

Precombustion Control of Hazardous Air Pollutants

Michael A. Nowak and Victoria L. McLean

U.S. Department of Energy
Pittsburgh Energy Technology Center
P.O. Box 10940
Pittsburgh, PA 15236-0940

KEY WORDS: trace elements, air toxics, coal preparation

INTRODUCTION

The air toxics provision of the 1990 Clean Air Act Amendments (CAAA) requires the Environmental Protection Agency (EPA) to promulgate regulations establishing emission standards for Hazardous Air Pollutants (HAP). Precursors of 13 of the HAPs are found in trace quantities in coal: As, Se, Hg, Pb, Cl, F, Be, Co, Ni, Cr, Sb, Cd, and Mn. The EPA is currently conducting a Congressionally mandated study of HAPs emissions from coal-fired power plants; the results of the study may lead to regulations governing the emissions of specific trace elements from coal. Influenced by the potential risk to coal utilization by possible future HAP emissions regulations, the Department of Energy, in cooperation with coal users and other government agencies, is seeking to evaluate the information on these elements of environmental concern in coal and to examine methods of measuring and controlling these emissions.

One control option is precombustion coal cleaning, which can significantly reduce mineral matter concentration and consequently has the ability to remove trace elements associated with the mineral matter liberated from the coal matrix. Primary factors controlling the precombustion removal of trace elements are the extent of association of the element with mineral matter within the coal matrix and the crushed coal particle size. The finer the coal is crushed, the more mineral matter is liberated and the further the trace elements associated with the mineral matter are reduced in the product coal.

The affinities of coal-related HAP precursors have been discussed extensively in the literature. This paper will review and summarize the literature on trace element affinities in coals, and the ability of precombustion coal cleaning to remove those trace elements from coals.

TRACE ELEMENTS AND COAL CLEANING

Finkelman,¹ in his 1980 dissertation, examined in depth the Waynesburg and Upper Freeport seam coals. In addition, he briefly examined 80 U.S. coals from every major basin and an additional 20 coals from around the world. He relied on a Scanning Electron Microscope equipped with an Energy Dispersive X-ray detector (SEM/EDX) to determine the mode of occurrence. His analysis discusses the problems associated with using float-sink testing as an analytical tool. Finkelman's float-sink data for the Waynesburg and Upper Freeport coals showed that, in general, trace element separation is dependent on mesh size, and, for the trace elements examined, approximately one-half of each trace element found in the whole coal was retained in the fractions with a specific gravity less than 1.50.

Finkelman summarized the literature that evaluated float-sink studies. His summary covered 12 float-sink studies involving a number of trace elements in several specific gravity fractions and whole coal samples for over 60 coals.

Finkelman briefly reviewed a number of studies that discussed the use of various leaching agents, including HCl, HF, HNO₃, and pyridine. His summary suggests that organic affinity index determinations may be exaggerated due to experimental error and indicates that a common error in each study is the assumption that the leaching was quantitative. In his discussion of correlation of trace elements, several studies on coals from around the globe are cited. His conclusion was that correlation coefficients do not necessarily reflect the mode of occurrence, but rather a common original source of the element. For example, Hg and As have very high correlation coefficients for pyrite and for each other. Finkelman's SEM/EDX experiments found that Hg and As are in solid solution with pyrite, (probably as sulfides) thus suggesting that the Hg and As had a common source. For any given trace element, there does not appear to be any coefficient that indicates a correlation between that trace element's concentration in coal and any other coal constituent's concentration that can be applied to more than one coal.

In summarizing his findings on the trace elements in coal, Finkelman states:

- Most trace elements appear to have an inorganic association in most high-rank coals.
- The organic complexing of trace elements, however, is not unimportant.
- Even in any one coal, the mode of occurrence can vary.

According to Gluskoter² and Ruch et al.³, organic affinity numerical values change with particle size distribution of the coal. The reason for this interpreted behavior is due to the misuse of the term "organic affinity." Gluskoter and Ruch developed the organic affinity index as a single numerical value to replace washability curves in an effort to simplify comparison of trace element reductions among different coals. Some researchers have misinterpreted the term to imply that trace elements may be chemically bound to the organic matrix, i.e., as in organometallic complexes, porphyrins, etc., but the vast majority of the organically associated trace elements in coal are very fine mineral particles that are dispersed and are difficult to liberate and separate. Examining the inorganic material frequently referred to as syngenetic, authigenic, or inherent mineral matter, Nicholls⁴ noted that some elements appear to be predominantly dispersed in the organic fraction, that is, the concentration of the element is constant with rising ash content. This suggests that those trace elements were present when the plant material was deposited prior to coalification and not introduced through later mineral deposition.

Kuhn et al.⁵ examined the trace elements of Davis, Blue Creek, Pittsburgh, Illinois No. 6, Rosebud, and Black Mesa coals. They examined the trace element concentrations of whole coal and float-1.40 sp. gr. fractions for 33 elements and the effects of acid leaching with HNO₃, HCl, and HF, and reactions with lithium aluminum hydride (LAH) on demineralization. They also examined Cr in five specific gravity fractions of Illinois No. 6 coal. Trace element concentrations and organic affinities were determined. With regard to the trace elements that

are potential precursors to HAPs cited in the 1990 CAAA, the following can be extracted from their summary:

- Be and Sb are consistently associated with the organic matrix.
- As and Cd are found with pyrite and can usually be substantially reduced with pyrite by gravity methods.
- Hg, Pb, and Mn have a high degree of inorganic association and are removed rather easily by conventional coal cleaning.

Akers^{6,7} examined conventional coal cleaning as a control method for trace elements. Akers' studies may be summarized by the following:

- Upper Freeport coal was found to be relatively high in As, Cd, and Cr. Conventional cleaning reduced As, Ba, Cd, Cr, F, Pb, Hg, Ag, and Zn by at least 50%. A significant reduction in Ni also occurred. An increase in Se concentration (ca. 30%) was noted.
- Conventional cleaning of Rosebud/McKay subbituminous coals showed significant reductions in As, Ba, and Ni. Small reductions of Cd and Se were observed. The Cr concentration was reported as increasing from 6 ppm to 10 ppm.
- Conventional cleaning of samples from the Croweburg seam indicated significant reductions in As, Ba, Cd, Cr, Pb, Ni, and Zn. In some cases, but not in others, reductions in F, Hg, and Ag correlate with ash reduction.
- A comparison of advanced coal cleaning to conventional cleaning was made with Sewickley seam coal. The Custom Coals International process (density separation of fine coal) was found to provide further reduction of all trace elements, except Hg, which is in disagreement with Kuhn's⁵ findings that Hg is readily removed with the ash. In one example, As was reduced from 14 ppm to 4 ppm (70%).
- Physical coal cleaning is effective in reducing the concentration of many trace elements, especially if they are in high concentration. Trace element removal is not, however, always proportional to ash removal. Potential changes in plant flow sheets and operating parameters may not lead to reduction in the ash content of the coal but may reduce trace element concentrations. Trace element reduction appears to be coal-specific, relating in part to the degree of liberation and the trace-element-bearing mineral matter. Thus, advanced coal cleaning methods that process more finely ground coals may provide greater reductions than conventional technologies.
- Conventional cleaning of Kentucky No. 11 coal led to large reductions in all trace elements measured.
- The Midwest Ore process, which involves extraction with hot perchloroethylene (PERC) followed by gravity separation in PERC, reduced nine trace elements by two-thirds or more.

White et al.⁸ prepared a very extensive report for the EPA that covered the entire coal utilization cycle, including a review of the literature on the following topics: occurrence of trace elements in U.S. coals; organic affinity studies, including the PETC Study⁹; photomicrographic studies; conceptual models for trace element modes of occurrence; coal washing, particularly partitioning of trace elements; and leaching of coal wastes.

The report concluded that:

- Organic affinity data are usually acquired by specific gravity fractionation, although acid leaching has also been used. The literature describing characterization and trace element washability of up to 27 elements was reviewed. Organic affinities and trace element concentrations for mineral-matter-free coals derived from reviewing the literature, including the work of Boyer et al.¹⁰, are presented in tables. The Boyer et al.¹⁰ report has a complete bibliography of 1,076 publications covering the fate of trace elements during mining, preparation, and utilization. The report cites earlier key studies by Buroff et al.^{11,12} and Miller et al.¹³, and includes where trace element removal at coal cleaning plants are cited, with a note that mass balances were not done.
- Although a thorough understanding of the response of various coals to sulfur and trace element removal does not yet exist, significant insight has been developed.
- Coals containing dispersed fine-grained minerals or free-swelling clays are more difficult to clean.
- A logical step in the process of better understanding trace element reduction potential is further statistical assessment of existing data.
- A statistical evaluation of existing ISGS and DOE data was performed. Linear correlations and regressions gave correlation coefficients (CC) ≥ 0.70 for the occurrence of several clustered groups of elements: As, Cd, Pb, Sb, and Zn; Al, Si, Ti, K, Co, V, and Cr; Fe and S; F with Al, K, Si, Ti, Cr, Cu, Be, and Ni. Regarding trace element reduction, a large number of elements showed coefficients greater than 0.70 and appeared to suggest that ash removal was more important than the removal of any individual element. Arsenic, Hg, and Fe reductions had CCs between 0.50 and 0.70 for pyrite removal and As, Co, Hg, Pb, Se, and Fe reductions had CCs greater than 0.50 for sulfur reduction. Efforts to correlate trace element reductions with an element's concentration in the whole coal were unsuccessful, except for the elements in the clays, suggesting that abundance of clays, and not the concentration of the element, determines the extent to which the element can be removed. Analysis of trace element removal data indicated elements in coal occur in two groups: 1) those associated with Al, K, Na, Si, Ti, Be, Cr, Cu, Mn, Ni, V, and ash; or 2) those associated with Fe, As, Hg, and pyrite.

- There is considerable disagreement among coal scientists on the methods of analysis and interpretation of the results of trace element studies of coal. A detailed framework for predicting trace element occurrence for a seam based on existing samples and associated geologic, geochemical, or paleoenvironmental data is lacking. Therefore, research priority needs for the coal resource appear to be in interpreting these data on a regional or seam basis. Given the magnitude of the U.S. coal resource base, combined with the extent and variability of existing data, collection and analysis of further samples (except as they relate to the evaluation of new mines and coal-using facilities) will provide little additional information.
- Pyritic sulfur and trace elements associated with pyrite and extraneous clays can be removed with relatively high efficiency by coal cleaning. Other trace elements are generally not removed during conventional cleaning. Variability in cleanability between regions or seams can be explained by the mode of occurrence, but the geologic processes responsible for these variations are poorly understood. Based on available (and in most cases, limited) data, it appears that the removal of most of the common trace elements can be reasonably correlated with the removal of ash and sulfur from coal using standard washability tests. For the chalcophile elements, the removal of sulfur is a better estimator of trace element removal than is the removal of ash. Removal of chalcophile elements from Allegheny formation coals is generally higher than from other U.S. coals. Interior Province coals exhibit significant variation in cleanability. Using a number of statistical techniques on existing washability data, White et al⁵ determined partitioning coefficients describing the relationship between trace element reduction and both sulfur and ash reduction for six major coal-producing regions of the U.S.
- Before additional data compilations on coal characteristics are made, the procedures for evaluating samples must be standardized.
- The trace element washability of forty-four coals was examined and compared to sulfur washability data for 750 coal samples. The authors concluded that specific attention should be given to major coal seams that are currently being washed or which are likely to be washed. Washability and statistical analysis studies similar to those described should be done, including analysis of minerals in the coals.
- Certain trace elements (e.g., V and Fe) have the potential for the catalytic conversion of SO_2 to SO_3 . Because of the increased efficiency by which SO_3 is absorbed onto the surface of fly ash particles, this catalytic effect may be important but has not been extensively investigated.

Conzemius et al.¹⁴ described the partitioning of 75 trace elements, sulfur, and ash in Illinois No. 6 and Upper Freeport coals processed in two dense-medium cyclone plants at sp. gr. of 1.4 and 1.6. Approximately two-thirds or more of Be, B, Cr, Mn, Co, Ni, As, Se, Cd, Sb, Hg, and Pb were removed. Chlorine and radionuclide concentrations were cut approximately by one-half and Mo by one-third.

The ISGS¹⁵ flotation studies on Illinois No. 6 coal have shown average reductions of selected trace elements of 58% and 77% for froth flotation and aggregate flotation, respectively.

Norton et al.¹⁶ described trace element reduction for a Texas lignite. Coal passing a 25- x 9.5-mm (1-in. x 3/8-in.) screen was cleaned by dense-medium cyclone and 9.5- x 0.15-mm (3/8-in. x 100 mesh) material cleaned on a concentrating table. Mercury, Ni, and Pb (3, 29, and 27 ppm in the feed coal, respectively) were reduced to below detectable levels. Selenium concentration was reduced by one-half.

Bechtel National¹⁷ performed a study on microbubble flotation for DOE and reported the trace element analyses for ROM, conventionally cleaned, and deeply cleaned Pittsburgh No. 8, Illinois No. 6, and Upper Freeport coals. The sources for the concentration data reported are not known, and no discussion of the data in the tables was available. The data presented indicate, that, except for arsenic reduced at every stage of processing, the trace element concentrations in the deeply cleaned coal were significantly lower than in the ROM coal, but higher than the conventionally cleaned coal used as the feed to the flotation unit.

A recent report prepared by Coal Technology Corporation¹⁸ for DOE describes the washability of coal for development of advanced cyclone processes. Four coals, Meigs No. 9, Illinois No. 6, Upper Freeport, and Pittsburgh No. 8, were ground to below 0.15 mm (minus 100 mesh) and deep cleaned using gravimetric techniques at a sp. gr. of 1.5. Deep cleaning of a plant-washed sample of Meigs No. 9 coal resulted in a change in ash content from 12.71% to 6.41%; a major (more than 50%) reduction of As, Mn, and V concentrations; a minor reduction (less than 50%) in Co, Se, and Zn concentrations; essentially no change in the Cd and Hg concentrations and an increase in concentration of Sb, Be, Cr, Cu, Pb and Ni. The ash content of the Illinois No. 6 coal was reduced from 11.05% to 4.7% and resulted in major reductions of As, Cd, Mn, Zn, and Hg concentrations; minor reductions in Co, Pb, Se, Ni, and V concentrations; and an increase in Sb, Be and Cu concentrations. Deep cleaning the Upper Freeport coal reduced the ash content from 23.49% to 4.49%; significantly reduced the Cd, Cr, Co, Pb, Mn, Hg, Ni and Zn concentrations; and mildly reduced Be and V concentrations; and increased the Sb, As and Se concentrations. The ash content of Pittsburgh No. 8 was reduced from 10.31% to 4.36% and provided major reductions in As, Mn and Hg; provided minor reductions in Cd, Cr, Co, Pb, Ni, Se and Zn; and increased Sb, Be, Cu, and V concentrations.

In examining the mode of occurrence and concentration of trace elements in U.S. and U.K. coals, Raask¹⁹ concluded that trace elements in bituminous coals are present chiefly in the mineral matter fraction and, in particular, a large number of chalcophilic elements are present. He also concluded that high-sulfur coals in the U.S. are relatively rich in Cd and Zn, the chalcophilic elements are preferentially removed upon coal cleaning, and between 40% to 50% of Be, Cd, Cu, Pb, Hg, and Zn are removed by reducing the ash content of cleaned coals to below 15%.

Norton et al.²⁰ examined the trace elements in chemically cleaned coals and concluded that hot aqueous carbonate, molten NaOH/KOH, and acid treatments can

effectively remove trace elements from coals. However, they cautioned that corrosion of the reaction vessels may elevate certain trace elements in the treated coals.

A project completed by the EPA's Industrial Environmental Research Laboratory and summarized by Harvey et al.²¹ investigated the distribution of trace elements in the Illinois No. 6 and Illinois No. 5 coals of the Illinois Basin. It was found that elements of environmental concern were present in the following concentrations: Pb (28 ppm), Cr and Ni (18 ppm), Cu (12.5 ppm), As (11 ppm), Mo (9.2 ppm), and Se (2.4 ppm). The other trace elements found in these specific coals average less than 2.4 ppm. From washability tests completed on the same coals, As, Cd, Mo and Pb were found to be trace elements associated with the mineral matter and were typically reduced by 50% or more. Some trace elements (Be, Ni and Sb) appear to be associated with the organic portion of the coal. Reductions in concentration of these elements were more difficult to achieve, their concentrations being reduced by less than 10%. Reductions in concentration of 15% to 30% were noted for several trace elements (Co, Cr, F, Hg, Se and Th) and those trace elements are assumed to be associated with both the mineral matter and the organic portion of the coal.

Researchers at Conso^{22,23} have assembled an extensive database characterizing trace element concentrations of ROM and coal preparation plant products. The database contains over 850 composite samples and 3,400 individual trace element analyses for 225 commercial coals. The Conso researchers concluded that:

- Individual trace elements are weakly to moderately correlated to ash content, but no correlation was noted for sulfur.
- Coal cleaning to remove ash is effective in removing a portion of many trace elements. The degree of trace element removal is often similar to the overall ash rejection.

SUMMARY AND CONCLUSIONS

The literature concerning the trace element concentration of U.S. coals, and coal preparation as it relates to trace element removal, is extensive. The subject has been of interest for at least 40 years and is of vital interest today. A computer search of papers published in the last decade on topics related to the subject readily revealed 200 citations on trace element concentrations in coals and their removal by physical methods. Nearly 100 additional references were found that address chemical and biological methods for removing trace elements from coal. Approximately 100 references were found that deal with the issue of trace element analyses of coal. A considerable amount of the material is contained in EPA reports and the EPRI PISCES Database.

The U.S. coal reserves are reasonably well characterized in terms of their trace element concentrations. However, there seems to be a great deal of inconsistency with regard to trace element washability of coal. As an example, it was noted in the discussion section that some authors report Hg as associated with the organic matrix (difficult to remove) while others report Hg as associated with the mineral matter (easy to remove). Inconsistencies like this suggest that each coal seam must be evaluated individually with respect to trace element washability.

Another example of an apparent inconsistency is the decrease in Cr concentration when Upper Freeport coal was cleaned, while Cr concentrations increased when Rosebud/McKay seam coal was subjected to cleaning. While it is possible that more carbon could be rejected than finely disseminated Cr, in this case the magnitude of Cr concentration increase suggests analytical errors. In reviewing the trace element literature, it is difficult to compare different research findings and determine where the errors may lie. Much of the trace element literature fails to discuss attempts at mass balance closure. Historically, a number of analytical techniques have been applied to trace element analysis of coal and older research efforts may have used analytical techniques which have subsequently been found to be lacking in accuracy. Even when newer methods were used, sampling procedures and sample preparation methods are often not discussed. There exist today analytical techniques which are capable of determining quite accurately trace element concentrations of homogeneous samples. It appears that coal sampling, good sample preparation techniques, and additional analytical standards appear to be the major obstacles to overcome in achieving good trace element analyses of coal.

There is a reasonable correlation between trace element removal during coal cleaning and ash rejection. This is apparently due to the "organic affinity" of certain trace elements. Some trace elements are so finely disseminated throughout the coal matrix that they are not removed by coal preparation methods in common practice. A conclusion based on a review of the literature is that all trace elements can be readily reduced by 40 to 50% by physical coal cleaning and any further characterization that may be deemed desirable should rely on statistical analysis of existing concentration and washability data. Further reductions could be achievable by advanced physical coal preparation methods which separate the mineral matter that has been more effectively liberated by grinding coal to finer particle sizes. To comply with potential regulation of HAPs from coal-fired power plants, it may be desirable to develop methods of removing specific trace elements, such as mercury or arsenic, which would suggest the need for chemical or biochemical coal cleaning methods.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial assistance provided by the Oak Ridge Associated Universities Research Associate Program in which Victoria McLean participated.

DISCLAIMER

References in this report to any specific commercial process, product, or service is to facilitate understanding and does not necessarily imply its endorsement or favoring by the United States Department of Energy.

REFERENCES

1. Robert B. Finkelman, "Modes of Occurrence of Trace Elements in Coal," Ph.D. Dissertation, University of Maryland, 1980.
2. H.J. Gluskoter, "Mineral Matter and Trace Elements in Coal," in Trace Elements in Fuel, S.P. Babu, ed., ACS Advances in Chemistry Series 141, ACS, Washington D.C., 1975.
3. R.R. Ruch, H.J. Gluskoter, and N.F. Shimp, "Occurrence and Distribution of Potentially Volatile Trace Elements in Coal," Environmental Geology Notes No. 74, ISGS, 1974.
4. G.C. Nicholls, "The Geochemistry of Coal-Bearing Strata," in D. Muchison and T.S. Westoll, eds., Coal and Coal-Bearing Strata: American Edition, American Elsevier, New York, 1968, pp. 269-307.
5. J.K. Kuhn, F.L. Fiene, R.A. Cahill, H.J. Gluskoter, and N.F. Shimp, "Abundance of Trace and Minor Elements in Organic and Mineral Fractions of Coal," Environmental Geology Notes, No. 88, ISGS, 1980.
6. D.J. Akers, "Precombustion Control of Trace Elements," Presented at the Sixteenth Annual Conference on Fuel Science, Palo Alto, June 18-19, 1990.
7. D.J. Akers, "Coal Cleaning: A Trace Element Control Option," Preprint for the EPRI Conference on Managing Hazardous Air Pollutants: State of the Art, Washington, D.C., November 4-6, 1991.
8. D.M. White, L.O. Edwards, A.G. Eklund, D.A. Eklund, D.A. DuBose, F.D. Skinner, and D.L. Richmann, Radian Corp., "Correlation of Coal Properties with Environmental Control Technology Needs for Sulfur and Trace Elements," U.S. EPA Final Report EPA 600/7-84-066, June 1984.
9. J.A. Cavallaro, A.W. Duerbrouck, G. Gibbon, E.A. Hattman, H. Schultz, and J.C. Dickerman, "A Washability and Analytical Evaluation of Potential Pollution from Trace Elements in Coal," EPA-600/7-78-038, March 1978.
10. J.F. Boyer, J.P. Constantino, C.T. Ford, V.E. Gleason, and K.A. Rosnick, "Evaluation of the Effect of Coal Cleaning on Fugitive Elements, Phase II, Part III, State-of-the-Art: Fate of Trace Elements In Coal During Mining, Preparation, and Utilization," U.S. Department of Energy Report No. De-AC22-77EV04427, 1981, 263 pp.
11. J.M. Buroff, J. Straus, A. Jung, and L. McGilvray, Environmental Assessment: Source Test and Evaluation Report: Coal Preparation Plant No. 1, VERSAR, Inc., Springfield, Va., U.S. Environmental Protection Agency Report No. EPA-600/7-81-071a, 1981, 287 pp.
12. J.M. Buroff, J. Straus, A. Jung, and L. McGilvray, Environmental Assessment: Source Test and Evaluation Report- Coal Preparation Plant No. 2, VERSAR, Inc., Springfield, Va., U.S. Environmental Protection Agency Report No. EPA-600/7-81-071b, 1981, 290 pp.

13. F.A. Miller, T.L. Bell, R.C. Patyrak, and J.M. Wyatt, Environmental Studies on a Level C Coal Cleaning Plant, Tennessee Valley Authority, Chattanooga, Tenn., U.S. Environmental Protection Agency Report No. TVA/OP/EDT-81/46, 1981, 137 pp.
14. R.J. Conzemius, C.D. Chriswell and G.A. Junk, Fuel Processing Technology, 1988, 19, pp. 95-106.
15. R.B. Read, R.R. Ruch, H.P. Ehrlinger, P.J. DeMaris, D.M. Rapp, L.R. Camp, and J.A. Fitzpatrick, "ISGS Aggregate Flotation Fine-Coal Cleaning Process," Technical Report for January 1, 1983 - August 31, 1986, CRSC.
16. G.A. Norton, W.H. Buttermore, R. Markuszewski, and D.J. Akers, "The Removal and Control of Trace Elements in Coal and Coal Wastes," Proceedings of the EPRI Seminar on Reducing Power Plant Emissions by Controlling Coal Quality, Bethesda, Md., October 27-28, 1987.
17. Advanced Physical Fine Coal Cleaning: Microbubble Flotation, DOE Final Report DE-AC22-85PC81205, Bechtel National, Inc., September 1988.
18. Coal Technology Corporation, Phase I Report, DOE Contract DE-AC222-90PC90177, June 1992.
19. E. Raask, "The Mode of Occurrence and Concentration of Trace Elements in Coal," Prog. Energy Combust. Sci., 1985, 11, pp. 97-118.
20. G.A. Norton, R. Markuszewski, and H.G. Araghi, "Chemical Cleaning of Coal: Effect on the Removal of Trace Elements," Am. Chem. Soc. Symposium Series 319, Fossil Fuels Utilization: Environmental Concerns, R. Markuszewski, and B.D. Blaustein, eds., ACS, Washington, 1986.
21. R.D. Harvey, R.A. Cahill, C.L. Chou, and J.I. Steele, Mineral Matter and Trace Elements in the Herrin and Springfield Coals, Illinois Basin Coal Field, EPA Report No. EPA-600/S7-84-036, 1984.
22. P.R. Tumati and S.M. DeVito, Trace Element Emissions from Coal Combustion - A Comparison of Baghouse and ESP Collection Efficiency, Proceedings of the EPRI Conference on the Effect of Coal Quality on Power Plants, August 25-27, 1992, San Diego, Ca.
23. E.L. Obermiller, V.B. Conrad, and J. Lengyel, "Trace Element Contents of Commercial Coals," EPRI Conference on Managing Hazardous Air Pollutants: State-of-the-Art, Washington, D.C. November 1991.