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*CHARACTERIZING THE STRUCTURE OF
ASH DEPOSITS FROM COAL COMBUSTORS*

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*DEVELOPMENT/TESTING OF AN
INDUSTRIAL-SCALE COAL-FIRED
COMBUSTION SYSTEM*

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MICROFINE COAL FIRING RESULTS FROM A RETROFIT

GAS/OIL-DESIGNED INDUSTRIAL BOILER

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INTRODUCTION/ BACKGROUND

Under U.S. Department of Energy, Pittsburgh Energy Technology Center (PETC) support, the development of a High Efficiency Advanced Coal Combustor (HEACC) has been in progress since 1987 at the ABB Power Plant Laboratories (Rini, et al., 1987, 1988). The initial work on this concept produced an advanced coal firing system that was capable of firing both water-based and dry pulverized coal in an industrial boiler environment (Rini, et al., 1990).

Economics may one day dictate that it makes sense to replace oil or natural gas with coal in boilers that were originally designed to burn these fuels. In recognition of this future possibility, the U.S. Department of Energy, Pittsburgh Energy Technology Center (PETC) has continued to support this program led by ABB Power Plant Laboratories and the Fuels Research Center of Penn State University to develop the HEACC concept. The objective of the current program is to demonstrate the technical and economic feasibility of retrofitting a gas/oil designed boiler to burn micronized coal. In support of this overall objective, the following specific areas were targeted:

- A coal handling/preparation system that can meet the technical requirements for retrofitting microfine coal on a boiler designed for burning oil or natural gas.
- Maintaining boiler thermal performance in accordance with specifications when burning oil or natural gas.
- Maintaining NO_x emissions at or below 0.6 lb/MBtu (~450 ppm)
- Achieving combustion efficiencies of 98% or higher
- Calculating economic payback periods as a function of key variables

The overall program has consisted of five major tasks:

- 1.0 A review of current state-of-the-art coal firing system components.
- 2.0 Design and experimental testing of a prototype HEACC burner.
- 3.0 Installation and testing of a HEACC system in a commercial retrofit application.
- 4.0 Economic evaluation of the HEACC concept for retrofit applications.
- 5.0 Long term demonstration under commercial user demand conditions

This paper will summarize the latest key experimental results (Task 3) and the economic evaluation (Task 4) of the HEACC concept for retrofit applications.

BURNER INSTALLATION AND TESTING IN AN INDUSTRIAL BOILER

The overall objective of this program has been to assess the technical and economic viability of displacing premium fuels with micro-fine coal by retrofitting the previously developed High Efficiency Advanced Coal Combustor (HEACC) to a gas/oil designed industrial boiler. This paper summarizes the work involving the retrofit of a complete micro-fine pulverized coal milling and firing system to an existing 15,000 lb/hr package boiler located in the East Steam Plant of Penn State University. Combustion performance-related objectives included steady state operation on 100% coal while achieving a carbon conversion efficiency of 98%, without increasing NO_x emissions above 0.6 lb/MBtu (~450 ppm). The testing was also designed to show that consistent, reliable operation of entire coal storage/handling and pulverization system could be achieved. Reliable operation of the coal preparation system in concert with satisfactory burner performance would serve as a prerequisite to the demonstration phase of the project.

The HEACC burner was previously tested (Task 2) in the Industrial Scale Burner Facility (ISBF) located at Combustion Engineering's ABB Power Plant Laboratories (PPL) in Windsor, Connecticut. A key objective of the 100 hour burner validation tests at PPL was to fine-tune the burner operating characteristics and demonstrate operation over the range of conditions expected for the field boiler tests. All performance goals were successfully achieved during these ISBF tests. The testing at PPL demonstrated the technical validity of the design improvements incorporated into the second generation HEACC. This burner was then installed as part of a complete coal handling and firing system in Penn State's commercial boiler for a 400 hour proof-of-concept test program (Task 3).

A schematic of the micronized coal preparation/firing system at Penn State is shown in Figure 1. As can be seen, the cleaned coal comes on site and is stored in a large hopper. The coal is crushed and sent via a screw feeder to a micronized coal mill (TCS system). The coal is then micronized to ~80% through 325 mesh (~18 microns MMD) in the TCS mill and pneumatically conveyed to the HEACC burner where it is then burned in the boiler. This boiler is an oil/gas designed Tampella Keeler Model DS-15; a package D-type watertube boiler capable of producing 15,000 lb/hr of saturated steam at 300 psig. It represents a typical gas/oil - designed system with a furnace volumetric heat release of 50,000 Btu/hr ft³, standard for this class of boiler. Furthermore, its design is similar to that of many other manufacturers' (including Combustion Engineering) models.

EXPERIMENTAL TESTING RESULTS

A) OVERVIEW

During the long term test period, the boiler system was operated over a range of operating conditions. Specifically, the boiler was tested over a variety of load ranges, excess air, combustion air damper settings and burner swirl levels. Two coals Brookville Seam and Kentucky were used. Their analyses are summarized in Table 1. During the test period, boiler performance data, emissions data, electric parasitic power and house compressed air consumption data, as well as other data required for the technical and economical analysis of the system were obtained.

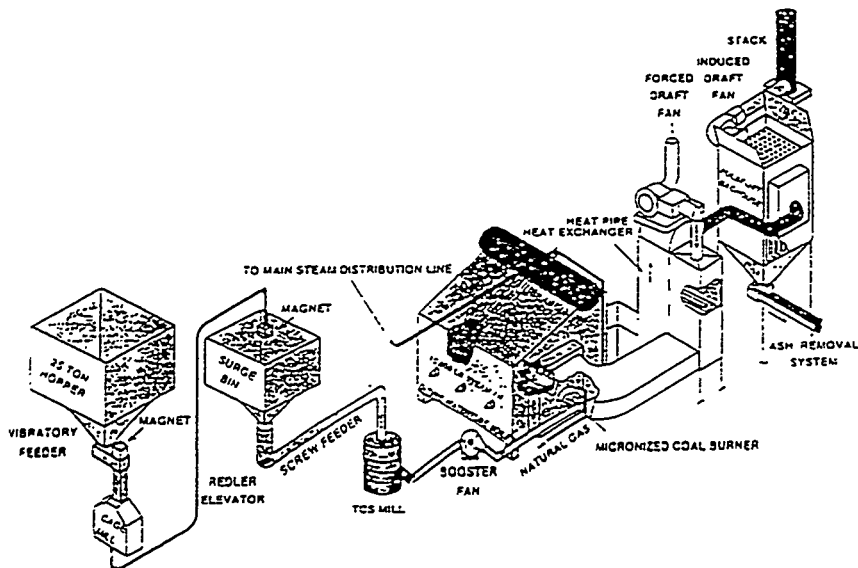


Figure 1 Micronized Coal Combustion System at Penn State

The initial burner tests included a shakedown series of runs using natural gas firing (Jennings, et al., 1994a, 1994b). At the conclusion of baseline natural gas firing, the boiler operation was directed towards hardware optimization (e.g., coal handling/preparation, burner settings) and testing with 100% coal firing. During this phase of the work, a major objective was to obtain consistent, repeatable 100% coal fired runs. This goal, along with minor modifications to the system (discussed in the next section) to increase boiler and carbon conversion efficiency resulted in several short term tests. Subsequently, the chosen hardware configuration was then used during the long term (~400 hr) test program (Task 3).

Table 1 Selected Analyses of the Brookville and Kentucky Coals

	<u>Brookville Seam</u>	<u>Kentucky</u>
Proximate, wt%		
Moisture	8.2	6.8
Volatile Matter	33.1	33.3
Fixed Carbon	55.8	55.4
Ash	2.9	4.5
HHV, Btu/lb	13,260	13,010
Ash Fusion Temp, °F		
IDT	2,820	2,803
ST	+3,000	+3,000
FT	+3,000	+3,000

B) SYSTEM CHARACTERIZATION/MODIFICATIONS

A key objective of the proof of concept testing was to determine the operating characteristics of the complete, integrated system in contrast to the operation of the individual components. Although all of the system components installed at the demonstration boiler host site were proven in either commercial operation or prior testing, the complete system from micro-fine coal production to steam production at this scale had not been previously demonstrated/proven.

The testing at Penn State indicated areas that should be carefully engineered in a commercial design. Furthermore, it was anticipated that if any problems occurred, they would likely be related to the burner (the least developed system component). However, the coal handling/feeding sub-system as it related to boiler system operability proved to be a critical component during initial testing. Some of the key system modifications and operational problems relating to the Penn State boiler are discussed below.

TCS Mill

The TCS mill and booster fan operated well without constant supervision. Initial system testing, however, revealed a coal settling problem in the mill outlet duct. This problem was corrected by a specially designed diffuser/transition section fitted to the mill exit. In addition, a detailed experimental study was carried out to characterize the effect of mill air flow rate and mill speed, on coal particle size distribution (PSD) and top size for the two coals tested. This was done as part of an effort to determine the milling conditions necessary to reduce the coal PSD and top size in order to achieve maximum coal combustion efficiency. In addition, the results were used to evaluate the feasibility for external classification to reduce the coal top size. The mill speed was a most important parameter to obtain the desired coal PSD. The results from these tests were used to optimize the mill settings for coal fineness during the experimental test program. Table 2 presents typical optimized mill operating conditions.

Table 2 Mill Performance Summary

- Typical mill air flow rate: 370-400 acfm
- Typical coal feed rate: 16.5- 18.5 lb/min

<u>Particle Size (microns)</u>	<u>Brookville Seam Coal</u>	<u>Kentucky Coal</u>
Top Size	190-300	250-275
D ₈₀	50-70	50-70
D ₅₀	25-30	25-30

Furnace Modifications

The furnace geometry was slightly altered during the test program by installing a ceramic wall at the exit of the radiant section of the boiler. The basic idea was to improve carbon burnout by making better use of the entire boiler volume through changing the gas patterns and temperature profile in the boiler. This was done because analytical (CFD) modeling showed that the flame was skewed from the burner to the furnace outlet and that the entire furnace volume was not being effectively used (Model results were subsequently verified by suction pyrometry).

Boiler System Operability

During the initial testing period, a number of operational problems involving the coal handling and boiler system were encountered. They were primarily related to the weather (cold, snow), the coal (particle size, moisture content), the burner/boiler system (unstable/ low u.v. flame scanner signal), or mechanical difficulties (feedwater pump, steam valves). With the exception of the coal handling problems caused by high moisture, these problems were all addressed and solved during the shakedown test series. The coal moisture problems will be fully addressed prior to beginning the 1000 hour demonstration test (Task 5).

C) SUMMARY OF EXPERIMENTAL RESULTS

Under the 400 hour test program, Brookville Seam and Kentucky coals were evaluated, the furnace geometry was modified by installing a ceramic wall, two coal guns (the RO-II with and without a coal deflector/accelerator and the I-Jet) were tested, and the operating conditions

and without a coal deflector/accelerator and the I-Jet) were tested, and the operating conditions (excess air and firing rate) were varied. During the course of the long term coal only tests, no support fuel was required and the burner operated with excellent ignition stability. A typical summary of the microfine coal firing (both coals) is given in Table 3.

Table 3 Microfine Coal Firing Results

Boiler Operation:

Steam Flow Rate (lb/hr)	13,240
Boiler Efficiency (%)	84.1 (3% O ₂)

Combustion Performance

Carbon Conversion Efficiency (%)	95.3
NO _x at 3% O ₂ (ppm)	413 (0.56 lb/MBtu)
Burner Pressure Drop (in H ₂ O)	8

During this test program, key performance variables were monitored in detail: boiler efficiency, combustion efficiency, and NO_x emissions. A summary of the results involving these parameters follows.

Boiler Thermal Performance

Boiler thermal performance when firing micro-fine coal was essentially comparable to that achieved when firing natural gas. In fact, because of the greater latent heat loss when burning natural gas (greater formation of water due to higher hydrogen content), firing micro-fine coal actually gave slightly higher boiler efficiencies despite the need to run at higher excess air levels.

During the relatively short operating periods, usually less than 16 hours, ash deposits did not cause significant changes to the boiler thermal performance. It is recognized, however, that longer term operation could result in greater build-up of ash deposits which could impact heat transfer. Because of the relatively short duration of the tests, any build-up of ash deposits would slough off when the boiler was shut down. A better test of the possible impact of ash deposits will occur during the long term demonstration phase of the work (Task 5.0).

NO_x Emissions

The NO_x emissions target was 0.6 lb NO_x per million Btu fired; this translates to about 450 ppm at 3% O₂. Testing with 100% microfine coal showed that this target was achieved (in general a NO_x emissions value of 0.56 lb NO_x per million Btu was routinely met) while meeting nearly all other required conditions. It is acknowledged that the optimum conditions for low NO_x will generally exacerbate carbon conversion efficiencies. Indeed, this was the case with the HEACC burner and the challenge was to find a reasonable balance between meeting the NO_x target while not aggravating the carbon conversion efficiency.

Combustion Efficiency

The target for combustion efficiency was 98%. The highest combustion efficiency obtained during the test program was slightly over 96%. However, this value was not compatible with meeting the NO_x target, and was not able to be routinely repeated. A value of 95% combustion efficiency was able to be routinely achieved, and was compatible with meeting the NO_x target.

Considerable effort was spent in trying to determine how combustion efficiency might be improved to meet the target. The challenge to meet the combustion efficiency target of 98% is, indeed a very difficult one. The bulk boiler residence time is about 0.7 seconds. Further complicating the task is the aspect ratio of the boiler, i.e. the length of the boiler is not very much greater than its height or width (approximately 8 ft long x 8 ft high x 6 ft wide). It is

aggravates the situation. Burner modifications are being looked at which might increase the particle residence time.

Coal particle size distribution was also evaluated, the premise being that carbon content must be directly proportional to particle size. While the larger particle size fraction of the collected particulate (fly ash) did contain higher carbon contents than the smaller size fractions, the differences were not as great as expected. For example, it would not be possible to dramatically reduce the carbon content of fly ash by eliminating coal particles larger than 150 microns.

SYSTEM ECONOMICS

This phase of the work involved an economic evaluation of coal firing for existing small industrial boiler installations. In addition to a base case evaluation (the 15,000 lbm/hr natural gas fired Penn State boiler), various economic sensitivity studies which provide insight into the economics for other unit sizes, fuel price scenarios, capacity factors and other variables were carried out. The primary objective of this analysis was to determine how the coal option compares with natural gas firing on an annual basis. With coal firing the capital costs for the retrofit modifications as well as some additional operating and maintenance costs must be justified by the savings in fuel costs. The evaluation summarized here defines the incremental costs and savings on an annual basis as a result of the use of coal as a substitute for natural gas firing. The first year incremental operation and maintenance cost savings and the total retrofit capital requirement were then used to determine a simplified payback period. The details of the data and results have been summarized in a recent publication (Patel, et al., 1995).

KEY RESULTS FROM THE ECONOMIC EVALUATION

A series of economic comparisons were carried out for the base case and other systems involving different economic input parameters. For these studies a range of differential fuel costs were used, and other sensitivity studies were carried out to determine the effect of unit size, annual operating time, and carbon heat loss on simplified pay back time. Figures 3 to 5 show the results of these sensitivity studies. In addition to differential fuel costs (see Fig. 3), other sensitivity variables studied were shown to have significant effects on payback period. As shown in Fig. 4, increasing unit size is shown to quickly improve the economics. Also, as shown in Fig. 5, changes in the annual operating time from 4000 to 8000 hrs/yr showed significant effects on payback period. Typically industrial boilers have very high capacity factors (the base case for this study used 7000 Hrs/yr (equivalent to an 80 percent capacity factor)). Fig. 8 is of most interest as it shows that variations in carbon heat loss (combustion efficiency) have no significant effect on payback period for the range studied (2 to 6%).

Although this analysis was done relative to natural gas as the base fuel, the results can also be generally applied to oil firing as well. By knowing the differential fuel cost the payback period can be approximated from the attached curves. Although boiler efficiency with oil firing is typically about 5 percent better than with natural gas, the effect on payback period is relatively insignificant as was shown by the results of the carbon heat loss sensitivity study.

CONCLUSIONS/ RECOMMENDATIONS

The following specific conclusions are based on the results of the coal fired testing at Penn State and the initial economic evaluation of the HEACC system:

- A coal handling/ preparation system can be designed to meet technical requirements for retrofitting micro-fine pulverized coal.

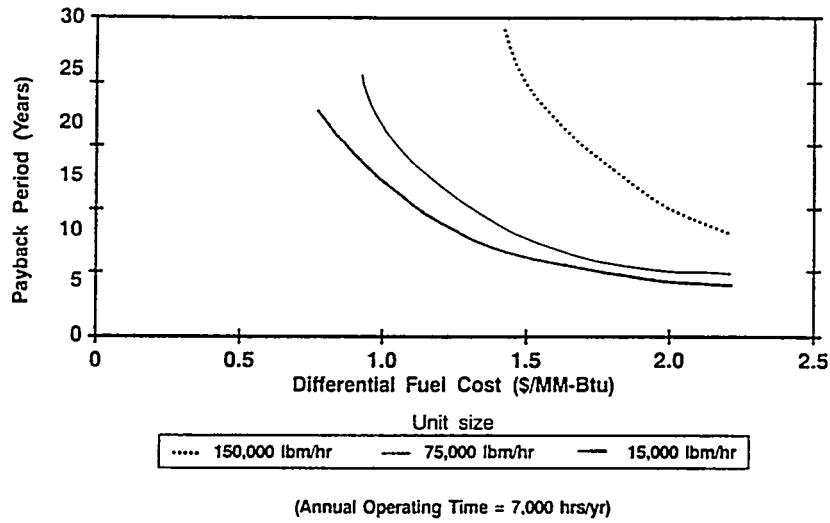


Figure 3 Payback Period as a function of Differential Fuel Cost and Unit Size

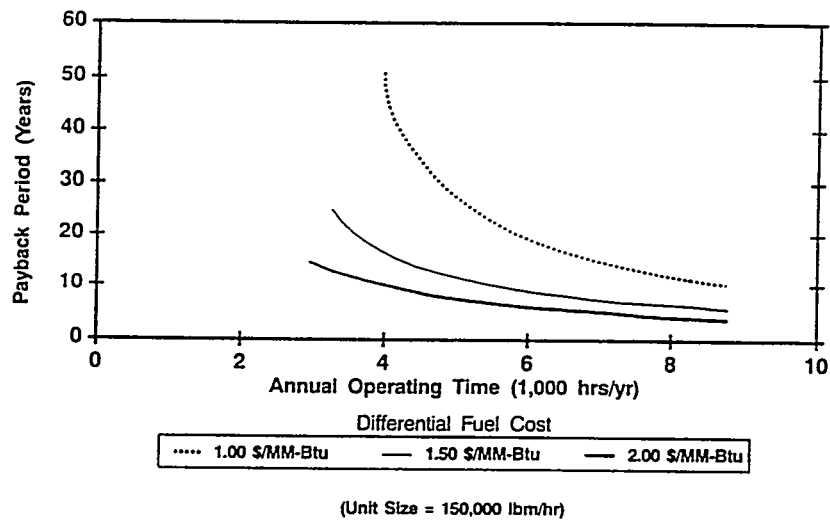


Figure 4 Payback Period as a function of Annual Operating Time

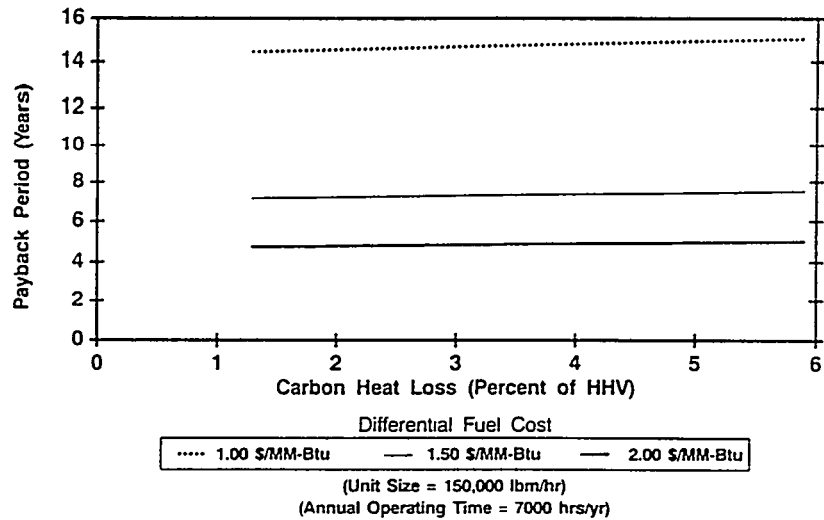


Figure 5 Payback Period as a function of Carbon Heat Loss

- The boiler thermal performance met requirements
- Combustion efficiencies of 95% could be met on a daily average basis, somewhat below the target of 98%
- NOx emissions can meet the target of 0.6 lb/million Btu
- The economic payback was very sensitive to fuel differential cost, unit size, and annual operating hours

As a result of recent long term tests using micronized coal (in another program), Penn State has experienced some convective pass ash deposition problems. To alleviate this problem they are planning to install additional soot blowers. Also, as a result of problems encountered during the 400 hour testing, the following modifications are planned for the Penn State system:

Coal feeding improvements

- a) Improved raw coal/ storage and transport
- b) Redesign/installation of a surge bin bottom
- c) Installation of a gravimetric feeder

Monitoring of ash deposit effects

- a) Air sparge/soot blower systems
- b) Monitoring effects on heat transfer in the furnace and the convective pass
- c) The use of ash deposition probes

In addition, ABB CE plans to modify the burner for more precise aerodynamic control of the fuel and air streams to improve the combustion efficiency and NOx emissions. Based on the results summarized in this paper the ABB/Penn State team and DOE/PETC have decided to conduct a 1000 hr demonstration (Task 5) of this program; it is currently scheduled to begin in July 1995.

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*DEVELOPMENT/TESTING OF A COMMERCIAL-SCALE
COAL-FIRED COMBUSTION SYSTEM*

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*DEVELOPING COAL-BASED FUEL
TECHNOLOGIES FOR DOD FACILITIES*

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COMBUSTION CHARACTERIZATION OF BENEFICIATED COAL-BASED FUELS

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Contract No. DE-AC 2289 PC 88654

INTRODUCTION

The Pittsburgh Energy Technology Center (PETC) of the U.S. Department of Energy is sponsoring the development of advanced coal-cleaning technologies aimed at expanding the use of the nation's vast coal reserves in an environmentally and economically acceptable manner. Because of the lack of practical experience with deeply beneficiated coal-based fuels, PETC has contracted Combustion Engineering, Inc. to perform a multi-year project on "Combustion Characterization of Beneficiated Coal-Based Fuels."

The objectives of this project include: 1) the development of an engineering data base which will provide detailed information on the properties of Beneficiated Coal-Based Fuels (BCFs) influencing combustion, ash deposition, ash erosion, particulate collection, and emissions; and 2) the application of this technical data base to predict the performance and economic impacts of firing the BCFs in various commercial boiler designs.

The technical approach used to develop the data base includes: bench-scale fuel property, combustion, and ash deposition tests; pilot-scale combustion tests, and full-scale combustion tests. Subcontractors to CE to perform parts of the test work are the Massachusetts Institute of Technology (MIT), Physical Science Inc. Technology Company (PSIT), and the University of North Dakota Energy and Environmental Research Center (UNDEERC).

To date, twelve beneficiated coal-based fuels have been acquired through PETC and tested at ABB Power Plant Laboratories Fireside Performance Test Facility (FPTF). These fuels included products from the micro-bubble flotation (Feeley, et al, 1987), spherical oil-agglomeration (Schaal, et al, 1990) selective micro-agglomeration (Corser, et al, 1992) and advanced froth flotation (Harrison, et al, 1992) processes. The results from these fuels indicate that firing the BCFs improved furnace heat transfer and fly ash erosion compared to their respective feed coals (Chow, et al, 1992). The predicted boiler performance and economic impacts when firing similar fuels in a 560 MW coal-designed and a 600 MW oil-designed unit showed good results (Hargrove, et al, 1994). However, there are still various technical aspects that need to be addressed for the effective utilization of BCFs. The beneficiated products are usually in wet filter cake form, they must be prepared in a fuel form that can be handled and re-dispersed prior to firing. The preparation process can change the original fuel particle size and association of inorganic particles, and hence can affect fly ash formation and deposition behaviors. Also, it is not clear how much of the improved performance is associated with grinding alone and how much of the benefit is attributed to the advanced coal cleaning process.

This paper will discuss the results from a series of combustion test runs recently conducted in the FPTF to address the effect of fuel fineness on performance. A conventionally cleaned at the mine Pittsburgh No. 8 was acquired and prepared at standard pulverized-coal fuel grind (70% through 200 mesh), fine grind (90% through 200 mesh) and ultra-fine grind (three fuel fineness. The three fuels were tested at firing rates ranged from 3.0×10^6 Btu/h to 4.0×10^6 Btu/h, under no staging and staged low NOx firing conditions.

RESULTS

Test Fuel

The ASTM analyses of the Pittsburgh No. 8 test coal is shown in Table 1. In general, the fuel and ash properties of this coal are consistent to those of typical Pittsburgh No. 8 feed coals previously evaluated in this program. It has approximately 2 % total sulfur. The ash fusion temperatures were relatively low to moderate, and moderate to high iron content in the ash.

Table 1

ASTM ANALYSES OF PITTSBURGH No. 8 COAL

Quantity	Pittsburgh No.	Quantity	Pittsburgh No.
Proximate, wt. %		Ash Fusion Temp., °F	
Moisture	3.4	I. T.	2310
Volatile Matter	33.3	S. T.	2420
Fixed Carbon	56.5	H. T.	2480
Ash	6.8	F. T.	2530
Ultimate, wt. %		Ash Composition, wt%	
Hydrogen	5.0	SiO ₂	47.8
Carbon	73.5	Al ₂ O ₃	25.8
Sulfur	1.8	Fe ₂ O ₃	16.8
Nitrogen	1.5	CaO	2.8
Oxygen	8.0	MgO	0.7
Ash Loading, lb/10 ⁶ Btu	4.97	Na ₂ O	0.4
HHV, Btu/lb	13,673	K ₂ O	1.3
		TiO ₂	1.1
		P ₂ O ₅	0.2
		SO ₃	2.5

The test coal was prepared in three grinds to provide a wide range of fuel fineness for evaluation. The standard (70% through 200 mesh) and fine (90% through 200 mesh) grinds were prepared in a ABB-CE size 271 bowl mill, and the ultra-fine (100% through 200 mesh) grind coal was prepared in a roller mill equipped with a turbine classifier. The resulting particle size distributions and mass mean diameter for each fuel fineness are shown in Figure 1.

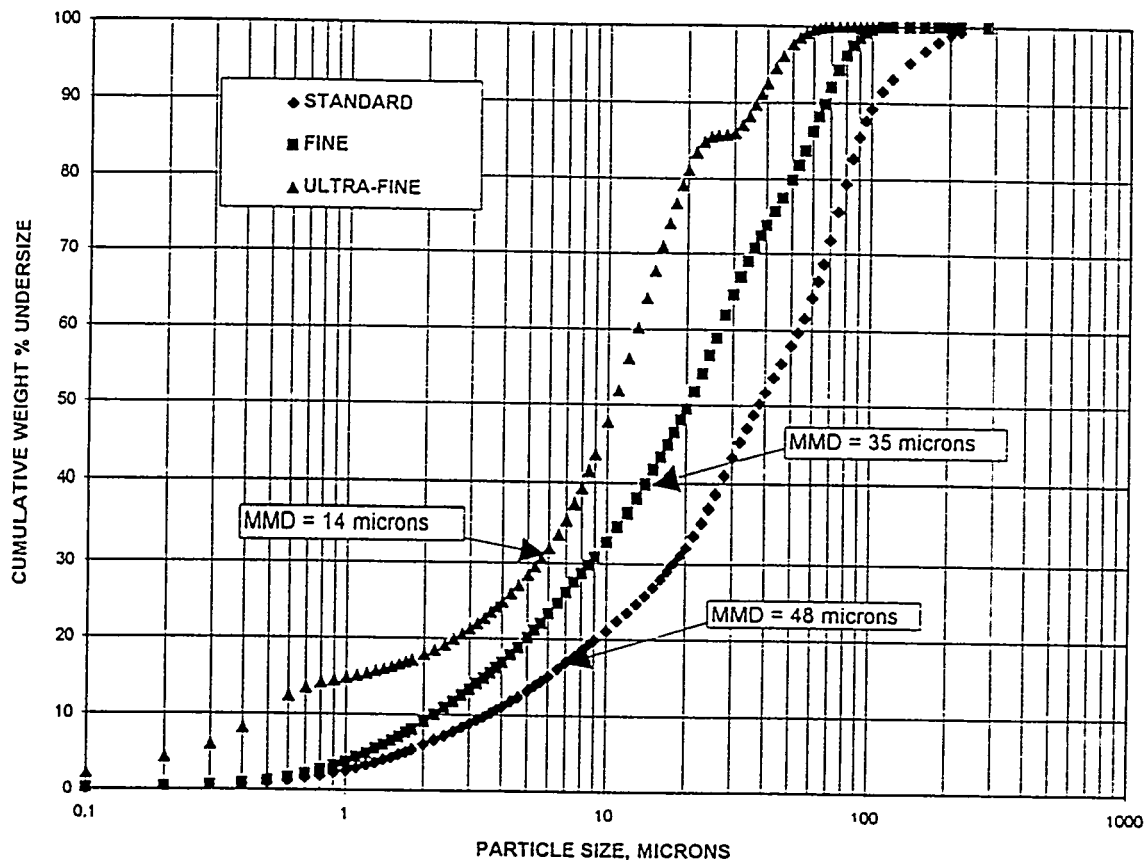


Figure 1. Particle size distributions of the standard, fine and ultra-fine grind Pittsburgh No. 8 fuels

Combustion Characteristics

In general, good, stable flames were obtained firing the Pittsburgh No. 8 at the three fuel fineness under standard and staged firing conditions. In all cases, carbon conversions improved with finer grind fuels.

A summary of the carbon conversions at the lower furnace of the FPTF is shown in Table 2. In all test runs, carbon conversions were greater than 99% at the FPTF stack exit. Carbon conversions at the lower furnace were significantly higher firing the finer grind fuels than the standard grind at either unstaged or staged firing conditions. However, the ultra-fine did not show significant improvement over the fine grind. During ultra-fine firing, the fine particles tended to agglomerate together and to form a scale on the feed system walls, resulting in occasional pulsing flame.

Table 2

Carbon Conversions of Pittsburgh No. 8 in The FPTF Lower Furnace

Fuel Fineness	Firing Rate, 10 ⁶ Btu/h	Burner Stoichiometry	Carbon Conversion, %
Standard	4.0	1.2	95.6
	3.7	0.85	89.2
	3.0	0.6	88.1
Fine	4.0	1.2	99.3
	3.7	0.85	96.5
	3.0	0.6	89.5
Ultra-fine	4.0	1.2	99.2
	3.7	0.85	97.6
	3.0	0.6	96.8

Furnace Slagging

The furnace slagging characteristics of the Pittsburgh No. 8 coal significantly improved with finer grind fuels. A summary of the waterwall heat flux test results is shown in Table 3. The firing rate for the two staged conditions was reduced in anticipation of worsened furnace slagging performance. Previous test results from the FPTF firing a similar Pittsburgh No. 8 coal have shown furnace deposits developed under staged firing conditions were more tenaciously bonded to the waterwall panels (Chow, et. al., 1994).

Table 2

Heat Flux Summary of Beneficiated Micro-Agglomerate Fuels

Fuel Fineness	Firing Rate 10 ⁶ Btu/h	Burner Stoichiometry	Furnace Temp., °F	Avg. Heat Flux, Btu/h/ft ²	Heat Flux Recovery, %
Standard	4.0	1.2	2990	64,104	37
	3.7	0.85	2900	65,348	41
	3.0	3.0	2740	44,217	67
Fine	4.0	1.2	2970	69,152	74
	3.7	0.85	2920	75,558	83
	3.0	0.6	2720	55,946	89
Ultra-fine	4.0	1.2	2960	83,271	77
	3.7	0.85	2920	96,687	100
	3.0	0.6	2720	51,579	92

Firing the two finer grind fuels resulted in higher average heat fluxes than with the standard grind. These results are most likely caused by the more rapid heat release rate from burning smaller coal particles. There was no noticeable difference in deposit coverage or deposit thickness developed from firing either fuel grinds. Thin, molten deposits were developed at all firing conditions with each fuel. However, deposit removal by soot blowing significantly improved firing the two finer grind fuels. Waterwall heat flux recoveries after soot blowing were significantly higher with the two finer grinds than the standard grind under similar firing and flame temperature conditions (Figure 2).

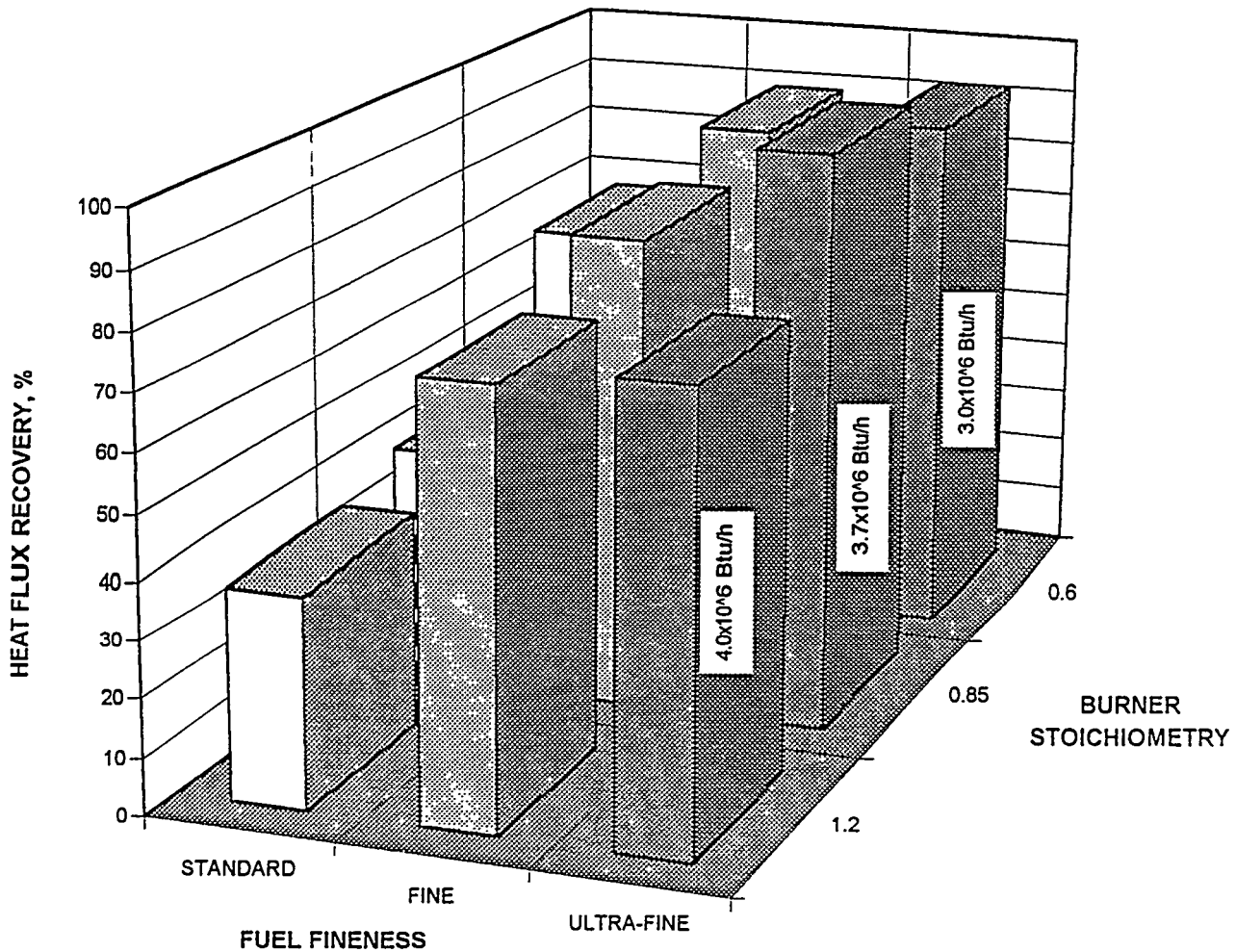


Figure 2 Effect of Fuel Fineness on Waterwall Deposit Cleanability

Convection Pass Fouling

The fouling characteristics of the Pittsburgh No. 8 coal was not affected by the fuel fineness. The FPTF results showed all three grinds had low fouling potentials at the gas temperature range tested (2100°F to 2350°F). The deposit buildup rates in the convective pass were low. Soot blowing was not required over a 12-hour period. Deposits developed were sintered, and could be easily removed from the tube surfaces. There was little difference in fouling characteristics between firing the fuels under standard or staged low NO_x firing conditions.

Fly Ash Erosion

Fly ash erosion rate decreased with finer grinds. However, the reduction was relatively small compared to the BCF test results. As illustrated in Figure 3, the normalized erosion rate was reduced only by 6% and 15%, fine grind and ultra-fine grind, compared to standard grind.

The above results would indicate that the significant improvements observed firing the BCFs (over 60%) are mostly due to beneficiation. The cleaning process was effective in removing the larger inorganic particles and more erosive constituents such as quartz in the fuels.

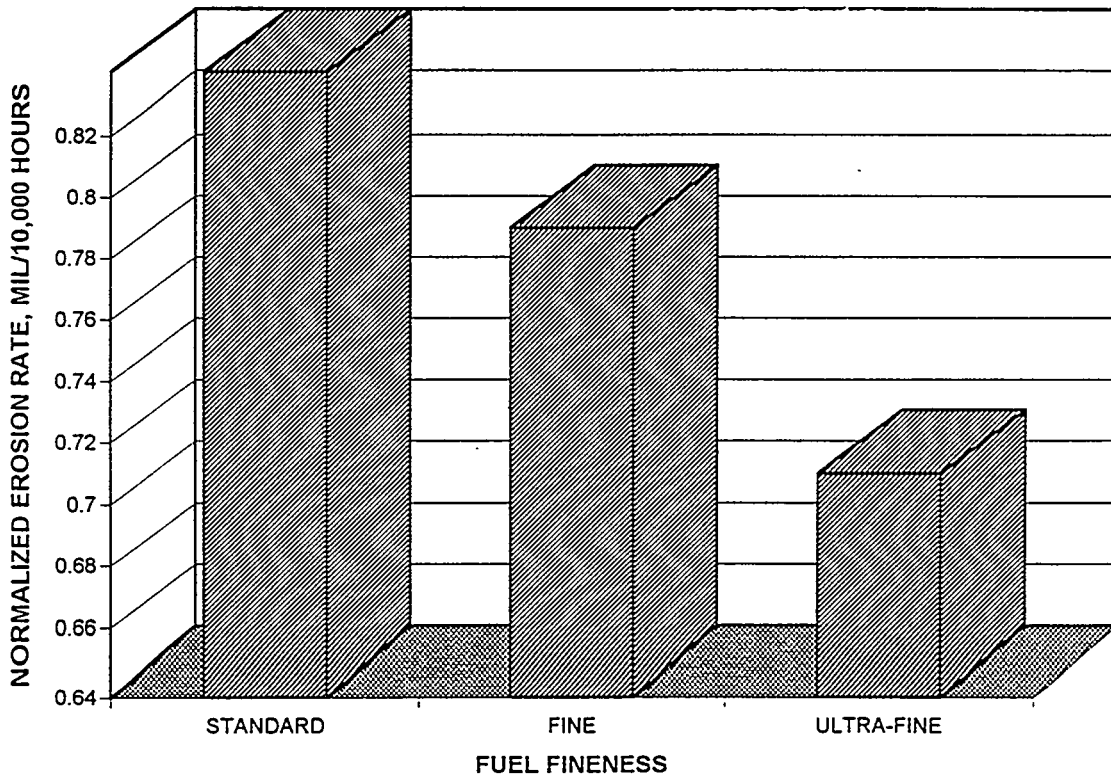


Figure 3 Effect of Fuel Fineness on Fly Ash Erosion Rates

CONCLUSIONS

Many of the beneficial effects associated with firing BCFs were observed with firing finer grind fuels. The combustion and carbon conversions of Pittsburgh No. 8 coal improved with finer fuel grinds at either unstaged or staged firing conditions. Furnace slagging also show significant improvement. Although similar waterwall deposits were generated between the three fuel grinds, deposit cleanability by soot blowing was significantly improved. Firing the finer grind fuels also resulted in higher average heat flux in the lower furnace. Improvement in ash fouling was not detected due to the low fouling characteristics of the test coal. Fly ash erosion was also reduced firing the finer grind fuels. However, the improvement was not as significant as with the BCFs.

A technical and economic evaluation of firing finer grind fuels in commercial units should be undertaken to compare with the BCF results.

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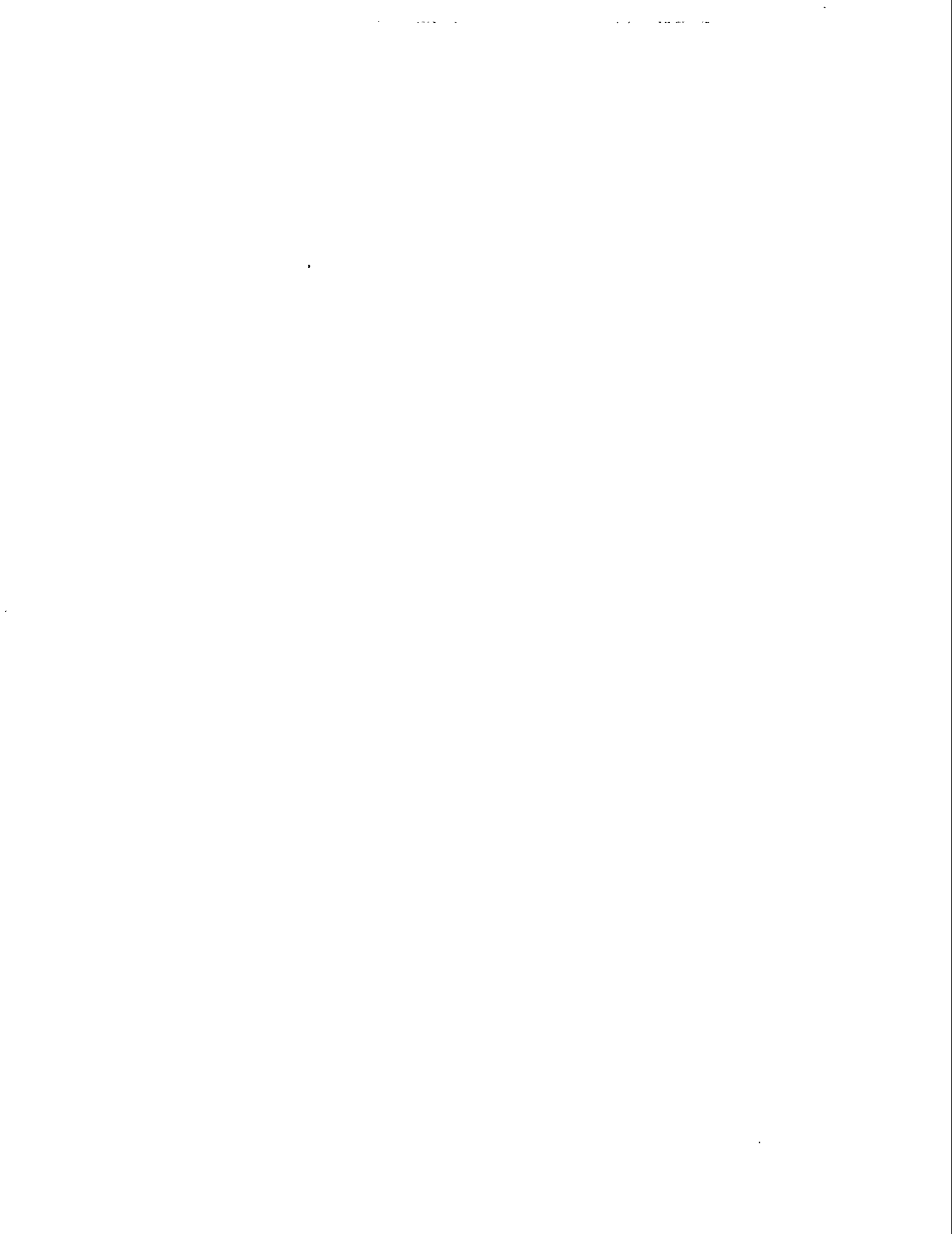
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DEVELOPMENT OF A PHENOMENOLOGICAL MODEL

FOR COAL SLURRY ATOMIZATION

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BACKGROUND AND INTRODUCTION

Highly concentrated suspensions of coal particles in water or alternate fluids appear to have a wide range of applications for energy production. For enhanced implementation of coal slurry fuel technology, an understanding of coal slurry atomization as a function of coal and slurry properties for specific mechanical configurations of nozzle atomizers should be developed.

GOALS AND OBJECTIVES OF PROPOSED PROGRAM

As has been demonstrated, the complexity of coal slurries has prohibited obtaining a reasonable understanding of coal slurry atomization. The complex rheological behavior of many types of coal slurries requires an extensive characterization for each type of coal, each type of coal particle size distribution, chemical additive composition, and coal concentration. The relationship of these properties to the atomization process is therefore unclear and the ability to make a prediction as to whether a specific slurry will atomize well or whether a specific coal is suitable for combustion applications does not exist unless extensive testing is performed for each slurry. The overall objective of this program is to develop a phenomenological model for coal slurry atomization which has the capability of distinguishing atomization properties for different coal slurries. In order to avoid complications due to mechanical factors, the model will be developed for one type of air blast atomizer configuration.

Subsidiary technical objectives include:

- Ascertain the effect of physio-chemical properties of coal slurries on atomization.
- Ascertain the statistical influence on coal slurry atomization.
- Predict the atomized drop size of a coal slurry from a few basic coal and slurry properties.

ATOMIZATION MODELING (PHENOMENOLOGICAL APPROACH)

In order to model spray atomization of coal slurry fuels it is important to extract those elements of liquid fuel atomization which are most important. These are listed as follows:

* Particle Size Distribution of spray droplets

* Mechanical Parameters

Atomization air or steam

Orifice size

Nozzle velocity of air

Exit velocity of liquid

Nozzle pressure

* Physical Characteristics of Liquid Fuel

Viscosity

Density

Gas-liquid interfacial tension

The next step is to examine the theoretical basis for jet breakup and atomization. The first step is to analyze the basic hydrodynamics of liquid jets.

General Theory of the Break Up of Liquid Masses

For small amplitude perturbations, the Navier Stokes Equation can be replaced by

$$\delta V / \delta t = - \nabla p / \rho + \nu \nabla^2 V \quad (1)$$

where ν is the kinematic viscosity, i.e. $\eta = \rho \nu$

With low velocities and the low viscosity

$$\delta V / \delta t \sim V / \tau \sim a / \tau^2$$

$$\nabla p / \rho \sim p / a \rho$$

where τ is a characteristic time and a the characteristic dimension, i.e. jet radius. Noting that $P\sigma = \sigma / a$ is the pressure due to surface tension.

$$\delta V / \delta t \sim a / \tau^2 \sim P\sigma / \rho a \sim \sigma / \rho a^2$$

which gives a break up time τ of

$$\tau \sim \sqrt{\rho a^3 / \sigma} \quad (2)$$

The intact length of the jet with velocity U_0 is given by

$$L \sim \eta_0 \tau$$

With low velocities and large viscosity,

$$\delta V / \delta t \sim 0$$

$$\nu \nabla^2 V \sim \nu V / a^2 \sim \nu / a\tau$$

$$\nu V / a^2 \sim \nu / a\tau \sim P\sigma / \rho a \sim \sigma / \rho a^2$$

yielding a break up time τ

$$\tau \sim \rho a / \sigma \sim \eta a / \sigma$$

The analysis presented here is based on techniques described in Levich.⁽¹⁾

Intact length is $L \sim U_0 \tau$

For high air velocities, V_A the pressure due to the air P_A is important, i.e.

$$P_A \sim \rho_A V_A^2 \gg P\sigma.$$

If the viscosity, ν is small

$$\delta V / \delta t \sim a / \tau^2 \sim P_A / \rho a \sim \rho_A V_A^2 / \rho a \quad (3)$$

$$\tau \sim a / V_A \sqrt{\rho / \rho_A}$$

where ρ_A is the air density.

Intact length is $L \sim \tau V_A \sim \sqrt{\rho/\rho_A} a$

For large viscosity,

$$\nu / a\tau \sim \rho_A V_A^2 / \rho a$$

$$\tau \sim \nu \rho / \rho_A V_A^2 \sim \eta / \rho_A V_A^2 \quad (4)$$

Intact length of jet $\sim \tau V_A = \mu / \rho_A V_A$

These phenomenological estimates provide the necessary relationship to develop a phenomenological model since the underlying breakup mechanisms are delineated under varying conditions that can occur in spray atomization. The next step in the analysis considers the break up of drops formed from jet disintegration.

Drop Break Up

The case Non-Turbulent Flow is considered first. As the drop impinges on the air stream, it is flattened as shown in Figure 1.

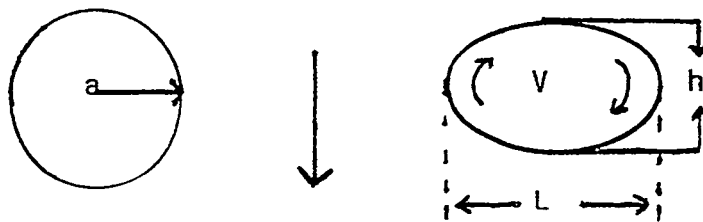


Figure 1.

The flattened drop will develop a minimum surface tension pressure on the flattened end

$$(P_\sigma)_{\min} \sim \sigma h/l^2 .$$

If the internal pressure generated by the fluid in the drop circulating with a velocity V exceeds $(P_\sigma)_{\min}$ then the drop will rupture. The force exerted by the external air on the

drop is given by $\rho_A V_A^2$ and that exerted by the circulating fluid on the drop surface is ρV^2 . These must balance and equal the minimum surface tension.

$$\rho V^2 \sim \rho_A V_A^2 \sim \sigma h/l^2$$

If v is the volume of the drop then

$$l^2 h = v$$

$$l^2 = v/h$$

$\Delta p \sim \sigma/h \sim \rho_A V_A^2$ is the work done by compressing the drop which is equal to the increase in surface energy.

Therefore,

$$h = \sigma / \rho_A V_A^2$$

It follows that

$$\rho_A V_A^2 \sim \sigma / v h^2 \sim \sigma^3 / v \rho_A^2 V_A^4 = \sigma^3 / (4/3\pi) a_{cr}^3 \rho_A^2 v_A^4$$

or

$$(4/3\pi) a_{cr}^3 \sim \sigma^3 / \rho_A^3 U_A^6$$

$$a_{cr}/a \sim \sigma / \rho_A V_A^2 a \sim We^{-1} \quad (5)$$

What this means is that drops greater than a_{cr} in size will break up until the drop size is less than a_{cr} .

For turbulent flow, the results are modified as follows:

$$a_{cr}/a \sim (We)^{-3/5} (\rho_A / \rho)^{2/5} \quad (6)$$

In the next section, progress in determining the extensional viscosity of fluid are discussed.

EXTENSIONAL VISCOSITY MEASUREMENTS

The definition of extensional viscosity can be visualized in the simple case of the uniform extension of a cylinder of an incompressible Newtonian fluid along its axis. In a cylindrical coordinate system where z is oriented along the cylinder axis and the radial dimension is r , we may write the following for the case of symmetry about the ϕ direction:

$$\sigma_{rr} = -p + 2\mu \frac{\delta v_r}{\delta r} \quad (7)$$

$$\sigma_{\phi\phi} = -p + 2\mu \frac{v_r}{r} \quad (8)$$

$$\sigma_{zz} = -p + 2\mu \frac{\delta v_z}{\delta z} \quad (9)$$

For the stress equation where p is the hydrostatic pressure, and σ_{rr} , $\sigma_{\phi\phi}$, and σ_{zz} are the extra stresses normal to planes perpendicular to the r , ϕ , and z axis, respectively. The equation of continuity for an incompressible fluid is given by

$$\frac{v_r}{r} + \frac{\delta v_r}{\delta r} + \frac{\delta v_z}{\delta z} = 0 \quad (10)$$

We now note that

$$\sigma_{rr} + \sigma_{\phi\phi} = -2p + 2\mu \left(\frac{v_r}{r} + \frac{\delta v_r}{\delta r} \right) = -2p - 2\mu \frac{\delta v_z}{\delta z} \quad (11)$$

but since for equilibrium, $\sigma_{rr} = \sigma_{\phi\phi} = 0$, we obtain

$$p = -\mu \frac{\delta v_z}{\delta z} \quad (12)$$

Combining equations to eliminate p yields

$$\sigma_{zz} = 3\mu \frac{\delta v_z}{\delta z} = n_e \frac{\delta v_z}{\delta z} \quad (13)$$

where n_e is defined as the extensional viscosity, which is 3μ for a Newtonian fluid. There is evidence that the extensional viscosity can have an effect on atomization.^(2,3)

Adelphi Extensional Viscometer

The Adelphi extrusion rheometer was modified to provide extensional flow. The viscometer is comprised of a testing chamber approximately 2 feet in length and 2 inches in diameter, followed by a 15" tube of diameter 0.19 inches. The diameter ratio of 10:1 provides adequate convergence for extensional effects. The sample is placed in the testing chamber. The testing chamber cover is fastened to the chamber wall and extrusion pressure is adjusted to an initial pressure. Samples are extruded and weighed and flow rates determined. The pressure is increased as determined by sample viscosity. Characteristic pressure versus shear rate curves are drawn and evaluated. From the resultant curve, the power law index, n , and the viscosity are determined. The extensional viscosity is determined using Binding's ⁽⁴⁾ analysis which subtracts the pressure losses in the extrusion tube which is viscometric in nature, leaving data on the entry pressure to the contraction which is directly related to the extensional viscosity.

In order to determine the effectiveness of the extensional viscometer, a verification was made using Binding's analysis to determine power law behavior of extensional viscosity. Figure 2 shows a log plot of the entry pressure vs. flow rate. Analysis indicates a slope of 1.2 consistent with the Newtonian calibration fluid.

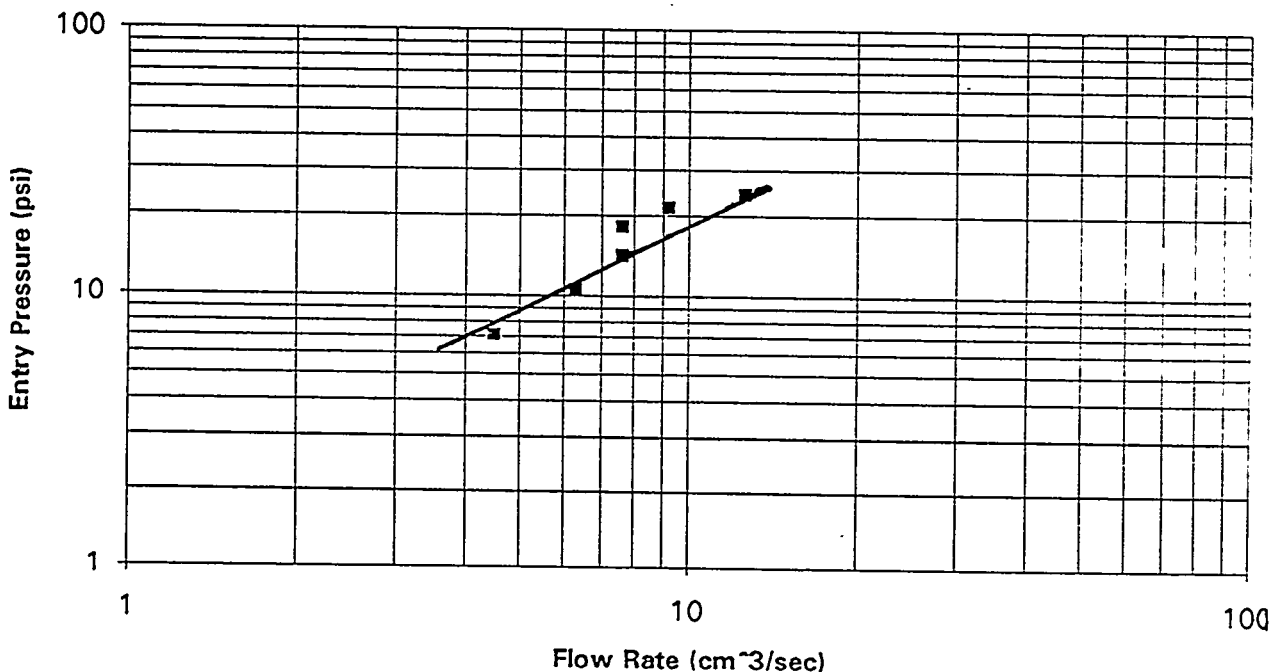


Figure 2. Log Plot of Entry Pressure vs. Flow Rate - Calibration Curve

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KRAKÓW CLEAN FOSSIL FUELS AND ENERGY EFFICIENCY PROJECT

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The Support for Eastern European Democracy (SEED) Act of 1989 directed the U.S. Department of Energy (DOE) to undertake an equipment assessment project aimed at developing the capability within Poland to manufacture or modify industrial-scale combustion equipment to utilize fossil fuels cleanly. This project is being implemented in the city of Kraków as the "Kraków Clean Fossil Fuels and Energy Efficiency Project." Funding is provided through the U.S. Agency for International Development (AID). The project is being conducted in a manner that can be generalized to all of Poland and to the rest of Eastern Europe [1].

The historic city of Kraków has a population of 750,000. Almost half of the heating energy used in Kraków is supplied by low-efficiency boilerhouses and home coal stoves. Within the town, there are more than 1,300 local boilerhouses and 100,000 home stoves. These are collectively referred to as the "low emission sources" and they are the primary sources of particulates and hydrocarbon emissions in the city and major contributors of sulfur dioxide and carbon monoxide.

PROJECT DESCRIPTION

The project plan includes three phases which have been developed through extensive working contacts between DOE and Polish representatives. Phase I was planned to gather information about the characteristics of the existing sources, the costs and performance expectations for some selected pollution reduction options, options for municipal actions promoting pollution reduction, and relative cost-effectiveness of options. In the second phase, a series of public meetings was conducted to inform U.S. and Polish companies about the program. Phase III is the largest part of the program. In this phase, 50% cost-share funding is provided to develop U.S./Polish joint ventures producing goods or services addressing the low emission sources. At present eight U.S. companies are active in Kraków as part of this program.

Brookhaven National Laboratory has been involved with Phase I of this program which involves efforts both on the Polish and the U.S. side. A part of the Phase I work has addressed building energy demands and the impacts which conservation measures may have on fuel use and emissions. DOE's Office of Conservation and Renewable Energy is the lead DOE office for this part of the work and results from this effort are not included here. All other aspects of the program are being managed by DOE's Office of Fossil Energy through the Pittsburgh Energy Technology Center (PETC). Brookhaven National Laboratory (BNL) as well as Burns and Roe Services Corp. have been supporting PETC. Work being done in Kraków is being managed by the Biuro Rozwoju Krakowa (BRK or Kraków Development Office) and BRK is working under subcontract to BNL.

The Phase I work started in 1991 and parts of it have been presented in papers and a series of reports. A report summarizing all of the Phase I work, including the building energy conservation activities, has recently been completed. Major components of Phase I are as follows:

TESTING

Heating stoves in Kraków are very large masonry furnaces with ornate tile exteriors. It has been estimated that there are about 7 million of these stoves throughout Poland. During the heating season, these stoves are fired once or twice each day. The fire burns actively for about an hour. During this time the masonry is heated and this stored heat keeps the apartment warm for the next 12 hours. During Phase I a testing program on these stoves was completed. One of the objectives of the test program was to provide baseline thermal efficiency and emissions data as input to evaluations of costs and benefits of alternative options for heating these flats as discussed below. The second primary objective was to provide an assessment of the possibility of reducing emissions by using improved fuels in these stoves. A facility for studying the emissions and efficiency of home stoves was built at the Academy of Mining and Metallurgy in Kraków with guidance and test equipment provided by U.S. participants. The system uses a dilution tunnel method to determine gaseous pollutant emission rates and flue gas sensible heat loss rate on a continuous basis. Particulates are sampled in the dilution tunnel and are averaged over the firing cycle. One of the U.S. companies currently active in Kraków is continuing to use this facility in their work on improved briquettes.

A second aspect of the Phase I testing work included hand-fired and stoker-fired boilers. Tests were conducted at two of the larger stoker-fired boiler houses and included investigations of the benefits of using improved fuels. Hand-fired boilers in Kraków include steel and cast iron units and coke, coal/coke mixtures, and coal are used as fuels. Tests were done at two sites with each of these fuels and also some locally made briquettes.

Details of the testing program and results have been presented earlier [2,3]. Using these results as well as results of an inventory done of the boiler and stove population in the city the contribution of the most important source categories to the total emissions inventory in the city can be estimated. This is presented in Table 1.

Table 1. Comparison of Contribution of Boilers and Home Stoves to Kraków Emissions

	Fuel Use (MT/yr.)	Annual Emissions (metric tons per year)				
		Particulates	CO	Volatile Organics	NOx	SO ₂
Stokers without cyclones	20473	173	415	0	73	600
Stokers with cyclones	217193	911	2717	0	685	6350
Hand-fired boilers-coke	51748	77	3622	28	74	918
Hand-fired boilers - coal/coke mixtures	51953	256	3866	325	60	1033
Hand-fired boilers - coal	32276	339	1688	132	71	585
Home stoves - coal fired	85000	1530	3620	221	470	782
Totals:	458642	3286	15928	706	1433	10270

ENGINEERING STUDIES

The Phase I engineering studies examined specific options for reducing emissions which were selected by the program's Bilateral Steering Committee as the most promising for the future. The purpose of

this analysis was to determine the costs of implementing the options. In some cases these costs are very specific to the part of the city and here site specific analyses were done. These studies included:

- Extension of the district heating system to allow local, hand-fired boilers to be shut down.
- Replacement of existing hand-fired boilers with new gas-fired units.
- Conversion of home stoves to electric heating
- Modernization of boiler houses (new boilers and pollution controls)
- Supply of improved fuels for the home stoves.

AIR QUALITY ANALYSIS

For each specific option dispersion modelling studies were done to provide estimates of the impacts that implementation would have on local air quality. These results have been very important in showing city groups specific benefits which they will realize from options which may have economic burdens. Also analyses were done to evaluate the impact of completing the most promising measures throughout the entire city, effectively eliminating pollution from these small sources. The results show that success in eliminating the low source pollution would greatly improve the city's air quality. It is not enough, however, to bring the city fully into compliance with targeted ambient air quality standards.

INCENTIVES ANALYSIS

The primary objective of incentives analysis is to define and evaluate incentives that the city could offer to encourage implementation of options under investigation in this project. Based on an economic analysis of each of these options, possible incentives are identified. The incentives are then evaluated in terms of their technical and legal feasibility, cost, and effectiveness. Some results of the incentives analysis are discussed in more detail below.

PUBLIC RELATIONS

A public opinion survey was administered to the residents of Kraków. Results show that most residents consider air pollution to be an important issue and that most residents consider industry and traffic to be the main sources of air pollution. A significantly higher portion of Old Town residents feel that the low-stack sources are the most important sources, however. While residents state that they are willing to pay to reduce pollution, the amount that they are willing or able to pay is probably not sufficient. Residents also feel that city authorities should take responsibility for cleaning the air.

Based on the survey results, a public relations campaign has been defined to inform Kraków's residents about the low-stack sources and about this project. This is being done through press releases and briefings for journalists, seminars, and production of brochures and educational films.

COMPARISON OF OPTIONS

At the present time the studies described above have largely been completed and a comprehensive Phase I report has been prepared and is being reviewed by various groups within the city. With all of this information in-hand it becomes appropriate to make comparisons of the relative costs and benefits of the various options. Generally, reducing pollution from these sources will present a cost burden which can be met in a variety of ways including direct capital subsidies, higher energy costs, increased rents, directed tax reliefs, low interest loans from environmental funds etc. Regardless of how the costs are absorbed it is clearly in the best interest of the city to promote the most cost-

effective options. There are many different ways in which options can be compared. One approach being used in this program is based on a spreadsheet program written under DOE sponsorship specifically for making simple comparisons between such options [4].

The spreadsheet program was written as a screening tool, providing a rapid method of analysis of many options primarily to aid policy decisions on a city-wide scale. Two important simplifying assumptions are used in the model including: 1) constant fuel and electric energy prices over the project life, and 2) the use of averaged capital costs for conversions between options and other costs averaged for large categories of emission sources. This spreadsheet was never intended and should not be used for project investment analysis which must be done on a case-specific basis with energy price escalation scenarios based on actual expected project start dates. This second point is especially important in Poland and other Central European countries where energy prices have been changing rapidly. Even with these limitations the spreadsheet program is a very effective and efficient tool for the kind of rapid comparisons for which it is intended.

In the spreadsheet program all of the low emission sources in the city are placed into categories based on physical characteristics and type of fuel used. This spreadsheet has been developed as a general tool and has been applied to several Central European cities. In the application to Kraków the low emission sources have been divided into 25 categories. For each of these categories information is entered on total current (baseline) fuel use, efficiency, fuel type and cost, air pollutant emission factors, operating costs, and maintenance costs. In Kraków this information was derived from surveys made of the boiler and stove populations and also from the engineering cost studies and the source testing program conducted as part of this work. For some categories the baseline fuel use is input as zero, but all other parameters are fully defined. These categories which have zero current fuel use are considered possible future options as replacements for some portion of the current capacity. For example one category is coal-fired tile stoves with a very substantial current fuel use and another is the same stoves firing smokeless briquettes which are not yet available in Kraków. In a spreadsheet run the impacts of using such a candidate alternative fuel in some or all of the home stoves can be evaluated.

In evaluating options using the spreadsheet there are several choices:

1. heating capacity can be changed from one category to another (for example from hand-fired boilers to gas-fired boilers);
2. the efficiency of boilers or stoves in a category can be increased (by adding economizers to boilers for example);
3. heat demand and fuel use in a specific category can be reduced through building energy conservation measures;
4. pollution controls can be added or upgraded in a specific source category.

For each of these choices capital costs of the modifications must be input as well as operating, fuel, and maintenance costs. Output from a spreadsheet run includes total emissions for each pollutant before and after the option is implemented, and total annual "user" costs before and after. The user costs include energy costs, operating costs, and maintenance costs.

Capital costs include direct costs which the end users must pay for implementation of the project but generally do not include all infrastructure costs such as upgrading electrical or gas distribution networks to meet increased demand following conversions. It is assumed that such costs are met by the utilities and are reflected in current energy prices.

The spreadsheet program provides details of costs and emissions of specific pollutants before and after conversion in tabular and graphical form. It is useful, also, to have a single number which indicates the cost effectiveness of each case being evaluated. To do this emissions of specific pollutants are first combined into a single "Equivalent Emission" defined as:

$$E_e = 2.9 (E_p + E_{NO_x}) + 0.5 E_{CO} + E_{SO_2}$$

where: E_e = Equivalent Emissions, metric tons per year
 E_p = particulate emissions, metric tons per year
 E_{NO_x} = nitrogen oxide emissions, metric tons per year
 E_{CO} = carbon monoxide emissions, metric tons per year
 E_{SO_2} = sulfur dioxide emissions, metric tons per year

Conversion or upgrade capital costs are then annualized assuming a project life of 20 years and an interest rate of 15%. This annualized capital cost is then added to the annual user cost and the result is termed the "user combined cost". Finally, for any specific option implemented the change in user combined cost is calculated per-ton of reduction of equivalent emissions. This user combined cost-per-ton of E_e reduction is then taken as a primary basis for comparing options. In addition to this relative measure of option cost-effectiveness it is also necessary to consider the impact of options on total emissions. Options which are highly cost effective but which do not have substantial impacts on total emissions obviously should not be given high priority.

Table 2 shows a comparison of a selected group of options. The comparison is based on the combined cost-per-ton of Equivalent Emission reduced as discussed above and also the capital investment required per ton on Equivalent Emission reduction. Options 1 to 5 address the home stoves. In options 1,2, and 3 the stoves would simply change to the use of smokeless briquettes. In the Phase I test work fuels of this type were tested and produced very dramatic reductions in emissions, most notably particulates which decreased by a factor of 10. This fuel is not currently on the market however, and there is some uncertainty about its actual price. Also during the Phase I test program a new procedure for operating the stove was developed which led to reduced emissions with the briquettes and increased efficiency. Options 1-3 in Table 1 include different assumptions about price and efficiency for the briquettes. Option 1 is very optimistic and assumes that the briquettes can be sold for about the same price as current coal and that the new operating procedure will be promoted with the new fuel. In this case the residents will have reduced annual operating costs leading to a negative value for the combined cost per ton figure. Option 2 represents the same price assumptions but does not take credit for increased efficiency with briquettes. Again the option looks very attractive. In Option 3 the briquettes are assumed to cost much more than coal - \$115/ ton compared to \$80/ton - and there is no credit taken for efficiency improvement. This option is certainly less attractive but it is still very competitive with some of the others.

Under Option 4 home stoves in the Łobzow part of Kraków are converted to electric heating. This part of the city has spare electric power capacity and is considered to be very suitable for such electric conversions. In making these conversions the stove is not removed but electric resistance heating elements are simply inserted into the firebox. It is assumed that the owner of the converted stove will have installed a dual rate electric meter and only use the heating inserts during the low-rate daily time periods. In Option 5 the stoves are removed, and a small gas-fired boiler and hydronic heating system are installed in each flat. This option has been receiving considerable attention in the city and is being implemented in some areas. It is clearly, however, an expensive approach.

Table 2. Comparison of Selected Options for Reducing Emissions From Low Sources in Kraków

	Option	Combined Cost per Metric Ton of Equivalent Emission Reduction	Capital Cost per Metric Ton of Equivalent Emission Reduction
1	Use of smokeless briquettes in home stoves assuming current efficiency is 52% and efficiency with briquettes is 72%. Same price for both fuels.	-\$ 507.	\$ 0.
2	Use of smokeless briquettes in home stoves assuming efficiency is 52% both with current fuel and briquettes. Similar price for both fuels.	- \$237.	\$ 0.
3	Use of smokeless briquettes in home stoves assuming efficiency is 52% both fuels. Current coal price is \$80/metric ton and briquette price is \$115/metric ton.	\$ 390.	\$ 0.
4	Conversion of home stoves to electric heating in Łobow part of Kraków.	\$ 473.	\$ 5,181.
5	Replacement of home stoves with small, gas-fired heating boilers.	\$1,267.	\$ 8,500.
6	Conversion of hand-fired boilers which use coal to gas	\$1,070.	\$3,160.
7	Conversion of hand-fired boilers which use coke to gas.	\$1,730.	\$9,035.
8	Conversion of hand-fired boilers which use coal to coal/coke mixtures.	\$1,245.	\$ 0.
9	Elimination of hand-fired boilers which use coke by connection to the district heating system	-\$177.	\$6,100.
10	Elimination of hand-fired boilers which use coal by connection to the district heat system	-\$114.	\$2,190.
11	Stoker-fired boilers - use of graded coal, addition of controls and improved operations	\$ 84.	\$ 946.
12	Stoker-fired boilers - boiler house modernization including new boilers and pollution controls	\$3,280.	\$10,900.

Options 6 to 10 address the small hand-fired boilers. In options 6 and 7 boilers currently firing coal and coke are converted to gas firing (boiler replacement). This option is clearly an expensive one but it is being promoted very strongly within some parts of the city for which no other option is available. Conversion of coal-fired boilers to gas is more attractive than coke-fired boilers simply because of the higher emission factors with coal-firing. In option 8 boilers which currently fire coal are converted to coal/coke mixtures which yield considerable reductions in particulate emissions. It is interesting to note that this approach is less attractive than direct conversion to gas. With conversion to the mixed fuel the emissions reductions are not as great as with conversion to gas and there is still the need for operators to be present. In Options 9 and 10 the hand-fired boilers are eliminated by connecting their load to the district heating system. This involves the replacement of the boilers by heat exchanger stations. The figures in Table 1 show this to be a very attractive option. It should be noted, however, that capital costs for connection to the district heat system are very site specific. For the areas evaluated during the Phase I engineering studies these costs ranged from \$22 to \$598 per kW of capacity. An average value of around \$90/kW was used for the figures listed in Table 2.

Options 11 and 12 address the larger, stoker-fired boilers. In Option 11 it is assumed that the performance of the existing boilers is improved through the addition of automatic controls which will allow the boilers to operate at lower excess air levels and higher efficiency. In addition it is assumed that the current fine coal used in these boilers is replaced by graded coal, properly sized. With this approach it is assumed that the boiler efficiency is improved by about 10% and the capital cost of the controls is \$17/kW. The graded coal is assumed to cost \$42/ton compared to \$31/ton for the baseline coal. Option 12 represents a drastic modernization of the boiler houses including the installation of Polish made fluid bed boilers burning very low grade fuel with a sorbent added, and a baghouse dust collector. The capital cost for this option is \$244/kW. This option was developed during the Phase I studies as part of a general modernization study conducted jointly by Polish and American firms. Work in the U.S. was done by Burns and Roe Services Co. and Burns and Roe Engineering Co. Of the options considered this was the lowest cost approach.

Another approach towards comparing options involves examining the amount of emission reduction per dollar required from the city. During the Phase I work recommendations were developed for incentives programs to promote specific options [5]. These options in every case involve some cost to the city. The level of incentive was developed to make the option economically attractive to the owner, investor, or resident involved. The economic evaluations done as part of these were more site specific and detailed than those included in the spreadsheet discussed above. Several scenarios were used for energy price trajectories. Table 3 shows the results of this comparison using one energy price scenario.

Table 3 includes two cases for the use of briquettes in home stoves. Both assume that initially subsidies will be applied to effectively make this fuel less expensive than coal. The difference in the two scenarios is the rate at which those subsidies would later be withdrawn.

Generally the results in Table 3 show a relationship between options which is similar to the results of the simpler spreadsheet analysis. The use of the briquettes and connection to the district heating system are more attractive than the other options.

Table 3. Incentives and Equivalent Emission Reductions

Option	Incentives Required (Present Value over 20 Years)	Equivalent Emissions Reduction per \$1,000 (tons)
Connect hand-fired boilers to the district system	\$198,005.	17.43
Convert hand-fired boilers in Old Town to gas	\$759,858.	5.19
Convert tile stoves to electric inserts	\$975,571.	5.04
Briquettes (gradual withdrawal of subsidies)	\$1,360,000.	24.63
Briquettes (rapid withdrawal of subsidies)	\$600,743.	55.77

PLANS

Currently, eight U.S. companies are working to develop joint venture projects in Kraków as part of Phase III program. These projects are focused in the option areas which now appear most attractive for the city including: briquettes, modernization of the stoker-fired boiler houses, and expansion of the district heating system. BNL in cooperation with BRK in Kraków are now beginning some new activities which have been designed to help both these joint venture projects as well as the city of Kraków more directly. This work includes: seminars for other Polish cities on the work in Kraków, a conference to be held in Kraków in October, 1995, the development of a master plan for the reducing pollution from the low emission sources, the development of a Geographical Information System within Kraków to allow rapid evaluation of low emission source projects, site-specific feasibility studies in support of the Phase III projects, and direct assistance to the U.S. companies currently working in Kraków.

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STUDIES OF THE COMBUSTION OF COAL/REFUSE DERIVED FUELS USING
THERMOGRAVIMETRIC- FOURIER TRANSFORM INFRARED-MASS SPECTROMETRY

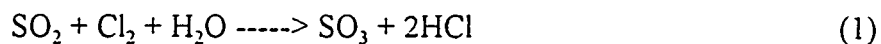
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INTRODUCTION

According to a report of the Environmental Protection Agency (EPA), "Characterization of Municipal Solid Waste (MSW) in the United States", the total MSW produced in the U.S. increased from 179 million tons in 1988 to 195 million tons in 1990.¹ The EPA predicted that the country would produce about 216 million tons of garbage in the year 2000.² The amount of waste generated and the rapidly declining availability of sanitary landfills has forced most municipalities to evaluate alternative waste management technologies for reducing the volume of waste sent to landfills. The fraction of MSW that is processed by such technologies as separation and recycling, composting, and waste-to-energy was forecast to increase from a few percent today to 30-40% by the year 2000.³

Waste-to-energy conversion of MSW can appear to be attractive because of the energy recovered, the economic value of recycled materials, and the cost savings derived from reduced landfill usage. However, extra care needs to be taken in burning MSW or refuse-derived fuel (RDF) to optimize the operating conditions of a combustor so that the combustion takes place in an environmentally acceptable manner. For instance, polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) have been found in the precipitator fly ash and flue gas of some incinerator facilities in the United States and Europe. The amount of PCDDs and PCDFs occurs only in the parts-per-billion to parts-per-trillion range, but these chlorinated organics exhibit very high toxicity ($LD_{50} < 10 \mu\text{g/Kg}$). The compound 2,3,7,8-tetrachlorodibenzodioxin has been found to be acnegenic, carcinogenic, and teratogenic. This has slowed or even stopped the construction and operation of waste-to-energy plants.⁴⁻⁷

Some important studies have been conducted to reduce the release of chlorinated organics. Recently, Lindbauer⁸ reported that co-firing an MSW combustor with 60% coal drastically reduced the PCDD/PCDF levels. Sulfur in coal was also found to reduce PCDD/PCDF formation, even at S/Cl ratios as low as 0.64.⁹ It was indicated that sulfur can suppress the production of Cl_2 so that the formation of chlorinated aromatics is inhibited by the Deacon reaction:



However, it is important to note that, depending on the coal type, the coal combustion environment can contain organic precursors and Cl_2 that can actually facilitate PCDD/PCDF formation. Additional research is needed to develop optimum co-firing conditions and parameters. Investigations are also needed to determine why and how the co-firing of high sulfur coals with MSW reduces the polychlorinated organic residue emissions from the MSW.

In this paper we report the thermal analytical behavior of two coals, polyvinyl chloride (PVC), cellulose, and newspaper. The PVC, cellulose, and newspaper can be used to formulate a "representative" synthetic MSW.

EXPERIMENTAL

The materials used in this project included two bituminous coals, a medium molecular weight PVC resin from the OxyChem Corporation, cellulose from the Whatman Co., and shredded newspaper. Analytical data for the samples are given in Table 1.

A TA Instruments Model 951 Thermogravimetric Analyzer (TG) interfaced to a Perkin Elmer 1650 Fourier Transform Infrared Spectrometer (FTIR) was used in this study. The horizontal quartz furnace of the TG was connected to the 10 cm gas cell of the FTIR using an insulated teflon tube heated to a temperature of 150°C. The TG was also interfaced to a VG Thermolab Mass Spectrometer (MS) using a fused silica capillary sampling tube heated to approximately 170°C. A teflon splitter divides the gases from the TG into two parts, one to the FTIR (~95%), and the other to the MS (~5%). Figure 1 is a schematic of the TG-FTIR-MS system.

In the TG experiments all samples (~300 mg each) were heated in air (50 mL/min) at a rate of 10°C/min to 700°C. The spectra and profiles of gaseous species evolving from the TG system were recorded and analyzed by the TGA-FTIR-MS analytical system.

RESULTS AND DISCUSSION

TG-DTG Results

A comparison of the TG curves for the five raw materials (cellulose-001, newspaper-002, PVC-003, coal 90003-005, and coal 92073-006) are shown in Figure 2. The TG thermograms reveal some distinguishing characteristics of the five raw materials:

- There is no moisture in the PVC.
- The PVC, newspaper, and cellulose decompose at much lower temperatures and more rapidly than the coals.
- Ignition peaks are obvious for the newspaper (388°C) and cellulose (372°C) samples.
- Residues decrease in the order of coal 92073 (24.8%), coal 90003(8.75%), newspaper (6.58%), cellulose (0.57%), and PVC (0%).
- Newspaper continues to decompose until nearly 700°C

For PVC, the initial weight loss is clearly due to the loss of HCl. This can be inferred from the percentage (47.5%) of HCl in PVC and is confirmed by FTIR data. The second and third weight loss are contributed by different molecular weight PVC chains. The newspaper is not decomposed completely, possibly owing to the presence of mineral fillers.

FTIR Results

Figures 3 and 4, as examples, are three-dimensional FTIR graphs of Coal 92073 and PVC. The relative axes are absorbance (vertical), wavenumber (horizontal) and time (perspective). However, there are some differences between the two spectra. There are more water peaks in 90003 than in 92073 (1300-1700 cm⁻¹ and 3500-4000 cm⁻¹). This can be attributed to more volatile matter

and hydrogen in 90003. The COS (2073 cm^{-1}) and SO_2 (1374 cm^{-1}) peaks are stronger for coal 92073 than for 90003 due to the higher sulfur content. In coal 92073 spectra, the peaks at 1771 and 1171 cm^{-1} can be attributed to acetic acid by comparing their shapes and wavenumber with standard spectra. Since the absorption of acetic acid from 3300 to 2500 cm^{-1} may overlap the HCl peaks around 2800 cm^{-1} , the HCl peaks cannot be seen even though there is chlorine (289 ppm) in 92073.

Another way to present results from the FTIR spectra is to construct evolved gas profiles at a specific wavenumber. Much more CO_2 than any other gas is released during combustion and as a consequence must be plotted on a scale different from the other gases. In the PVC evolved gas profile, HCl is released first at 230-400°C with some CO_2 from the low molecular weight PVC groups. This is in accordance with the TG/DTG results. CH_4 peaks are obvious, while they cannot be found in the spectra of newspaper and cellulose. In the spectra of newspaper and cellulose, there are a lot of water peaks between 250-450°C that correspond to the release of CO_2 and CO. This is because of a large oxygen content and OH functional groups in these materials. Also, compared with PVC many more organic acids (mainly as formic and acetic acids) are produced during the combustion of newspaper and cellulose. These can be identified in the three dimensional spectra by groups of peaks at 2500-3400 (OH), 1700-1800 (C=O), 1033 for methanol, 1106 for formic acid and 1175 cm^{-1} for acetic acid. The appearance of these materials can be attributed to the poly-hydroxyl structures of newspaper and cellulose.

The evolved gas profile curves for PVC are quite characteristic. The HCl gas is released first and the absorbance reaches its maximum at approximate 320°C. However, the combustion of PVC occurs at 570°C, which is shown by the profiles for carbon dioxide and monoxide from PVC. This corresponds to the third weight loss in its TG-DTG curve. These results imply that the PVC is not readily flammable due to its chlorine content. In the profiles of newspaper and cellulose, the absorbance curves of carbonyl (C=O) and C-O have the same shape and reach their maxima at about 370°C. This indicates that these two peaks belong to the same compound, formic acid.

As a comparison of methane profiles for the two coals and PVC, it shows that methane forms at about 500°C. As previously mentioned, because of the high oxygen content in newspaper and cellulose, no methane forms during the combustion of these materials. It is notable that there is some methane released from the coals between 230°C and 380°C, but not from PVC. This is probably due to initial pyrolysis of the coals. The methane around 500°C is produced from the combustion of the coal matrix and the PVC carbon chain.

In summary, the identified characteristic peaks (not including water peaks which appear in every sample) in the FTIR spectra of the five raw materials are listed in Table 2.

VG Thermolab Gas Analyzer Results

The Thermolab Gas Analyzer, is a low-range, low-sensitivity quadrupole mass spectrometer, operating currently to a maximum of 200 amu. As it analyzes unchromatographed mixtures of gaseous molecules, its output requires great care in interpretation. Nevertheless, some useful information can be obtained, especially in conjunction with other sources of structural information, such as from FTIR spectra.

For Coal 92073 the profiles of peaks M/Z 18, 32, 44, 60 and 64 can be attributed to the ions of H_2O , O_2 , CO_2 , COS, and SO_2 , respectively. The water profile shows three peaks. The first peak around 100°C is the moisture in coal. The second and third peaks are produced by the combustion and decomposition of coal. The oxygen profile remains stable until about 350°C after which the

oxygen decreases due to its consumption through combustion of the coal matrix. The inverse peak indicates a maximum consumption of oxygen. In addition, sulfur dioxide shows three peaks. This result is the same as that obtained in the FTIR spectra. In 92073, carbonyl sulfide is very obvious and SO₂ shows three decomposition phases (See Figure 5).

Figure 6 shows some mass peak profiles for PVC. The M/Z 36 and 38 are formed at the same time over a range of 200 to 450°C and strongly suggest the isotopes HCl³⁵ and HCl³⁷. Also, the M/Z 70, 72 and 74 suggest the isotopes ³⁵Cl₂, ³⁵Cl-³⁷Cl and ³⁷Cl-³⁷Cl. This conclusion can be demonstrated by the ratio of their integration areas. The ratio of M/Z 36 to 38 is 0.333, which is close to the chlorine isotope fraction 0.325. Furthermore, M/Z 70 to 72 to 74 appear at exactly the same point, with mass ratio 0.26 : 0.663 : 1.00, as compared with the predicted mass ratio of 0.11 : 0.65 : 1.00. The major aromatic volatile components, toluene, indane, biphenyl, anthracene, styrene and indene form at the second decomposition step 420-460°C.

CONCLUSIONS

The TG-FTIR-MS system was used to identify molecular chlorine, along with HCl, CO, CO₂, H₂O, and various hydrocarbons in the gaseous products of the combustion of PVC resin in air. This is a significant finding that will lead us to examine this combustion step further to look for the formation of chlorinated organic compounds.

The combination of TG-FTIR and TG-MS offers complementary techniques for the detection and identification of combustion products.

The TG-MS technique allows one to study reaction pathways for the formation of gaseous products during combustion.

ACKNOWLEDGEMENTS

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Table 1. Analytical Data for Raw Materials

<u>Parameter</u>	<u>Coal 93003</u> <u>IL # 6</u>	<u>Coal 92073</u> <u>KY # 9</u>	<u>PVC</u> <u>Resin</u>	<u>Cellulose</u>	<u>Newspaper</u>
% moisture ^A	8.76	9.88	0	3.12	4.21
% ash	8.12	26.34	0.36	0	4.30
% vol. matter	34.3	32.6	99.6	100	84.8
% carbon	75.07	59.53	38.79	44.84	47.68
% hydrogen	5.21	3.50	4.21	6.66	6.48
% nitrogen	1.64	1.17	0	0	0.07
% sulfur	1.26	4.44	0.22	0.02	0.05
% oxygen	8.32	4.99	8.97	48.5	41.4
% chlorine	0.38	0.029	47.46	0.010	0.016
Btu/lb	13,428	10,335	8,556	6,940	8,081

^A Moisture is as-determined. All other analyses are reported a dry basis.

Table 2. Identification of Peaks (wavenumber, cm⁻¹) in FTIR Spectra

	<u>90003</u>	<u>92073</u>	<u>PVC</u>	<u>Newspaper</u>	<u>Cellulose</u>
CH ₄	3016	3016	3016	-----	-----
HCl	2798	2798	2798	-----	-----
CO ₂	2356	2356	2356	2356	2356
CO	2178	2178	2178	2178	2178
Carbonyl Sulfide (COS)	2073	2073	-----	-----	-----
C=O	-----	-----	1798	1790	1790
			1788	1773	1777
			1776	1747	1746
			1734	1734	1734
			1717	1717	1724
SO ₂	1374	1374	-----	-----	-----
Acetic acid	-----	-----	1175	1175	1175
Formic acid	-----	-----	1106	1107	1107
Methanol	-----	-----	1036	1033	-----
Ethylene	950	950	950	950	950
1,3-Butdiene	910	-----	910	-----	-----
Furan	-----	-----	-----	745	744
Xylene	740	741	741	-----	-----
HCN	712	712	-----	-----	-----

TGA-FTIR-MS ANALYTICAL SYSTEM

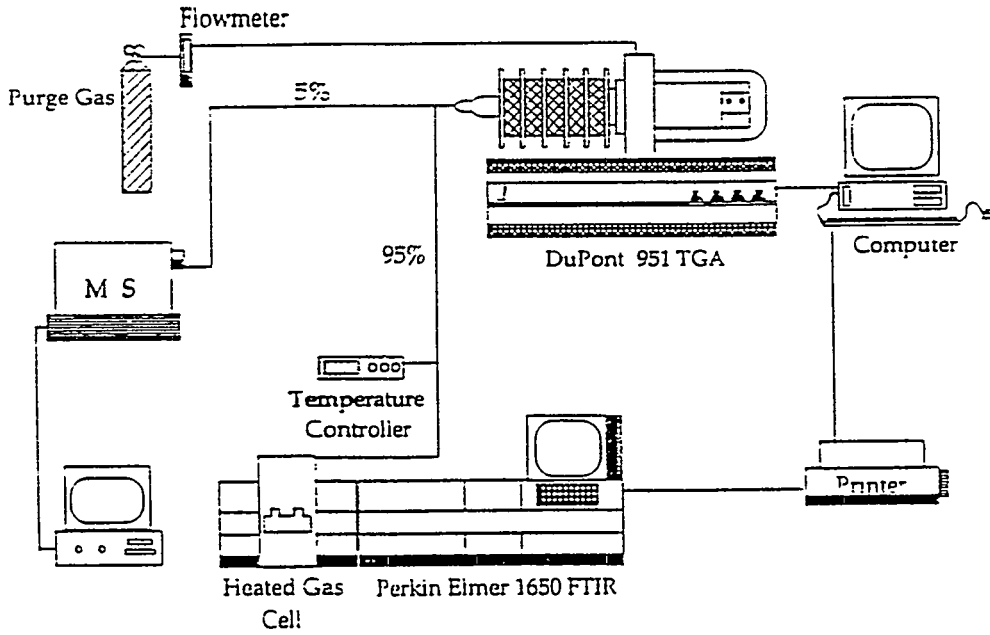


Figure 1

COMPARISON OF TGA CURVES OF RAW MATERIALS
 Files: C90003.D05 92072.D06 PVC.D03 NEWSPAPER.D02 CELLULOSE.D01

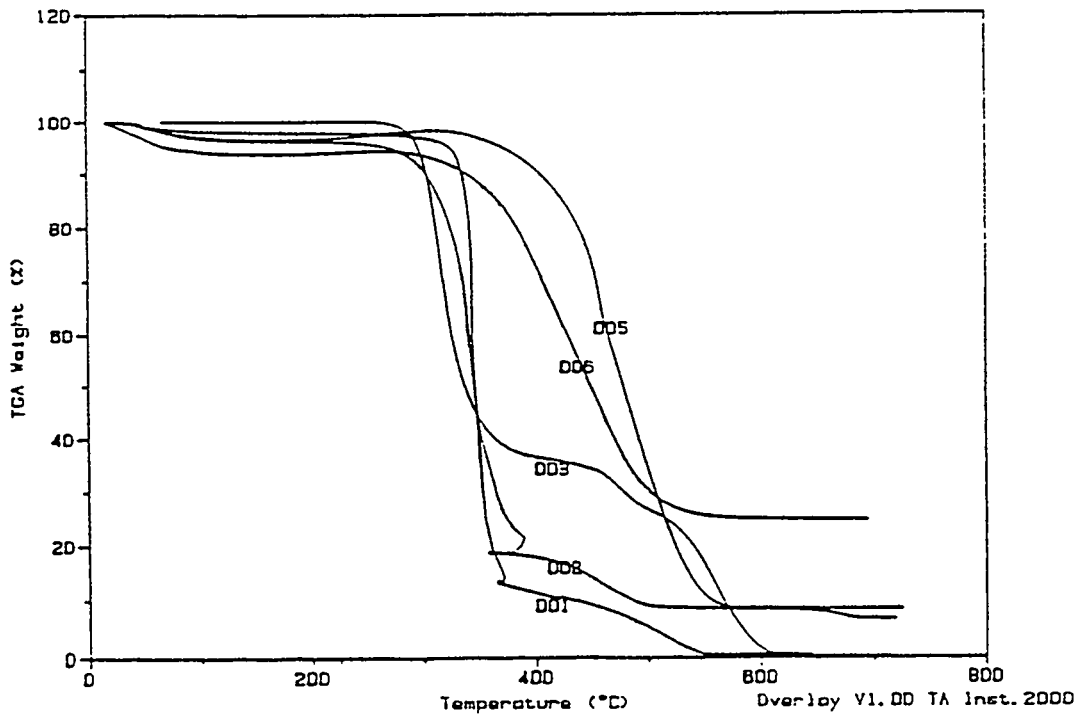


Figure 2

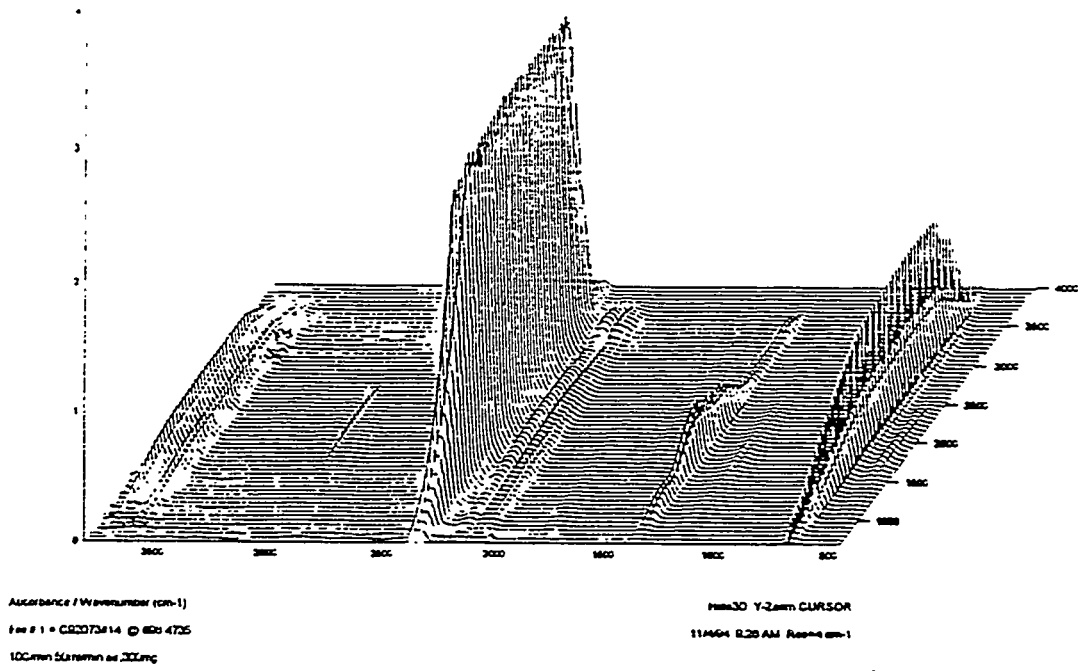


Figure 3

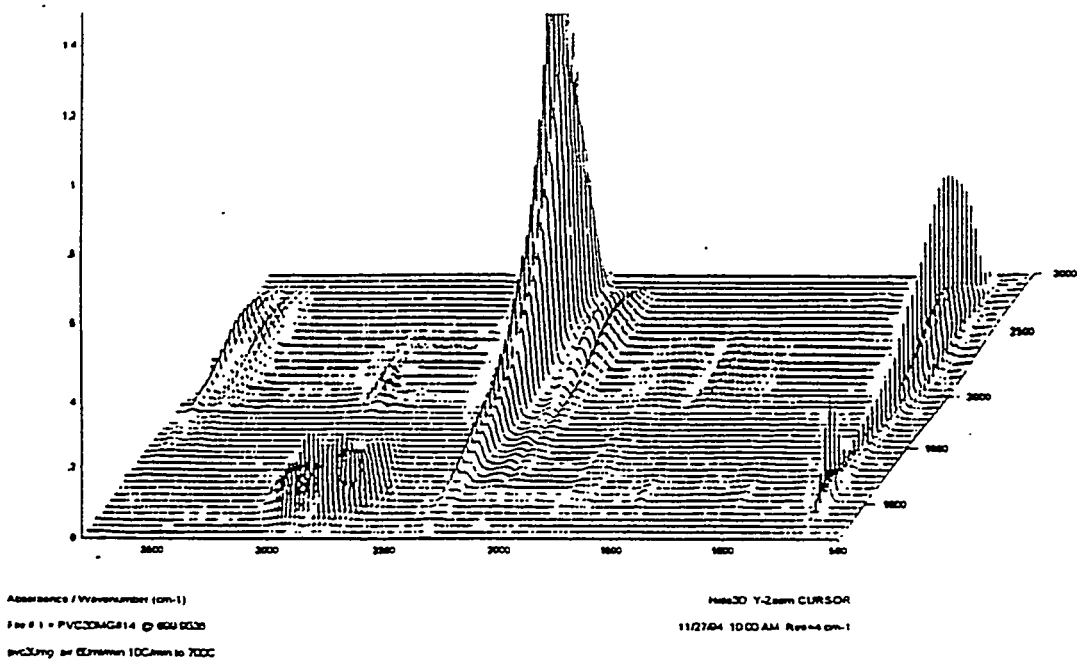


Figure 4

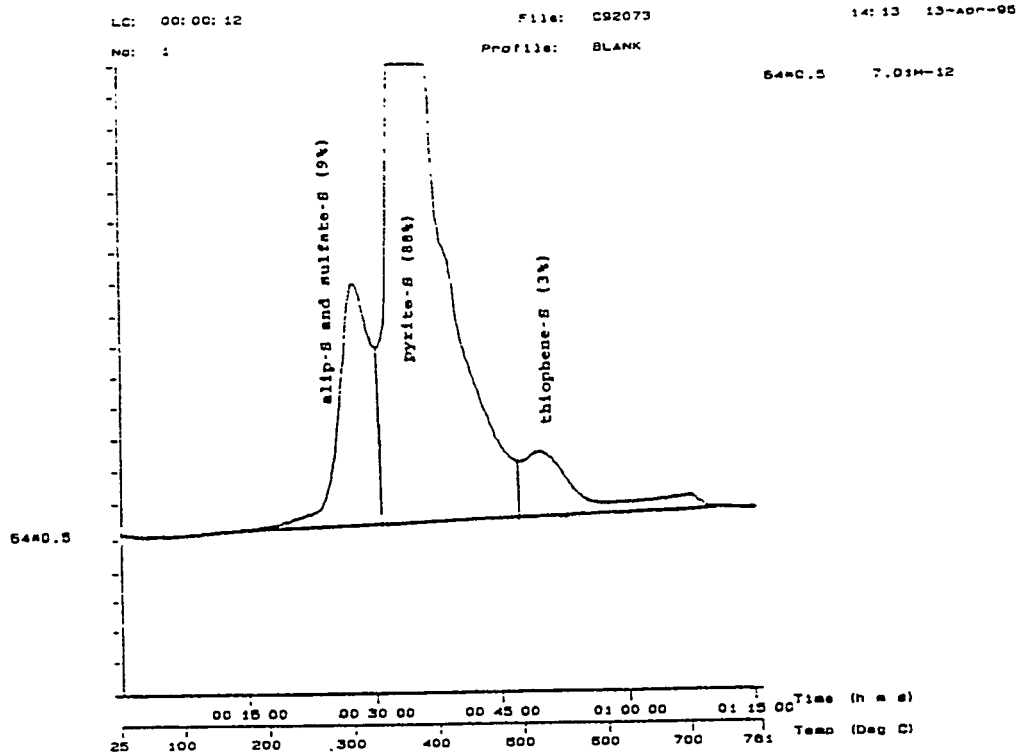


Figure 5

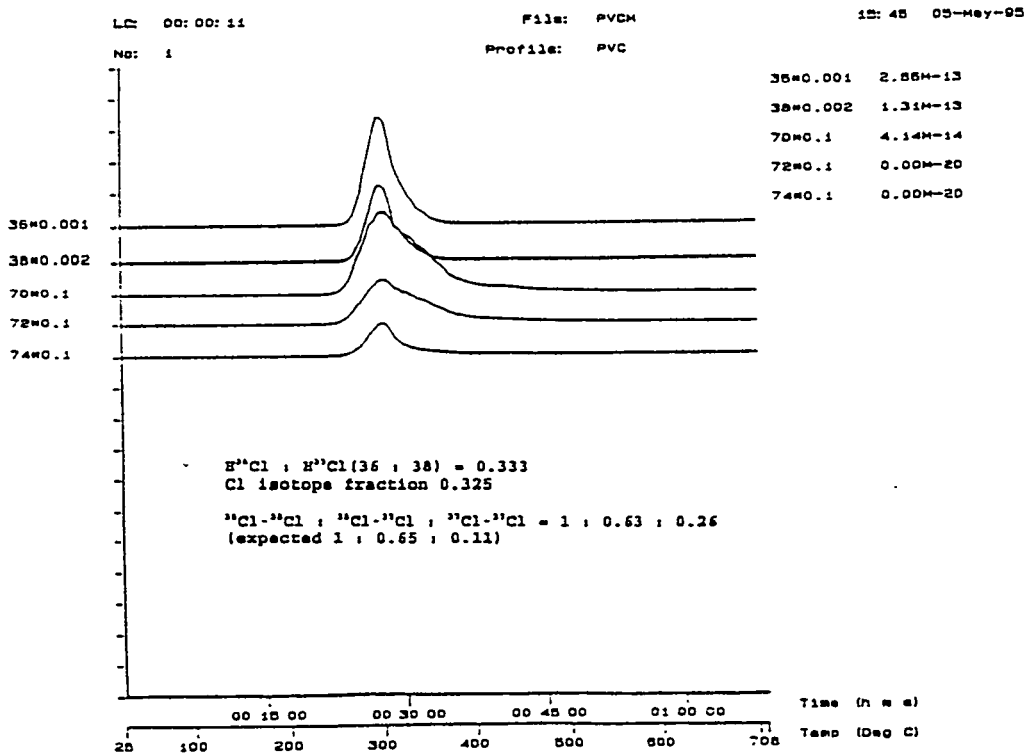


Figure 6

The following manuscript was unavailable at time of publication.

*COMBUSTION CHARACTERIZATION OF
COAL FINES*

Dr. Houshang Masudi
Prairie View A&M University
Prairie View, TX 77446

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*THE EFFECT OF COAL BENEFICIATION ON THE
RHEOLOGY/ATOMIZATION OF COAL-WATER SLURRIES*

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Grambling, LA 71245

Please contact author(s) for a copy of this paper.

**CONTROLLING MERCURY AND SELENIUM EMISSIONS FROM COAL-FIRED
COMBUSTORS USING A NOVEL REGENERABLE NATURAL PRODUCT**

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ABSTRACT

This program successfully demonstrated the key components that are needed for a practical, regenerable sorption process for removing and recovering mercury from flue gas streams: 1) a proprietary natural product removed mercuric chloride from synthetic flue gas, 2) several new noble metal sorbents were shown to capture elemental gas-phase mercury from synthetic coal combustion flue gas, and 3) both the natural product and the noble metal sorbents could be regenerated in the laboratory (chemical method for the natural product, thermal method for noble metal sorbents).

Several sorbents were tested for their ability to collect selenium oxide during the program. These tests, however were not definitive due to inconclusive analytical results. If follow-on testing is funded, the ability of the proposed sorbents to collect selenium and other metals will be evaluated during the field testing phase of the program.

A preliminary economic analysis indicates that the cost of the process appears to be substantially less than the cost of the state-of-the-art method, namely injection of activated carbon, and it also appears to cost less than using noble metal sorbents alone.

INTRODUCTION

Mercury is emitted from industrial sources in a variety of chemical forms depending on the specific process and flue gas conditions. For example, mercury is known to exist as elemental mercury [Hg⁰] and as mercuric chloride [HgCl₂] in coal combustion flue gas (Schmidt and Brown, 1994). The fate and subsequent environmental and health impact of mercury in coal combustion flue gas is determined by the chemical speciation of the mercury and by the nature of the air pollution control devices in operating coal-fired power plants. A knowledge of the relative concentrations of mercury between its different forms will be required for air pollution control devices to operate effectively. An example of this principle is given in Table I for coal-fired power plants. In attacking the problem of mercury and selenium emissions from coal

combustion facilities, it is logical to take separate (but not unrelated) approaches for systems with scrubbers and for systems without scrubbers.

The purpose of this research program was to investigate sorbents that are capable of removing elemental mercury, mercuric chloride, and selenium from a synthetic flue gas.

Table I. Mercury Removal Under Different Process Conditions

Plant	Ash Loading to Spray Dryer	Coal Cl	% Mercury Removed
A	High	Low	14
B	High	Low	23
C	High	Low	6
G	High	Low	16
E	Low	High	55
H	Low	High	44
F	Medium	High	89
D	High	High	96

TEST APPARATUS

Phase I testing consisted of the following: 1) evaluating the mercury uptake capability (using elemental mercury) of a number of candidate sorbents having the potential of being regenerated, 2) evaluating the uptake capability of selected sorbents to mercuric chloride and selenium, and 3) evaluating the regenerability of selected sorbents.

In the natural product test, the sorbent was held in a Teflon tube with an inside diameter of 3/8". We used two grams of the material, one gram of 1/16"-diameter beads and one gram of 1/8"-diameter beads. The gas flow rate through the bed was 100 standard cubic centimeters per minute (sccm). The sorbent bed was held at 130°F and at ambient pressure (12 psia); at these conditions the 100 sccm flow rate calculates to a superficial velocity of 3.4 cm/sec and an approximate bed residence time of four seconds.

The noble metal sorbents were tested in a separate apparatus wherein the sorbent was held in a 0.5"-I.D. quartz tube that was placed inside an oven. This oven was held at 300°F during the sorption tests and was heated to 700°F to thermally regenerate the sorbents. The gas flow rate through the bed during these tests was 600 sccm, and the mass concentration of elemental mercury was 2,843 µg/m³. The mass of sorbent in each test was approximately 5 grams, and the sorbents occupied approximately 10 cm³ of volume. The pressure in the quartz tube was 12.5 psia. Under these conditions, the superficial velocity of the gas through the sorbent bed was 15 cm/sec, and the bed residence time was approximately 0.5 sec. The concentration of mercury was well above that of actual coal combustion flue gas but gave us the ability to load the sorbents with mercury in a reasonable amount of time. In a typical run of four

hours duration between regeneration steps, 0.41 milligrams of mercury was delivered to the sorbent bed.

TEST RESULTS

Natural Product Sorbents

The natural product was found to take up mercuric chloride from the gas phase but it did not take up elemental mercury. This result is in keeping with the current understanding of the mechanism by which this material sorbs metals, specifically, formation of a charge complex of a metallic ion with the electron pair on the nitrogen atom in the structure of the sorbent molecule. The mercuric chloride was removed from the synthetic gas stream with an efficiency of 58% in the single test that was done.

Although we were successful in making a constant source of selenium oxide (permeation tube with gravimetric calibration), we were unable to find the selenium in our acid impinger bottles when a carrier gas flowed over the permeation tube and straight through three impinger bottles in series. Follow-up testing will be performed during Phase II to ascertain the fate of selenium within the proposed sorbent system.

Early Phase I testing was directed at using the natural product exposed to synthetic flue gas at temperatures of 300°F. The material was not stable at this condition due to its high surface area. To address the thermal resistance of the sorbent, a small sample was made with low surface area (10 m²/g). This form was much more resistant to higher temperatures based on thermal gravimetric analysis. The low surface area sorbent was just as stable as the native material (no weight loss until the temperature exceeds 450°F) whereas the high surface area material began to lose weight at about 290°F. This test shows that the natural product can be fabricated in a form to be stable at higher temperatures if this property is desired. It is believed that surface area is a less important factor when using the material to capture mercuric chloride than the thermal stability.

Noble Metal Sorbents

Four sorbents containing noble metals were evaluated during Phase I. All of the sorbents were capable of collecting elemental mercury. In addition, all sorbents were capable of releasing the mercury by subjecting them to a thermal cycle. A real-time elemental mercury analyzer was used in the testing to measure mercury concentrations entering and exiting sorbent test beds. All tests were conducted at 280°F.

Figure 1 shows the results of a test of one of the sorbents. The sorbent was collecting virtually 100% of the mercury between the time periods of 6,000 and 22,000 seconds. Occasionally (at 13,000 sec., 16,000 sec., and 22,000 sec.) the inlet mercury concentrations were checked by bypassing the gas flow directly to the analyzer. Figure 2 shows the results of regenerating this sorbent. The temperature of the sorbent was raised to 600°F, where a substantial amount of mercury was driven from the sorbent. The temperature was increased in

several steps to a maximum of 950°F. Little additional mercury was released above a temperature of 750°F.

Although all the noble metal sorbents exhibited a capacity to collect elemental mercury, an optimization of the sorbents was not attempted during Phase I.

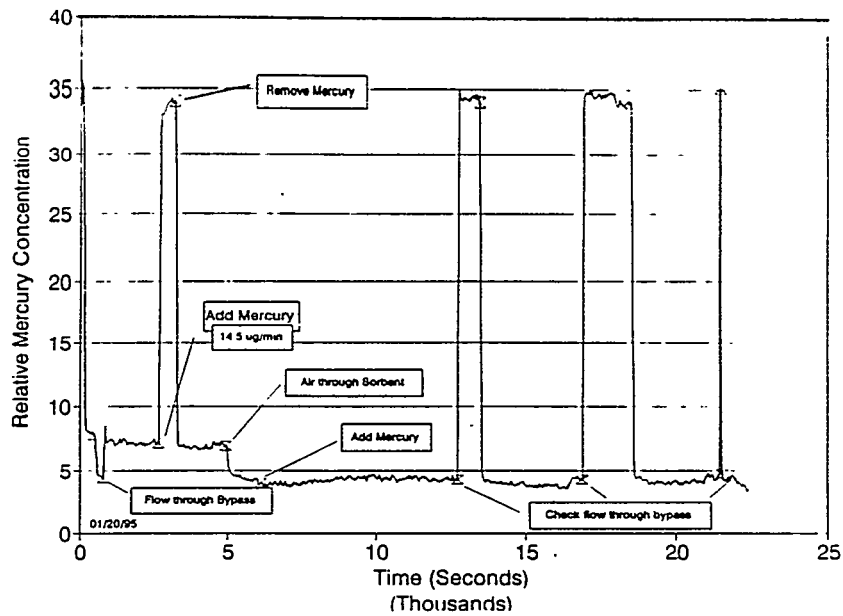


Figure 1. Sorption test of a noble-metal sorbent.

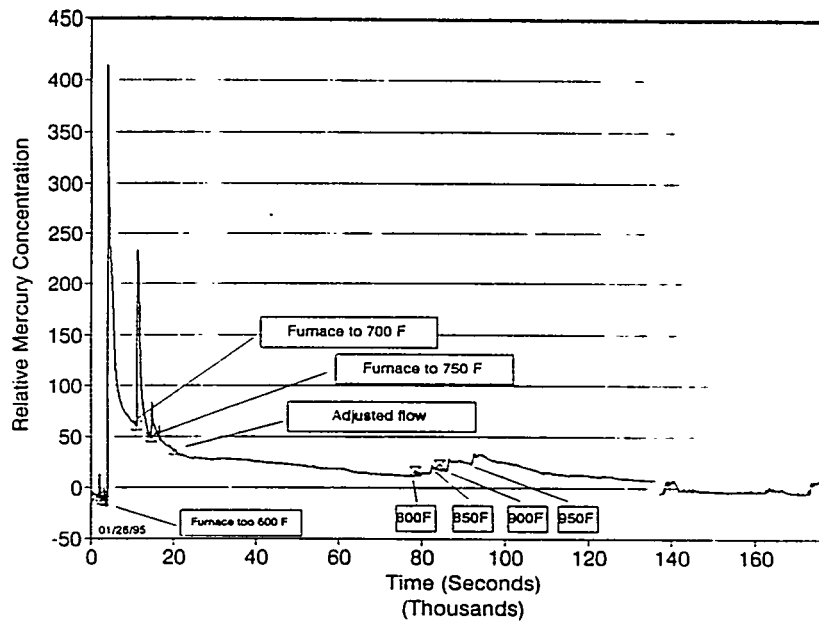


Figure 2. Regeneration of noble metal sorbent.

CONCLUSIONS

Following are conclusions based on the results of the Phase I program:

- Natural product beads, when appropriately wetted in a gel form, will effectively sorb mercuric chloride from synthetic flue gas.
- Noble metal sorbents collect elemental mercury and are regenerable by thermal treatment.
- Taken together, the gelled natural product beads and the new noble metal sorbents are the only set of sorbents that can solve vapor phase mercury contamination problems generated by mercury in the flue gas of coal combustors.
- A combination of noble metal sorbents with gelled natural product beads would potentially have substantial cost savings over the use of solely noble metal sorbents.
- Natural product beads with surface areas near $10 \text{ m}^2/\text{g}$ are as thermally stable as the native natural product (no decomposition at 450°F).

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The following manuscript was unavailable at time of publication.

*INTERACTIONS BETWEEN TRACE METALS,
SODIUM, AND SORBENTS IN COMBUSTION*

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*LOW COST SYNTHESIS OF NANOCRYSTALLINE SiC
WITH FULLERENE PRECURSORS*

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The following manuscript was unavailable at time of publication.

*MATERIALS SUPPORT FOR THE DEVELOPMENT
OF A HIGH-TEMPERATURE ADVANCED FURNACE*

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INVESTIGATION OF THE EFFECT OF THE COAL PARTICLE SIZES
ON THE INTERFACIAL AND RHEOLOGICAL PROPERTIES
OF COAL-WATER SLURRY FUELS

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ABSTRACT

Experiments were conducted to investigate the effect of particle size on coal-water slurry (CWS) surface tension properties. Two different coal powder samples of different size ranges were obtained through sieving of coal from the Upper Elkhorn Seam. The surfactant (anionic DDBS-soft, dodecylbenzene sulfonic acid) concentration varied from 0 to 1.0% in weight while the coal loading remained at 40% in weight for all the cases. A du Nouy ring tensiometer and a maximum bubble pressure tensiometer measured the static and dynamic surface tensions, respectively. The results show that both static and dynamic surface tensions tend to increase with decreasing coal particle sizes suspended in CWS fuels. Examination of the peak pressure, minimum pressure, surfactant diffusion time, and dead time were also made to correlate these microscopic pressure behavior with the macroscopic dynamic surface tension and to examine the accuracy of the experiment.

INTRODUCTION

Coal-water slurry atomization involves interactions between three different phases: solid (coal particles), liquid (water and additives), and gas (air or steam). Surface or interfacial tension is one of the significant properties in determining atomization characteristics of liquid or slurry fuels. Under the quasi-equilibrium conditions of low shear-rates of excessively slow atomization, the static surface tension of the fluid is an appropriate measure of the fluid's ability to form small radius droplets. However, the surfactants, additives or wetting agents presented in the CWS formulation do not reach an equilibrium concentration throughout the solid-liquid or liquid-vapor interfaces at higher shear rates. Therefore, dynamic surface tension should be a more appropriate measure in assessing the atomization that usually occurs at high shear rates.

The dynamic surface tension of a fluid is simply a measurement of the surface tension at a particular rate of surface formation or shear rate. The static and dynamic surface tension values are the same for pure fluids, such as water. The values of dynamic surface tension for slurry mixtures containing solid particles and various additives may be much higher than the corresponding static surface tension because insufficient time exists for the migration of surfactant additives to the atomized interface from the bulk mixture. The difference between the two surface tension values increases at higher shear rates that allows less time for the surfactant migration.

It is the intention of the present work to examine the effect of coal particle sizes on CWS static and dynamic surface tension properties. Rheology shows that the slurry viscosity generally increases with decreasing mean particle size [1]. When particles are suspended in the solution dispersed with additives and/or solvents, adsorption or solvation layers are formed on the particle surface which increases the effective volume (f) of the particle. This effective volume increase is particularly significant for small particles which can explain the increase of the slurry viscosity with

decreasing mean particle size. To the extent of our literature survey, no such correlation for surface tension, whether static or dynamic, has been published. Examination of particle size effect on interfacial properties of CWS fuels is attempted using specially prepared coal particle samples.

EXPERIMENTAL PROCEDURES

Maximum Bubble Pressure Technique

Figure 1 illustrates the operating principle of the maximum bubble pressure tensiometer technique for dynamic surface tension measurement [2]. The CWS sample was contained in a vessel into which is inserted a specially designed capillary tube with a small outlet diameter of one millimeter. As bubbles were formed, grew, and detached from the capillary tube orifice, variations of the bubble pressure occurred because of the change in bubble radius. For each bubble, maximum pressure was recorded when the bubble radius reached its minimum at the orifice radius. For different bubble generation frequencies, the dynamic surface tension was calculated from the measured maximum bubble pressure substituted into a simple relation

$$\sigma = (p_{\max} - \rho gh) r_c / 2 \quad (1)$$

where ρ is the sample fluid (CWS) density, g is the gravitational acceleration, h is the height above the capillary outlet, and r_c is the radius of the capillary outlet. The maximum bubble pressure, p_{\max} , corresponds to the inside air pressure when the radius of the growing bubble is equal to the capillary radius, r_c . The KRUSS Model BP1 tensiometer was adopted to measure dynamic surface tension of CWS fuels. The accuracy of the tensiometer was tested by measuring surface tension for distilled and deionized water. The result ensured a satisfactory measurement accuracy showing less than 2% deviations from the surface tension values listed in the CRC Handbook [3].

Modification of the Existing Kruss Tensiometer

Analog signal output from the diaphragm type pressure transducer of the Kruss tensiometer is interfaced with an A-to-D board installed in an 386 PC. ATLAB data acquisition software from Data Translation Co. samples the analog signal at a rate of 0.2 kHz and digitizes them into the computer hard disk memory. One batch of data scanning over the specified bubble frequency range from one to ten per second requires approximately 1 MB hard disk memory capacity. A simple FORTRAN program identifies the peak voltage, minimum voltage, bubble life time, and dead time.

Figure 2 shows a temporal history of voltage readings for a typical case of 1% DDBS-soft aqueous solution. One cycle period of the curve is equivalent to the bubble life time, or the reciprocal of the bubble frequency. The bubble pressure increases as the nitrogen gas inflow makes the bubble grow and the bubble diameter decreases from the infinitely large curvature of the initially flat interface at the orifice exit. The bubble pressure increase as the bubble diameter decreases with time. The bubble pressure increases at a faster rate when a surfactant acts to reduce the surface "holding" tension. While the bubble pressure increases, the surfactant migrates to the newly created bubble surfaces. The surface is 'aged' with surfactant diffusion during the period of ascending curve, which is now called 'Diffusion time'. The bubble pressure reaches its maximum value (peak voltage) when the bubble grows to the orifice diameter.

Further growth of the bubble beyond the peak voltage increases the bubble diameter and the bubble pressure decreases first smoothly, and then the descending pressure curve becomes irregular most probably because of the geometrical distortion of the enlarged bubble. The enlarged and distorted bubble detaches from the orifice and the cycle completes at the time of the minimum voltage reading. The duration from the peak till the cycle completion does not directly influence the measurement of the maximum bubble pressure, and this time period is now called 'Dead time'.

Preparation of CWS Fuel Samples of Different Coal Particle Size Ranges

Coarsely ground Upper Elkhorn Seam coal provided by DOE-PETC was classified into several different size ranges using a sieve shaker. To minimize the coal oxidation during the sieving, the sieve array was sealed with tape and the duration of sieve shaking was kept at a minimal necessary level. In most cases, the sieving was completed within thirty minutes. Two samples containing the largest and the finest particles were selected for testing so the effect of particle size on surface tension values could be distinctively observed. The coarse sample contains coal particles in the range of 180 to 250 μm , and the fine sample contains coal particles less than 63 μm . The present report presents results for only DDBS-soft surfactant which shows the best performance among the tested five surfactants [4]

The coal and water was completely mixed by a rotating mixer running for twelve to twenty-four hours. The specified amount of surfactant was then added and mixed by a magnetic stirrer for 5 minutes. All the present experiment used 40% weight CWS fuels. The slurry viscosity increases with increasing ratio of the packing density which is defined as the ratio of the solid volume fraction to the maximum attainable solid volume fraction, i.e., f/f_m [1]. The relatively uniform size distribution of the sieved coal particles tends to reduce the maximum attainable solid volume fraction and increases the packing density compared with coal powder of a wide size distribution. 50% or higher weight CWS fuel samples were too viscous and the tensiometers were not able to function with acceptable accuracy.

RESULTS AND DISCUSSION

Static Surface Tension

A du Nouy ring tensiometer measured static surface tension for the coarse and fine CWS samples mixed with DDBS-soft surfactant in Fig. 3. The static surface tension decreases with increasing surfactant concentration and approaches a saturated value beyond a certain surfactant concentration. Before reaching this certain concentration, which is called a critical micelle concentration (CMC), the fine CWS sample shows larger surface tension values than the coarse sample and the CMC of the fine CWS is higher than the coarse CWS.

The dashed arrows indicate the CMC of the fine sample, the solid arrows represent the CMC of the coarse sample, and the empty arrows are for the CMC of an aqueous solution of the specified surfactant. The CMC values for CWS fuels are higher than their aqueous counterparts. The primary reason for this is believed to be the surfactant adsorption on the coal particle surfaces which requires more amount of surfactant than the aqueous solution (Fig. 4). The higher CMC of the fine CWS compared with the coarse CWS can also be explained by the surface adsorption. Smaller coal particles create more total surface area than larger particles for the same coal loading, which causes the overall surface adsorption of surfactant to increase. This needs higher surfactant concentration for the saturated surface tension level and higher CMC.

Dynamic Surface Tension

Figure 5 shows dynamic surface tension versus bubble frequency for the two selected CWS samples of 40% coal weight containing DDBS-soft surfactant. The family of curves in each plot, from the top to the bottom, correspond to 0, 0.1%, 0.5% and 1.0% concentrations. At each surfactant concentration, the fine CWS fuel shows consistently higher dynamic surface tension values than the coarse CWS under the same bubble frequency. Two reasons can be listed for the distinction: (1) smaller coal particles of higher number density contained in the fine CWS sample

enhance the physical blockings against the surfactant migration to the bubble-created surface and reduce the surfactant diffusion into the bubble surface (Fig. 4), and (2) the increased total particle surface areas of the fine CWS sample increase the surfactant adsorption.

For the case with no surfactant mixed, the top curve in each plot, the higher surface tension for the fine CWS is attributed to the different bubble surface characteristics depending on the particle size. When the surfactant concentrations are zero or close to the static CMC level of 0.1%, the dynamic surface tension is nearly independent of the bubble frequency, which shows that the dynamic effect on surface tension is not pronounced for low surfactant concentrations. With increasing surfactant concentration, however, the dynamic surface tension shows a gradual increase with increasing bubble frequency, as the increased bubble frequency does not allow sufficient migration time for the surfactant.

Peak Voltage and Minimum Voltage

Figures 6-a and b show the temporal history of peak and minimum voltage readings for the fine and coarse CWS samples, respectively. The peak voltage data directly convert to evaluate the dynamic surface tension values. The peak voltage data obtained for the fine sample (Fig. 6-a) and the coarse sample (Fig. 6-b) show close similarity to the dynamic surface tension curves presented in Figs. 4-a and b, respectively. The higher dynamic surface tension of the fine CWS sample, which has been discussed in depth in the previous section, explains the higher peak voltage and the relatively lower dynamic surface tension of the coarse CWS results in the lower peak voltage. This finding is consistent regardless whether the surfactant is presented (1.0%) or not.

The nearly constant minimum voltage over the range of bubble frequencies at a given surfactant concentration shows that the system recovers to an identical initial condition before beginning of the next cycle. This also ensures the accuracy of the dynamic surface tension measurement that assumes an identical initial condition regardless of the bubble frequency. The minimum voltage for the coarse sample gradually varies with the bubble frequency range, but not showing any particular temporal correlation. This variation is attributed to the bubble pressure detection uncertainties associated with the presence and movement of relatively large coal particles at the gas-liquid interface.

The minimum voltage represents the hydrostatic pressure at the depth of the interface at the time of cycle completion or of new cycle initiation. The minimum voltage can decrease when the gas-liquid interface recedes from the orifice exit and stays inside the orifice at the time of cycle completion. The receding of the gas-liquid interface is likely to occur at higher surfactant concentration that enhances the solution wetting and increases the interface penetration inside the orifice. Results for both fine and coarse samples (Figs. 6-a and b) show that the minimum voltage level decreases with increasing surfactant concentration.

Increase in the minimum voltage could occur when the hydrostatic pressure is higher than that at the orifice exit. This may occur as a result of an incomplete bubble detachment at the end of the cycle. The remaining undetached portion of the bubble can result in a deeper initial depth than the orifice exit and the pressure transducer will detect a higher hydrostatic pressure than it should be. This type of bias may occur at extremely high bubble frequencies where the dead time is insufficient for full recovery of the cycle with a complete bubble detachment. A high-speed synchronized cinematograph could be employed to carefully visualize the bubble growth and detachment as a future investigation.

Dead Time

Figures 7-a and b show the percent dead time over the bubble life time as a function of the bubble frequency for the fine and coarse CWS samples with or without surfactant. This ratio increases linearly with increasing bubble frequency and also increases with increasing surfactant concentration. Reduced surface tension at higher surfactant concentrations expedites the bubble growth rate and shortens the diffusion time. The dead time, which occupies the remainder of the bubble life time, increases and the percent dead time goes up with increasing surfactant concentration for a given bubble life time.

For a fixed surfactant concentration the dead time ratio increases with the bubble frequency. This implies that the percent diffusion time decreases with increasing bubble frequencies and the surface aging by the surfactant migration is insufficiently achieved. This relatively short diffusion time at higher bubble frequencies retards a full benefit of surfactant. Larger dynamic surface tension values measured at higher bubble frequencies (see Figs. 4-a and b, for example) are attributed to the shortened diffusion time with increasing bubble frequency.

CONCLUSION

The effects of coal particle size on the CWS interfacial properties by measuring the dynamic surface tension using a Kruss tensiometer and by examining the detailed bubble pressure variation with time. Fundamental conclusions reached are:

- 1) Examination of interfacial properties of CWS fuel samples of different coal particle size ranges shows that the CWS static and dynamic surface tensions tend to increase with decreasing coal particle sizes. This finding consists with the measured peak voltages, which converts into the dynamic surface tension.
- 2) For the case of coarse CWS sample, the relatively larger coal particles cause the minimum voltage to slightly fluctuating, but remaining nearly constant through the range of bubble frequencies considered. The minimum voltage remains constant for the fine CWS sample.
- 3) The dead time ratio over the bubble life time increases with the bubble frequency and also increases with the surfactant concentration. This is attributed to the expedited bubble pressure rise rate due to the increased surfactant dispersion.

ACKNOWLEDGMENT

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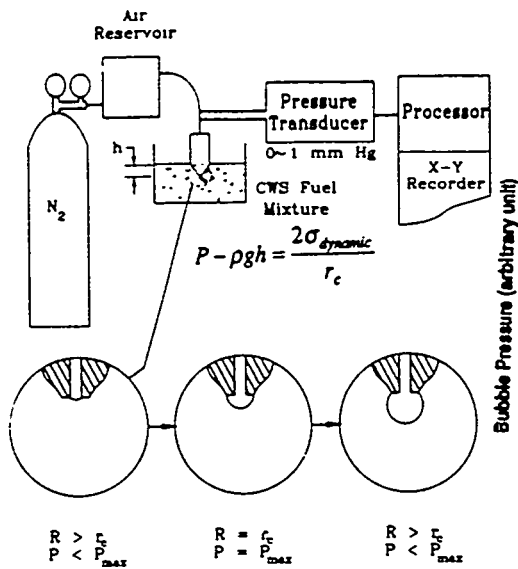


Fig. 1 Schematic illustration of maximum bubble pressure technique.

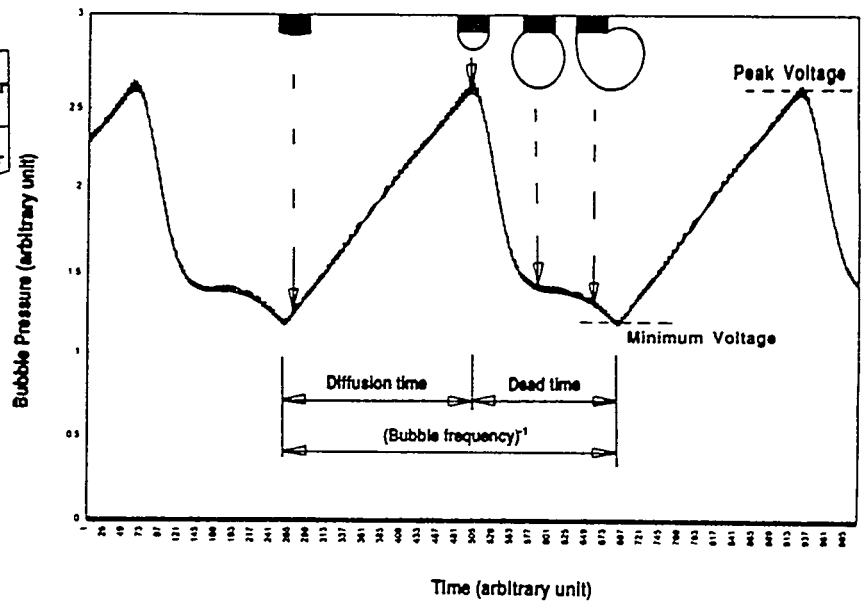


Fig. 2 Temporal history of the bubble pressure.

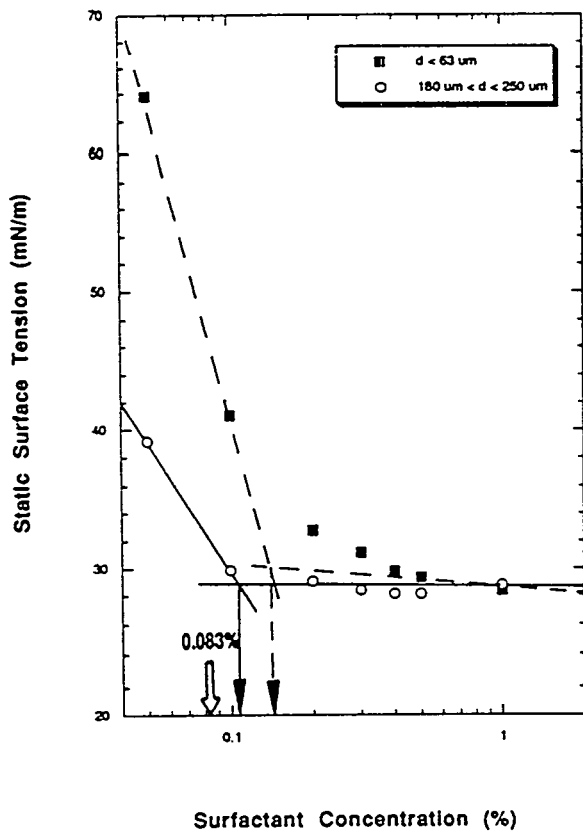


Fig. 3 Static surface tension versus concentration of DDBS-soft surfactant for 40% weight CWS fuels containing different particle sizes.

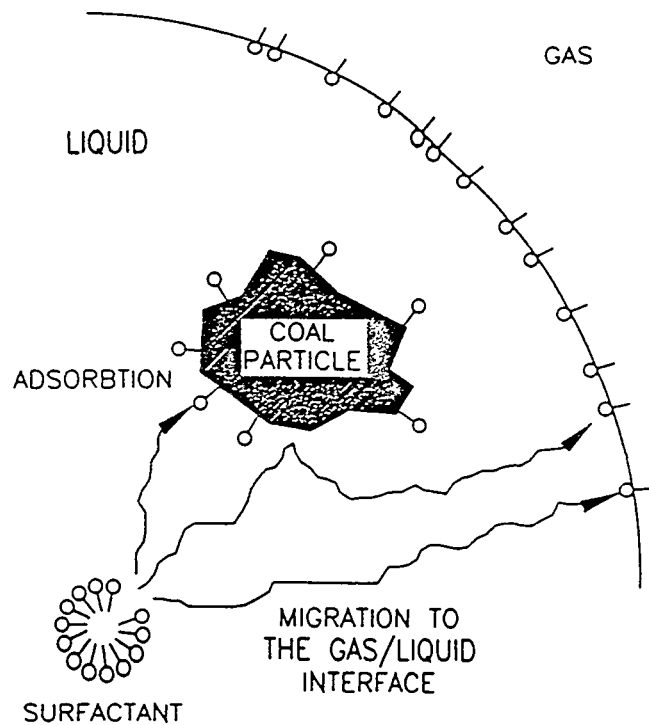


Fig. 4 Schematic illustration of adsorption of surfactant at coal surfaces and physical blocking of surfactant migration by coal particle.

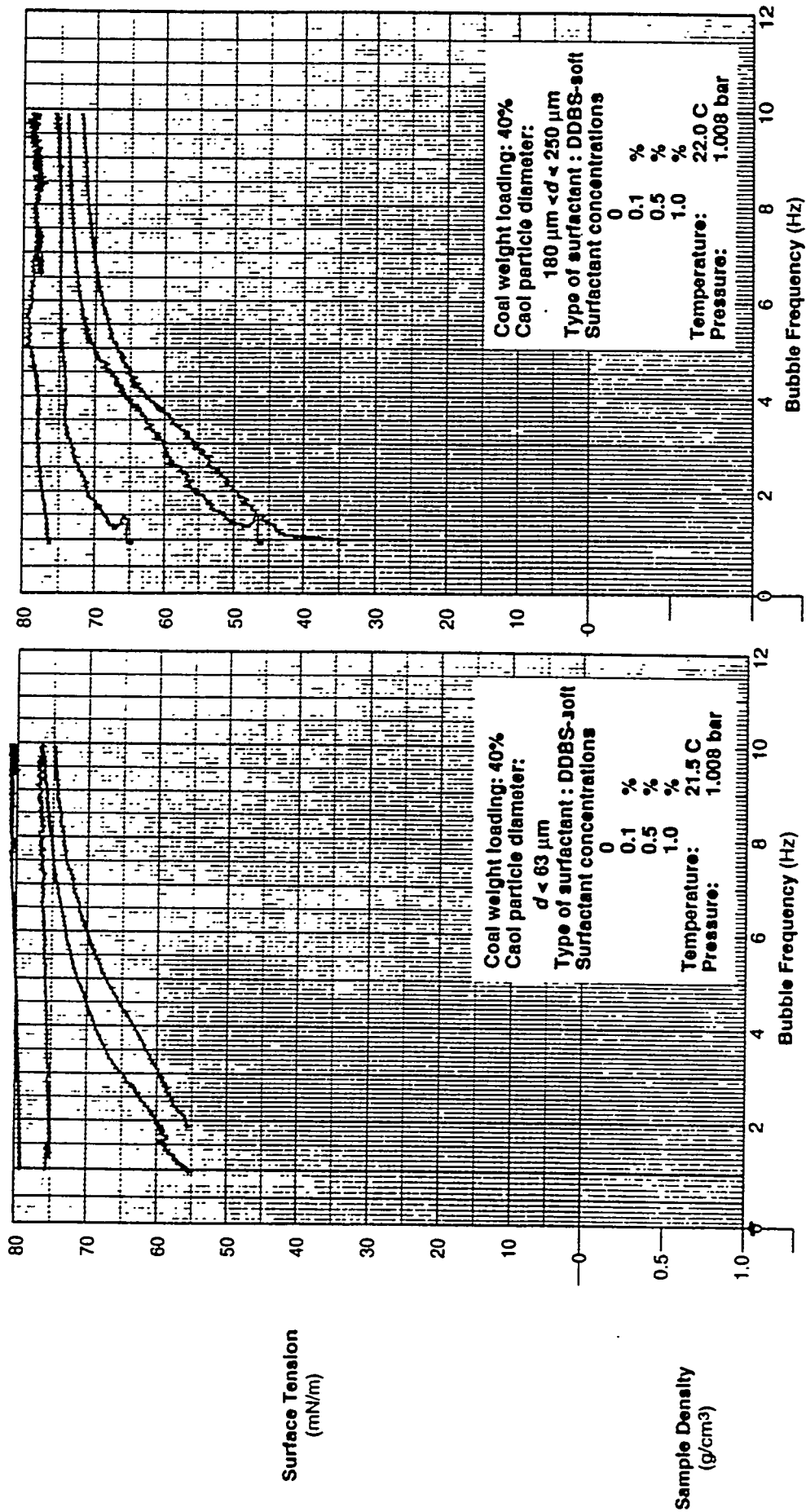


Fig. 5 Dynamic surface tension versus bubble frequency for different surfactant concentrations.

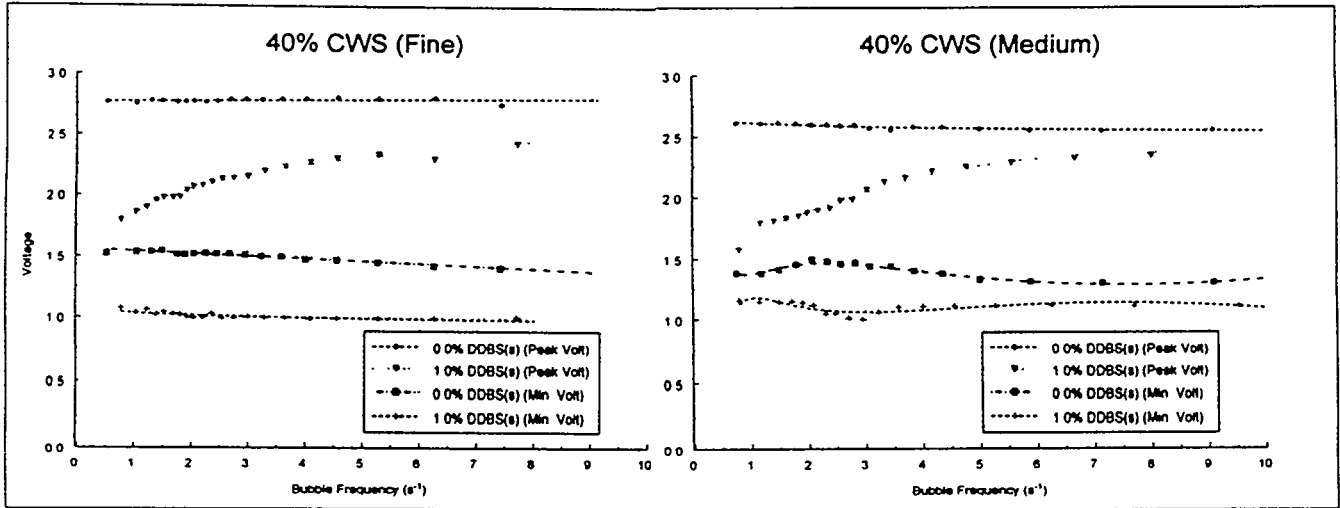


Fig. 6 Peak and minimum voltages versus bubble frequency for (a) fine CWS sample, and (b) coarse CWS sample.

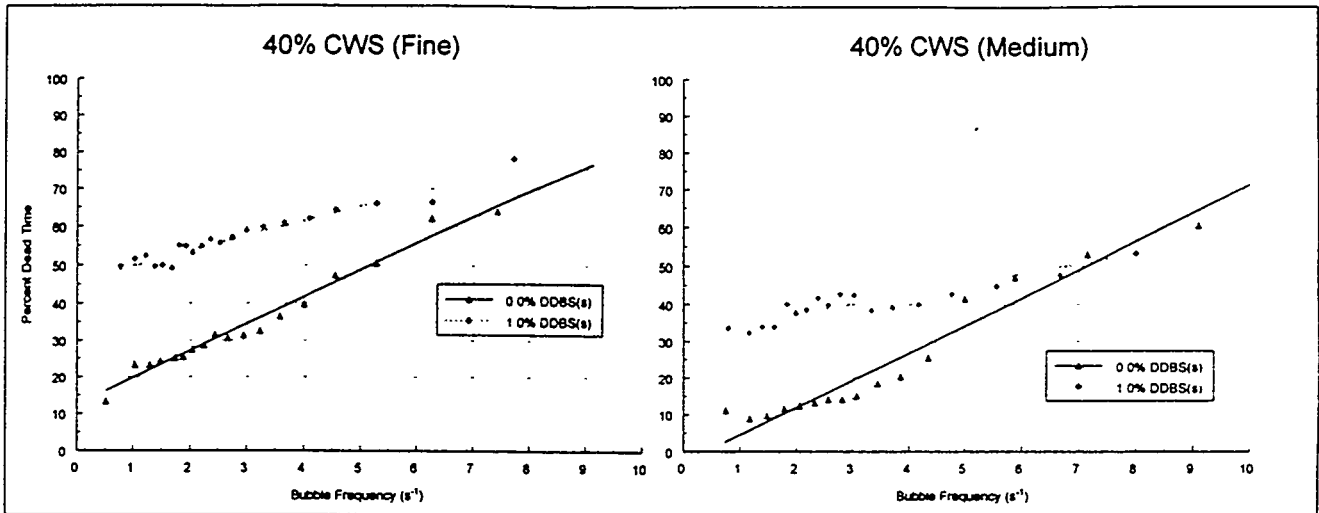


Fig. 7 Percent dead time over the bubble life time versus bubble frequency for (a) fine CWS sample, and (b) coarse CWS sample.

RECENT ADVANCES IN THE USE OF SYNCHROTRON RADIATION FOR THE

ANALYSIS OF COAL COMBUSTION PRODUCTS

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Two major coal combustion problems are the formation and build-up of slag deposits on heat transfer surfaces and the production and control of toxic species in coal combustion emissions. The use of synchrotron radiation for the analysis of coal combustion products can play a role in the better understanding of both these phenomena.

An understanding of the chemical composition of such slags under boiler operating conditions and as a function of the mineral composition of various coals is one ultimate goal of this program.

The principal constituents in the ash of many coals are the oxides of Si, Al, Fe, Ca, K, S, and Na. The analytical method required must be able to determine the functional forms of all these elements both in coal and in coal ash at elevated temperatures. One unique way of conducting these analyses is by x-ray spectroscopy.

The Extended X-Ray Absorption Fine Structure (EXAFS) and X-Ray Absorption Near Edge Structure (XANES) spectroscopic techniques and other applications to the chemical speciation of coal combustion products have been described previously.¹ Therefore only a short summary will be included here. The experiment involves scanning through the K- or L-shell absorption edge of the element in question. The structure of the absorption edge, consisting of transitions to unoccupied molecular levels, can be compared to those of model compounds for identification. The relative position of the absorption edge can yield information regarding the oxidation state of the element. This portion is the XANES portion of the spectrum. The EXAFS region, extending from about 60 eV above the absorption edge, represents scattering from neighboring constituents and can be used to determine the coordination number and coordination distance of a specific element from its neighboring atoms.

The best source of excitation energy for these experiments is an electron storage ring emitting synchrotron radiation (SR).² The National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory is a 2.5-GeV storage ring and emits a continuous spectrum of x-rays to an energy of about 30 keV. Beam line X-19A is dedicated to XANES and EXAFS and is being adapted to the performance of this investigation.

The program involves a combined effort between the staff of the University of Kentucky, PSI Technology, Inc. and Brookhaven National Laboratory. The principal responsibility of the staff at Brookhaven National Laboratory is to upgrade the X-19 beam

line facility to permit the entire series of light element analyses and to permit high temperature *in-situ* analysis.

Speciation analysis of S, K, Ca, and Fe compounds have been accomplished with the Si(111) crystals and Si(220) crystals. As can be seen from Figure 1, the soft x-ray capability of this beam line can be extended by using large D-spacing crystals such as InSb, YB₆₆, and mica. An InSb crystal and a mica crystal have been obtained and will be tested.. In both cases it is anticipated that the heat loading of the first crystal in the white beam will change the lattice constant of the crystals due to thermal expansion. Even if the mica crystals can only be used for a few experiments, they are inexpensive enough to be replaced.

For the analysis of compounds of elements present in low concentrations and particularly for the analysis of compounds of toxic trace elements it is important that the sensitivity of the system be high. The originally designed X-19A beam line system could speciate compounds of light elements present in the 100 ppm concentration range.

Recent advances have permitted a marked improvement in the systems sensitivity. We have recently replaced the original 10-mil Be window with an 8 μmBe window. As can be seen in Figure 2, the thin window will permit us to study elements as light as sodium and will increase the flux of sulfur edge radiation at the target by a factor of 3-4.

In addition, we have installed a strong focussing mirror which provides, at least, a 25-1 horizontal beam focus (i.e., 25.4 mm of horizontal beam squeezed into ~1 mm.) The results are better beam uniformity and 2-3 times more flux on the sample.

The combination of these two improvements now permit us to speciate compounds of light elements present in the 20-30 ppm range.

A 100-element detector is under development which should provide much higher sensitivities. The data collection path is straightforward with 100 detecting elements in a single Si wafer feeding charge proportional to the energy of the detected photon into 100 fast/slow shaping amplifiers which provide further gain and condition the slow signals for energy discrimination via pulse height analysis with 100 single channel analyzers. Diagnostics and calibration components make it possible to view, in close to real time, the energy spectrum of the photons being emitted from the sample. The technical advantage of such a detector is provided by the ability to use energy discrimination to separate the desired fluorescence signal from scattering and to alleviate the dead time associated with individual detectors at high count ranges.

Two examples of the application of x-ray near edge spectroscopy to coal combustion problems are the analysis of iron compounds in an *in-situ* combustion cell and the analysis of chromium compounds in a utility boiler ash.

During combustion, iron may become incorporated into glassy aluminosilicate-derived as particles. Because glassy particles are often sticky, these particles may also deposit on and adhere to available surfaces. In prior research conducted at PSI, particle stickiness has been

shown to be a function of particle viscosity. Thus, knowledge of the precise composition of iron-containing glass particles is an important parameter in determining their viscosity and stickiness. In addition to composition, the oxidation state of iron-containing glasses must also be known. For iron dissolved in glass, the (+2) oxidation state results in a significantly lower viscosity than does the (+3) oxidation state.

To understand and eventually predict the deposition of iron-containing ash particles, it is therefore critical that the precise chemical state of iron at the point of encounter with an impaction surface be known. XANES spectroscopy is one technique useful for determining the chemical speciation of iron. Typically XANES spectroscopic analysis is conducted on a sample that has been quenched and removed from the combustion process. While this provides valuable insight into the possible state of iron, the possibility of quench-induced phase formation cannot be avoided.

In this program, an *in-situ* combustion furnace and measurement cell have been constructed by PSI, U. Kentucky, and Brookhaven National Laboratory personnel to permit measurement of the forms of iron and other elements without the need for quenching and sample removal. This permits the state of iron to be measured in deposit samples.

Figure 3 illustrates the spectra from Fe K edge spectroscopy of an *in-situ* deposit of K energy #9 coal tailings at 1500°C under oxidizing and reducing conditions. The spectra indicate principally Fe_2O_3 at 20% oxygen and Fe_{1-x}S (pyrrhotite)- Fe_3O_4 at 5% oxygen. Further *in-situ* combustion runs are planned to improve our knowledge of Fe combustion chemistry.

In previous work at PSI and the University of Kentucky it was shown that chromium in coal and fly ash may be present in the more benign (+3) oxidation state. In these samples of fly ash and coal analyzed, no evidence for the highly carcinogenic (+6) form was obtained. While encouraging, these results were obtained for only a few coals that were burned in the laboratory. Further, measurements of only 'bulk ash' were made; no effort at analyzing form or concentration as a function of particle size was attempted. The possibility that the small amount of chromium associated with fine respirable particles may be in the (+6) oxidation state cannot be ruled out from the bulk ash measurements, because the (+6) signal would be overwhelmed by the (+3) signal from the bulk of the ash mass.

Because the air emissions of any trace element are dependent upon the element's association with the finest fly ash particles, it is desirable to determine the form of elements such as chromium *as a function of particle size*. Previous work with the "major" coal ash elements has indicated that combustor size does not significantly affect the ash formation process, so we do not expect a large difference for chromium (or any other trace element). Nevertheless, the statement that combustor size does not affect chromium transformations cannot be made with certainty until comparative measurements have been made.

Two samples of fly ash were obtained from a field TVA unit. The samples contain only particles <2.5 μm in size and were collected under conditions of "high load" and "low load." Elemental analysis of the ash by ICP-MS indicate a chromium concentration of 1304 ppm in the high load sample and 1670 ppm in the low load sample.

We plan to analyze these samples by near edge spectroscopy for Cr(+3) and Cr(+6). It is further planned to address remaining uncertainties in the combustion behavior of chromium by a series of laboratory experiments with TVA coal to generate size fractionated fly ash samples. Subsequent measurements will provide data on the dependence of chromium oxidation state on particle size and comparative data on chromium evolution in small and full scale systems.

Acknowledgments

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SOFT X-RAY MONOCHROMATOR CRYSTALS

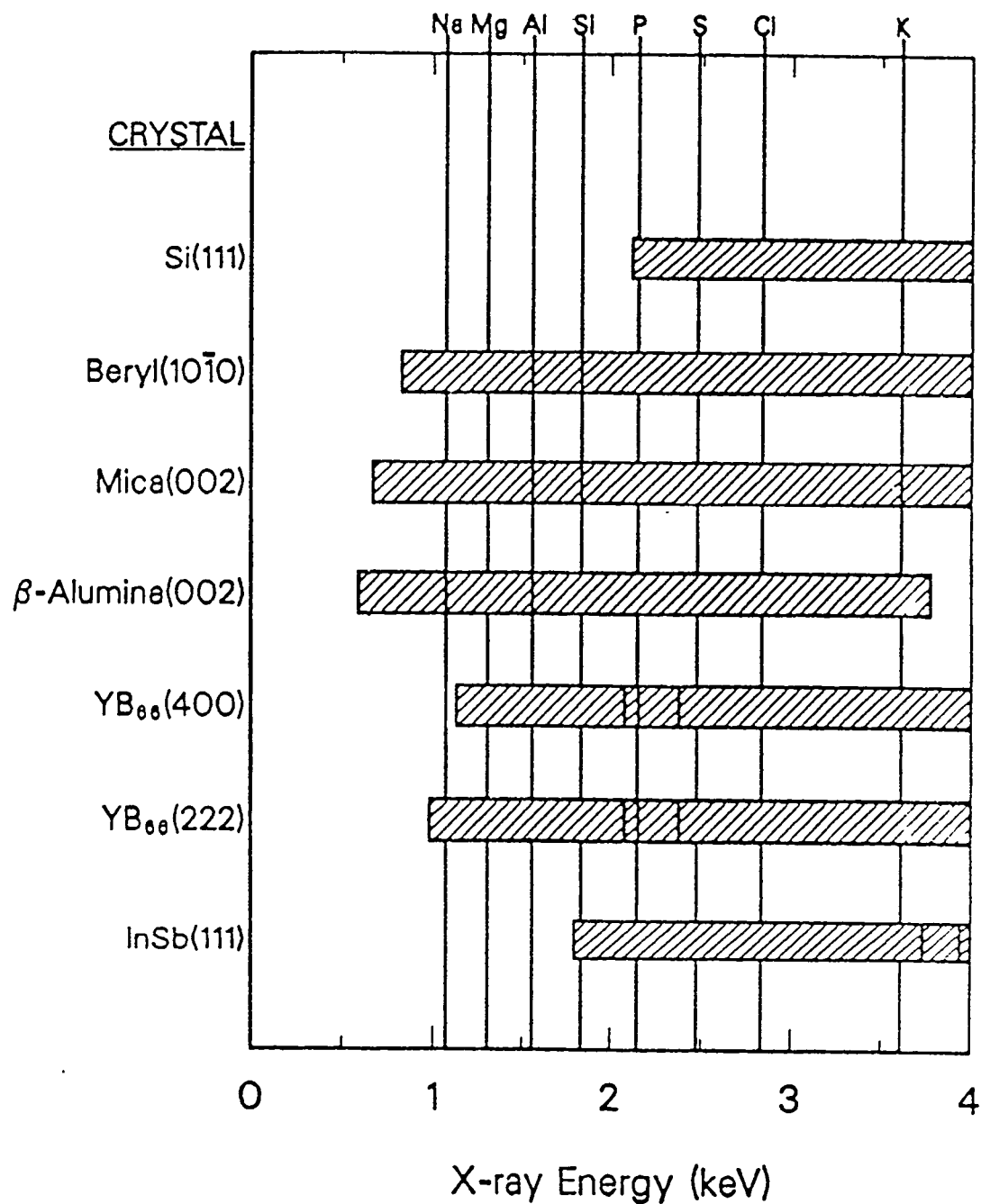


Figure 1. Ranges of energy accessible using listed monochromator crystals. Elemental absorption edge energies are shown on abscissa at top.

WINDOW TRANSMISSION

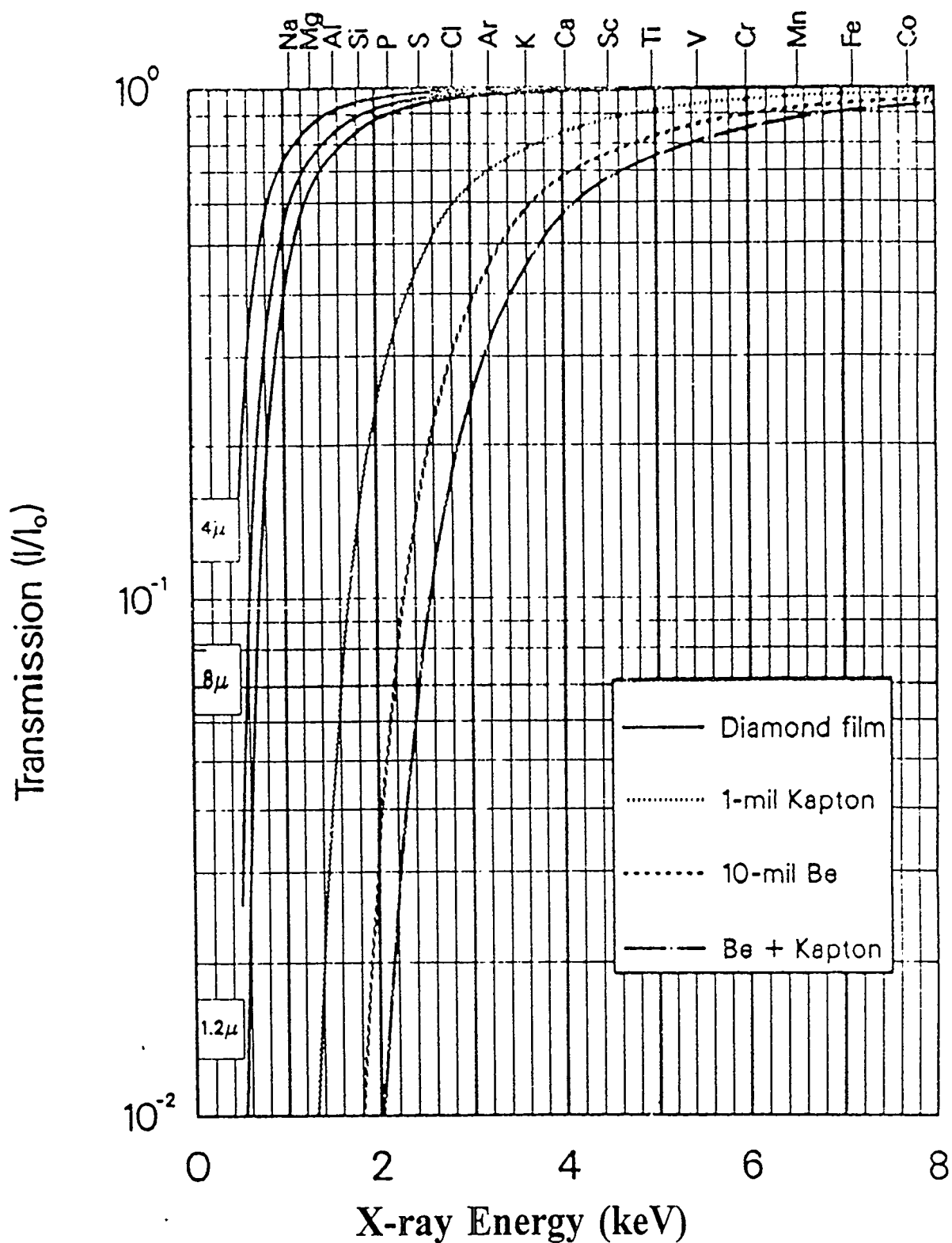


Figure 2. Transmission for beam line windows in the soft x-ray range. The new film window is $0.8\ \mu\text{m}$ thick.

KY #9 feed, 6 g/min, 1500C

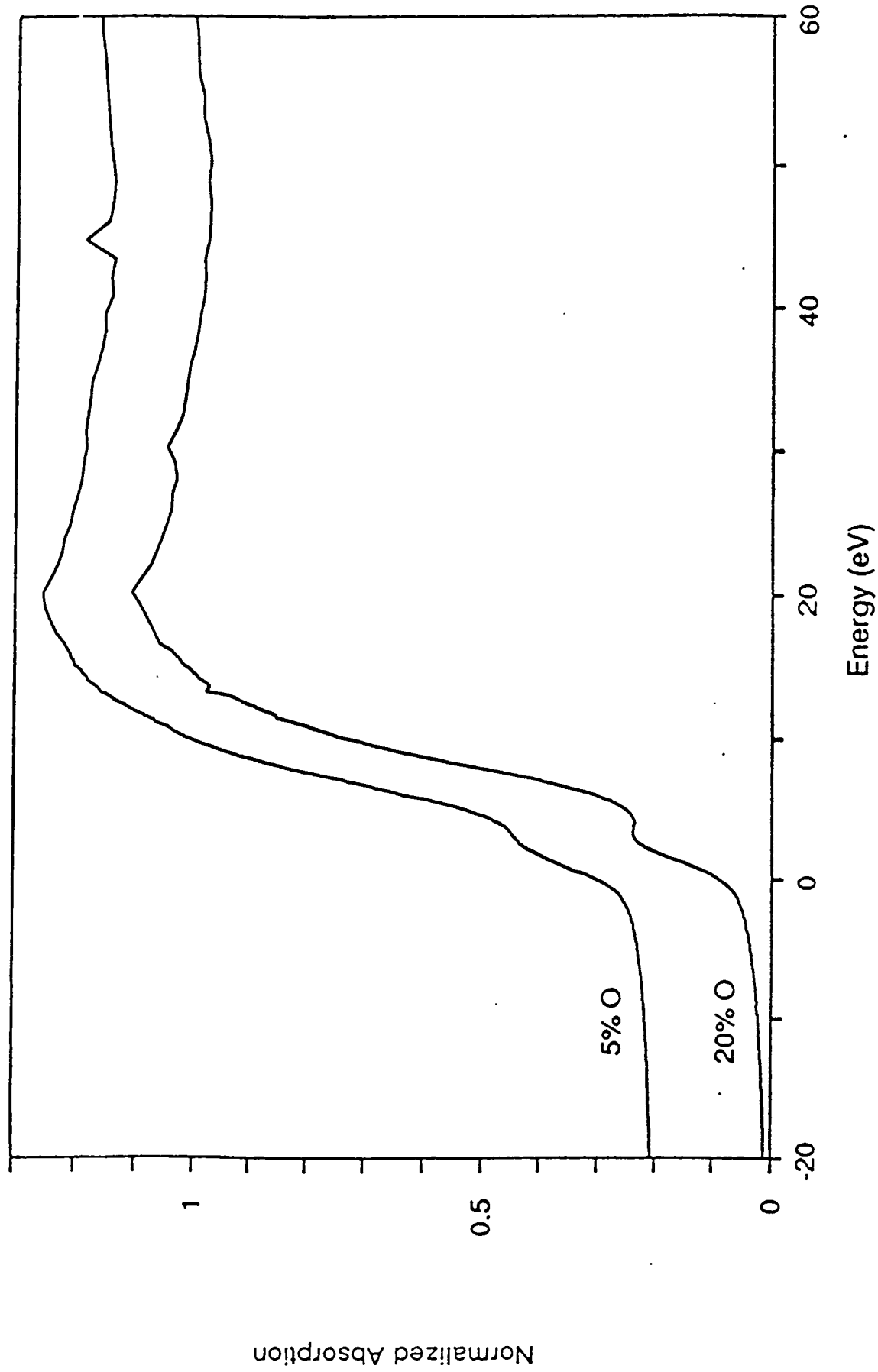


Figure 3. Fe K-edge XANES of *in-situ* deposit of Kentucky #9 coal at 1500°C under oxidizing and reducing conditions.

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*DEVELOPMENT OF A ROTARY COMBUSTOR FOR
REFIRING PULVERIZED COAL BOILERS*

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The following manuscript was unavailable at time of publication.

FLUID DYNAMICS OF ASH DEPOSITION

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Please contact author(s) for a copy of this paper.

PARTICULATE EMISSION ABATEMENT FOR
KRAKOW BOILER HOUSES

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LSR Technologies, Inc.
Acton, MA U.S.A.

Jan Surówka
Polish Foundation for Energy Efficiency
Katowice, Poland

Miroslaw Litke
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Introduction

Environmental clean-up and pollution control are considered top priorities in Poland. The magnitude of environmental problems and public awareness of it has forced the Polish government to implement more aggressive regulatory controls. The extent of this condition has in fact prompted the government to designate pollution control as a top priority for foreign investment.

During the past five years, Poland has also made significant progress in reorienting its central-planned economy to one based on open market principals. Efforts to decentralize has led to the privatization of many government-owned businesses with a concomitant shift in buying decisions to privately-owned enterprises. This movement toward privatizing the economy along with cleaning and protecting the environment has created numerous business opportunities for both Polish and foreign companies. As a result, there's been a drastic downsizing of large formerly state-owned companies. And, new startups and small businesses have become the main hope in reviving the Polish economy.

The Krakow Clean Fuels and Energy Efficiency Program was promulgated by the U.S. AID and Department of Energy to assist Poland in its effort to restructure. The City of Krakow has experienced severe environmental damage during the past two or three decades due to its heavy dependency and inefficient use of low grade coals, lack of pollution controls, and because of its climate and weather patterns. Airborne pollutants, especially particulate matter, are discharged from low stacks burning coal, mainly unwashed. As a result, levels of suspended particulate matter can reach dangerous levels during the winter heating seasons.

This paper discusses one of the eight projects for environmental cleanup in Krakow initiated by the Department of Energy. The project uses a newly developed technology for particulate control, called a *Core Separator* developed by LSR Technologies, Inc. in the U.S.A. The Polish Foundation for Energy Efficiency has assisted LSR in identifying appropriate markets for the *Core Separator* and in implementing the new technology. Eco Instal, a leading manufacturer of environmental equipment in central Poland, has also participated in this project and has already produced a number of units for commercial applications.

Technology Description

The *Core Separator* is a new technology developed through research sponsored by the Department of Energy and Environmental Protection Agency. Some *Core Separator* units have been placed in commercial operation in the U.S. All of the units now in service are performing difficult separations, i.e., those involving dust particles with small aerodynamic diameters. Historically, mechanical separators have been ineffective in removing dust particles with diameters below 10 microns. In comparison, the *Core Separator* is able to remove a high percentage of particles even at 2-3 microns in diameter. This is roughly equivalent to the performance of a medium-efficiency electrostatic precipitator (ESP).

Some of the features and benefits of the *Core Separator* relative to other devices for particulate control are as follows:

- Operation based entirely on centrifugal principals
- A three component system utilizing gas recirculation
- Roughly 4-8 times lower dust penetration than from cyclones
- High efficiency in removing respirable (PM10) particles
- Very high turndown performance
- High temperature capability
- Ease of operation and maintenance

A simplified schematic of the *Core Separator* system is shown in Figure 1. The system includes two conventional components, a cyclone collector for extracting solids and a fan for flow recirculation. The *Core Separator* is actually a multitude of cylindrical units. Each unit has a single inlet for the stream to be treated and two outlets, one for the cleaned gas stream and the other containing a highly concentrated recirculation stream. The dust-laden recirculation stream is fed to the cyclone and then returns again by means of the fan. The processes of separation and collection are accomplished separately in different components. The *Core Separator* cleans the inlet stream and detains dust particles in the system. Since its efficiency is quite high, the dust particles cannot leave the system. They recirculate again and again until collected in the cyclone.

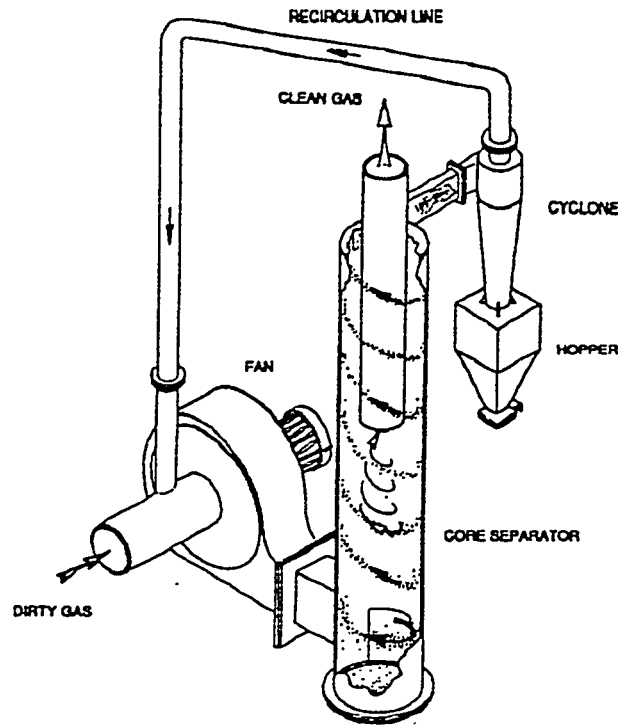


Figure 1

Two factors govern the performance of *Core Separator* systems: (1) a high separation efficiency of the *Core Separator*, and (2) an interaction between individual components. To achieve high separation efficiency, a proper recirculation flow is required. By varying recirculation flow in the *Core Separator*, the tangential and radial velocities can be controlled independently to maintain them in the proper ratio.

The *Core Separator* System can be arranged in a variety of configurations depending on process conditions, required performance, inlet dust concentration, abrasiveness of solids, etc. The *Core Separator* component actually predetermines the efficiency of the system even if the collector efficiency is low. The following formula can be used to calculate partial collection efficiency when the collector is situated downstream of the *Core Separator*,

$$E_{sys} = \frac{E_{cs} \times E_{cyc}}{1 - E_{cs}(1 - E_{cyc})}$$

When the collector is situated upstream of the *Core Separator*,

$$E_{sys} = \frac{E_{cyc}}{1 - E_{cs}(1 - E_{cyc})}$$

Here E_{cs} , E_{cyc} and E_{sys} relate to the *Core Separator*, collector and *Core Separator* system partial separation efficiencies, respectively.

During the past year, a series/parallel modular design has been developed to facilitate scaleup in capacity. It has been tested under a wide range of conditions and with numerous dust compositions, primarily coal flyash. The efficiency of the *Core Separator* has been generalized and compared against other dust collector types. As shown in Table 1, the penetration of dust emissions from it are several times lower than from cyclonic collectors, which are commonly used in Krakow boilers. For this reason, the *Core Separator* can make a significant contribution to emissions reduction in Krakow.

Table 1. Normalized Emissions from Various Dust Collectors

Dust Collectors	Collection Efficiency, %	Penetration (Emission), %	Normalized Penetration (Emission)
Cyclone	50.6	49.4	14.5
Multiple Cyclone /Medium Efficiency/	78.0	22.0	6.47
Multiple Cyclone /High Efficiency/	86.3	13.7	4.03
Wet Scrubber	88.7	11.3	3.32
Venturi	96.6	3.4	1.0
ESP /Medium Efficiency/	98.2	1.8	0.53
Fabric Filter /Medium Efficiency/	96.6	3.4	1.0
ESP /High Efficiency/	99.58	0.42	0.12
Fabric Filter /High Efficiency/	99.77	0.23	0.07
Core Separator	99.92	0.08	0.02

Environmental Regulations in Krakow

Krakow with its 750,000 population relies heavily on hard coal as a heating fuel. In 1992, it was estimated that 35% of the heating needs were provided by more than 2,900 local boilers consuming about 370,000 tons of coal annually. A major portion of heating needs was also provided by two local power plants, Łeg and Skowina. By 1995, the district heating system was extended to several new parts of the city. Also, many old boilers were retired and others were converted to natural gas. As a result, it is estimated that in mid-1995 the boiler population in Krakow had been reduced approximately in half.

All of the regional counties of Poland (called voivoids) including Krakow have developed medium and long range plans for emission abatement that are more in line with western Europe. The intent of the medium range plan (five years in length and complete by the year 2000) is to bring Poland closer to European environmental standards and enabling it to join the European Union (EU) in due course. The Polish government has shown a commitment to enact legislation which is in line with its international obligations and EU recommendations concerning emissions. In July 1994, Poland signed in Oslo the Sulfur Protocol for interborder contamination of air. Its obligations from this protocol are substantial, including a 90% reduction in SO₂ from new plants and specific targeted reductions.

However, while Polish standards for SO₂ and other gaseous pollutants are in line with its European neighbors, the limits for dust emissions are not. This can be seen in Table 2, which provides a summary of the relevant permitted emissions related to fuels combustion. To obtain limits expressed as mg/M³, the following conversion factors can be used:

- Coal Fuels 420 M³ Flue Gas/GJ
- Liquid Fuels 370 M³ Flue Gas/GJ
- Gaseous Fuels 300 M³ Flue Gas/GJ

The relevant permitted emissions related to combustion processes presented in Table 2 are from the Ministry of Environmental Protection Natural Resources and Forestry.

In comparison with standards used in other nations, the particulate standard in Poland is not very stringent. Unlike the limits proposed for SO₂, NO_x, and other gaseous pollutants, the proposed limits for dust emissions are many times higher than those of other countries as shown in Table 3. In order to meet the ambient air quality standards set for protected areas such as Krakow, these standards may have to be tightened significantly.

Table 2. Permitted Emission Limits (Poland)

Fuel	Furnace	Permitted Emissions for Combustion Processes (g/GJ)								
		Group A ¹⁾			Group B ²⁾			Group C ³⁾		
		SO ₂	NO ₂ ⁴⁾	Dust	SO ₂	NO ₂ ⁴⁾	Dust	SO ₂	NO ₂ ⁴⁾	Dust
Hard Coal	Fixed Grate	990	35	1850	720	35	1370	650	35	1370
	Mechanical Grate	990	160	800	640	95	600	200	95	600
	Pulverized Coal 1	1240	495	170	870	170	90	200	170	90
	Pulverized Coal 2	1240	330	260	870	170	130	200	170	130
Brown Coal	Pulverized Coal 1	1540	225	140	1070	150	70	200	150	70
	Pulverized Coal 2	1540	225	140	1070	150	95	200	150	95
Coke	Fixed Grate	410	45	720	410	45	235	410	45	235
	Mechanical Grate	500	145	310	250	145	235	250	110	235
Oil	Boilers < 50 MW	1720	120	—	1250	120	—	125	90	—
	Boilers > 50 MW	1720	120	—	1250	160	—	170	120	—
Nat. Gas	Boilers < 50 MW	—	60	—	—	35	—	—	35	—
	Boilers < 50 MW	—	145	—	—	85	—	—	85	—
Wood	Grate	—	50	—	—	50	—	—	50	—

- 1) Group A relates to existing installations during the day of the Ordinance (1990) until Dec. 31, 1997.
- 2) Group B relates to existing installations during the day of the Ordinance (1990) and after Dec. 31, 1997.
- 3) Group C relates to new installations placed in operation after Dec. 31, 1994.
- 4) Signifies the sum of NO and NO₂ converted to NO₂.

Table 3. Particulate Emission Standard, Various Countries

Country	Size	Particulate Standard	Dust Emission (mg/M ³)
U.S. (after 1978)	> 73 MW _T	13 g/GJ	40
U.S. (after 1984)	> 29 MW _T	22 g/GJ	67
U.S. (after 1971)	> 73 MW _T	43 g/GJ	133
Germany	< 5 MW _T	65 g/GJ	185
Germany	> 5 MW _T	20 g/GJ	57
Netherlands	> 10 MW _T	10 g/GJ	28
Czech Republic	< 25 MW _T	52 g/GJ	150
Czech Republic	> 25 MW _T	20 g/GJ	56
European Union	> 50 MW _T	20 g/GJ	56
China	< 5 MW _T	52 g/GJ	150
Australia	< 5 MW _T	70 g/GJ	200
Chile	> 5 MW _T	20 g/GJ	56
Poland	Traveling Grate/Coal	600 g/GJ	1,715
Poland	Pulverized Coal	90 g/GJ	257

Summary and Conclusions

There is a sizeable stoker-fired boiler population in Krakow and throughout Poland. Emissions from these boilers, especially dust emissions, have caused a significant deterioration in ambient air quality in Krakow. The combination of extensive coal combustion and the city's location in a valley having a thermal inversion often results in a heavy smog containing suspended particulate matter.

Several approaches have been suggested to improve air quality including coal cleaning, fuel switching, extension of the district heating system, and the use of more efficient control technology. The *Core Separator* fits into this last category as a more efficient dust collector. Dust emissions from the *Core Separator* are typically 4 to 8 times lower than from conventional cyclonic collectors. The implementation of this device can therefore have a significant impact on air quality in Krakow.

However, the widespread use of improved technology can only result if appropriate emission regulations are in place and those regulations are enforced. In this regard, the particulate standard in Poland is conspicuously less ambitious than those of its neighbors. For example, the Czech Republic which uses coal from adjacent coal basins has a particulate standard that is many times lower than Poland's. Since Poland is both an importer and exporter of air pollution, its emission standards should be compatible with those of its neighbors.

Three *Core Separator* units have been sold in early 1995 and are scheduled for commercial operation this year. These units will be for use on both stoker-fired and fluidized bed boilers. While this represents some success for this project, it is generally believed that many more units could be sold if tougher regulations for dust emission were in place. Such a measure has been recommended to the U.S./Polish Bilateral Steering Committee.

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