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EFFECTS OF CHANGING COALS ON THE EMISSIONS OF METAL HAZARDOUS AIR POLLUTANTS FROM THE COMBUSTION OF PULVERIZED COAL

Final Report

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

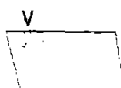
A series of tests were conducted at the U.S. Environmental Protection Agency's National Risk Management Research Laboratory, Air Pollution Prevention and Control Division (APPCD), formerly the Air and Energy Engineering Research Laboratory, to evaluate the effects of changing coals on the emissions of metal hazardous air pollutants (HAPs) from coal-fired boilers. The tests were conducted on a small scale combustor, and samples were taken prior to any pollution control equipment to allow application of different control efficiencies to the uncontrolled emissions. Six different coals were burned in APPCD's Innovative Furnace Reactor (IFR) under the same combustion conditions, and each coal was sampled for 10 metals: antimony, arsenic, beryllium, cadmium, chromium, lead, manganese, nickel, selenium, and mercury. Each of these metals is on the list of 189 compounds and compound classes listed as HAPs under Title III of the 1990 Clean Air Act Amendments. The results of the tests showed that changes in the uncontrolled emissions tended to correlate well with the corresponding changes in the as-fed metal content of the coals in the cases of mercury, selenium, and arsenic. For beryllium, chromium, manganese, and nickel, changes in the uncontrolled emissions with different coals did not correlate well with the changes in the as-fed trace metal contents. The remaining three metals, antimony, cadmium, and lead, did not show conclusive results when comparing emissions to as-fed trace metal contents. The factor that determines the degree of correlation between the as-fed trace metal concentration and the uncontrolled stack emissions appears to be the vapor pressure of the metal. Metals that have high vapor pressures tend to exhibit strong correlations between the as-fed metal concentration in the coal and the uncontrolled emissions, while metals with low vapor pressures tend to show a much weaker correlation. In summary, the study illustrates that predictions of metal emissions based only on the trace metal content of the coal do not yield accurate results in all cases. Such predictions cannot be used with any confidence for refractory metals, but do have some degree of validity for the more volatile metals of interest.

Based on average emission factors (in lb/10⁶ Btu), the Illinois coals had higher emissions of arsenic, beryllium, cadmium, lead, and selenium than did the western coals, while the western coals had higher emissions of chromium, manganese, and nickel. Antimony and mercury emissions were similar for both coals. These results must be carefully interpreted, however, given the limited scope of testing and the fact that the tests were conducted on a small scale unit.

Comparisons of the small scale results with U.S. Department of Energy (DOE) field data show that the highest measured full scale emissions tend to be lower than the small scale results, with the exception of mercury, which was higher in the DOE field data. This is in contrast to the data taken from a full scale test using one of the coals used in this study. In this case, measurements upstream of any pollution control equipment showed the small scale results to be 30-50% lower than the full scale emissions for manganese, nickel, and selenium, with the remaining emissions being similar between the two tests. The correlation between full scale and small scale emissions remains unclear in general. However, trends seen in the small scale tests are expected to be similar to trends from the full scale testing, to the degree that similar changes in coals are made.

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Executive Summary

I. Introduction

Title III of the 1990 Clean Air Act Amendments includes significant provisions for the reduction of hazardous air pollutants (HAPs) from a wide range of sources, including combustion sources. The Act defines 189 compounds and compound classes as HAPs, and requires maximum available control technology (MACT) to be applied to sources that emit over 10 tons (9.07 tonnes) per year of any single HAP, or 25 tons (22.7 tonnes) per year of any combination of HAPs. These provisions do not immediately apply to utility units, pending the results of a Congressionally mandated Study and Report to Congress on the risk to human health from the emissions of HAPs from utility boilers. That study is currently being conducted by EPA's Office of Air Quality Planning and Standards.

The provisions of Title III may result in a significant impact on coal-fired utility boilers because of the presence of metal compounds in coal, many of which are listed as hazardous under Title III. The immense volumes of coal burned in a large boiler may result in annual emissions of such compounds that exceed the 10 ton per year level, making utility boilers subject to the application of MACT if the Title III provisions are applied to utility boilers without modification.

Other provisions of the Act require utilities to reduce their total annual emissions of sulfur dioxide (SO₂). Because the sulfur content of some coals is lower than others, one control strategy that has been applied is to replace the use of higher sulfur coals with those having a lower sulfur content, thereby removing the need for installation of flue gas desulfurization systems. However, this approach (known as fuel switching) will also alter the emissions of metal compounds due to the differences in metal content of the different coals. This adds an additional factor to the process of planning for compliance with the provisions of the Act.

II. Behavior of metals in coal combustion systems

Coal naturally contains a variety of different metal compounds, and the combustion of pulverized coal results in the release of those compounds from the coal into the combustion environment. Unlike organic compounds, which can be chemically broken down into more basic and nonhazardous constituents, metal compounds are not chemically transformed by the combustion process to the degree that they lose their toxic nature. Therefore, when a fuel-bound metal compound is introduced into a combustion environment, it must exit the furnace or combustor. However, the routes each metal may take through the combustor can differ based on combustor design, operating conditions, or the properties of the coal.

The percentage of a given metal that exits via a particular effluent stream is referred to as the "partitioning" behavior of that metal toward that stream. Different metals will exhibit different partitioning behavior for similar conditions, and changes in those conditions can change the partitioning behavior of a single metal. Of considerable concern are the metals which exit the combustor with the flue gases, since these may result in emissions into the atmosphere if adequate pollution control strategies have not been implemented. The metals which pass through the combustion process may exit as a metal vapor, an aerosol composed of small particles, in condensed form on larger solid-phase particles entrained in the flue gases, or as a combination of the three.

In many instances, one or more of the effluent streams will exhibit a concentration of a given metal that is higher than would be expected if the metal were evenly distributed among all the various streams. This partitioning behavior is known as "enrichment" of that particular stream by that metal. Enrichment is of interest because air pollution control systems are typically much less efficient in removing particles smaller than 1 μm in diameter than they are in removing larger particles. Larger particles are often removed from the flue gases even without air pollution control systems, due to their inability to remain entrained in the flue gases. Thus, if metals partition preferentially to the smaller size ranges, they are more likely to be emitted from the stack, even if air pollution control systems are present. The combustion conditions, presence of other compounds, and the way the metal is contained in the coal matrix can all affect the partitioning behavior of the metal. Thus, the partitioning and enrichment behavior make the prediction of metal compound emissions very difficult, even when the metal content of the coal is well known.

III. Experiment

To study the behavior of metal emissions from different coals in a single combustion environment, the Illinois Clean Coal Institute and the National Risk Management Research Laboratory, Air Pollution Prevention and Control Division (formerly the Air and Energy Engineering Research Laboratory) of the Environmental Protection Agency's Office of Research and Development entered into a cooperative research project. This project was designed to combust several different coals in the same small scale research combustor, and sample and analyze the resulting flue gases for metal compounds.

Six different coals were tested during the test program. An Illinois #5 and Illinois #6, two western coals, and two other "test comparison" coals were used. The last two coals were used in other tests evaluating HAP emissions from coal to provide comparison with other tests, including a full scale field test. The Illinois coals were higher in sulfur than the two western coals, and represented the "high sulfur" cases, with the western coals representing the "low sulfur" cases.

The coals were burned in APPCD's Innovative Furnace Reactor (IFR), which is a down-fired refractory-lined furnace rated at 29.3 kW (100,000 Btu/hr), capable of firing natural gas, fuel oil, or pulverized coal. Continuous emission monitors (CEMs) were used to provide continuous readings and records of the levels of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), oxygen (O₂), and carbon dioxide (CO₂).

Combustion conditions were chosen to most closely simulate the combustion of pulverized coal in a typical utility boiler. A stoichiometric ratio of 1.25 (25% excess air) was chosen to provide a stable flame and relatively low CO and NO_x values. Gas and particulate samples were taken upstream of any flue gas cleaning equipment in order to evaluate the uncontrolled emission levels. The metals emissions were collected using the Multiple Metals sampling train (MMT), and mercury emissions using the Method 101A sampling train.

The project was conducted following an EPA-approved Quality Assurance (QA) Project Plan. CEMs were calibrated before and after each test run to check zero and span. Samples were collected in complete accordance with EPA method guidelines. Duplicate samples were collected for each test condition, and field and method blanks were used to evaluate potential contamination during sampling and analysis. The sampling and analysis procedures followed during the testing were identical to those that are required under more stringent QA levels.

The major problem affecting data quality was the contamination of one sample with permanganate solution during the sampling and analysis process. Extremely high levels of manganese were found in this sample (WC2 test number 1) resulting from permanganate contamination, and this value was not included in the data used to calculate emissions. Analyses of the method blanks showed that the analysis of all metals except manganese correctly indicated the levels of metal compounds sampled from the flue gases. For manganese, the reported levels are (at worst) higher than actually present in the gases, but are of the same order of magnitude.

IV. Results

The study compares the measured results to the maximum possible emissions, both on a per unit energy basis. Using an energy-specific basis for comparison accounts for differences in energy, ash, and moisture contents in the different coals. An estimate of the maximum possible emissions of metals exiting the stack is based on an assumption that 100% of the metals' mass passes through the combustor to the stack. This assumption is extremely simplified, but such calculations can provide a benchmark against which measured metal emissions can be compared. On a per unit energy basis, the maximum theoretical metal emissions (or the calculated emissions) can be determined by dividing the trace element concentration of the raw coal by the energy content of the coal, resulting in a maximum emission factor in pounds per trillion (10¹²) Btu or grams per megajoule. The measured emissions factors per unit energy were determined

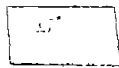
by measuring the total mass of metal in each collected sample and dividing by the total amount of energy input from that test run.

For the calculated emissions, the highest theoretical emissions were found for chromium, lead, manganese, and nickel, with a maximum value of 1.34×10^4 lb/10¹² Btu for manganese from one of the "comparison coals" (coal B2). Cadmium and mercury yielded the lowest of these calculated maximum emissions, with the lowest calculated maximum being 6.41 lb/10¹² Btu for mercury from coal B2. These results are similar to the distribution of metals concentrations in the coals; however, some differences are noted due to the difference in heating values between the coals, which in general increase the emission factors of the western coals W1 and W2 relative to the Illinois coals.

While the metals that were found in the highest concentrations in the coals tended also to result in the highest measured emission factors, there were considerable differences in the measured emission factor results and the as-found concentrations. As was the case for the calculated emissions, the highest measured emissions were for nickel, lead, and chromium, with the maximum measured emission being 2740 lb/10¹² Btu for nickel from coal W1. The lowest measured emissions were from mercury and cadmium, with the minimum being 0.14 lb/10¹² Btu for cadmium from coal B2.

The ratio of measured to calculated emissions of metal HAPs can provide a considerable amount of information. In some cases, the measured emissions may exceed the calculated emissions (which are based on 100% of the metal in the coal exiting the combustor). This can be due to one or more reasons: the measured value of the trace metal content of the coal is in error, and indicates a lower level than is actually present; the measured value of the concentration of the metal in the flue gas is in error, and indicates a higher level than actually present; or both measurements may be correct, but the particular sample of coal used to determine the trace metal content of the coal had a lower than average amount of the particular metal. Because of the low concentrations of trace metals, the accuracy of the measurements can also add to the uncertainty of the final results. However, these sources of error and uncertainty do not remove the usefulness of this ratio. By focusing on consistent results and trends, much can be determined from these values. First, if the ratio of theoretical to measured emissions of a given metal is similar for a wide range of coals, then it is likely that the partitioning behavior of the metal is similar for the different type coals tested, and may therefore be more dependent on the combustion and furnace characteristics than on the coal type or composition.

As noted above, there is some concern that the measurements of cadmium, chromium, lead, manganese, and nickel in coal B2 were higher than the levels actually in the coal. This possibility is strengthened by the very low percentages of those metals that are measured in the stack relative to the rest of the coals. While there is no quantitative evidence from the laboratory



data that the as-received trace metal analyses of coal B2 were faulty, the comparisons of these values with the other cases indicate that these values may not be as reliable as the remaining data.

V. Discussion

To enable a clearer view of how the emissions change between the different coals, both the calculated and measured emissions results are linearly scaled to the maximum value in each respective category, and the two plots are presented side by side. This provides two distributions of emissions, one presenting a relative view of how the emissions from the different coals would be if 100% of the metal were emitted from the stack, and the other presenting the relative view of how the emissions were measured. This enables an immediate comparison of how the emissions of the tested metals are affected by their presence in the different coals. For example, the relative emission levels of nickel change significantly when comparing calculated emissions based on the as-fed trace metal concentration to the measured emissions from the six different coals. On the other hand, the comparison of the scaled calculated and measured emissions for arsenic or the six different coals tested showed relatively little difference in the distributions. This information indicates that the relative levels of emissions from burning the six different coals are roughly the same as the relative levels of arsenic found in the as-received coals.

The data gathered from these plots indicate that the more volatile metals such as mercury and arsenic tend to be emitted in similar ratios for all coal types. However, the more refractory metals such as nickel differ significantly between the different coals, indicating that there are mechanisms that affect the partitioning of these metals that change as the coal characteristics change. This is not a new result, but one that must be re-emphasized as increasing focus is placed on predicting toxic metal emissions using the trace metal content of the coal. The ability to predict how metals behave in combustion systems is currently beyond the state of the art. Therefore, broad statements regarding the behavior of these metals during the combustion of coal cannot be considered accurate in general.

A further comparison can be made to full scale results that used the same coal to evaluate the ability of small scale tests to predict behavior in full scale systems. This was done using one of the test coals, which was taken from a coal pile being used during tests of a prototype pollution control system. The prototype system was tested on a slip stream of flue gases from a full scale utility boiler, and emissions upstream of the pollution control system should accurately reflect the uncontrolled emissions in a manner similar to those measured in the small scale system used in these tests. However, it is reasonable that the uncontrolled pilot scale emissions will be lower than uncontrolled emissions from full scale units, for several reasons: (1) lower gas velocities in the pilot scale compared to full scale units, making it more difficult for particles to remain entrained in the flue gases; (2) a smaller ratio of gas volume to wall surface area in the pilot scale unit, leading to increased condensation of the metals in the flue gas at the small scale; and (3)

tighter gas turns in the pilot scale that are likely to lead to increased amounts of particles being deposited on the walls and removed from the flue gases. These changes should affect the refractory metals to a greater degree than the volatile metals, and lower values were indeed seen in the small scale for chromium and manganese. However, the small scale results also were less for mercury and selenium, indicating other scale-related factors may also play a role. It is important to keep in mind, however, that although the small scale emissions of mercury were six times higher than those in the full scale, there was only a net difference of approximately 200 μg in the total sample collected. This small change in total sample collected highlights the difficulty in drawing significant conclusions based on such small levels of a compound.

VI. Conclusions

The primary conclusion to be drawn from this study is that there are mechanisms and processes that influence the partitioning of metal compounds during the combustion of pulverized coal that are dependent upon the characteristics of the coal being burned. Because these mechanisms are not well understood, particularly in quantifiable ways, the prediction of metal emissions based on the trace metal content of the coal is likely to be inaccurate. While trends can likely be predicted based on changes in trace metal content, quantifying the levels of stack emissions is likely to involve a significant level of uncertainty, even when removal efficiencies of pollution control equipment are well known. These conclusions are especially true for refractory metals. While the results indicate that such predictions are more likely to be adequate for volatile metals, much is yet unknown regarding the behavior of trace metal compounds in pulverized coal combustion systems.

In general, the Illinois coals tended to show higher emissions of arsenic, beryllium, cadmium, lead, and selenium than did the western coals, based on average emission factors (in pounds per trillion Btu). The western coals had higher average emissions of chromium, manganese, and nickel than did the Illinois coals. Antimony and mercury emissions were similar for both Illinois and western coals. Because of the limited number of tests, these results cannot be used to make a general conclusion that Illinois coals are higher emitters of air toxics than western coals. The differences in trace element content and combustion behavior of those elements are not well enough quantified to generate such conclusions based on the results of these tests. The use of a small scale combustor also introduces a measure of uncertainty into how these results can be compared at full scale.

Based on comparisons of the highest measured emissions from DOE field tests, the full scale emissions tend to be lower than the small scale results, with the exception of mercury. In the case of mercury, the highest measured emission from a full scale unit was higher than any of the small scale emissions. No information was given regarding the coal origin or sulfur content in the DOE field data, making it impossible to compare emissions based on these categories.

Additional comparisons between full scale and small scale emissions were made based on a series of full scale tests using a coal which was also used in this study. In this case, full scale measurements upstream of any pollution control equipment showed emissions of manganese, nickel, and selenium to be 30-50% lower for the small scale than for the full scale, with the remaining emissions being similar between the two tests.

In general, there is no clear correlation between small scale and full scale results. However, with the exception of manganese, nickel, and selenium, there was relatively good correlation between the two tests, and trends seen in the small scale tests are expected to be similar to trends from the full scale testing, to the degree that similar changes in coals are made. It must be kept in mind that the most common generalization that has been noted in testing of air toxics emissions is that there is significant scattering of results even for repeat tests at a single site using a single coal. The degree of variability in the trace element contents and the operating characteristics of any particular unit make it extremely difficult to obtain repeatable data over any period of time, and discrete data points must be compared with caution.

I. Introduction

In 1990, the Clean Air Act Amendments of 1990¹ (CAAAAs) were passed into law, resulting in lowering the emission limits for the acid rain precursor gases of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) from existing utility sources, with the intent of significantly lowering emissions of these pollutants on a national scale. In addition to addressing emissions of the traditional criteria pollutants such as SO₂, NO_x, and carbon monoxide (CO), Title III of the CAAAs also placed emission limits on a list of 189 distinct compounds and compound classes defined in the Act as hazardous air pollutants (HAPs), and which are released by a wide variety of sources.

While electric utility steam generating units were not made immediately subject to the requirements of Title III, the CAAAs mandated that the Environmental Protection Agency (EPA) conduct a study to quantify the risks to human health posed by utility emissions of HAPs, and placed the responsibility on the EPA Administrator of determining the regulatory status of utilities based on the findings of that study.¹ This study is now being conducted by EPA's Office of Air Quality Planning and Standards (OAQPS) with inputs from other government agencies and industry groups. The CAAAs also required EPA to conduct a study on the health and environmental effects of mercury from all sources, plus a study of the effects of atmospheric deposition of all pollutants to the Great Lakes, Chesapeake Bay, Lake Champlain, and coastal waters on human health and the environment. A further study by the Electric Power Research Institute (EPRI) has been underway to quantify the emissions of a limited number of HAPs under their Power Plant Integrated Systems: Chemical Emissions Study (PISCES) through a review of the existing literature and other data sources as well as a program of field testing at a number of operating power generating sites.^{2,3} The result of these legislative requirements and industry efforts has been to significantly increase attention regarding HAP emissions from utility sources, and to emphasize the shortage of quality data available to address these concerns.

Because HAPs from utility sources have not been subject to regulation in the past, the quantity of information regarding HAP emissions from coal is limited, resulting in large uncertainties for utilities considering the potential advantages and disadvantages of fuel switching as an SO₂ control strategy. Fuel switching is one SO₂ reduction option which is being considered by a number of utilities as a means of reducing emissions. In this strategy, coals with a lower sulfur content (found in the U.S. primarily in the western part of the country) would be used rather than higher sulfur coals common to the eastern U.S. The use of the low sulfur coals would eliminate or reduce the requirement of flue gas cleaning equipment such as wet scrubbers in order to meet the lower emission limits. It has been suggested that an increased use of western

coals because of fuel switching may lead to higher uncontrolled emissions of HAPs.⁴ With the regulatory status of HAP emissions from utility sources yet to be determined, a thorough evaluation of potential SO₂ control strategies should also address the impacts of those approaches on HAP emissions. For example, as part of the OAQPS study on HAP emissions from utilities, trace metal contents of high, medium, and low sulfur coals are being evaluated to provide information concerning the effects of fuel switching on the metal HAP emissions.

Although evaluating the trace metal contents of different coals can provide valuable information about the potential for metal HAP emissions, it is difficult to accurately predict actual stack emissions of metal HAPs due to the complex behavior of metals in combustion systems. The assumption that a fixed percentage of a metal will be emitted from the stack based only on data from a limited set of emissions tests may not be valid for the full operating range of the unit, for other plants of similar design, or from different coals. Such an assumption in some cases may provide order of magnitude accuracy; however, changes in furnace design, fuel, or operating conditions can have a significant impact on the percentage of the as-fed coal which is ultimately emitted from the stack of a particular unit. Therefore an examination of how toxic metal emissions are related to the concentrations of those metals in coal under controlled conditions is very important. In order to conduct such an evaluation, the Illinois Clean Coal Institute (ICCI) entered into a cooperative research agreement with EPA's National Risk Management Research Laboratory, Air Pollution Prevention and Control Division (formerly the Air and Energy Engineering Research Laboratory) to evaluate the differences in HAP emissions from the combustion of pulverized coals of different geographic origin in a single small-scale test combustor. These tests were designed to focus on the emissions of metal HAPs, as coals from different regions tend to show relatively large variations in their contents of such metals; while variations in energy content and volatility may affect organic HAP emissions, it was felt that the effect of changing coals would have a larger impact on the metals emissions. Therefore, a series of combustion tests designed to provide information on the emissions of metal HAPs was performed at AEERL, located at EPA's Environmental Research Center in Research Triangle Park, NC.

II. Metal Emissions from the Combustion of Pulverized Coal

Coal naturally contains a variety of different metal compounds, and the combustion of pulverized coal results in the release of those compounds from the coal into the combustion environment. Unlike organic compounds, which can be chemically broken down into more basic and nonhazardous constituents, metal compounds are not chemically transformed by the combustion process to the degree that they lose their toxic nature. In this respect, organic

compounds are analagous to NO_x , which is primarily controlled via combustion process modifications, while metal compounds find their analog in SO_2 , where the control focus shifts to the fuel properties and post-combustion flue gas treatment. As with sulfur, there is no breakdown of the metals during the combustion process. Therefore the total mass of metal entering the furnace in the coal is the same as the mass of metal exiting the boiler, whether via the stack or other routes.

A. Partitioning and Enrichment

When a metal compound is introduced into a combustion environment due to its presence in the fuel, it may exit the furnace or combustor via several pathways. The metal may exit the combustor via the slag, bottom ash, or other furnace ash, or it may pass completely through the combustor with the combustion gases. The major entrance and exit paths that metal compounds may take through a pulverized coal boiler are shown in Figure 1. The metals that are retained in the slag or bottom ash or are removed by the pollution control equipment may be of concern from the perspective of solid or liquid waste disposal. However, investigation of solid or liquid effluents containing toxic metal compounds is beyond the scope of this study; the emphasis here is on the emissions of metal hazardous air pollutants.

The percentages of the input metal exiting through these various waste streams are referred to as the *partitioning* behavior of the metal; in general, different metals exhibit different partitioning behavior. Of specific concern here are metals which exit the combustor with the flue gases, since these may result in emissions into the atmosphere if adequate pollution control strategies have not been implemented. The metals which pass through the combustion process may take one or more physical forms: a metal vapor; an aerosol* composed of small particles; in condensed form on larger, solid-phase particles entrained in the flue gases; or as a combination of the three. In many instances, one or more of the effluent streams will exhibit a concentration of a given metal that is higher than would be expected if the metal were evenly distributed among all the various streams. This behavior is known as *enrichment* of that particular stream by that metal.

The different exit paths that a metal may take are determined by complex physical and chemical processes which occur during the combustion of the fuel and the flow of the flue gases through the unit.⁵ Thermodynamic properties of the metal, combustion temperature, presence of other compounds, flue gas velocities, and the physical means by which the metal is bound in the coal are among the factors which can affect the ways a metal will be partitioned to the different

* An aerosol is defined as a distribution of particles suspended in a gas. Aerosols may be composed of a combination of large (supermicron) and small (submicron) particles, or either of the two individually. Aerosol particles can be either solid or liquid, or a combination of both.

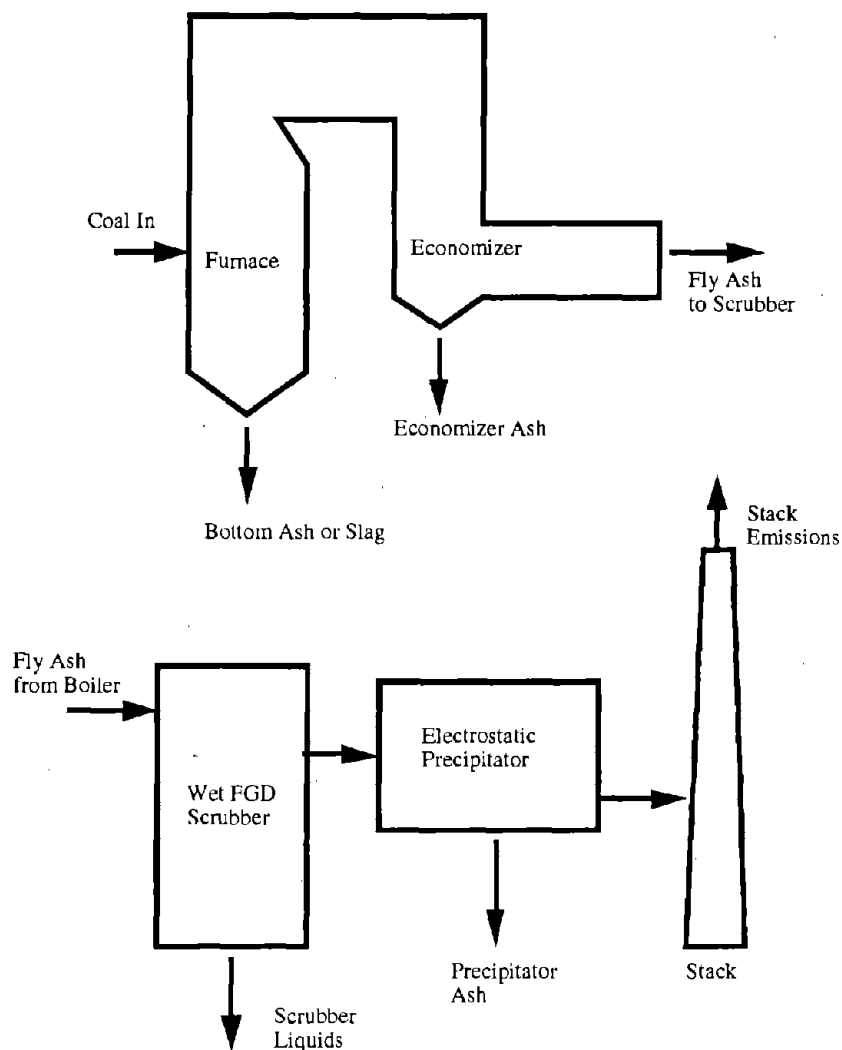


Figure 1. Potential pathways of metal compounds through a utility boiler and air pollution control systems.

combustor exit streams. A number of studies have been conducted to determine the partitioning behavior of different metals,[†] with the finding that some metals tend to partition toward the submicron aerosol form.⁶⁻¹¹

This “submicron enrichment” results in higher levels of the metal being present in the stack as a submicron aerosol than would be expected if that metal were to exit the unit via all possible waste streams in a percentage identical to its percentage of the input fuel. Because of this enrichment process, and the less efficient removal efficiencies of particulate control equipment for these smaller particles, for some metals the total mass of that metal in the form of a

[†]A comprehensive list of references on the subject of the partitioning behavior of different metals in combustion systems can be found in Reference 5.

submicron aerosol may be on the same order as the total mass of the metal condensed on particulate material of supermicron size.¹² Table 1 shows the enrichment behavior of several metals; arsenic, antimony, cadmium, chromium, lead, mercury nickel, and selenium are seen to be metals which tend to be enriched in the submicron particulate fraction, making them more difficult to control.

Table 1. Submicron flyash elemental enrichment in coal combustion investigations (adapted from Reference 5).

Source	Submicron enriched	No enrichment trend	Submicron depleted
Ref. 6	Sb, As, Cd, Cr, Pb, Ni, Se, S, Tl, Zn	Al, Be, C, Fe, Mg, Mn, Si, V	Bi, Ca, Co, Cu, K, Sn, Ti
Ref. 7	Sb, As, Cu, Pb, Mo, Po, Se, Zn	Al, Fe, Nb, Rb, Sr, Y	
Ref. 8(a)	As, Cu, Cr, Ga, Ge, Pb, Mo, Ni, Se, Sn, V, Zn	Al, Ba, Ca, Ce, Fe, La, Mn, Nb, K, Rb, Si, Sr, Ti, Y, Zr	
Ref. 9(b)	Sb, As, Cd, Pb, Mo, Se, W, Zn	Ba ^(c) , Cr, Co, Ni, Mn, Na, Sr, V	Al ^(d) , Ca, Ce, Hf, Fe, Mg, K, Si, Ti
Ref. 10	As, Pb, K, Na, Zn	Al, Ca, Fe, Mg, Mn, Si, Ti	
Ref. 11	Ca, Cd, Cu, Pb, Sr, S, V	Al, Fe, Mg, Mn, Na, Si, Ti, Zn	
Ref. 12	Sb, As, Cd, Cr, Ni, Rb, Se, V, Zn	Fe, Ti	Al, Hf, Mg, Mn, Ta

^aSpecies As, Br, Cl, I, Hg, Se in vapor phase, high filter penetration.

^bLiterature review.

^cSlight enrichment or no change.

^dNo change or slight depletion.

The enrichment process is influenced by a number of factors. One of these is the physico-chemical environment into which the metals are released during the combustion process. As the temperature increases, a higher fraction of bound metals susceptible to submicron enrichment will be released as vapor into the combustion gases. The actual fraction is highly dependent upon the equilibrium vapor pressure of each metal, which in turn may vary due to the presence of other compounds. Further, the composition of the gases, including the presence of particulates, will strongly determine the final form the metal vapors take; for example, the lack of available oxygen will limit the formation of metal oxides, resulting in higher levels of pure metal aerosol. In addition, the presence of chlorine has been shown to have a strong influence on the equilibrium behavior of metal vapors, which can result in significant differences in the size distribution of the metal aerosols.⁵ Because of these complex interacting influences, the approach of estimating metal emissions only from the original trace metal content of the fuel is highly simplified. This is because a number of variables may strongly affect the form each metal takes as it exits the combustion zone in addition to affecting the size distribution of the metal

aerosols and condensed metals on particulate matter. Thus, changes in the combustion environment or changes in fuel properties (aside from trace metal content) can lead to significant changes in the ability of pollution control equipment to remove metal compounds from the gas stream.

B. Trace Metals in Coal

Metals exist in pulverized coal in three ways: as included mineral matter, which is present in inorganic forms trapped as crystalline or glassy structures throughout the fuel particles; as inherent mineral matter chemically bound as individual atoms within the coal organic matrix; and as excluded mineral matter which is composed of particles distinct and separate from the majority of fuel particles containing the combustible fraction, and which, originally having been included mineral matter, are either released during the grinding process or have their origins in the overburden added through the mining/transportation process. It has been found that the inherent ash content is important in determining the likelihood of a coal to produce submicron ash particles (particles which are less than 1 μm in diameter) during the combustion process.⁵

Of these, it is much more difficult to control metal aerosol and vapor emissions than metals condensed on the particulate. This is because the metal aerosols are typically much smaller in size than the particulate matter which act as nuclei for condensation of the metal vapors. The metals in aerosol form are often less than 1 μm in diameter (often referred to as submicron particles), and most commercially installed pollution control equipment is less efficient in removal of these small particles, with removal efficiencies in the range of 80-97%, versus greater than 99% for larger particles (those over 1 μm in diameter, or supermicron particles). A study of five full-scale electrostatic precipitators (ESPs) found moderate to high particulate removal rates for particles larger than a few micrometers or smaller than a few hundredths of a micrometer in diameter, while minimum removal efficiencies were found to occur for particles of a few tenths of a micrometers in diameter.¹³ A more recent study presented removal efficiency curves for venturi scrubbers, high efficiency particulate air filters, and ESPs.^{14,15} For all three types of equipment, the minimum collection efficiency occurred for submicron particles, with minima at different sizes for the three device types. Therefore, although the submicron particle fraction may not comprise the majority of the particulate entering the pollution control system, it may account for the largest fraction of toxic metal emissions from the stack.

In summary, the emissions of metals from the combustion depend not only upon the content of the metals in the coal, but also upon a variety of other factors. These include, but are not limited to, how the metals are found in the coal, the presence of other elements (both functions of the particular coal of interest), the preparation of the coal prior to its use as a fuel, the thermal

conditions to which the metals are exposed, and the particulate control system efficiency over the entire range of particle sizes (functions of the design and operation of the combustion and pollution control systems). For these reasons it is important to measure actual emissions from different coals under the same combustion environment to isolate the effects of changes in coal properties on metal emissions.

III. Project Description

A. Facility and Equipment

EPA's Air Pollution Prevention and Control Division of the National Risk Management Research Laboratory, located in Research Triangle Park, NC, has conducted a wide variety of research on air pollution control technologies. As part of this research, a number of research combustors have been constructed, some of which are capable of firing pulverized coal at relatively low rates, but which are also capable of reasonably simulating combustion conditions typical of full scale coal combustion systems. One of these units, the Innovative Furnace Reactor (IFR), was utilized for the experiments reported here.

The IFR is a down-fired refractory-lined furnace rated at 29.3 kW (100,000 Btu/hr), and is capable of firing natural gas, fuel oil, or pulverized coal. A schematic of the IFR is shown in Figure 2. The furnace has a number of access ports along the vertical length of the unit which can be used for sampling probes, injection of additional fuel or air for staged combustion tests, or injection of sorbents for pollution control. A horizontal section at the bottom of the vertical section (labelled as the Flue Gas Sampling Section in Figure 2) is used to sample flue gases downstream of the combustion zone, and provides adequate length for isokinetic sampling. For the current series of tests, a smaller diameter horizontal duct was installed in order to increase the flow velocity and the total amount of flue gas collected. The inside diameter of the vertical furnace section is 15.2 cm (6 in), with a 10.2 cm (4 in) diameter horizontal sampling duct. The length of the vertical combustion section is 4.57 m (15 ft). The flue gas cleaning system for the IFR consists of a wet packed-bed scrubber for removal of acid gases, and a pulse-jet baghouse for particulate emissions control.

The burner utilized for combustion of pulverized coal is specially designed for use in conjunction with the IFR. A schematic view of the burner is presented in Figure 3. The burner is of a variable-swirl design, providing adjustment of the axial air to tangential air ratio as a means of changing the flame shape. For this series of tests, a flame with high swirl was used. The coal is fed into a primary hopper by a screw feeder, from which it is pneumatically fed into

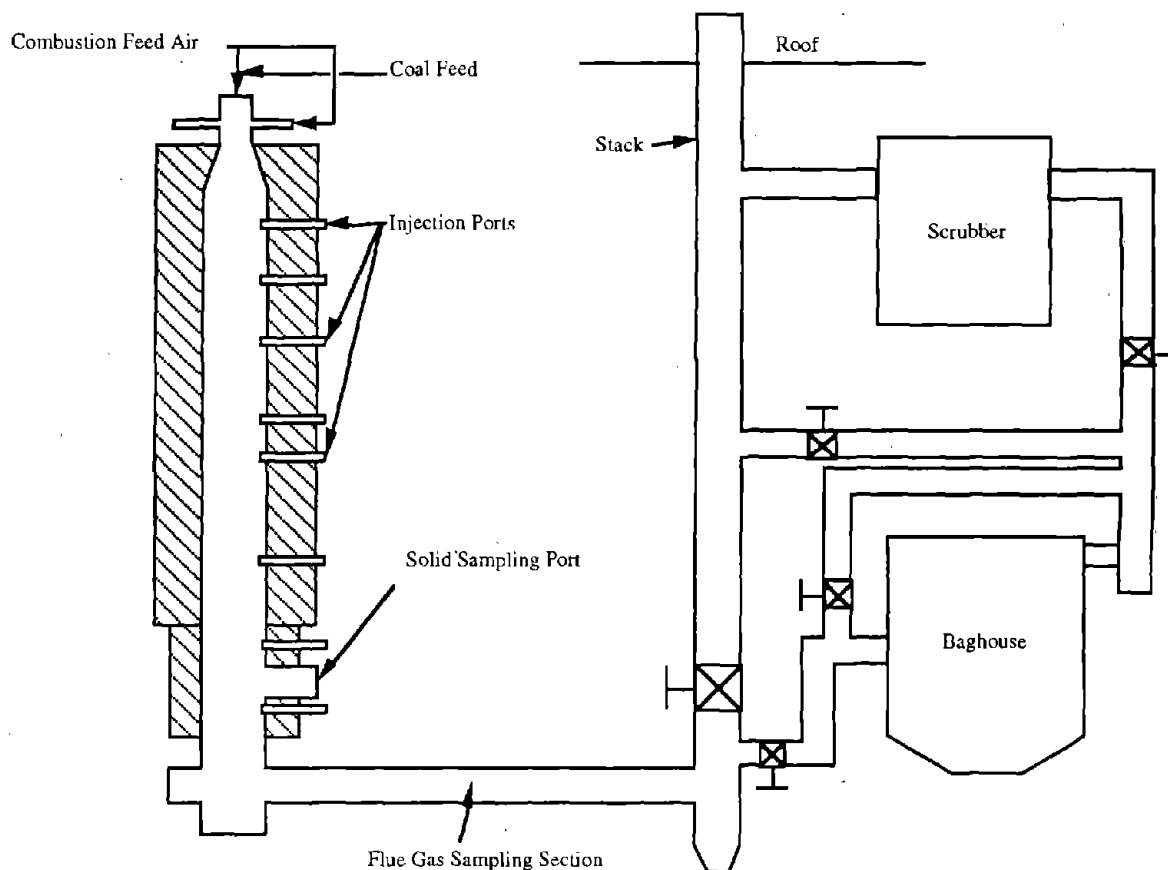


Figure 2. Schematic of Innovative Furnace Reactor.

the burner through the central axial burner port. The axial tip was used in the coal/primary air port during this series of tests.

Continuous emission monitors (CEMs) were used to provide continuous readings and records of the levels of CO, NO_x, SO₂, oxygen (O₂), and carbon dioxide (CO₂). These values were used for evaluation of the combustion process as well as determination of pollutant levels. The location of the monitor probes is shown in Figure 4.

B. Experimental Approach

Six different bituminous coals were tested during the test program. The coals were chosen for specific reasons to evaluate the potential differences in emissions of toxic metal compounds. Two Illinois coals (Illinois #5 and Illinois #6, referred to here as I1 and I2, respectively), two western coals (referred to as W1 and W2), and two other coals (designated B1 and B2). Coals B1 and B2 were used in other air toxics test programs; B1 was used in a small scale test at Battelle that was designed to mimic load changes in a full scale unit, and B2 was used in actual

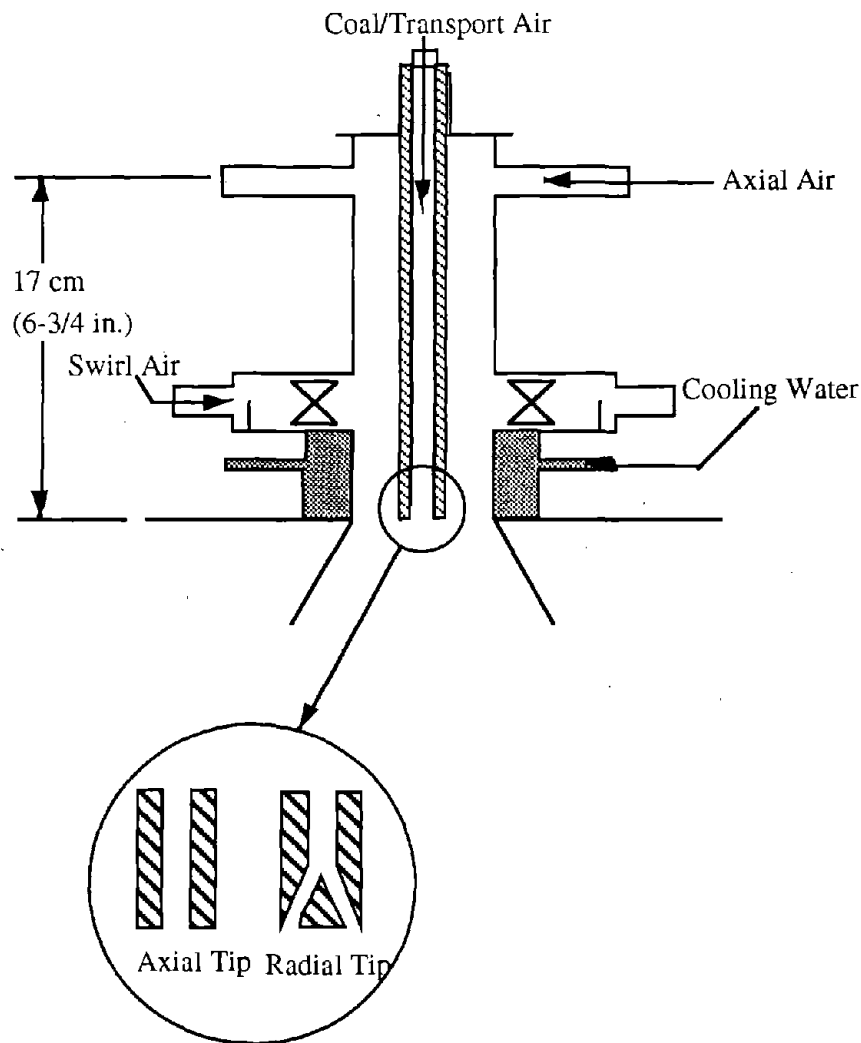


Figure 3. Schematic of coal burner used on IFR.

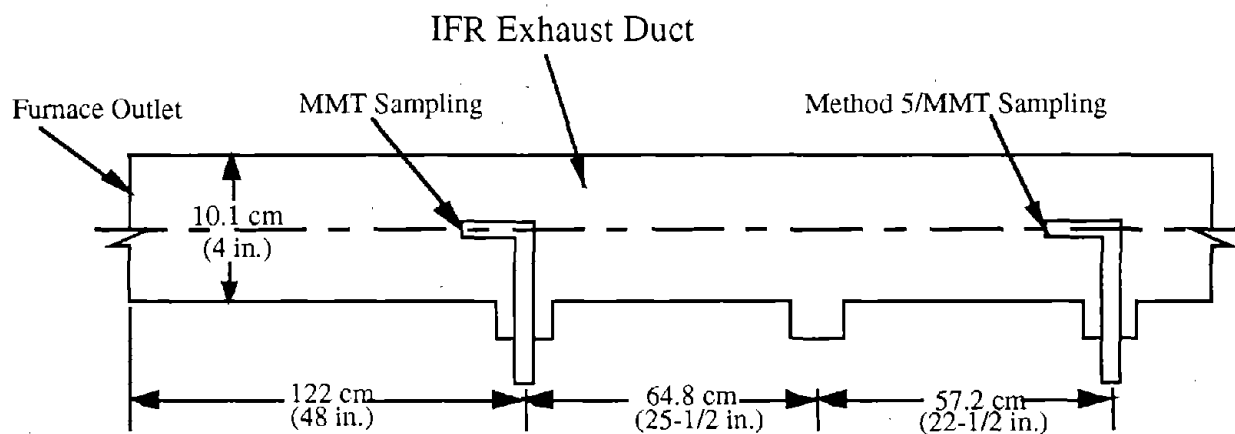


Figure 4. Schematic of the IFR exhaust duct showing sampling locations. Shown are the locations of the multi-metals train (MMT) sample probe and the Method 5 (M5) probe. The duct diameter is not drawn to the same scale as the length.

full scale testing of air toxics emissions by Babcock & Wilcox. The results from these two tests have not yet been published.

Coals I1 and I2 were higher in sulfur than W1 and W2, and represent the "high sulfur" cases, with coals W1 and W2 representing the "low sulfur" cases. B1 and B2 were used to provide a comparison to other tests that used the same coals as a measure of compatibility of test results. Tables 2 and 3 present the proximate and ultimate analyses of these six coals, respectively, and the concentrations of trace metals are shown in Table 4 and plotted in Figure 5. The concentration of manganese in coal B2 was the highest of any of the trace elements. Concentrations of antimony and cadmium were at the detection limit of the analysis methods for all coals, except for the cadmium concentration of coal B2. In general, the metal concentrations of coals I1 and I2 were greater than for coals W1 and W2, with the exception of manganese, which was higher in coal W1 than for either I1 or I2. Trace metal concentrations for coal B2 were generally the highest of all the coals tested, except for arsenic, beryllium, and mercury, in which cases coal B1 had the maximum concentrations. In the case of mercury, B2 showed the lowest concentration of the six coals.

Table 2. As-received proximate analysis of the six coals used in the combustion tests.

	I1	I2	W1	W2	B1	B2
Moisture	4.01%	6.48%	20.22%	18.50%	1.90%	2.08%
Volatile Matter	33.64%	33.65%	35.34%	35.22%	32.97%	37.02%
Fixed Carbon	53.44%	51.46%	36.87%	39.72%	52.62%	49.24%
Ash	8.91%	8.41%	7.57%	6.56%	12.51%	11.66%
Heat Content, Btu/lb	12831	12128	9033	9623	12501	12483

Table 3. Dry proximate and ultimate analyses of the six coals used in the combustion tests.

	I1	I2	W1	W2	B1	B2
Volatile Matter	35.05%	35.98%	44.30%	43.22%	33.61%	37.81%
Fixed Carbon	55.67%	55.03%	46.21%	48.73%	53.64%	50.28%
Ash	9.28%	8.99%	9.49%	8.05%	12.75%	11.91%
Heat Content, Btu/lb	13367	12968	11322	11807	12743	12748
Carbon	74.53%	71.79%	66.04%	69.53%	71.42%	70.74%
Hydrogen	5.01%	4.97%	4.77%	4.70%	4.84%	4.95%
Nitrogen	1.67%	1.51%	1.18%	1.03%	1.44%	1.29%
Sulfur	1.51%	2.95%	0.47%	0.67%	2.43%	3.79%
Oxygen (a)	8.00%	9.79%	18.05%	16.02%	7.30%	7.32%

(a) Oxygen content is calculated by difference.

The concentrations of cadmium, chromium, lead, manganese, and nickel in coal B2 were much higher than expected, and there is some concern that these values may not accurately reflect the levels of metal that were actually in the coal. Unfortunately, the remainder of the coal sample was combusted prior to the receipt of the final results, making additional analysis of the coal sample impossible. The potential for the as-received concentrations to be higher than the actual case should be considered when evaluating the results in the following section.

Each of the coals was burned in the IFR under conditions chosen to most closely simulate the combustion of pulverized coal in a typical utility boiler. A stoichiometric ratio of 1.25 (i.e. 25% excess air) was chosen to provide a stable flame and relatively low CO and NO_x values at the

Table 4. Trace metal concentrations for the four coals used in the combustion tests. All concentrations are given in $\mu\text{g/g}$ (10^{-6} lb/lb), on a dry basis.

	I1	I2	W1	W2	B1	B2
Antimony	1	< 1	< 1	< 1	< 1	< 1
Arsenic	6	4	1	2	15	4
Beryllium	0.9	1.3	0.2	0.2	2	0.8
Cadmium	< 0.2	< 0.2	< 0.2	< 0.2	0.2	4
Chromium	21	20	17	5	18	47
Lead	21	36	3	3	14	50
Manganese	12	19	9	21	30	167
Mercury	0.10	0.15	0.09	0.10	0.33	0.08
Nickel	53	18	42	3	15	70
Selenium	2	1	< 1	1	3	3

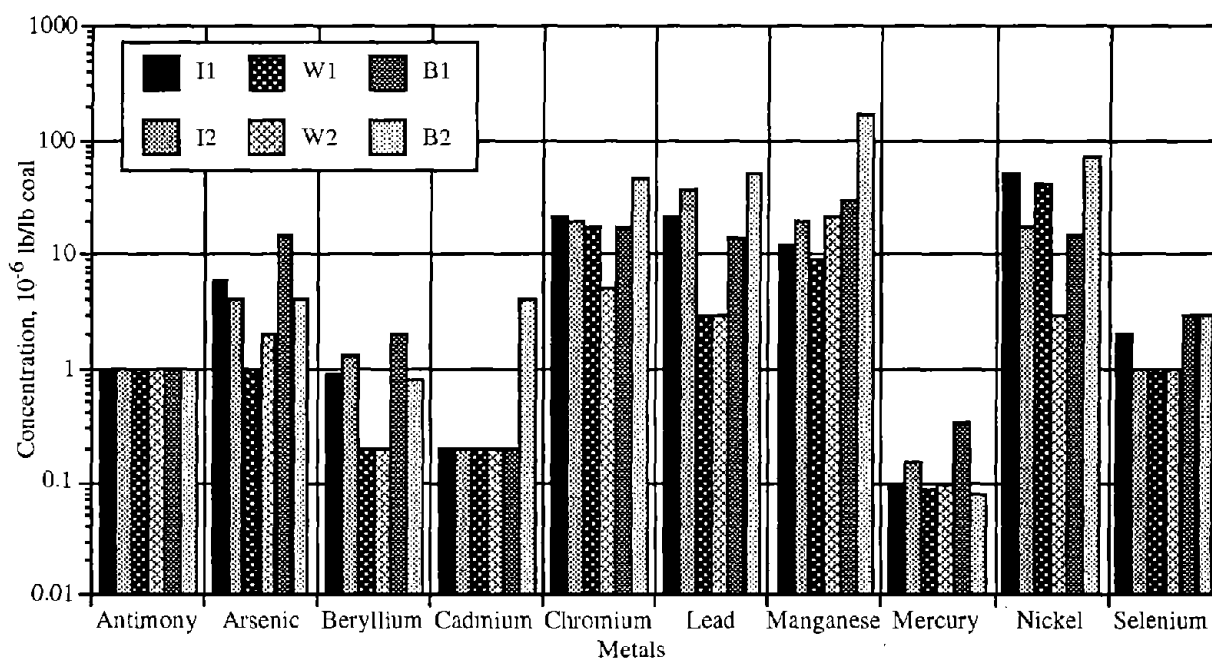


Figure 5. Concentrations of trace metals in as-fed coal for the six coals tested.

test firing rate of approximately 13.2 kW (45,000 Btu/hr). While the actual time-temperature history of the IFR is not the same as a full-scale unit, the combustion zone temperatures are quite similar, providing conditions for metal release and formation of metal aerosols similar to full-scale.

C. Sampling and Analysis

The metals emissions were collected using the Multiple Metals sampling train (MMT),¹⁶ and mercury emissions using the Method 101A sampling train.¹⁷ Sampling ports were installed in the horizontal section at locations specifically determined for the conditions expected for this series of experiments. Emissions samples were collected simultaneously at two different axial locations. These locations were located according to isokinetic sampling requirements, given the duct size and flue gas velocity for these tests. This ability allowed the particulate to be collected without excessive fluid influence on the particle stream from the duct walls, entrance, or exit. Sampling locations are shown in Figure 4. Note that all samples were collected upstream of any pollution control equipment. This was done to provide data that would be applicable to all systems firing pulverized coal; collection efficiencies of various pollution control equipment can then be used to estimate emissions from a wide range of full scale systems.

The collected samples were then analyzed in accordance with the respective EPA analytical methods.^{16,17} The MMT does provide for simultaneous sampling of all the metals listed in Table 3; however, this procedure must be done with care when both mercury and manganese measurements are required. Individually, mercury can be collected using Method 101A or by the MMT. In both methods, mercury is captured using a permanganate solution. Even though the mercury capture and analysis procedures are identical in both trains, the permanganate solution can alter measured manganese concentrations through glassware contamination. However, it was desirable to use only a single sampling train, and the first series of tests included mercury sampling and analysis using the MMT. This initial series included all test runs for I1, I2, and W1 coals, and one run using W2. The remaining tests were conducted as the additional coals were received, and in these tests, mercury was collected using a separate train (i.e., a Method 101A train).

D. Quality Assurance and Quality Control

Several steps were taken to maintain data quality. The project was conducted following an EPA-approved Quality Assurance (QA) Project Plan, using AEERL QA Level IV. QA/QC requirements apply to this project. Data are supported by QA/QC documentation as required by the U.S. EPA's QA policy. Although Level IV is the least stringent QA level for AEERL experimental projects, the measurement, sampling, and analytical work incorporated several

procedures designed to ensure data quality at a higher QA level. CEMs were calibrated before and after each test run to check zero and span. Samples were collected in complete accordance with EPA method guidelines. These methods include measures for leak checks, isokinetic sample collection, and sample custody records. Duplicate samples were collected for each sampling and analytical method, and field and method blanks were also used to evaluate potential contamination during sampling and analysis. Since the data were not intended to be used for regulatory purposes or enforcement, more stringent QA procedures were not deemed to be necessary. However, the sampling and analysis procedures followed during the testing were identical to those that are required under more stringent QA plans.

With the exception of W2 test number 2, all samples were collected within 85% of isokinetic conditions. The major problem affecting data quality was the contamination of one sample with permanganate solution during the sampling process. Extremely high levels of manganese were found in this sample (W2 test number 1) resulting from permanganate contamination, and this value was not included in the data used to calculate emissions. Analysis of the field/method blank yielded detectable concentrations for antimony, cadmium, and manganese, with levels of all other metals (including mercury) below the method detection limits. In the cases of antimony and cadmium, the quantities detected in the blank were at least one order of magnitude less than the lowest value measured in the samples. The amount of manganese in the blank was, however, of the same order of magnitude as found in the test samples, although all test samples were higher than the blank. The conclusion drawn from these results was that the analyses of all metals except manganese correctly indicated the levels of metal compounds sampled from the flue gases. For manganese, the reported levels are (at worst) higher than actually present in the gases, but are of the same order of magnitude.

IV. Results

Rather than focusing only on the measured emissions data, it is more useful to compare the measured results to the maximum possible emissions. It is a relatively straightforward calculation to estimate the maximum possible emissions of metals exiting the stack by assuming that none of the metals' mass remains in the combustor as slag or bottom ash, or is collected in the flue gas cleaning systems. This assumption is extremely simplified, and does not accurately reflect the true behavior of metals in either small scale or full scale coal combustion systems. However, such calculations do provide a benchmark against which measured metal emissions can be compared. Because the primary goal of the study was to evaluate the differences in toxic metal emissions between different coals, it is necessary to consider the basis on which such comparisons are made. While a direct comparison of flue gas concentrations is of some interest,

it is in this case much more informative to evaluate emissions based on equivalent energy inputs to the combustor. Using an energy-specific basis for comparison accounts for differences in energy, ash, and moisture contents in the different coals.

On a per unit energy basis, the maximum theoretical metal emissions can be determined by merely dividing the trace element concentration by the energy content of the coal. This provides a maximum emission factor in grams per megajoule (or pounds per trillion [10^{12}] Btu). The measured emissions factors per unit energy were determined by measuring the total mass of metal in each collected sample and dividing by the total amount of energy input from that sample's coal. It is expected that the measured values will be lower than the theoretical maximum values for several reasons. The primary reason is that a portion of each metal will exit the combustor via pathways other than out the stack as discussed earlier. A second reason is that the measurements of metals in the flue gas stream are taken over a considerable period of time, effectively integrating out short-term fluctuations in the concentration of a particular compound. The measurements of trace metals in the coal, however, are based on discrete samples of the coal. Because of the heterogeneous nature of coal, the possibility of significant fluctuations in the trace element concentrations is likely, leading to corresponding fluctuations in the calculated emissions (this could also lead to values of the measured emissions being higher, rather than lower, than the calculated emissions). Finally, the concentrations of these metals in both the coal and in the flue gases are typically very low. In some cases, the concentration of a particular metal in either the coal or the flue gas may be below the method detection level. In these instances, the only assumptions that can reasonably be made are that the actual concentration is either at the detection level (the maximum possible concentration) or at zero concentration (the minimum possible concentration). Assuming either of these values introduces further, and often significant, uncertainty into the calculations.

A. Calculated Emissions

The theoretical maximum calculated emission factors (hereafter referred to as the calculated emission factors) for each of the metals analyzed are presented in Table 5 for the six coals tested, in pounds per trillion (10^{12}) Btu, and are shown graphically in Figure 6. In general, the calculated emission factors follow the trends shown in Figure 5, as would be expected. As noted above, this calculation assumes 100% of the metal entering via the coal will exit the combustor, either in condensed form on the fly ash or in the vapor phase. The highest calculated emissions were for nickel, lead, and chromium, with a maximum value of 1.34×10^4 lb/ 10^{12} Btu for manganese from coal B2. The lowest calculated emissions were for mercury and cadmium, with the minimum emission being 6.41 lb/ 10^{12} Btu for mercury, also from coal B2. These results are similar to the distribution of metals concentrations in the coals; however, some differences are

noted due to the difference in heating values between the coals, which in general increase the emission factors of the western coals W1 and W2 relative to the Illinois coals.

The calculated emissions are based upon the as-received concentrations in the coals, and as noted above, the values reported for the trace concentrations in coal B2 seemed high relative to the rest of the coals. This results in high values for the calculated emissions, and alters the

Table 5. Maximum calculated trace metal emissions in lb/10¹² Btu. Values are calculated based on as-received metal and Btu contents of the coal. The calculated values assume 100% of the metal in the coal will pass through the combustor to the stack.

	I1	I2	W1	W2	B1	B2
Antimony	75	77	88	85	78	78
Arsenic	449	308	88	169	1177	314
Beryllium	67	100	18	17	157	63
Cadmium	15	15	18	17	16	314
Chromium	1571	1542	1501	423	1413	3687
Lead	1571	2776	265	254	1099	3922
Manganese	898	1465	795	1779	2354	13100
Mercury	7	12	8	8	26	6
Nickel	3965	1388	3709	254	1177	5491
Selenium	150	77	88	85	235	235

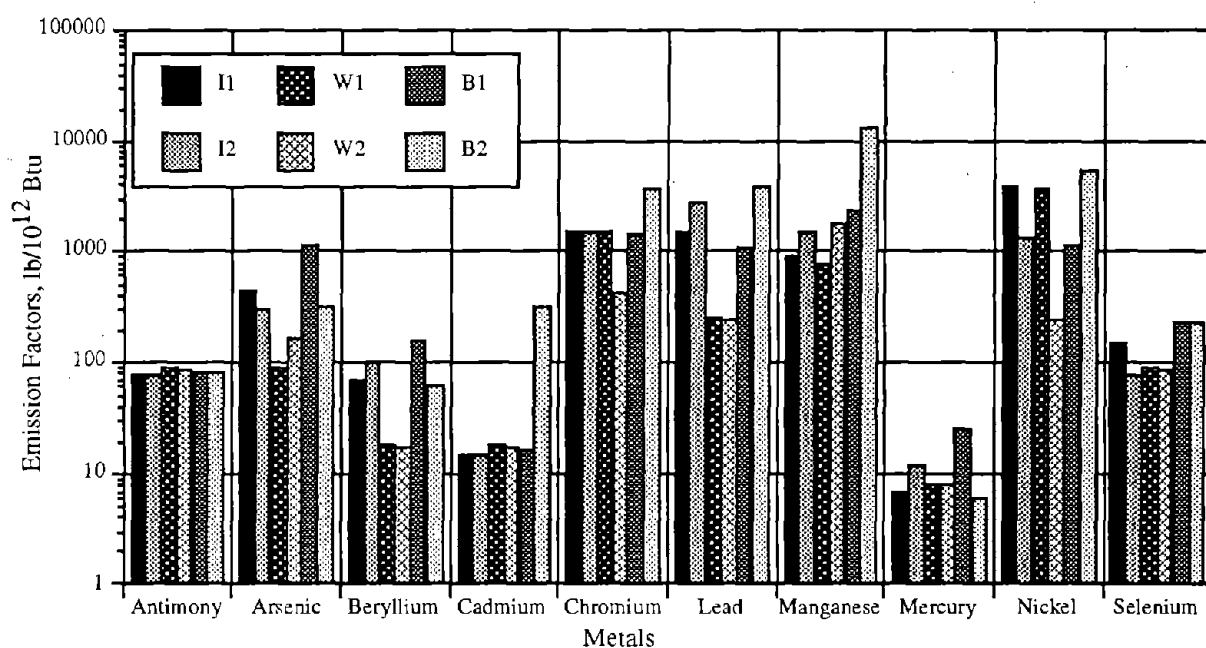


Figure 6. Maximum calculated emission factors for the six coals tested.

relative comparisons between calculated and measured emissions. This must be kept in mind when evaluating the comparative results presented below.

B. Measured Emissions

The measured uncontrolled emission factors (hereafter referred to as the measured emission factors) of each of the metals of interest are tabulated in Table 6 for the six coals tested, in pounds per trillion (10^{12}) Btu, and are presented graphically in Figure 7. In contrast to the similarity between the as-fed trace element concentrations and the calculated emission factors, Figure 7 shows significant differences in the emission factors compared to the as-fed concentrations. While the metals that were found in the highest concentrations in the coals tend also to result in the highest measured emission factors, there are considerable differences in the measured emission factor results and the as-found concentrations.

As was the case for the calculated emissions, the highest measured emissions were for nickel, lead, and chromium. The maximum measured emission was 2740 lb/ 10^{12} Btu for nickel from W1. In some cases, the measured value exceeds the maximum calculated emission factor. However, as mentioned above, this occurrence is not uncommon; this problem will be discussed further in the following section. The lowest measured emissions were from mercury and cadmium, with the minimum being 0.14 lb/ 10^{12} Btu for cadmium from coal B2. It is interesting to note that, based on the concentration of metal found in the coal, it would be expected that coal B2 would have the highest cadmium emission factor, rather than the lowest. In several other instances as well, the calculated emission factors based on the trace metal concentrations in the coals seem to have a very weak relationship to the measured emission factors, highlighting the differences in the coals' trace metal contents and the metals emissions resulting from the combustion of those coals.

Table 6. Measured trace metal emissions in lb/ 10^{12} Btu.

	I1	I2	W1	W2	B1	B2
Antimony	19.7	35.7	29.2	23.5	20.1	6.72
Arsenic	419	329	126	229	666	275
Beryllium	35.2	68.9	15.7	25.8	31.4	11.8
Cadmium	3.96	13.9	3.77	5.28	2.58	1.36
Chromium	545	957	1150	743	254	199
Lead	707	1310	152	132	192	107
Manganese	408	685	655	712	394	216
Mercury	3.20	7.02	3.62	5.78	6.15	1.55
Nickel	1210	1650	2740	1378	286	167
Selenium	51.9	65.2	22.5	25.2	92.9	52.6

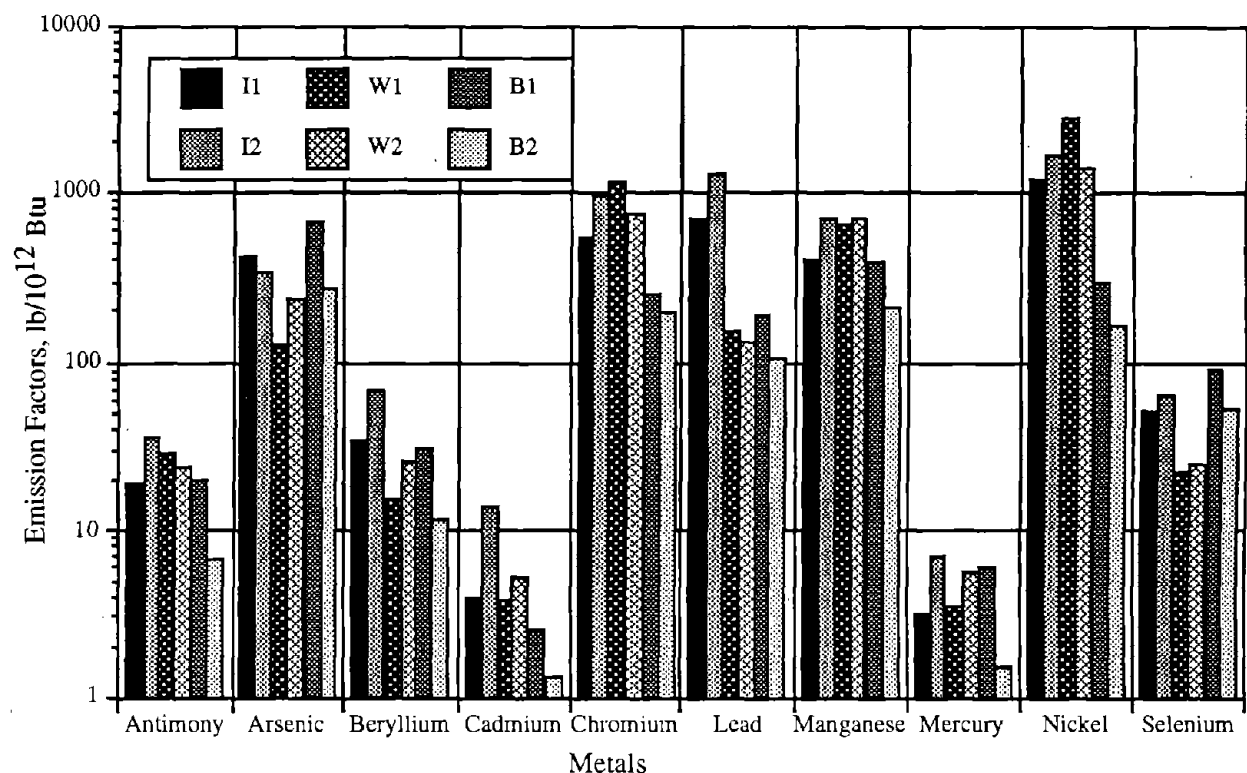


Figure 7. Measured emission factors for the six coals tested.

C. Comparison of Measured and Calculated Emissions

The ratio of measured to calculated emissions of metal HAPs can provide a considerable amount of information. These values are presented in Table 7 below, expressed as the percent of as-fed maximum calculated emissions. In some cases, the measured emissions may exceed the calculated emissions (which are based on 100% of the metal in the coal exiting the combustor). This can be due to one or more reasons: the measured value of the trace metal content of the coal is lower than is actually the case; the measured value of the concentration of the metal in the flue gas is higher than actual; or both measurements may be correct, but the discrete sample of coal used to determine the trace metal content of the coal had a lower than typical amount of the particular metal. Because of the low concentrations of trace metals, the accuracy of the measurements is also an area that can add to the uncertainty of the final results. However, these sources of error and uncertainty do not remove the usefulness of this ratio. By focusing on consistent results and trends, much can be determined from these values. First, if the ratio of theoretical to measured emissions of a given metal is similar for a wide range of coals, then it is likely that the partitioning behavior of the metal is similar for the different coals tested, and may therefore be more dependent on the combustion and furnace characteristics than on the coal type or composition.

Table 7. Ratio of measured trace metal emissions to calculated emissions, in percent.

	I1	I2	W1	W2	B1	B2
Antimony	26	46	35	27	26	9
Arsenic	93	107	74	259	57	88
Beryllium	52	69	93	146	20	19
Cadmium	26	90	22	30	16	0
Chromium	35	62	272	49	18	5
Lead	45	47	60	50	17	3
Manganese	45	47	37	884	17	2
Mercury	43	61	43	73	24	25
Nickel	30	119	1079	37	24	3
Selenium	35	85	27	29	39	22

The cases where the measured emissions are below the calculated emissions are more frequent because of the fact that some percentage of each metal typically exits the combustor via the bottom ash and is therefore not measured in the stack sampling. This is not to say that there are no measurement errors in the instances where the measured emissions are lower than the calculated emissions; however, such errors are more difficult to detect and require repeated measurements to determine average values and identify outlying points.

As noted above, there is some concern that the as-received concentrations for coal B2 showed levels of cadmium, chromium, lead, manganese, and nickel higher than those actually in the coal. This possibility is strengthened by the very low percentages of those metals that are measured in the stack relative to the rest of the coals. While there is no quantitative evidence from the laboratory data that the as-received trace metal analyses of coal B2 were faulty, the comparisons of these values with the other cases indicate that these values may not be as reliable as the remaining data.

V. Discussion

A. Scaled Results

To more clearly see the differences between the calculated emissions and the measured emissions and how they change for the different coals and the different metals as the coals are combusted, it is useful to plot both in the same figure. In order to clearly view the information, it is also helpful to look at the results for each metal separately. Because the absolute values of the emissions (both calculated and measured) can sometime differ by one or more orders of magnitude, it is helpful to normalize the results so that they both have the same maximum value. The scaling is done by dividing the value for each coal by the maximum for that particular series of calculations or measurements. For example, Table 5 shows that the maximum calculated

emission of arsenic is for coal B1, at 1177 lb/10¹² Btu. Each of the values for calculated arsenic emissions is then divided by 1177 lb/10¹² Btu to obtain scaled values between 0 and 1.

Likewise, each measured arsenic emission value in Table 6 is scaled by the value for coal B1, 666 lb/10¹² Btu. For each metal, then, plots are produced that show the distribution of relative emissions (both measured and calculated) for each of the six coals tested. Figures 8 through 17 plot the scaled as-received distributions and the scaled measured emission factors for each metal tested.

Figure 8 provides relatively little information concerning changes in the calculated and measured antimony emissions, since the calculated emissions are different due only to the differences in heat content of the coals. In each case, the concentration of antimony in the coal was below the method detection level, making it impossible to accurately compare the calculated emissions which are based on the as-received trace compound levels; however, the figure is included for completeness.

Figure 9 compares the scaled calculated and measured emissions for arsenic for the six different coals tested. While there is some difference in the heights of the columns in the two plots, the same general shape is obvious for both. The only substantial difference is that coals

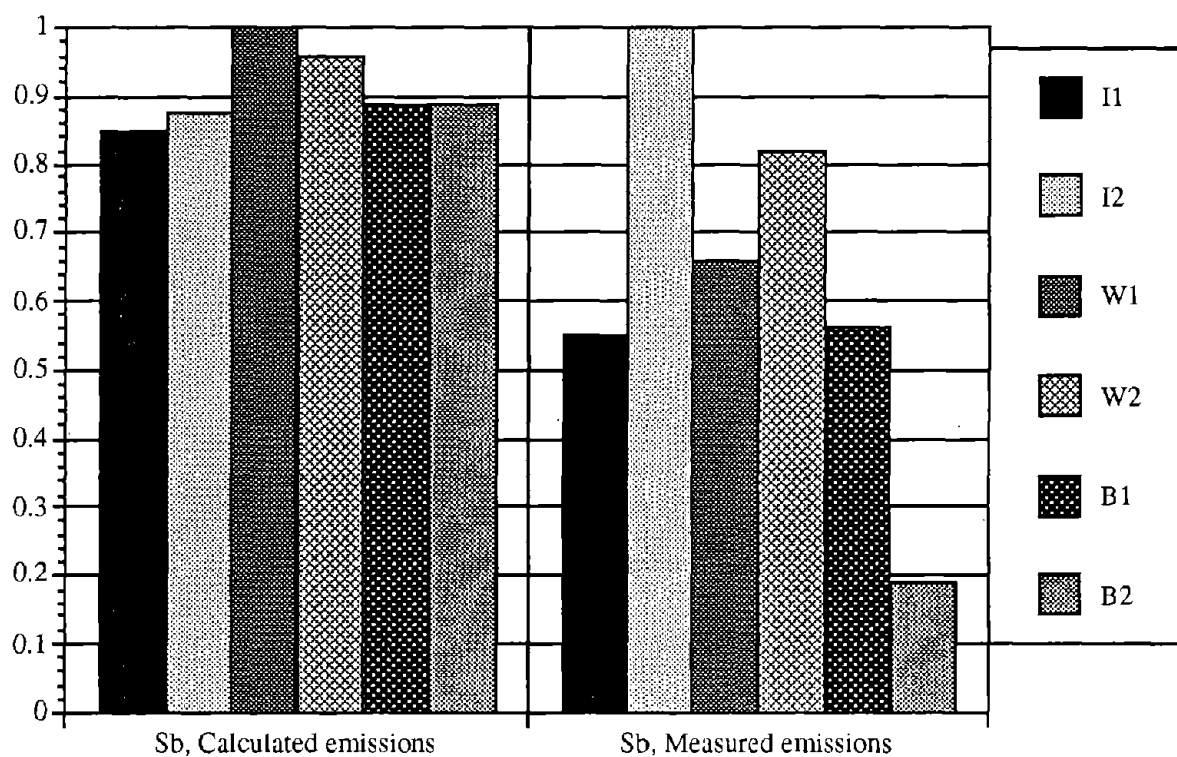


Figure 8. Comparison of scaled calculated and measured emissions of antimony for the six coals tested. Results are scaled to the maximum value in each category.

W2 and W1 have traded rankings, with W2 showing the lowest calculated emissions and W1 the second lowest, but W1 having the lowest measured emissions and W2 the second lowest. Coal B1 has an as-received concentration approximately twice as great as the next highest coal (I1), and similarly, emissions of roughly twice those of I1. The information from Figure 9 indicates that the relative levels of emissions from burning the six different coals are roughly the same as the relative levels of arsenic found in the as-received coals.

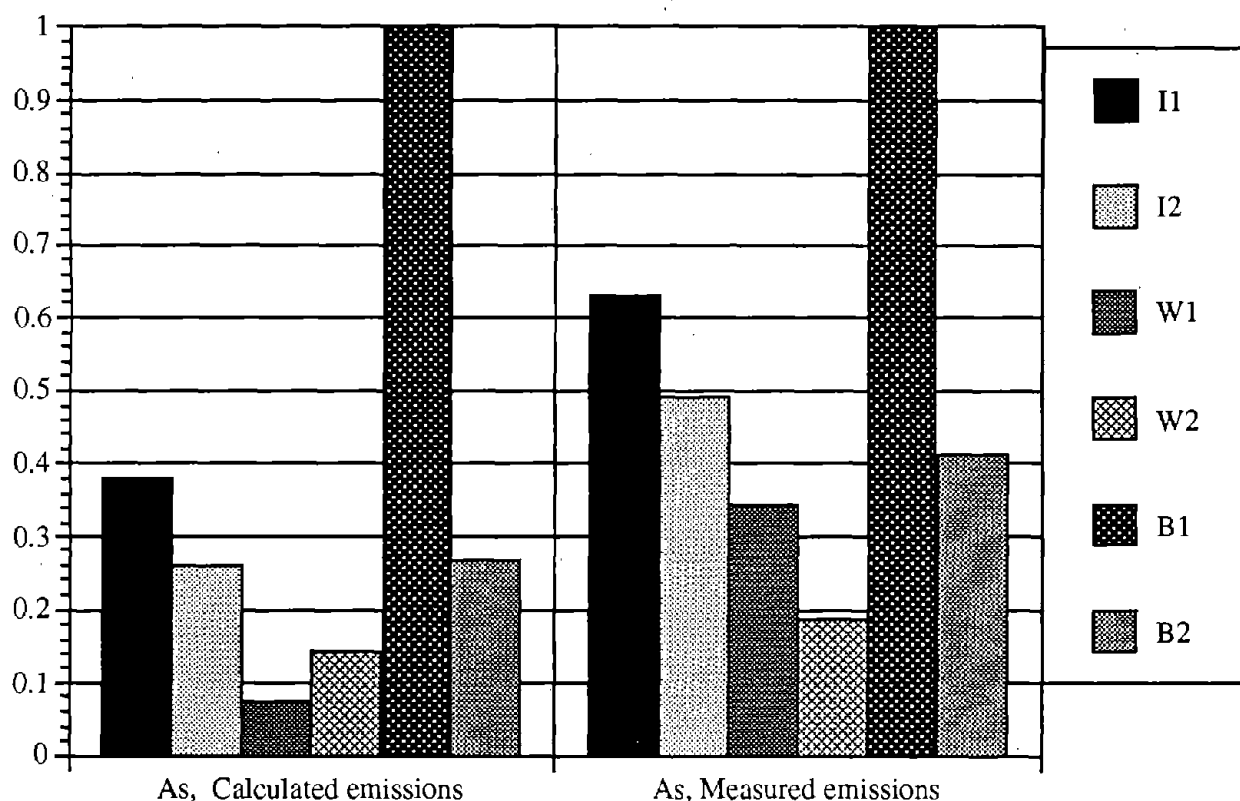


Figure 9. Comparison of scaled calculated and measured emissions of arsenic for the six coals tested. Results are scaled to the maximum value in each category.

The situation changes for beryllium, as shown in Figure 10. The left side of Figure 10 shows that the as-received concentration of beryllium is greatest in coal B1, with the second greatest concentration in coal I2 at roughly 65% that of B1. However, the measured emissions show that I2 has the greatest level of beryllium emissions, with I1 at about 50% of I2 and B1 at less than 50%. The relative levels of emissions from the other coals also changed, making it impossible to accurately predict even the relative levels of beryllium emissions based on the amounts of beryllium in the coals.

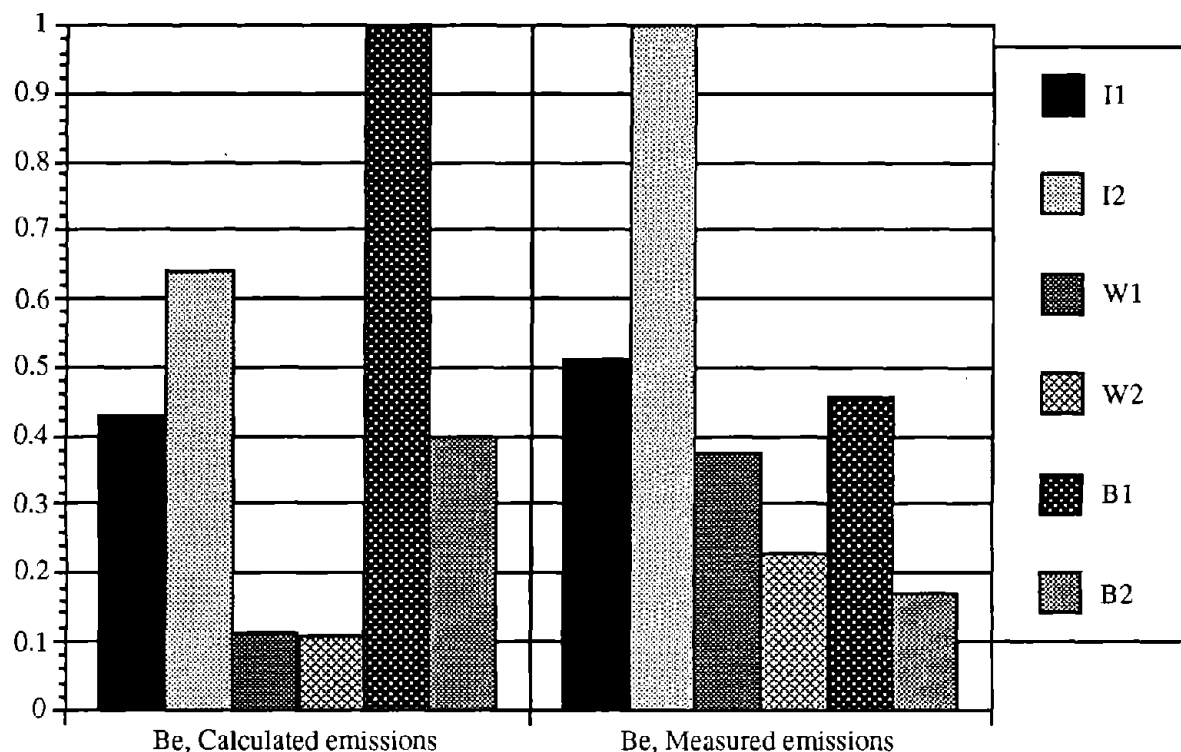


Figure 10. Comparison of scaled calculated and measured emissions of beryllium for the six coals tested. Results are scaled to the maximum value in each category.

Because the calculated emission levels of cadmium were so low (at the detection limit of the test method), the comparison of calculated versus measured emissions shown in Figure 11 does not provide a significant amount of information. Again the figure is included for completeness.

As was the case in Figure 10, the relative levels of calculated emissions of chromium versus measured emissions show a marked change, as can be seen in Figure 12. Here coal B2 shows the highest level of calculated emissions, while W1 actually measured the highest, with B2's measured emissions being less than 20% of W1. Again, the conclusion to be drawn from this comparison is that the relative emissions of chromium cannot be accurately predicted from the relative amounts of trace chromium in the coal, based on the behavior exhibited by these results.

Similar results are seen in Figures 13 through 15, which compare lead, manganese, and nickel, respectively. In each case, the relative emission levels change significantly when comparing calculated emissions based on the as-fed trace metal concentration to the measured emissions of the same metal. The change in relative lead emissions is not as great as for manganese and nickel, but in each of these cases the use of the as-found trace metal concentration as a predictor of the relative emissions is seen to give significantly different results than what might be expected. In the cases of lead, manganese, and nickel, the high calculated

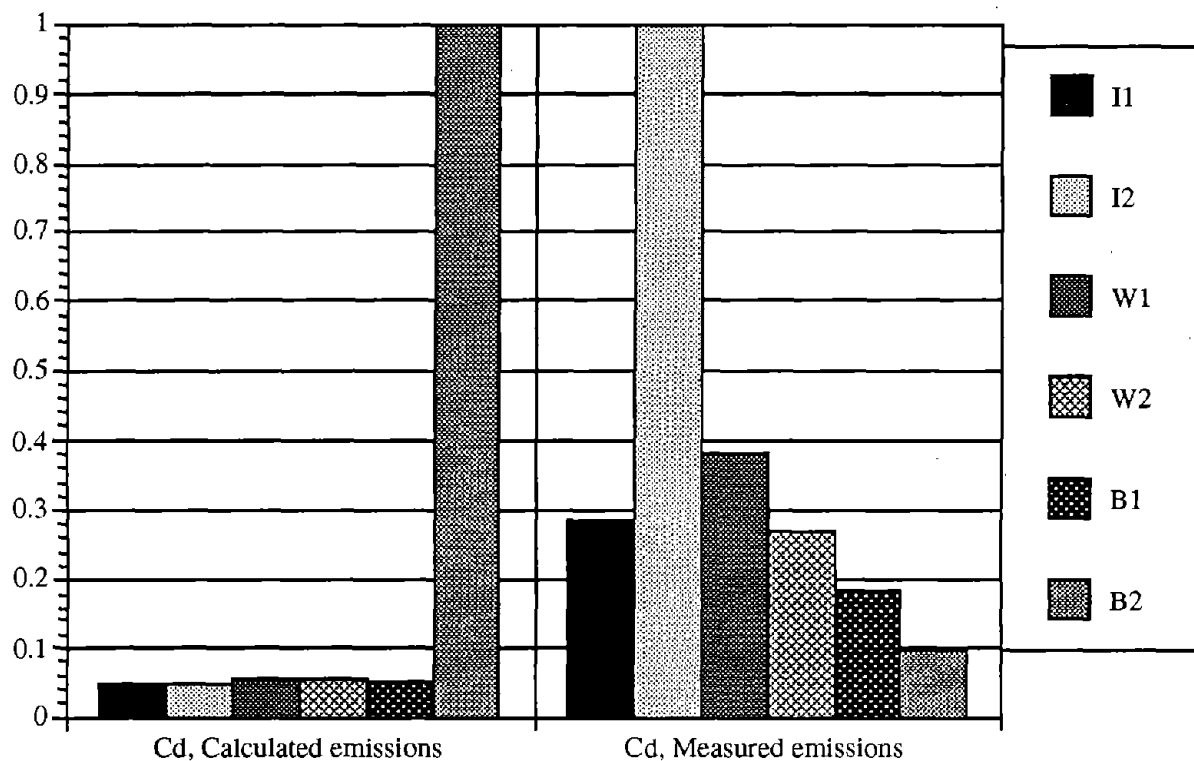


Figure 11. Comparison of scaled calculated and measured emissions of cadmium for the six coals tested. Results are scaled to the maximum value in each category.

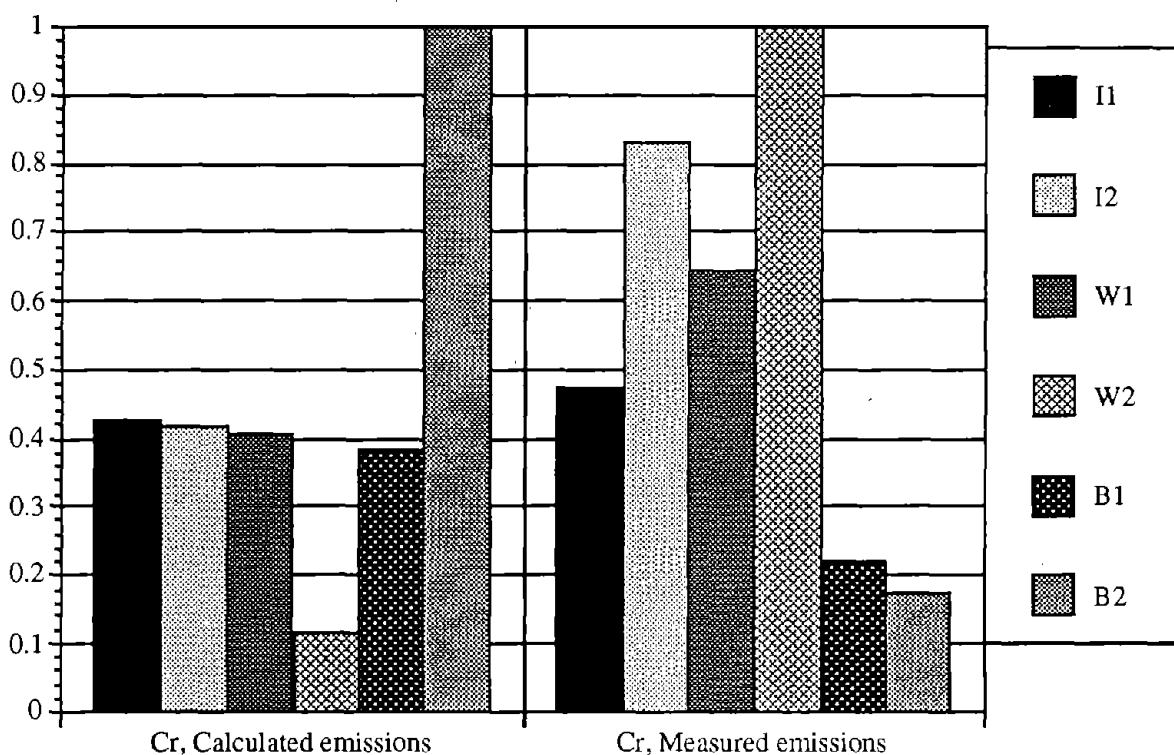


Figure 12. Comparison of scaled calculated and measured emissions of chromium for the six coals tested. Results are scaled to the maximum value in each category.

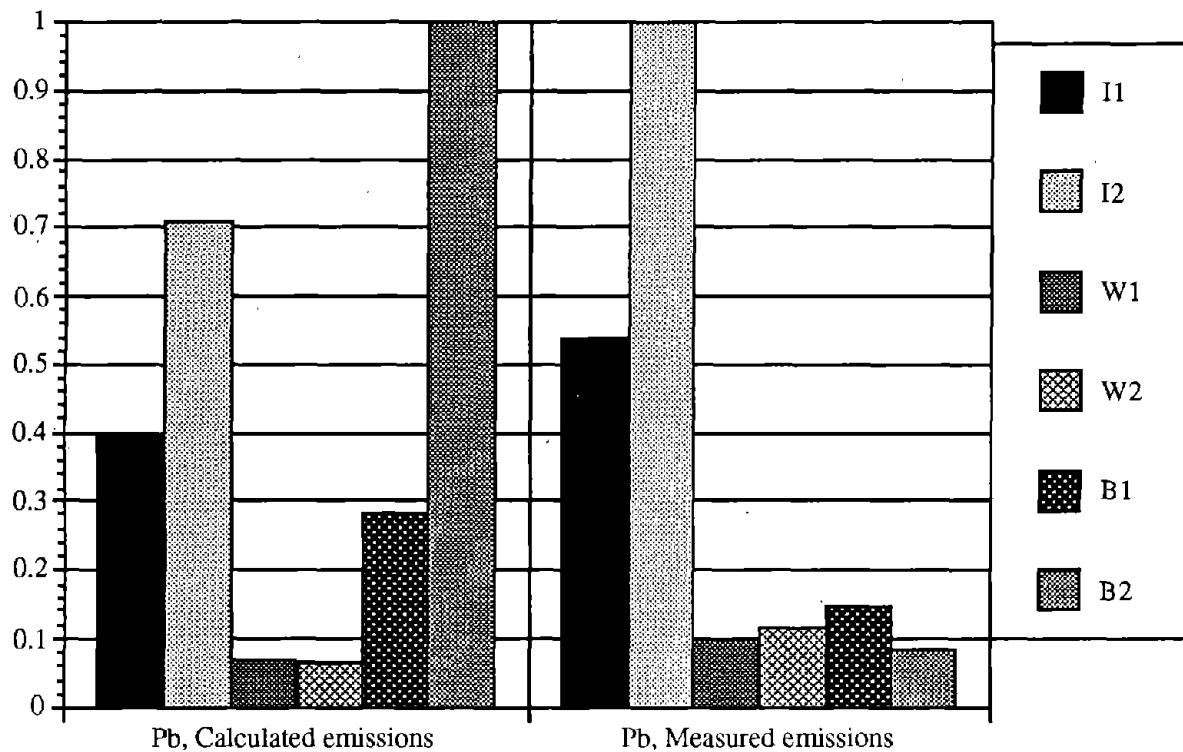


Figure 13. Comparison of scaled calculated and measured emissions of lead for the six coals tested. Results are scaled to the maximum value in each category.

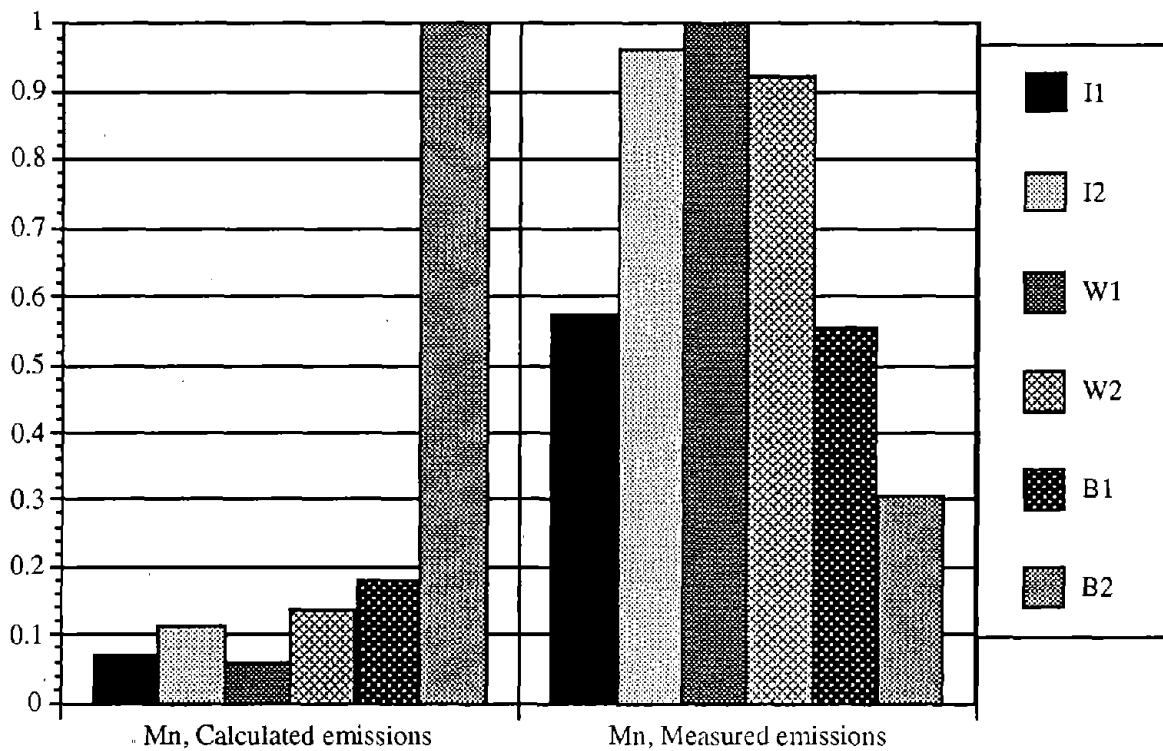


Figure 14. Comparison of scaled calculated and measured emissions of manganese for the six coals tested. Results are scaled to the maximum value in each category.

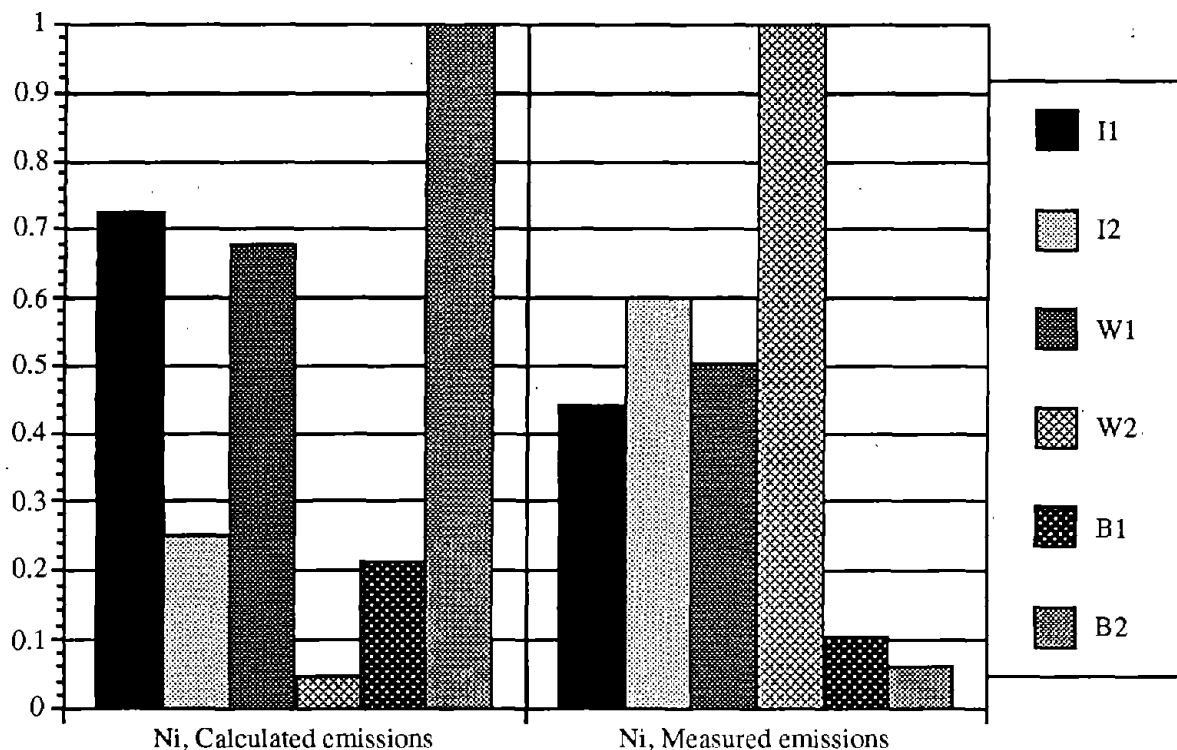


Figure 15. Comparison of scaled calculated and measured emissions of nickel for the six coals tested. Results are scaled to the maximum value in each category.

emissions from coal B2 shown in Figures 13 through 15 shift the remaining values strongly lower. It is very possible that the as-received coal analyses do not accurately reflect the true levels of these compounds, and that the reported values are high. If this is the case, the relative metal emission levels of the remaining five coals should be compared.

In Figure 16, relative calculated and measured emissions are plotted for selenium. Here the differences between calculated and measured are much less dramatic, and while there are some changes between the two plots, the same general shape is maintained, with B1 exhibiting the greatest relative emissions for both the calculated and measured values, coals W1 and W2 being the lowest, and I1 and I2 lying between the western coals and the “B” coals.

Figure 17, which plots calculated and measured relative emissions for mercury, also exhibits less dramatic differences than the earlier plots. There is a significant change in that the measured emissions of I2 were the highest, while B1 had the highest calculated emissions. However, there is little change in the qualitative shape of the two plots, in contrast to the marked change shown by nickel (Figure 15).

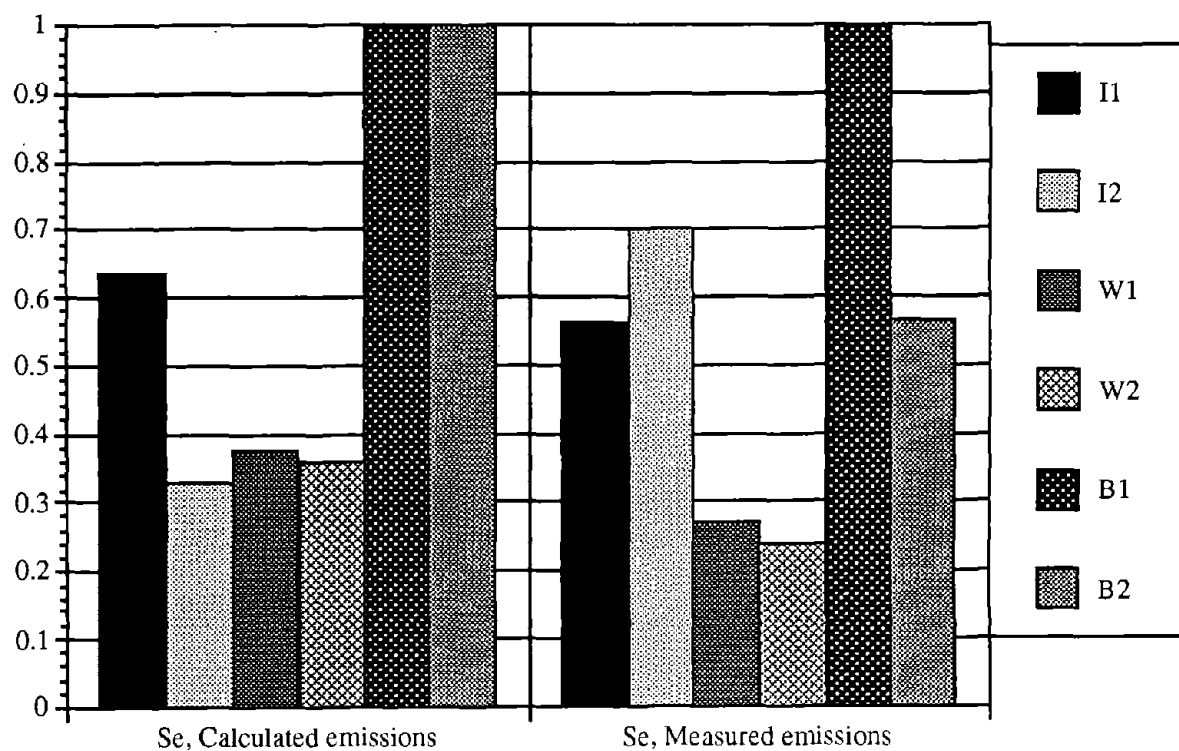


Figure 16. Comparison of scaled calculated and measured emissions of selenium for the six coals tested. Results are scaled to the maximum value in each category.

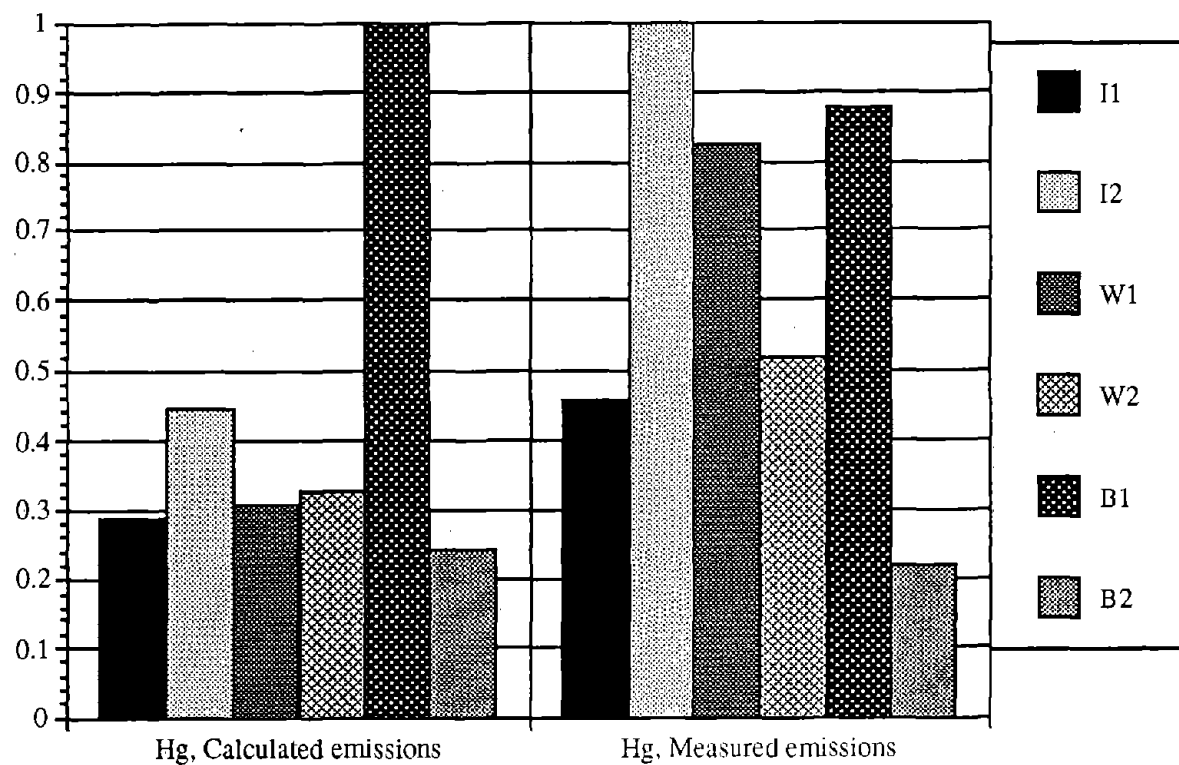


Figure 17. Comparison of scaled calculated and measured emissions of mercury for the six coals tested. Results are scaled to the maximum value in each category.

From the above comparisons, a significant conclusion can be drawn. In this series of tests, the distributions of emissions change most markedly for beryllium, chromium, manganese, and nickel; least markedly for arsenic, selenium, and mercury; and are inconclusive for antimony, cadmium, and lead. These results show that emissions of the least refractory metals (arsenic, selenium, and mercury) tend to be more strongly affected by the levels of those metals in the coals, while the more refractory metals (beryllium, chromium, manganese, and nickel) do not show such a strong correlation. This behavior is to be expected, since the refractory metals tend to be enriched in the larger particles, which are typically collected as bottom ash or at other points prior to the combustor exit. The most volatile metals tend to be enriched in the submicron particle fraction, and are therefore much more likely to pass through the combustor with the flue gases.

The dominating mechanisms governing this behavior are the vapor pressures of the individual metals. For the refractory metals, such as nickel, the vapor pressure is so low that no additional nickel can vaporize from the coal or ash particles. No matter how much additional nickel may be in the coal, it will not be released into the flue gases to form particles small enough to pass through the combustor and be collected, but rather remains in the larger particles and falls out of the flue gas flow stream. On the other hand, the metals with high vapor pressures, such as mercury, will easily vaporize and form either vapors or particles small enough to pass through to the combustor exit. For mercury, selenium, and arsenic, the flue gases and the coal- or ash-bound metal particles have not yet reached a state of equilibrium; therefore, higher levels of these metals fed into the combustor will easily vaporize and allow collection at the combustor exit. For this reason, a doubling of a volatile metal will result in roughly a doubling of the emissions. Conversely, for the refractory metals, a doubling of a coal's metal content will not result in a doubling of the uncontrolled emissions, since the dominant mechanism governing the release of these metals is no longer the vapor pressure. Because the solid and vapor phases of the refractory metals are essentially in equilibrium, other mechanisms will govern the release of the metals into the flue gases and the subsequent aerosol formation. Therefore, factors such as the way the metal is bound in the coal, the presence of other compounds such as chlorine, or local combustion conditions must be taken into account when attempting to predict the uncontrolled metals emissions.

In summary, the tests show that, for volatile metals, changes in the amounts of those metals from one coal to another can be a good predictor as to the changes in the emissions of those metals from the combustor. For the other metals, however, predictions of emission changes due to changes in the metal contents of the coal are much more likely to be in error. One may be able

to predict the direction of change for these metals, but attempting to predict the magnitude of that change is not likely to be accurate unless factors other than the trace metal contents of the comparative coals are also considered.

As mentioned above, some of the other factors that can play a significant role are the way the metals are bound in the coal, the presence of other elements in the coal, the preparation of the coal prior to feeding into the furnace, the combustion conditions, and the geometry of the furnace. As these tests have shown, however, even maintaining the same combustion conditions in the same furnace does not ensure that the emissions of refractory metals from different coals will change in the same manner as the as-fed trace concentrations of those metals in the coals. Since the coals were not specially prepared prior to burning them, the differences noted here are likely to be due to differences in the ways the metals were bound in the coal, or to the presence of other elements in the coals that affected the metal aerosol formation process during combustion. Unfortunately, studies of these effects were beyond the scope of this project; therefore, reasons for the differences in emissions cannot be explained definitively.

B. Comparison of Small Scale Results to Full Scale Tests

With the recent emphasis on HAP emissions from utility boilers, several significant field tests of HAP emissions have been undertaken by EPA, DOE, and EPRI. DOE recently reported results from coal-fired boilers¹⁸ (shown in Table 8), and it is useful to compare the results obtained in the small scale tests reported here to the field data reported by DOE. Figure 18 shows the average emission factors for the six coals tested in this study along with the maximum values reported by DOE. In this figure, the small scale studies yielded the highest emission factors for all metals tested except for cadmium, selenium, and mercury. For these three metals, the DOE field tests had higher emissions on a per energy input

Table 8. Full scale emission factors for hazardous metal air pollutants, from DOE test program.¹⁸ Emission factors are in lb/10¹² Btu.

Metal	Low value	High value
Antimony	< 0.1	2.4
Arsenic	0.1	42
Beryllium	< 0.1	1.4
Cadmium	< 0.1	3.0
Chromium	< 0.1	51
Lead	0.6	29
Manganese	1.1	22
Nickel	0.3	40
Selenium	< 0.1	130
Mercury	0.5	14

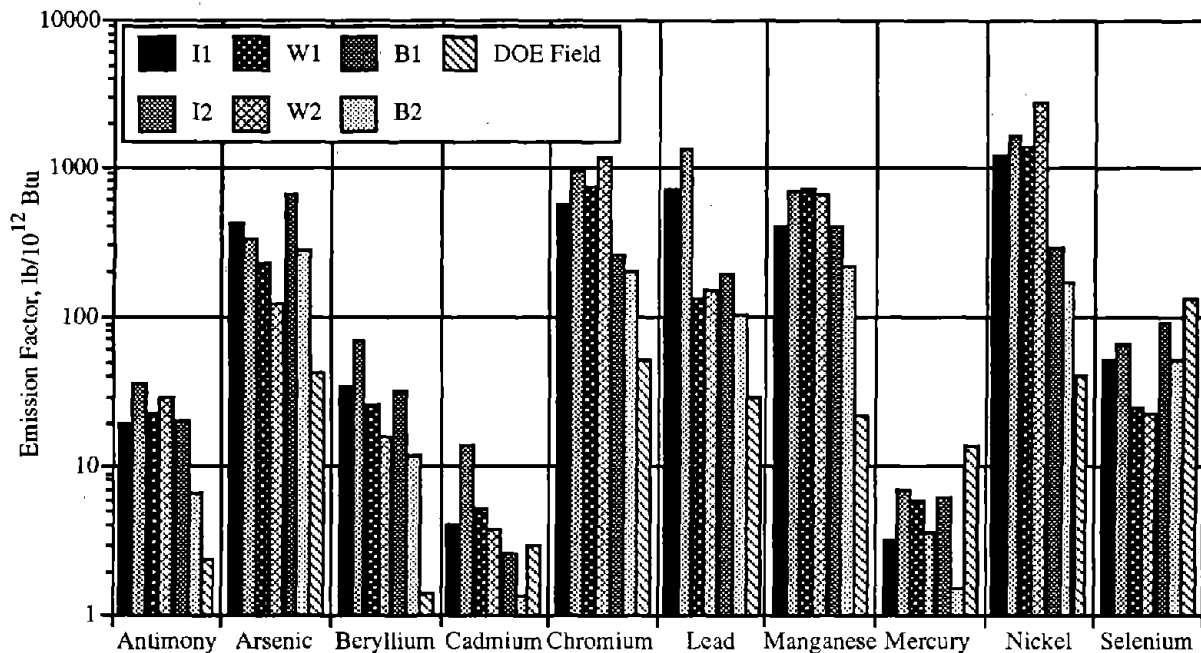


Figure 18. Comparison of measured emissions from small scale test program to upper range of DOE field test data.

basis. Again, it is worth noting that these three metals are very volatile, and the higher full scale emissions are likely to be due to higher levels of these metals in the coals.

While the remaining small scale results are very similar to the maximum reported values from the DOE study, it must also be emphasized that the small scale results are for uncontrolled emissions. The minimum and maximum reported emission factors from the full scale tests differ by as much as four orders of magnitude, with the differences likely due not only to differences in the metal contents of the coals, but also to the efficiency of pollution control equipment present at the different sites. Unfortunately, the DOE data are not in sufficient detail to allow a more definitive evaluation of the effect of controls; however, they do show that pollution control equipment can remove as much as 99% of some metals that exit the boiler. If the effects of pollution control equipment are accounted for, the emissions reported for the small scale tests would likely drop from 30 to 99%, depending upon the metal.

As a further measure of the correlation between emissions from the small scale combustor used in this study and emissions from a full scale unit, a set of small scale test runs was conducted using a coal that was also being used in full scale air toxics tests. The B2 coal was taken from a coal pile used during a full scale demonstration test of an innovative pollution control system for coal fired utility boilers. Therefore, the sampled emissions from the small

scale testing can be compared to the full scale results using this coal to quantify the similarities and differences between the full scale and small scale tests. The full scale tests were done at a 160 MWe wall fired boiler of a pre-NSPS (New Source Performance Standards) design. Coal B2 is a blend of bituminous Ohio coals with sulfur content of approximately 3.8% (see Table 3).

Figure 19 shows the emission factors for the 10 metals tested in this study compared to the emission factors for the same 10 metals measured upstream of any pollution control equipment in the full scale tests. In general, the results correlate well, with the major differences being for chromium and manganese. In each case, the full scale emissions were higher by approximately 50%. The uncontrolled mercury emissions from the full scale system was also significantly higher at about 9 versus 1.55 lb/10¹² Btu measured in the small scale tests. Uncontrolled selenium emissions were also higher in the full scale tests than in the small scale tests, by over 80%. For both mercury and selenium, the levels of input of both metals were found to be very similar between the two tests. However, the trace element concentrations of chromium and manganese seemed to be significantly higher for the small scale tests samples than for the full scale tests. These results were also much higher than the remaining coals, indicating that the analyses of the trace element concentrations were higher than actually in coal B2.

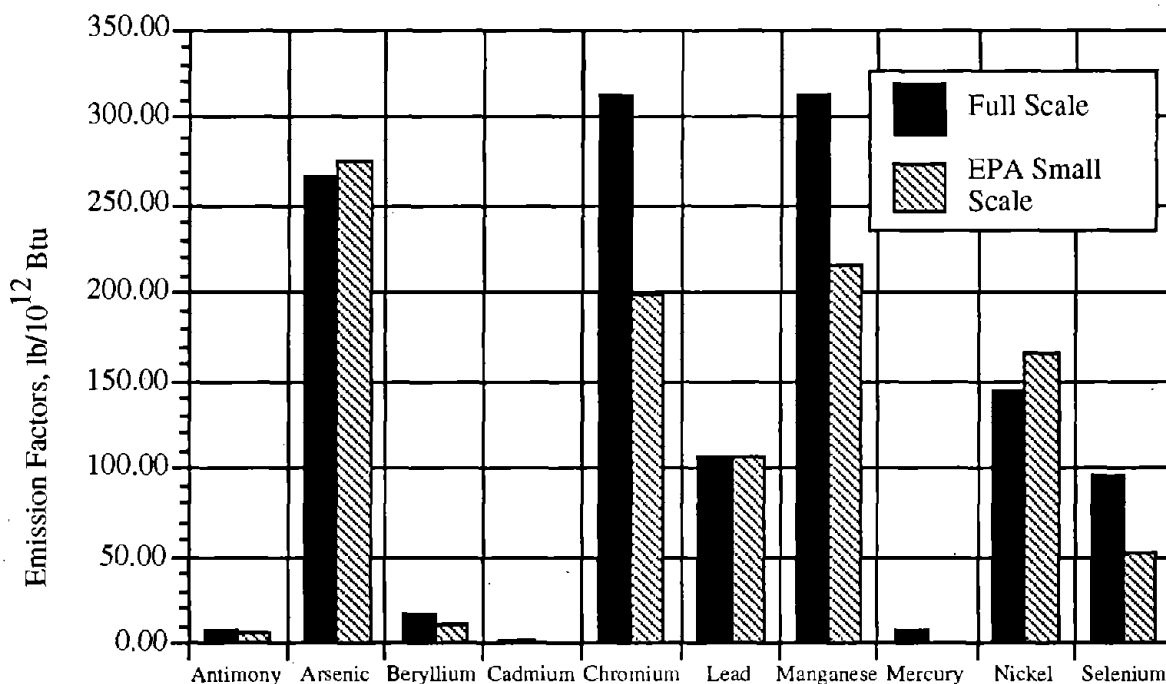


Figure 19. Comparison of uncontrolled emissions from a full scale pulverized coal utility boiler to those from the small scale IFR. The same coal was used in both cases.

It is reasonable that the uncontrolled small scale emissions will be lower than uncontrolled emissions from full scale units, for several main reasons. First, the gas velocities in the pilot scale sampling duct were not as high as those found in full scale units, making it more difficult for particles to remain entrained in the flue gases. Second, the ratio of gas volume to wall surface area is much smaller in the pilot scale unit, leading to increased condensation of the metals in the flue gas at the small scale. This increased cool wall area in the pilot scale is likely to have the effect of minimizing the volatilization of the metals, followed by more rapid condensation. This may lead to increased particle sizes and an accompanying increase in the amount of metal-containing particulate that falls out of the flue gas stream. The third main reason that the emissions from the pilot scale are likely to be less is that the smaller volume gas flow are the tighter turns that would be seen in the pilot scale, leading to increased amounts of particulate being deposited on the walls and removed from the flue gases. It was expected that the more volatile metals (mercury and selenium) would probably not exhibit this effect nearly as strongly as the refractory metals, and would be closer to the actual uncontrolled emissions seen in full scale units. However, the volatile metals seemed to show the largest differences between small and full scale tests.

The above differences in flows emphasize the fact that pilot scale results cannot be directly translated to full scale. The value of the pilot scale studies lies in their ability to more closely maintain consistency between test runs, allowing for a more reliable comparison between the emissions from different coals. The comparisons should be viewed as trends that are likely to occur at full scale. For instance, the conclusion that the emissions of refractory metals are likely to correlate less closely with their content in the as-fed coal than are the emissions of more volatile metals should hold regardless of scale.

C. Effects of Air Pollution Control Systems

The emissions reported here are uncontrolled. In comparing these values to those from full scale units, or in estimating stack emissions from the metal content in the coals, the effects of pollution control systems must be taken into account. This is not a simple task, however, since the different forms of control technologies will have different effects on the metals in question. The more volatile metals such as mercury and selenium will not be nearly as strongly affected by the presence of flue gas cleaning equipment as will be the more refractory metals such as chromium and nickel. Likewise, a wet flue gas desulfurization (FGD) scrubber will have less effect on emissions of the refractory metals than will an efficient particulate removal system such as an ESP. In addition, the treatment of flue gases by more than one type of pollution control system will have synergistic effects that can alter the removal efficiencies of a single piece of equipment. For instance, the removal of sulfur trioxide (SO_3) upstream of an ESP may have a

significant effect on the ESP's particulate removal performance, and therefore on the removal efficiency of metal-laden particles.

Currently, a significant amount of information is being generated on the capabilities of air pollution control equipment for removing metal HAPs from coal combustion flue gas streams. EPA's Electric Utility Study Report to Congress¹⁹ and EPRI's PISCES field test program^{2,3} are two primary efforts to quantify the emissions of HAPs from coal combustion, and the PISCES program in particular is evaluating the effects of pollution control systems on HAP emissions. Other data are also available to indicate the capabilities of pollution control systems to reduce the emissions of metal HAPs. EPA released a report in 1989 that estimated air toxic emissions from coal-fired utilities, and provided some data on the effects of pollution control systems on those emissions.²⁰ The report's estimates of pollution control device metal HAP removal efficiencies are shown in Table 9 for seven metal compounds (although copper is included in this table, it is not on the list of HAPs under Title III). Note that the testing data on which these estimates are based are very limited, and therefore do not adequately characterize the full range of coals, combustion equipment, or pollution control devices that are in place throughout the utility industry. Nevertheless, these values do show that significant levels of control can be attained for some metals with existing control technologies.

As noted earlier in Section II, particulate control is strongly dependent upon particle size, and also varies significantly according to the type of control technology applied. Venturi-type wet scrubbers usually remove at or below 50% of these smaller particles, as well as the metals that tend to be enriched in these smaller particle sizes. Packed-bed scrubbers may show metal removal levels of over 90% (see Table 9).^{20,21} However, utility scrubbers are usually designed for acid gas removal rather than for particulates, and will show a much greater ability to remove

Table 9. Removal efficiencies of air pollution control devices for seven metals. Values are given as percent removal measured between device inlet and device outlet. Data are from Reference 20.

Control Technology	Arsenic (a)	Beryllium	Cadmium	Chromium	Copper (b)	Manganese	Nickel
Wet Scrubber	6-97	94.3	94.4	91.8	91.4	89.1	96.4
ESP	87.5	91.9	74.6	71.5	85.0	78.1	79.1
ESP/Scrubber	98.9	NA	>67	92.9	97.4	97.7	97.2
Fabric Filter	99.6	NA	NA	99.1	NA	NA	NA

(a) Only two values were reported for arsenic removal efficiency for wet scrubbers. Because the values varied so significantly, the arsenic removal efficiency of a scrubber is given here as a range rather than as an average value.

(b) Copper is not listed as a hazardous air pollutant under Title III of the Clean Air Act Amendments.

NA - Data not available.

large particles (1 μm and larger) than small particles. Therefore, where significant amounts of metals are condensed on these larger particles, scrubbers may show relatively high removal rates of metal HAPs. Where the metals are concentrated in the smaller particles, scrubbers will not be as efficient.

ESPs comprise the primary particulate removal system for utility boilers firing pulverized coal, and are relatively efficient in removing a significant fraction of particles, both by mass and by number. As with most particulate removal equipment, ESPs are more efficient when the particle sizes are larger, and are less efficient when removing submicron particles. Particles of 0.1-0.3 μm in size are less likely to be captured by an ESP than are particles of 1 μm or larger.²² ESP performance can be significantly improved by "conditioning" the flue gas. Conditioning involves the injection of a chemical, typically ammonia (NH_3) or SO_3 , or in some cases sodium carbonate (NaCO_3), into the flue gas. Conditioning can improve the average capture rate by 2-5%. It is not clear what interactions may occur between conditioners and metals; however, it is likely that these interactions will primarily affect the volatile metals rather than the refractory metals, since the relatively low temperatures found in ESPs are not adequate to cause significant chemical interaction with the refractory metals. Emissions of metals such as mercury and selenium may, however, be affected by the conditioning agent, although currently no data are available to evaluate these potential effects.

Baghouses or fabric filters are the most efficient means of particulate removal, and in some instances are able to reduce the emissions of metal HAPs by over 99%. This is primarily true for those compounds that have condensed onto fly ash or into a solidified metal aerosol; the more volatile metals such as mercury are captured by fabric filters only when they are first absorbed onto particles that are then captured on the filter.

Spray dryer absorbers (SDAs) in conjunction with particulate removal equipment are also capable of high removal efficiencies, even in the case of mercury. In a study of eight power plants that used SDA systems, mercury captures of over 99% were measured across the SDA and particulate removal system.²³ However, the removal efficiencies ranged from a low of 6% to one case of over 99% removal. The most important factor that appeared to affect the removal efficiencies was the particulate loading of the flue gases, with the higher removal efficiencies correlating with higher particulate loadings. An additional factor appeared to be the chlorine content of the coal, which showed an apparent increase in mercury reduction efficiency with increasing chlorine content. Although these correlations were not examined in detail, it is clear from these results that it is difficult, if not impossible, to predict the emissions of mercury *a priori* based on the mercury content in the coal without considering other factors.

D. Effects of Coal Cleaning

The above results are based on the trace element analyses and combustion of the different coals with little or no preparation beyond grinding. In many cases, however, coals are washed to some degree prior to being fed into the furnace. This washing can vary from a simple washing with water to remove at least a portion of the excluded mineral fraction to much more sophisticated coal cleaning processes which can remove significant amounts of both sulfur and trace metals.

Coal cleaning is used to remove or reduce the inorganic fraction of the raw coal. The degree to which trace metals are removed from the coal during washing processes therefore depends strongly upon the degree to which each metal is physically or chemically associated with the organic fraction of the raw coal. Studies by Finkelman et al. examined the organic and mineral associations of trace elements in coal.²⁴⁻²⁵ When trace elements are embedded in the organic matrix of the coal, the ability of washing to remove that element decreases. The Finkelman results indicated that antimony, beryllium, and selenium were associated with the organic matrix, while arsenic, lead, and mercury were more closely associated with pyrite in the coals. In the coals tested, therefore, coal cleaning will reduce arsenic, lead, and mercury by a greater degree than antimony, beryllium, and selenium. As with the emissions, however, the degree to which coals can be washed of trace elements will be a function of the characteristics of the individual coals.

In general, the levels of metals in washed or cleaned as-fed coal will most likely be less than the trace concentrations of raw, as-mined coal, and the as-fed concentrations can be significantly less if the coal is cleaned extensively.²⁶⁻²⁸ The degree of reduction will vary from coal to coal depending on the cleaning process and on the composition of the coal. As with the as-found trace metal concentrations, the as-fed trace metal levels will vary among different coals, with no generally applicable correlation between trace metal concentration and sulfur content.

E. Other Approaches to Predicting Emissions

EPRI's PISCES field test program^{2,3} has gathered a considerable amount of full scale emissions data from a variety of utility power plants. These data have been taken from a range of plant sizes and types, with different pollution control equipment, and using different coal types and sources. In their approach to estimating emissions for the purpose of assessing the risk to human health from toxic emissions from utility boilers, EPRI has developed a series of metal-specific correlations to empirically estimate the emissions of trace metals from coal-fired utility boilers based on the trace metal and ash contents of the coals being used. These correlations do

not account for plant type or installed pollution control devices. This approach has been chosen by EPRI researchers as the best alternative available to them for providing a nationwide estimate of toxics emissions.

The approach taken by EPA's OAQPS, on the other hand, does distinguish emissions between plant and pollution control device type. While this approach requires more complex calculations to be performed to estimate emissions, it removes a large number of the uncertainties associated with a single correlation for all plants and control device types. Both EPRI and EPA estimates of HAP emissions are to be used as the basis for assessments of the risk to human health posed by those emissions from utility boilers. The risk assessment procedures contain considerable levels of uncertainty in themselves, and it is most desirable to minimize the uncertainties wherever possible. The OAQPS approach then seems to provide data that are more accurate than the EPRI approach, by accounting for differences associated with individual plant characteristics, rather than assuming that all changes in HAP emissions are due to changes in coal characteristics and feed rates.

In both cases, however, changes in trace element content of the feed coal was linearly translated into changes in metal emissions. While it is desirable to use a more accurate model that would account for the different behavior seen in these small scale tests, the state of the art is not yet adequate to produce an accurate predictive model.

VI. Conclusions

From the scaled distributions, it has been demonstrated that the coals tested behave differently with regard to the emissions of refractory metals. As is often the case in studies of metal emissions, the heterogeneity of the fuel and the relatively low metals concentrations typical of combustion systems lead to variations in the data from one run to another. It is therefore impossible to state that these differences will hold in all cases. However, the data are consistent enough to provide a strong indication that the common practice of estimating metals emissions based entirely upon the metals content of the coal is not completely accurate. Further, since the metals content does not in general correlate with sulfur content, it is therefore impossible to accurately make sweeping statements concerning the effects of using low sulfur coal on HAP emissions. While western coals typically contain higher ash and have a lower Btu content, the amounts of trace metals in these coals vary significantly when compared to high sulfur eastern coal, making it impossible to make generalizations concerning the effects of fuel switching on emissions of metal HAPs. A significant amount of additional study would help to provide a

more comprehensive means of estimating metals emissions based on the coal and combustion parameters.

It is therefore not possible to make a single broad statement about how changing coal will affect the emissions of toxic metals for the industry as a whole. Predicting metals emissions based entirely upon the trace metal concentrations of the coal is an overly simplified approach, although this approach may be necessary when evaluating broad national or regional impacts. While there will likely be some increase as concentrations of metals in the coal increase, it is impossible to accurately predict the actual changes, due to the effects noted above.

Predicting emissions of metals from the combustion of coal based only upon the as-received concentration of those metals in the coal is not accurate in all cases.

VII. References

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Appendix A. Data Sheets

I. Coal Analysis Data Sheets



COMMERCIAL TESTING & ENGINEERING CO.

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FAX: (708) 333-3060

February 19, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Western Coal

IL#5
Sample ID: W2 # 5

Sample taken at C-Wing C-225-C

Sample taken by

Date sampled

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49767

Page 1 of 2

PROXIMATE ANALYSIS

ULTIMATE ANALYSIS

	As Received	Dry Basis		As Received	Dry Basis
% Moisture	4.01	xxxxx	% Moisture	4.01	xxxxx
% Ash	8.91	9.28	% Carbon	71.54	74.53
% Volatile	33.64	35.05	% Hydrogen	4.81	5.01
% Fixed Carbon	53.44	55.67	% Nitrogen	1.60	1.67
	100.00	100.00	% Sulfur	1.45	1.51
			% Ash	8.91	9.28
Btu/lb	12831	13367	% Oxygen(diff)	7.68	8.00
				100.00	100.00
% Sulfur	1.45	1.51			
MAF Btu		14734			

Method: Moisture ASTM Designation D 3173
Ash per ASTM Designation D 3174
Volatile per ASTM Designation D 3175
Btu per ASTM Designation D 2015 or 3286
Sulfur per ASTM Designation D 4239 (Method C)
Fixed Carbon (calculated Value) is the
Resultant of the summation of percentage Moisture,
Ash, and Volatile matter subtracted for 100.
Carbon and Hydrogen by infrared detection, Nitrogen
by Thermal - conductivity.

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.

Manager, South Holland Laboratory

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FAX: (708) 333-3060

February 19, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Western Coal

Sample ID: WC # 5

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49767

Page 2 of 2

TRACE ELEMENT ANALYSIS

Element	Dry Basis, ug/g
Beryllium, Be	0.9
Chromium, Cr	21
Cadmium, Cd	<0.2
Lead, Pb	21
Arsenic, As	6
Manganese, Mn	12
Mercury, Hg	0.10
Nickel, Ni	53
Selenium, Se	2
Antimony, Sb	1

METHODS: The Sample was prepared according to ASTM, Part 05.05, D 3683. The sample was analyzed for trace elements by Inductively Coupled Plasma Emission Spectroscopy. Arsenic, Selenium and Antimony are Determined by Graphite Furnace Atomic Absorption. Mercury was determined by Double Gold Amalgamation Cold Vapor Atomic Absorption.

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.

Manager, South Holland Laboratory



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February 19, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Illinois Coal

Sample ID: IL # 6

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. NO. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49763

Page 1 of 2

PROXIMATE ANALYSIS

ULTIMATE ANALYSIS

	As Received	Dry Basis		As Received	Dry Basis
% Moisture	6.48	XXXXXX	% Moisture	6.48	XXXXXX
% Ash	8.41	8.99	% Carbon	67.14	71.79
% Volatile	33.65	35.98	% Hydrogen	4.65	4.97
% Fixed Carbon	<u>51.46</u>	<u>55.03</u>	% Nitrogen	1.41	1.51
	100.00	100.00	% Sulfur	2.76	2.95
			% Ash	8.41	8.99
Btu/lb	12128	12968	% Oxygen(diff)	<u>9.15</u>	<u>9.79</u>
% Sulfur	2.76	2.95		100.00	100.00
MAF Btu		14249			

Method: Moisture ASTM Designation D 3173
Ash per ASTM Designation D 3174
Volatile per ASTM Designation D 3175
Btu per ASTM Designation D 2015 or 3286
Sulfur per ASTM Designation D 4239 (Method C)
Fixed Carbon (calculated Value) is the
Resultant of the summation of percentage Moisture,
Ash, and Volatile matter subtracted for 100.
Carbon and Hydrogen by infrared detection, Nitrogen
by Thermal - conductivity.

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.

Manager, South Holland Laboratory

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February 19, 1993

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 ENVIRONMENTAL SYSTEMS DIVISION
 4915 PROSPECTUS DRIVE
 DURHAM, NC 27713
 ATTN: Kathy Hinton

Sample Identification by
 ACUREX CORP., DURHAM NC

Kind of sample
 reported to us Illinois Coal

Sample ID: IL # 6

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49763

Page 2 of 2

TRACE ELEMENT ANALYSIS

<u>Element</u>	<u>Dry Basis, ug/g</u>
Beryllium, Be	1.3
Chromium, Cr	20
Cadmium, Cd	<0.2
Lead, Pb	36
Arsenic, As	4
Manganese, Mn	19
Mercury, Hg	0.15
Nickel, Ni	18
Selenium, Se	1
Antimony, Sb	<1

METHODS: The Sample was prepared according to ASTM, Part 05.05, D 3683. The sample was analyzed for trace elements by Inductively Coupled Plasma Emission Spectroscopy. Arsenic, Selenium and Antimony are Determined by Graphite Furnace Atomic Absorption. Mercury was determined by Double Gold Amalgamation Cold Vapor Atomic Absorption.

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February 19, 1993

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ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Western Coal

Sample ID: WC # 1

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49765

Page 1 of 2

PROXIMATE ANALYSIS

ULTIMATE ANALYSIS

	As Received	Dry Basis		As Received	Dry Basis
% Moisture	20.22	xxxxx	% Moisture	20.22	xxxxx
% Ash	7.57	9.49	% Carbon	52.69	66.04
% Volatile	35.34	44.30	% Hydrogen	3.81	4.77
% Fixed Carbon	<u>36.87</u>	<u>46.21</u>	% Nitrogen	0.94	1.18
	100.00	100.00	% Sulfur	0.37	0.47
			% Ash	7.57	9.49
Btu/lb	9033	11322	% Oxygen(diff)	<u>14.40</u>	<u>18.05</u>
% Sulfur	0.37	0.47		100.00	100.00
MAP Btu		12509			

Method: Moisture ASTM Designation D 3173
Ash per ASTM Designation D 3174
Volatile per ASTM Designation D 3175
Btu per ASTM Designation D 2015 or 3286
Sulfur per ASTM Designation D 4239 (Method C)
Fixed Carbon (calculated Value) is the
Resulant of the summation of percentage Moisture,
Ash, and Volatile matter subtracted for 100.
Carbon and Hydrogen by infrared detection, Nitrogen
by Thermal - conductivity.

Respectfully submitted,
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ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Western Coal

Sample ID: WC # 1

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49765

Page 2 of 2

TRACE ELEMENT ANALYSIS

<u>Element</u>	<u>Dry Basis, ug/g</u>
Beryllium, Be	0.2
Chromium, Cr	17
Cadmium, Cd	<0.2
Lead, Pb	3
Arsenic, As	1
Manganese, Mn	9
Mercury, Hg	0.09
Nickel, Ni	42
Selenium, Se	<1
Antimony, Sb	<1

METHODS: The Sample was prepared according to ASTM, Part 05.05, D 3683. The sample was analyzed for trace elements by Inductively Coupled Plasma Emission Spectroscopy. Arsenic, Selenium and Antimony are Determined by Graphite Furnace Atomic Absorption. Mercury was determined by Double Gold Amalgamation Cold Vapor Atomic Absorption.

Respectfully submitted,
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Manager, South Holland Laboratory



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February 19, 1993

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ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Western Coal

Sample ID: WC # 2

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49764

Page 1 of 2

PROXIMATE ANALYSIS

ULTIMATE ANALYSIS

	As Received	Dry Basis		As Received	Dry Basis
% Moisture	18.50	XXXXX	% Moisture	18.50	XXXXX
% Ash	6.56	8.05	% Carbon	56.67	69.53
% Volatile	35.22	43.22	% Hydrogen	3.83	4.70
% Fixed Carbon	39.72	48.72	% Nitrogen	0.84	1.03
	100.00	100.00	% Sulfur	0.55	0.67
			% Ash	6.56	8.05
Btu/lb	9623	11807	% Oxygen(diff)	13.05	16.02
				100.00	100.00
% Sulfur	0.55	0.67			
MAF Btu		12841			

Method: Moisture ASTM Designation D 3173
Ash per ASTM Designation D 3174
Volatile per ASTM Designation D 3175
Btu per ASTM Designation D 2015 or 3286
Sulfur per ASTM Designation D 4239 (Method C)
Fixed Carbon (calculated Value) is the
Resultant of the summation of percentage Moisture,
Ash, and Volatile matter subtracted for 100.
Carbon and Hydrogen by infrared detection, Nitrogen
by Thermal - conductivity.

Respectfully submitted,
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Manager, South Holland Laboratory

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February 19, 1993

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 ENVIRONMENTAL SYSTEMS DIVISION
 4915 PROSPECTUS DRIVE
 DURHAM, NC 27713
 ATTN: Kathy Hinton

Sample identification by
 ACUREX CORP., DURHAM NC

Kind of sample
 reported to us Western Coal

Sample ID: WC # 2

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49764

Page 2 of 2

TRACE ELEMENT ANALYSIS

<u>Element</u>	<u>Dry Basis, ug/g</u>
Beryllium, Be	0.2
Chromium, Cr	5
Cadmium, Cd	<0.2
Lead, Pb	3
Arsenic, As	2
Manganese, Mn	21
Mercury, Hg	0.10
Nickel, Ni	3
Selenium, Se	1
Antimony, Sb	<1

METHODS: The Sample was prepared according to ASTM, Part 05.05, D 3683. The sample was analyzed for trace elements by Inductively Coupled Plasma Emission Spectroscopy. Arsenic, Selenium and Antimony are Determined by Graphite Furnace Atomic Absorption. Mercury was determined by Double Gold Amalgamation Cold Vapor Atomic Absorption.

Respectfully submitted,
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Manager, South Holland Laboratory

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February 19, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Battelle Coal

Sample ID: Battelle Coal

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49766

Page 1 of 2

PROXIMATE ANALYSIS

ULTIMATE ANALYSIS

	As Received	Dry Basis		As Received	Dry Basis
% Moisture	1.90	XXXXX	% Moisture	1.90	XXXXX
% Ash	12.51	12.75	% Carbon	69.89	71.24
% Volatile	32.97	33.61	% Hydrogen	4.75	4.84
% Fixed Carbon	52.62	53.64	% Nitrogen	1.41	1.44
	100.00	100.00	% Sulfur	2.38	2.43
			% Ash	12.51	12.75
Btu/lb	12501	12743	% Oxygen(diff)	7.16	7.30
				100.00	100.00
% Sulfur	2.38	2.43			
NAF Btu		14605			

Method: Moisture ASTM Designation D 3173
Ash per ASTM Designation D 3174
Volatile per ASTM Designation D 3175
Btu per ASTM Designation D 2015 or 3286
Sulfur per ASTM Designation D 4239 (Method C)
Fixed Carbon (calculated Value) is the
Resultant of the summation of percentage Moisture,
Ash, and Volatile matter subtracted for 100.
Carbon and Hydrogen by infrared detection, Nitrogen
by Thermal - conductivity.

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.

Manager, South Holland Laboratory



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February 19, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Kathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us Battelle Coal

Sample ID: Battelle Coal

Sample taken at C-Wing C-225-C

Sample taken by -----

Date sampled -----

P.O. No. CH 38900 E

Date received February 8, 1993

Analysis Report No. 71-49766

Page 2 of 2

TRACE ELEMENT ANALYSIS

Element	Dry Basis, ug/g
Beryllium, Be	2.0
Chromium, Cr	18
Cadmium, Cd	<0.2
Lead, Pb	14
Arsenic, As	15
Manganese, Mn	30
Mercury, Hg	0.33
Nickel, Ni	15
Selenium, Se	3
Antimony, Sb	1

METHODS: The Sample was prepared according to ASTM, Part 05.05, D 3683. The sample was analyzed for trace elements by Inductively Coupled Plasma Emission Spectroscopy. Arsenic, Selenium and Antimony are Determined by Graphite Furnace Atomic Absorption. Mercury was determined by Double Gold Amalgamation Cold Vapor Atomic Absorption.

Respectfully Submitted,
COMMERCIAL TESTING & ENGINEERING CO.

Manager, South Holland Laboratory



COMMERCIAL TESTING & ENGINEERING CO.

GENERAL OFFICES: 1919 SOUTH HIGHLAND AVE., SUITE 210 B, LOMBARD, ILLINOIS 60148 • TEL 708 953 9300 FAX 708 953 9306

Member of the SGS Group (Societe Generale de Surveillance)

PLEASE ADDRESS ALL CORRESPONDENCE TO:
P.O. BOX 127, SOUTH HOLLAND, IL 60473
TEL (708) 331-2900
FAX (708) 333-3060

December 21, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Cathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us ICCI Coal SURB

Sample No. 8602.326

Sample taken at -----

Sample taken by -----

Date sampled November 18, 1993

Date received November 23, 1993

P.O. No. CH 02040E

Analysis Report No. 71-65635

Page 1 of 3

PROXIMATE ANALYSIS

	<u>As Received</u>	<u>Dry Basis</u>
% Moisture	2.08	xxxxx
% Ash	11.66	11.91
% Volatile	37.02	37.81
% Fixed Carbon	<u>49.24</u>	<u>50.28</u>
	100.00	100.00
Btu/lb	12483	12748
% Sulfur	3.71	3.79
MAF Btu		14472

ULTIMATE ANALYSIS

	<u>As Received</u>	<u>Dry Basis</u>
% Moisture	2.08	xxxxx
% Carbon	69.27	70.74
% Hydrogen	4.85	4.95
% Nitrogen	1.26	1.29
% Sulfur	3.71	3.79
% Ash	11.66	11.91
% Oxygen(diff)	<u>7.17</u>	<u>7.32</u>
	100.00	100.00

METHODS

Moisture: ASTM D 3173

Ash: ASTM D 3174

Volatile: ASTM D 3175

Fixed Carbon: Calculated Value; ASTM D 3172

Btu/lb: ASTM D 2015 or D 3286

Sulfur: ASTM D 4239 (Method C)

Carbon, Hydrogen & Nitrogen: ASTM D 5373

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.

48 Manager, South Holland Laboratory





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Sample identification by
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Kind of sample
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Page 2 of 3

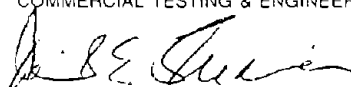
TRACE ELEMENT ANALYSIS

<u>Element</u>	<u>Dry Basis, ug/g</u>
Antimony, Sb	<1
Beryllium, Be	0.8
Arsenic, As	4
Mercury, Hg	0.08
Selenium, Se	3

METHODS

The Sample was prepared according to ASTM, Part 05.05, Method D 3683. The sample was analyzed for trace elements by Inductively Coupled Plasma Emission Spectroscopy. Arsenic & Selenium: Graphite Furnace Atomic Absorption. Mercury: Double Gold Amalgamation Cold Vapor Atomic Absorption.

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.



49 Manager, South Holland Laboratory



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FAX: (708) 333-3050

December 21, 1993

ACUREX CORP., DURHAM NC
ENVIRONMENTAL SYSTEMS DIVISION
4915 PROSPECTUS DRIVE
DURHAM, NC 27713
ATTN: Cathy Hinton

Sample identification by
ACUREX CORP., DURHAM NC

Kind of sample
reported to us ICCI Coal

Sample No. 8602.326

Sample taken at -----

Sample taken by -----

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Analysis Report No. 71-65635

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Ignited Basis, ug/g

Cadmium, Cd	4
Chromium, Cr	47
Lead, Pb	50
Nickel, Ni	70
Manganese, Mn	167

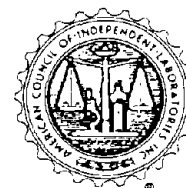
METHOD

Elements: ASTM D 3682

Respectfully submitted,
COMMERCIAL TESTING & ENGINEERING CO.

50

Manager, South Holland Laboratory



II. Sample Analysis Data Sheets



Sample ID: 080792 Volume 2.31 M³
Sampled

Conditions: Coal #5 - Test Date 8/7/92

Analyte	Concentration	
	Total ug	ug/M ³
Antimony	120	51.9
Arsenic	1720	744.6
Beryllium	163	70.6
Cadmium	12.6	5.5
Chromium	2940	1272.7
Lead	3210	1389.6
Manganese	1850	800.9
Nickel	6560	2839.8
Selenium	180	77.9
Mercury		
Front half	8.47	3.7
Imp 1-3	< 2.45	< 1.1
Imp 4-6	< 4.90	< 2.1
Total Mercury	< 15.82	< 6.8

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #5
 LOCATION: EPA C-WING

TEST #: 1A
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-07-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)		4.00
Pitot corr factor S type= 0.85cp		0.85
Strai ght type= 0.99cp		
Stack temp (deg R)		913.90
Molecular weight of gas (g/mol)		29.00
	0.90	0.95
Stack gas velocity (ft/s) (at stack conditions)		2.87
Gas volume exiting stack (ACFM)		15.00
Gas volume exiting stack (SCFM)		8.70
Gas volume exiting stack (SCMH)		14.78

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)		127.00
Uncorrected gas volume from meter (cubic feet)		88.17
Average meter temp (deg R)		567.10
Orifice delta H (inches H ₂ O)	not measured	
Sampling duration (minutes)		240.00
Sample nozzle diameter (inches)		0.88
Nozzle face area (square feet)		0.0042
Barometric Pressure (inches Hg)		29.92
Stack pressure (in Hg)		29.92
Stack pressure corrected for delta H (in Hg)		29.92
	451856.24	5154.79

Sample was collected at 87.66 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	87.29
Dry volume corrected to stp (cubic feet)	81.58
Dry volume corrected to stp (cubic meters)	2.31
Volume of condensed water as gas at stp (cubic feet)	6.00
Total wet volume of gas at stp (cubic feet)	87.57
Percent moisture of gas sampled	6.85
Mass of particulate captured (grams)	7.8980
Particulate loading:	
(mg solids/cu ft wet gas)	90.1853
(mg solids/cu mtr wet gas)	3184.8714
(mg solids/cu ft dry gas)	96.8150
(mg solids/cu mtr dry gas)	3418.9996

Sample ID: 081192 Volume 2.13 M³
Sampled

Conditions: Coal WC-2 Test Date 8/11/92

Analyte	Concentration	
	Total ug	ug/M ³

Antimony	66.2	31.1
Arsenic	680	319.2
Beryllium	79.5	37.3
Cadmium	14.8	6.9
Chromium	2230	1046.9
Lead	284	133.3
Manganese	37400	17558.7
Nickel	4200	1971.8
Selenium	83	39.0
Mercury		
Front half	5.97	2.8
Imp 1-3	< 2.65	< 1.2
Imp 4-6	< 4.90	< 2.3
Total Mercury	< 13.52	< 6.3

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #WC-2
 LOCATION: EPA C-WING

TEST #: 1
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-11-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)	4.00
Pitot corr factor S type= 0.85cp	0.85
Strai ght type= 0.99cp	
Stack temp (deg R)	979.10
Molecular weight of gas (g/mol)	29.00
	0.96
Stack gas velocity (ft/s) (at stack conditions)	3.00
Gas volume exiting stack (ACFM)	15.70
Gas volume exiting stack (SCFM)	8.50
Gas volume exiting stack (SCMH)	14.44

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)	168.50
Uncorrected gas volume from meter (cubic feet)	83.10
Average meter temp (deg R)	579.60
Orifice delta H (inches H ₂ O)	not measured
Sampling duration (minutes)	240.00
Sample nozzle diameter (inches)	0.88
Nozzle face area (square feet)	0.0042
Barometric Pressure (inches Hg)	29.92
Stack pressure (in Hg)	29.92
Stack pressure corrected for delta H (in Hg)	29.92
	459844.21
	5395.59
Sample was collected at	85.23 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	82.27
Dry volume corrected to stp (cubic feet)	75.23
Dry volume corrected to stp (cubic meters)	2.13
Volume of condensed water as gas at stp (cubic feet)	7.93
Total wet volume of gas at stp (cubic feet)	83.16
Percent moisture of gas sampled	9.54
Mass of particulate captured (grams)	6.7019
Particulate loading:	
(mg solids/cu ft wet gas)	80.5907
(mg solids/cu mtr wet gas)	2846.0418
(mg solids/cu ft dry gas)	89.0870
(mg solids/cu mtr dry gas)	3146.0862

Sample ID: 081392 Volume 1.41 M³
Sampled

Conditions: Coal WC-2 Test Date 8/13/92

Analyte	Total ug	Concentration ug/M ³
Antimony	43.4	30.8
Arsenic	398	282.3
Beryllium	43.2	30.6
Cadmium	9.92	7.0
Chromium	1280	907.8
Lead	300	212.8
Manganese	1320	936.2
Nickel	2330	1652.5
Selenium	38.5	27.3
Mercury		
Front half	5.01	3.6
Imp 1-3	< 2.65	< 1.9
Imp 4-6	< 4.90	< 3.5
Total Mercury	< 12.56	< 8.9

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #WC-2
 LOCATION: EPA C-WING

TEST #: 2
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-13-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)		4.00
Pitot corr factor S type= 0.85cp		0.85
Strai ght type= 0.99cp		
Stack temp (deg R)		942.40
Molecular weight of gas (g/mol)		29.00
	0.92	0.96
Stack gas velocity (ft/s) (at stack conditions)		2.89
Gas volume exiting stack (ACFM)		15.11
Gas volume exiting stack (SCFM)		8.50
Gas volume exiting stack (SCMH)		14.44

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)		51.00
Uncorrected gas volume from meter (cubic feet)		53.70
Average meter temp (deg R)		564.50
Orifice delta H (inches H ₂ O)	not measured	
Sampling duration (minutes)		210.00
Sample nozzle diameter (inches)		0.88
Nozzle face area (square feet)		0.0042
Barometric Pressure (inches Hg)		29.92
Stack pressure (in Hg)		29.92
Stack pressure corrected for delta H (in Hg)		29.92

278375.47 4544.18

Sample was collected at 61.26 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	53.16
Dry volume corrected to stp (cubic feet)	49.91
Dry volume corrected to stp (cubic meters)	1.41
Volume of condensed water as gas at stp (cubic feet)	2.40

Total wet volume of gas at stp (cubic feet) 52.31

Percent moisture of gas sampled 4.59

Mass of particulate captured (grams) 3.0936

Particulate loading:

(mg solids/cu ft wet gas)	59.1359
(mg solids/cu mtr wet gas)	2088.3715
(mg solids/cu ft dry gas)	61.9793
(mg solids/cu mtr dry gas)	2188.7862

Sample ID: 081492 Volume 2.06 M³
Sampled

Conditions: Coal # 6 Test Date 08/14/92

Analyte	Concentration	
	Total ug	ug/M ³
Antimony	70.2	34.1
Arsenic	585	284.0
Beryllium	163	79.1
Cadmium	42	20.4
Chromium	2410	1169.9
Lead	3400	1650.5
Manganese	1700	825.2
Nickel	4060	1970.9
Selenium	174	84.5
Mercury		
Front half	6.92	3.4
Imp 1-3	< 2.35	< 1.1
Imp 4-6	< 4.90	< 2.4
Total Mercury	< 14.17	< 6.9

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #6
 LOCATION: EPA C-WING

TEST #: 1
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-14-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)		4.00
Pitot corr factor S type= 0.85cp		0.85
Strai ght type= 0.99cp		
Stack temp (deg R)		1047.00
Molecular weight of gas (g/mol)		29.00
	1.03	1.01
Stack gas velocity (ft/s) (at stack conditions)		3.28
Gas volume exiting stack (ACFM)		17.19
Gas volume exiting stack (SCFM)		8.70
Gas volume exiting stack (SCMH)		14.78

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)		116.00
Uncorrected gas volume from meter (cubic feet)		79.04
Average meter temp (deg R)		563.80
Orifice delta H (inches H ₂ O)		not measured
Sampling duration (minutes)		210.00
Sample nozzle diameter (inches)		0.88
Nozzle face area (square feet)		0.0042
Barometric Pressure (inches Hg)		29.92
Stack pressure (in Hg)		29.92
Stack pressure corrected for delta H (in Hg)		29.92
	467191.30	5167.34

Sample was collected at 90.41 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	78.25
Dry volume corrected to stp (cubic feet)	73.56
Dry volume corrected to stp (cubic meters)	2.08
Volume of condensed water as gas at stp (cubic feet)	5.46
Total wet volume of gas at stp (cubic feet)	79.02
Percent moisture of gas sampled	6.91
Mass of particulate captured (grams)	6.0633
Particulate loading:	
(mg solids/cu ft wet gas)	76.7329
(mg solids/cu mtr wet gas)	2709.8050
(mg solids/cu ft dry gas)	82.4285
(mg solids/cu mtr dry gas)	2910.9446

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #6
 LOCATION: EPA C-WING

TEST #: 2
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-18-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)		4.00
Pitot corr factor S type= 0.85cp		0.85
Strai ght type= 0.99cp		
Stack temp (deg R)		1040.00
Molecular weight of gas (g/mol)		29.00
	1.02	1.01
Stack gas velocity (ft/s) (at stack conditions)		3.26
Gas volume exiting stack (ACFM)		17.07
Gas volume exiting stack (SCFM)		8.70
Gas volume exiting stack (SCMH)		14.78

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)		133.00
Uncorrected gas volume from meter (cubic feet)		86.12
Average meter temp (deg R)		556.40
Orifice delta H (inches H ₂ O)		not measured
Sampling duration (minutes)		240.00
Sample nozzle diameter (inches)		0.88
Nozzle face area (square feet)		0.0042
Barometric Pressure (inches Hg)		29.92
Stack pressure (in Hg)		29.92
Stack pressure corrected for delta H (in Hg)		29.92
	513729.44	5866.05

Sample was collected at 87.58 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)		85.26
Dry volume corrected to stp (cubic feet)		81.21
Dry volume corrected to stp (cubic meters)		2.30
Volume of condensed water as gas at stp (cubic feet)		6.26
Total wet volume of gas at stp (cubic feet)		87.47
Percent moisture of gas sampled		7.16
Mass of particulate captured (grams)		7.9998
Particulate loading:		
(mg solids/cu ft wet gas)		91.4541
(mg solids/cu mtr wet gas)		3229.6822
(mg solids/cu ft dry gas)		98.5035
(mg solids/cu mtr dry gas)		3478.6288

Sample ID: 081992 Volume 1.79 M³
Sampled

Conditions: Coal #6 Test Date 8/19/92

Analyte	Total ug	Concentration ug/M ³
Antimony	69.6	38.9
Arsenic	990	553.1
Beryllium	177	98.9
Cadmium	33.1	18.5
Chromium	2290	1279.3
Lead	3110	1737.4
Manganese	1740	972.1
Nickel	4400	2458.1
Selenium	176	98.3
Mercury		
Front half	12.50	7.0
Imp 1-3	< 2.30	< 1.3
Imp 4-6	< 4.90	< 2.7
Total Mercury	< 19.7	< 11.0

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #6
 LOCATION: EPA C-WING

TEST #: 3
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-19-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)		4.00
Pitot corr factor S type= 0.85cp		0.85
Strai ght type= 0.99cp		
Stack temp (deg R)		1090.00
Molecular weight of gas (g/mol)		29.00
	1.07	1.03
Stack gas velocity (ft/s) (at stack conditions)		3.42
Gas volume exiting stack (ACFM)		17.69
Gas volume exiting stack (SCFM)		8.70
Gas volume exiting stack (SCMH)		14.78

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)		96.00
Uncorrected gas volume from meter (cubic feet)		67.12
Average meter temp (deg R)		557.70
Orifice delta H (inches H ₂ O)	not measured	
Sampling duration (minutes)		180.00
Sample nozzle diameter (inches)		0.88
Nozzle face area (square feet)		0.0042
Barometric Pressure (inches Hg)		29.92
Stack pressure (in Hg)		29.92
Stack pressure corrected for delta H (in Hg)		29.92
	416503.17	4611.05

Sample was collected at 90.33 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	66.45
Dry volume corrected to stp (cubic feet)	63.15
Dry volume corrected to stp (cubic meters)	1.79
Volume of condensed water as gas at stp (cubic feet)	4.52
Total wet volume of gas at stp (cubic feet)	67.67
Percent moisture of gas sampled	6.68
Mass of particulate captured (grams)	6.0081
Particulate loading:	
(mg solids/cu ft wet gas)	88.7904
(mg solids/cu mtr wet gas)	3135.6142
(mg solids/cu ft dry gas)	95.1430
(mg solids/cu mtr dry gas)	3359.9540

Sample ID: 082092 Volume 1.85 M³
Sampled

Conditions: Coal WC-1 Test Date 8/20/92

Analyte	Concentration	
	Total ug	ug/M ³

Antimony	80.6	43.6
Arsenic	308	166.5
Beryllium	40	21.6
Cadmium	9.36	5.1
Chromium	2550	1378.4
Lead	366	197.8
Manganese	1570	848.6
Nickel	5980	3232.4
Selenium	38.4	20.8
Mercury		
Front half	1.21	0.7
Imp 1-3	< 2.55	< 1.4
Imp 4-6	< 4.90	< 2.6
Total Mercury	< 8.66	< 4.7

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
TEST: COAL #WC-1
LOCATION: EPA C-WING

TEST #: 1
RUN PARAMETERS: Multi Metals Train
DATE: 08-20-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)	4.00
Pitot corr factor S type= 0.85cp	0.85
Strai ght type= 0.99cp	
Stack temp (deg R)	913.80
Molecular weight of gas (g/mol)	29.00
	0.90
Stack gas velocity (ft/s) (at stack conditions)	2.26
Gas volume exiting stack (ACFM)	11.81
Gas volume exiting stack (SCFM)	6.85
Gas volume exiting stack (SCMH)	11.64

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)	153.00
Uncorrected gas volume from meter (cubic feet)	68.59
Average meter temp (deg R)	551.30
Orifice delta H (inches H2O)	not measured
Sampling duration (minutes)	240.00
Sample nozzle diameter (inches)	0.88
Nozzle face area (square feet)	0.0042
Barometric Pressure (inches Hg)	29.92
Stack pressure (in Hg)	29.92
Stack pressure corrected for delta H (in Hg)	29.92
	374075.85
	4058.21

Sample was collected at 92.18 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	67.90
Dry volume corrected to stp (cubic feet)	65.28
Dry volume corrected to stp (cubic meters)	1.85
Volume of condensed water as gas at stp (cubic feet)	7.20
Total wet volume of gas at stp (cubic feet)	72.48
Percent moisture of gas sampled	9.93
Mass of particulate captured (grams)	6.6886
Particulate loading:	
(mg solids/cu ft wet gas)	92.2796
(mg solids/cu mtr wet gas)	3258.8331
(mg solids/cu ft dry gas)	102.4588
(mg solids/cu mtr dry gas)	3618.3101

Sample ID: 082192 Volume 1.85 M³
Sampled

Conditions: Coal WC-1 Test Date 8/21/92

Analyte	Concentration	
	Total ug	ug/M ³
Antimony	65.8	35.6
Arsenic	322	174.1
Beryllium	38.6	20.9
Cadmium	9.52	5.1
Chromium	3220	1740.5
Lead	394	213.0
Manganese	1710	924.3
Nickel	7760	4194.6
Selenium	74	40.0
Mercury		
Front half	1.42	0.8
Imp 1-3	< 2.60	< 1.4
Imp 4-6	5.50	3.0
Total Mercury	< 9.52	< 5.1

ISOKINETICITY AND PARTICULATE LOADING SUMMARY

PROJECT: METALS COAL
 TEST: COAL #WC-1
 LOCATION: EPA C-WING

TEST #: 2
 RUN PARAMETERS: Multi Metals Train
 DATE: 08-21-92

(To whomever uses this spreadsheet: the x's found below represent data that have to be manually inputted.)

Stack diameter (inches)		4.00
Pitot corr factor S type= 0.85cp		0.85
Strai ght type= 0.99cp		
Stack temp (deg R)		920.90
Molecular weight of gas (g/mol)		29.00
	0.90	0.95
Stack gas velocity (ft/s) (at stack conditions)		2.27
Gas volume exiting stack (ACFM)		11.90
Gas volume exiting stack (SCFM)		6.85
Gas volume exiting stack (SCMH)		11.64

CALCULATED ISOKINETIC VARIATION

Total volume of water condensed (ml)		161.00
Uncorrected gas volume from meter (cubic feet)		68.70
Average meter temp (deg R)		552.60
Orifice delta H (inches H ₂ O)		not measured
Sampling duration (minutes)		240.00
Sample nozzle diameter (inches)		0.88
Nozzle face area (square feet)		0.0042
Barometric Pressure (inches Hg)		29.92
Stack pressure (in Hg)		29.92
Stack pressure corrected for delta H (in Hg)		29.92
	378693.24	4089.74

Sample was collected at 92.60 percent of isokinetic

SAMPLE GAS VOLUME AND PARTICULATE DATA

Corrected dry volume from meter (cubic feet at meter temp)	68.01
Dry volume corrected to stp (cubic feet)	65.23
Dry volume corrected to stp (cubic meters)	1.85
Volume of condensed water as gas at stp (cubic feet)	7.58
Total wet volume of gas at stp (cubic feet)	72.81
Percent moisture of gas sampled	10.41
Mass of particulate captured (grams)	6.3218
Particulate loading:	
(mg solids/cu ft wet gas)	86.8268
(mg solids/cu mtr wet gas)	3066.2684
(mg solids/cu ft dry gas)	96.9136
(mg solids/cu mtr dry gas)	3422.4799

Sample ID:	082492	Volume Sampled	N/A M ³
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Conditions:	Field/Method Blank
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Analyte		Total ug	Concentration ug/M ³
Antimony		2.46	N/A
Arsenic	<	1.00	N/A
Beryllium	<	1.00	N/A
Cadmium		0.56	N/A
Chromium	<	20.0	N/A
Lead	<	20.0	N/A
Manganese		1180	N/A
Nickel	<	20.0	N/A
Selenium	<	1.00	N/A
Mercury			
Front half	<	0.49	N/A
Imp 1-3	<	1.81	N/A
Imp 4-6	<	4.90	N/A
Total Mercury	<	7.20	N/A

Sampling Results Summary -- Page 1

TEST RUN ----->		A1	A2
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Test Conditions:			
Fuel		ICCI Coal	ICCI Coal
Target FR (Btu/Hr)		45000	45000
Target SR		1.2	1.2
Furnace Settings:			
Draft ("H2O)		0.0	0.0
Fuel Feed (g/min)		24.83	24.94
Air: Tangential	SCFM	3.426	3.426
Axial	SCFM	1.612	1.612
Coal Trans.	SCFM	1.221	1.221
Sorb Trans.	SCFM	0.000	0.000
Pilot	SCFH	5.0	5.0
Aspiration	SCFH	20.0	20.0
Furnace Measurements:			
FR (Btu/hr)		40999	41173
SR		0.97	0.96
Temp: Port 3	°C	1105	1112
Port 40	°C	912	932
Front	°C	321	333
Middle	°C	235	244
Back	°C	194	198
Flue Gas:			
Oxygen (Dry %)		4.06	3.80
CO2 (Dry %)		15.04	15.02
Moisture (%)		7.5	6.1
Dry Mol. Wt.		30.6	30.6
Flow: Wet SCFM		7.580	7.470
Dry SCFM		7.014	7.015
Average Emissions:			
NOx	ppm	481.8	458.6
SO2	ppm	2646.8	2735.9
CO	ppm	196.8	132.4

Sampling Results Summary -- Page 2

TEST RUN ----->	A1	A2	A3	A4
<hr/>				
Test Conditions:				
Fuel	#5 Coal	#5 Coal	Battelle	Battelle
Target FR (Btu/Hr)	45000	45000	45000	45000
Target SR	1.2	1.2	1.2	1.2
Furnace Settings:				
Draft ("H2O)	0.1	0.1	0.0	0.1
Fuel Feed (g/min)	21.90	23.87	23.10	22.87
Air: Tangential SCFM	4.030	4.030	4.030	4.030
Axial SCFM	1.612	1.612	1.612	1.612
Coal Trans. SCFM	1.395	1.395	1.395	1.395
Sorb Trans. SCFM	0.000	0.000	0.000	0.000
Pilot SCFH	5.0	5.0	5.0	5.0
Aspiration SCFH	25.0	25.0	25.0	25.0
Furnace Measurements:				
FR (Btu/hr)	40971	44656	43779	43334
SR	1.30	1.19	1.25	1.26
Temp: Port 3 °C	1106	1117	1134	1133
Port 4U °C	1041	1053	1073	1079
Port A °C	349	342	362	362
Port B °C	321	295	326	315
Port C °C	291	270	297	287
Flue Gas:				
Oxygen (Dry %)	5.90	5.91	6.07	6.12
CO2 (Dry %)	13.71	13.60	13.35	13.28
Moisture (%)	6.2	6.0	5.7	5.6
Dry Mol. Wt.	30.4	30.4	30.4	30.4
Flow: Wet SCFM	8.780	8.829	8.740	8.723
Dry SCFM	8.236	8.299	8.242	8.235
Average Emissions:				
NOx ppm	653.2	632.2	522.9	543.5
SO2 ppm	1005.4	1039.5	1393.7	1311.6
CO ppm	30.0	32.6	26.2	25.0

Sampling Results Summary -- Page 3

Sampling:

Test Run ID A1-M5MM
 Location Port A
 Start Time 1248
 Stop Time 1648
 Sampling Time, min. 240
 Collected DSCF 111.543
 Isokinetic 90%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Antimony	158	46.92	0.200	0.06	4	1.27
Arsenic	2600	772.12	5.00	1.48	2605	773.61
Beryllium	200	59.39	0.100	0.00	200	59.39
Cadmium	28	8.32	0.550	0.16	29	8.48
Chromium	2510	745.40	3.40	1.01	2513	746.41
Lead	4050	1202.73	1.100	0.33	4051	1203.06
Manganese	2400	712.73	11.5	3.42	2412	716.14
Nickel	5500	1633.34	3.50	1.04	5504	1634.38
Selenium	200	59.39	155	46.03	355	105.42

Sampling:

Test Run ID A1-M101A
 Location Port B
 Start Time 1252
 Stop Time 1652
 Sampling Time, min. 240
 Collected DSCF 115.287
 Isokinetic 93%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Mercury	4.09	1.21	13.3	3.95	17	5.16

Sampling Results Summary -- Page 4

Sampling:

Test Run ID A2-N5MM
 Location Port A
 Start Time 0921
 Stop Time 1321
 Sampling Time, min. 240
 Collected DSCF 113.261
 Isokinetic 91%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Antimony	157	46.02	0.100	0.00	157	46.02
Arsenic	2550	747.38	5.00	1.47	2555	748.84
Beryllium	190	55.69	0.100	0.00	190	55.69
Cadmium	28	8.21	0.300	0.09	28	8.29
Chromium	2600	762.03	1.50	0.44	2602	762.47
Lead	3940	1154.77	0.200	0.18	3941	1154.95
Manganese	2200	644.30	11.5	3.37	2212	648.17
Nickel	5680	1664.78	2.75	0.81	5683	1665.56
Selenium	230	67.41	130	38.10	360	105.51

Sampling:

Test Run ID A2-M1014
 Location Port B
 Start Time 0914
 Stop Time 1314
 Sampling Time, min. 240
 Collected DSCF 116.836
 Isokinetic 94%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Mercury	2.49	0.73	13.7	4.02	16	4.74

Sampling Results Summary -- Page 5

Sampling:

Test Run ID A3-M5MM
 Location Port A
 Start Time 0947
 Stop Time 1347
 Sampling Time, min. 240
 Collected DSCF 112.776
 Isokinetic 91%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Antimony	150	44.29	<.100	0.00	150	44.29
Arsenic	5060	1494.17	2.00	0.59	5062	1494.76
Beryllium	240	70.87	<.100	0.00	240	70.87
Cadmium	18	5.32	1.200	0.35	19	5.67
Chromium	1830	540.38	2.30	0.68	1832	541.06
Lead	1460	431.12	1.400	0.41	1461	431.54
Manganese	2800	825.81	13.4	3.96	2813	830.77
Nickel	2100	620.11	2.30	0.68	2102	620.79
Selenium	480	141.74	200	59.06	680	200.80

Sampling:

Test Run ID A3-M101A
 Location Port B
 Start Time 0943
 Stop Time 1343
 Sampling Time, min. 240
 Collected DSCF 116.245
 Isokinetic 94%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Mercury	5.72	1.69	42.8	12.64	49	14.33

Sampling Results Summary -- Page 6

Sampling:

Test Run ID A4-M5MM
 Location Port A
 Start Time 0947
 Stop Time 1347
 Sampling Time, min. 240
 Collected DSCF 112.617
 Isokinetic 91%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Antimony	134	39.67	0.200	0.06	134	39.73
Arsenic	4370	1293.61	2.50	0.74	4373	1294.35
Beryllium	205	60.68	0.100	0.00	205	60.68
Cadmium	17	5.03	0.350	0.10	17	5.14
Chromium	1760	521.00	1.60	0.47	1762	521.47
Lead	1260	372.99	0.650	0.19	1261	373.19
Manganese	2750	814.06	12.4	3.67	2762	817.73
Nickel	1950	577.24	2.00	0.59	1952	577.83
Selenium	480	142.09	155	45.88	635	187.97

Sampling:

Test Run ID A4-M101A
 Location Port B
 Start Time 0944
 Stop Time 1344
 Sampling Time, min. 240
 Collected DSCF 116.086
 Isokinetic 94%

	--- Front Half ---		--- Back Half ---		----- Total -----	
	µg	µg/m ³	µg	µg/m ³	µg	µg/m ³
Mercury	2.88	0.85	35.7	10.57	39	11.42