-26	-76	-76	-36	-70	-68	-25	-47	-31	-2
C32771	4H	11	-66	-34	-76	45	-86	-54	-14	-44	-71	-78	-30	-61	-64	-33	-43	-39	-5
C32776	4H	7	-55	-22	-63	-7	-77	-36	-13	-46	-57	-74	-42	-61	-70	-17	-29	-36	6
C32662	4S	5	-48	-26	-63	93	-77	-36	-22	-48	-75	-60	-29	-58	-39	-20	-31	-37	-16
C32772	4S	6	-53	-37	-68	0	-65	-41	-11	-31	-71	-79	-31	-49	-52	-14	-23	-23	0
C32775	4S	4	-63	-36	-71	511	-95	-64	-7	-44	-81	-75	-39	-79	-73	-17	-61	-31	-18
C32781	4S	1	-47	-32	-67	120	-91	-37	-18	-36	-64	-73	-27	-70	-59	-29	-48	-25	-25
C32793	4S	14	-75	-42	-75	67	-70	-33	-46	-69	-77	-79	-32	-67	-61	-8	-18	-56	-25
mean	all	8	-53	-27	-63	118	-73	-33	-19	-35	-70	-70	-30	-58	-45	-18	-38	-28	-12
stdev	all	4	9	8	10	128	23	16	12	19	10	8	12	13	25	14	12	10	23

Appendix 6 Changes (%) in heating value and in ash, total S, and HAPs contents of <0.150-mm and <0.074-mm samples of ten marketed Illinois coals as a result of float-sink (F-S) separation with 80% combustibles recovery. Negative values indicate decreases, and positive values indicate enrichments. In the statistical computations, one-half of the detection limit was used for all values below the detection limit.

Feed coal lab no.	Region	Particle size (mm)	Heating value	Ash	Total S	As	Be	Cd	Co	Cr	F	Hg	Mn	Ni	P	Pb	Sb	Se	Th	U
C32773	1	<0.150	9	-43	-15	-62	0	-70	-13	-8	-17	-69	-67	-18	-50	33	0	-37	-17	-71
C32774	1	<0.150	8	-61	-47	-55	175	-83	-71	-24	-18	-64	-72	-60	-40	-28	-33	-25	-25	25
C32794	2	<0.150	11	-59	-32	-65	109	-20	-25	0	-18	-75	-73	-29	-61	-67	-33	-42	-21	-10
C32813	2	<0.150	12	-46	-27	-58	0	-73	-40	-48	-43	-83	-60	-42	-64	-46	-29	-46	-29	-24
C32784	3	<0.150	6	-59	-29	-48	94	-80	-40	-19	-72	-45	-62	-27	-30	-38	-9	-21	-36	-50
C32796	3	<0.150	17	-58	-30	-57	70	-96	-35	-26	-59	-67	-73	-21	-63	-55	0	-35	-47	-30
C32665	4H	<0.150	7	-60	-30	-70	-17	-77	-42	-8	-26	-76	-76	-36	-70	-68	-25	-47	-31	-2
C32771	4H	<0.150	11	-66	-34	-76	45	-86	-54	-14	-44	-71	-78	-30	-61	-64	-33	-43	-39	-5
C32772	4S	<0.150	6	-53	-37	-68	0	-65	-41	-11	-31	-71	-79	-31	-49	-52	-14	-23	-23	0
C32775	4S	<0.150	4	-63	-36	-71	511	-95	-64	-7	-44	-81	-75	-39	-79	-73	-17	-61	-31	-18
mean	all	<0.150	9	-57	-32	-63	99	-74	-42	-17	-37	-70	-71	-33	-57	-46	-19	-38	-30	-18
stddev	all	<0.150	4	7	8	8	149	21	16	13	18	10	6	11	14	30	13	12	8	26
C32773	1	<0.074	9	-44	-21	-54	60	-73	-22	-17	-43	-85	-38	0	-41	33	-50	-53	-25	-71
C32774	1	<0.074	8	-63	-54	-63	125	-83	-55	12	-34	-77	-72	-60	-40	-29	-25	-58	-25	25
C32794	2	<0.074	9	-46	-32	-57	55	0	-36	-34	-3	-50	-53	-7	-41	-53	-33	-53	-36	-20
C32813	2	<0.074	14	-61	-35	-67	93	-95	-34	-50	-50	-50	-58	-50	-69	-62	-14	-70	-43	-14
C32784	3	<0.074	7	-61	-42	-67	33	-80	-33	-18	-63	-64	-47	-27	-20	-50	-18	-43	-43	0
C32796	3	<0.074	17	-58	-30	-57	70	-93	-35	-26	-46	-83	-73	-21	-63	-65	0	-35	-47	-20
C32665	4H	<0.074	8	-63	-36	-80	58	-33	-36	-8	-17	-88	-56	-27	-61	-68	-50	-53	-38	-7
C32771	4H	<0.074	10	-59	-37	-73	64	-82	-32	0	-35	-86	-44	0	-50	-68	-33	-50	-33	-5
C32772	4S	<0.074	7	-61	-44	-79	40	-70	-28	-1	-33	-82	-62	-15	-55	-67	-14	-46	-31	0
C32775	4S	<0.074	4	-67	-39	-73	294	-90	-66	-14	-47	-90	-69	-39	-79	-73	-33	-67	-31	-15
mean	all	<0.074	9	-58	-37	-67	89	-70	-38	-16	-37	-76	-57	-25	-52	-50	-27	-53	-35	-13
stddev	all	<0.074	4	7	8	9	73	29	12	17	16	10	11	19	16	30	15	10	7	23