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**COMBUSTION CHARACTERIZATION
OF BENEFICIATED COAL-BASED FUELS**

QUARTERLY REPORT NO. 8 FOR THE PERIOD JANUARY TO MARCH 1991

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INTRODUCTION

The Pittsburgh Energy Technology Center of the U.S. Department of Energy has contracted with Combustion Engineering, Inc. (CE) to perform a three-year project on "Combustion Characterization of Beneficiated Coal-Based Fuels." The beneficiated coals are produced by other contractors under the DOE Coal Preparation Program. Several contractor-developed advanced coal cleaning processes are run at pilot-scale cleaning facilities to produce 20-ton batches of fuels for shipment to CE's laboratory in Windsor, Connecticut. CE then processes the products into either a coal-water fuel (CWF) or a dry microfine pulverized coal (DMPC) form for combustion testing.

The objectives of this project include: 1) the development of an engineering data base which will provide detailed information on the properties of 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 technical data includes: bench-scale fuel property, combustion, and ash deposition tests; pilot-scale combustion and ash effects 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).

Twenty fuels will be characterized during the three-year base program: three feed coals, fifteen BCFs, and two conventionally cleaned coals for full-scale tests. Approximately nine BCFs will be in dry ultra fine coal (DUC) form, and six BCFs will be in coal-water fuel (CWF) form. Additional BCFs would be characterized during optional project supplements.

SUMMARY

During the first quarter of 1991, the following technical progress was made.

- Calculated the kinetic characteristics of chars from the combustion of spherical oil agglomeration beneficiated products.
- Continued drop tube devolatilization tests of the spherical oil agglomeration beneficiated products.
- Continued analyses of the data and samples from the CE pilot-scale tests of nine fuels.
- Started writing a summary topical report to include all results on the nine fuels tested.

TASK 1 - FUEL PREPARATION

Beneficiated coals (BCs) and feed coals are acquired from other DOE projects and shipped to CE. These fuels are then processed into either a dry pulverized coal form by CE or a coal-water fuel (CWF) form using OXCE Fuel Company technology. The feed coals are fired as standard grind (70% minus 200 mesh) pulverized coal (PC), while the dry beneficiated fuels are generally dry microfine pulverized coal (DMPC).

Nine twenty-ton batches of test fuel have been produced under the DOE-PETC Coal Preparation program since 1987. These fuels include:

1. Illinois #6 feed coal
2. Pittsburgh #8 feed coal
3. Upper Freeport feed coal
4. Illinois #6 microbubble flotation product
5. Pittsburgh #8 microbubble flotation product
6. Upper Freeport microbubble flotation product
7. Illinois #6 spherical oil agglomeration product
8. Pittsburgh #8 spherical oil agglomeration product
9. Upper Freeport spherical oil agglomeration product

All these fuels were tested in the pilot-scale facility between October 1989 and June, 1990. Bench-scale testing continued through this quarter. Approximately fifty barrels of each spherical oil agglomeration product (SOAP) were unused and remained in storage.

TASK 2 - BENCH-SCALE TESTS

All test fuels are fully characterized using various standard and advanced analytical techniques. These tests evaluate the impacts of parent coal properties and beneficiation process on the resulting BCF's qualities.

A few selected fuels are tested in a laminar flow drop tube furnace to determine fly ash particle size and chemical composition. Results include mineral matter measurements and modeling of fly ash history.

A swirl-stabilized, entrained flow reactor is used to characterize the surface compositions and the states of ash particles formed during combustion. Deposition rates on a target are determined, and the size and compositions of the deposits from different fuels are compared.

The nine coal and BCF samples received to date have been completely analyzed for: (1) complete chemical analyses; (2) flammability index measurements; (3) weak acid leaching; (4) TGA reactivities and BET surface areas of chars produced in the DTFS-1 (Figure 2.2.1). All these data have been reduced and reported in the Quarterly Report for the Period July-September, 1990.

Work during this quarter focused on completing the analysis of all the DTFS-1 combustion test data obtained from the three SOAPs. The analysis of the SOAP data was completed and results are reported herein.

2.1 Characteristics of Test Fuels

Sources of Test Fuels

A total of nine fuels have been studied to date. They comprise three parent coals and six beneficiated coal-based fuels prepared therefrom, as identified below:

- o Illinois #6 high volatile C bituminous (hvCb) coal
 - Feed Coal
 - Microbubble Flotation Product (MFP)

- Spherical Oil Agglomeration Product (SOAP)
- o Pittsburgh #8 high volatile A bituminous (hvAb) coal
 - Feed Coal
 - MFP
 - SOAP
- o Upper Freeport medium volatile bituminous (mvb) coal
 - Feed Coal
 - MFP
 - SOAP

The MFPs were produced from an improved froth flotation process wherein finely ground coal (less than 44 μm) and mineral matter are separated in a water column by bubbles of approximately 100 μm in diameter, created by air injection (Feeley and Hervol, 1987). The SOAPs were produced in a cleaning process using heptane as a bridging liquid to agglomerate coal particles while rejecting ash-forming mineral matter with water from a slurry of finely ground coal (Huettenhain and Schaal, 1990). The sources of the feed coals are as follows:

- o The Illinois #6 Coal was from the Burning Star No. 4 Mine, Perry County, Illinois. Both MFPs and SOAPs were produced from coal samples from this particular mine.
- o The Pittsburgh #8 Coal was from two different mines: from Powhatan No. 6 Mine, Belmont County, Ohio, for producing the MFPs; and from Blacksville No. 2 Mine, Monongalia County, West Virginia, for producing the SOAPs.
- o The Upper Freeport Seam Coal was from Helen Mine, Indiana County, Pennsylvania. Both MFPs and SOAPs were produced from coal samples from this particular mine, but the degree of conventional pre-cleaning differed.

Standard Analyses

The chemical analyses of the nine test fuels are given in Tables 2.1.1 and 2.1.2. The analyses of the feed coals used to prepare the MFPs and SOAPs were performed by CE and Bechtel (Huettenhain and Schaal, 1990), respectively.

Table 2.1.1

ASTM STANDARD ANALYSES OF FEED COALS AND THEIR MFPs*

QUANTITY	ILLINOIS #6 hvCb		PITTSBURGH #8 hvAb		UPPER FREEPORT mvb	
	FEED COAL	MFP	FEED COAL	MFP	FEED COAL	MFP
Proximate (Wt.%)						
Volatile Matter	38.6	40.4	38.9	41.6	28.1	27.4
Fixed Carbon	52.4	55.4	51.6	55.1	61.2	67.2
Ash	9.0	4.2	9.5	3.3	10.7	5.4
HHV (Btu/lb)	12675	13185	13025	14030	13615	14525
Ultimate (Wt.%)						
Hydrogen	5.0	4.8	5.0	5.4	4.7	5.1
Carbon	69.3	75.5	71.4	77.3	76.9	81.3
Sulfur	3.0	2.7	4.5	3.3	1.8	1.3
Nitrogen	1.3	1.0	1.2	1.4	1.3	1.5
Oxygen	12.4	11.8	4.6	5.4	8.4	9.3
Ash	9.0	4.2	9.5	3.3	10.7	5.4
Carbon/Ash Ratio	7.7	18.0	7.5	23.4	7.2	15.1
Forms of Sulfur (Wt.%)						
Pyritic	0.53	0.09	1.34	0.05	0.49	0.05
Sulfate	0.35	0.40	0.55	0.56	0.44	0.51
Organic	2.12	2.2	2.72	2.74	0.76	0.78
Ash Fus. Temps. (RED. ATM)						
IDT (°F)	2000	2020	2130	1900	2010	1960
ST (°F)	2280	2180	2390	1980	2380	2120
HT (°F)	2420	2230	2440	2020	2450	2380
FT (°F)	2530	2280	2490	2120	2400	2430
Ash Composition (Wt.%)						
SiO ₂	51.7	42.0	39.3	34.1	43.8	41.0
Al ₂ O ₃	20.7	19.3	20.2	22.3	24.2	25.1
Fe ₂ O ₃	16.9	21.2	31.4	27.7	18.8	18.1
CaO	2.2	3.7	3.0	4.6	3.1	3.3
MgO	0.9	1.4	0.8	1.3	0.9	1.2
Na ₂ O	0.5	2.3	0.5	2.2	0.3	1.6
K ₂ O	2.0	2.3	1.5	1.6	2.2	2.6
TiO ₂	0.8	2.2	1.0	1.8	0.9	2.0
P ₂ O ₅	0	0.1	0.1	0.2	0.2	0.2
SO ₃	2.1	3.4	2.1	3.2	3.9	3.1

* All analyses are reported on dry basis

MFP = Microbubble Flotation Product

Table 2.1.2

ASTM STANDARD ANALYSES OF FEED COALS AND THEIR SOAPS^{*}

QUANTITY	ILLINOIS #6 hvCb		PITTSBURGH #8 hvAb		UPPER FREEPORT mvb	
	FEED COAL	SOAP	FEED COAL	SOAP	FEED COAL	SOAP
Proximate (Wt.%)						
Volatile Matter	38.3	42.9	37.3	41.7	24.8	30.5
Fixed Carbon	46.6	52.8	53.1	53.9	51.9	64.3
Ash	15.4	4.3	9.6	4.4	23.3	5.2
HHV (Btu/lb)	12222	13880	13635	14720	11764	14395
Ultimate (Wt.%)						
Hydrogen	4.8	5.8	5.0	5.6	3.8	4.7
Carbon	67.9	75.7	75.5	79.1	65.3	81.2
Sulfur	3.7	2.8	2.6	1.9	3.8	1.5
Nitrogen	1.3	1.5	1.4	1.6	1.2	1.4
Oxygen	7.2	9.9	5.9	6.0	2.6	7.4
Ash	15.4	4.3	9.6	4.4	23.3	5.2
Carbon/Ash Ratio	4.4	17.6	7.9	18.0	2.8	15.6
Forms of Sulfur (Wt.%)						
Pyritic	1.57	0.37	1.46	0.17	2.33	0.08
Sulfate	0.10	0.02	0.03	0.51	0.04	0.31
Organic	1.98	2.41	1.14	1.43	1.40	0.91
Ash Fus. Temps. (RED. ATM)						
IDT (°F)	2086	1850	2020	2000	2090	2100
ST (°F)	2287	1910	2169	2160	2281	2150
HT (°F)	2388	1950	2243	2200	2369	2190
FT (°F)	2510	2000	2360	2450	2453	2300
Ash Composition (Wt.%)						
SiO ₂	50.6	40.2	41.2	38.7	46.8	41.2
Al ₂ O ₃	19.7	19.9	19.6	24.1	21.1	24.5
Fe ₂ O ₃	16.4	25.6	18.9	19.7	20.1	19.2
CaO	4.1	3.4	7.1	5.3	3.1	3.3
MgO	0.9	1.4	1.3	1.4	1.0	1.2
Na ₂ O	0.8	1.6	0.7	1.1	0.3	1.6
K ₂ O	2.1	2.4	3.5	1.6	2.7	2.5
TiO ₂	1.0	2.5	0.9	1.7	0.9	1.9
P ₂ O ₅	0.2	0.2	1.6	0.4	0.4	0.3
SO ₃	2.7	2.0	5.0	3.9	2.4	2.7

* All analyses are reported on dry basis
 SOAP = Spherical Oil Agglomeration Product

The analyses of the feed coals used in preparing Illinois #6 MFP and SOAP are consistent with each other. The feed coals used in preparing the Pittsburgh #8 MFP and SOAP are also generally consistent with each other. The Pittsburgh #8 MFP feed coal shows slightly higher ash fusibility temperatures and iron content than its SOAP feedstock counterpart. These differences are due to the fact that the two feed coals came from different mines. The Upper Freeport MFP and SOAP were prepared from pre-cleaned and run-of-mine feed coals, respectively. This explains the observation that the ash content of the MFP feedstock is significantly lower than that of the SOAP feed coal. The ash fusibility temperatures and compositions of both feedstocks are nevertheless similar.

Both coal cleaning processes resulted in more than 50% reductions in ash contents and more than 5% increases in calorific values. The reductions in pyritic contents (greater than 80%) are believed to be due to both actual removal during coal cleaning and oxidation during sample storage. The pyrite may have been oxidized to form iron sulfate (FeSO_4) and perhaps iron oxyhydroxide (FeOOH) (Huffman, et al., 1985).

The two coal cleaning processes generally did not appear to significantly improve the qualities of the BCF ashes. The effects of cleaning appear to be coal-type dependent. For the Illinois #6 coal, both MFP and SOAP processes selectively removed certain mineral species, mainly silicates, and enriched others, specifically iron, alkali metals and alkaline earths. As a result of these changes in basic and acidic constituents, the ash fusibility temperatures of the two products are significantly lower than those of their respective feedstocks. For the Pittsburgh #8 and Upper Freeport coals, removals of mineral matters were less species-specific. There were slight reductions of silicate and enrichments of alkali and alkaline earth minerals. More details on the mineralogical characteristics of the coal feedstocks and BCFs are given in subsequent sections.

The particles of both microbubble flotation and spherical oil agglomeration products are very fine compared to coals commercially suspension fired. Figure 2.1.1 shows that while the mean weight particles sizes of the feedstocks are in the 44-51 μm range, those of the BCFs fall in the 16-21 μm range. The comminution of coal mineral matter constituents resulting from the two cleaning processes

FIGURE 2.1.1 PARTICLE SIZE DISTRIBUTIONS OF PARENT COALS AND THEIR BCF PRODUCTS

utilized are not, however, manifested to the same extent, as discussed below.

Special Analyses

Weak Acid Leaching (WAL). This test is designed to determine the concentrations of volatile alkali metals in an ash sample, which are leachable by a weak acid. The volatilizable alkali metals are known to initiate ash fouling phenomenon. Results obtained from this study are given in Table 2.1.3.

The microbubble flotation and spherical oil agglomeration coal cleaning processes did not improve the fouling qualities of the subject BCF ash samples. The lower ash contents of the BCF fuels can reduce ash deposition; however, the fluxing effect of their volatile alkali metals can produce lower melting ash deposits that can be tenaciously bonded to heat exchange surfaces.

Table 2.1.3
WEAK ACID LEACHING DATA FOR BENEFICIATED COAL-BASED FUELS

Fuel	Alkali Metals in Ash, Wt.%				Volatilizable Alkali Metals, Wt.%	
	ASTM Method		WAL Method			
	Na ₂ O	K ₂ O	Na ₂ O	K ₂ O	Na ₂ O	K ₂ O
Ill. #6 hvcb Coal	0.5	2.0	0.3	0.1	60	5
Ill. #6 MFP	2.3	2.3	1.9	0.1	83	4
Ill. #6 SOAP	1.6	2.4	1.0	0.2	63	8
Pitts. #8 hvAb Coal	0.5	1.5	0.2	0.1	40	6
Pitts. #8 MFP	2.2	1.6	1.1	0.1	50	6
Pitts. #8 SOAP	1.1	1.6	0.7	0.1	64	6
U. F. mvb Coal	0.3	2.2	0.1	0.1	33	5
U. F. MFP	1.6	2.6	0.9	0.1	56	6
U. F. SOAP	0.5	3.2	0.3	0.1	60	3

Specific Gravity Fractionation Analysis. Gravity fractionation analysis was carried out on each fuel to assess the impact of both cleaning process on the mineralogical characteristics of the BCFs. A Certigrav was used to provide four specific gravity fractions: 1.4F, 1.4Sx2.5F, 2.5Sx2.9F and 2.9S, where F and S stand for float and sink, respectively. Illinois #6 parent coal, MFP and SOAP data have been interpreted and are discussed in this topical report.

Illinois #6 Fuels The yield, ash contents and normalized elemental ash compositions of the specific gravity fractions of the Illinois #6 parent, MFP, and SOAP fuels are shown in Tables 2.1.4a-2.1.4c. A comparison of the yield values for the three fuels shows that the MFP process was more efficient than the SOAP process at liberating the mineral matter from the fuel leaving a higher 1.4 float fractions than in the parent coal. The ash compositions of the 1.4 float fractions of each fuel are similar to the ash compositions of the bulk fuels (See Table 2.1.1 for comparison).

Each of the beneficiated fuel fractions produced less ash than its corresponding parent coal fractions. Comparison of given fractions between the three fuels indicate species-specific removals from the parent coal. The removal of the silicon minerals was more efficient than the removal of the iron minerals. The Data also show relative enrichments of alkali and alkaline earth minerals.

The reduction in aluminum content as density increases shows that the clays in each fuel are predominantly present as very fine or included particles and, therefore, do not concentrate in the 2.5Sx2.9F specific gravity fraction, which covers the density of most clays (2.6 g/cm^3). In contrast, silicon is concentrated in the 2.5Sx2.9F fraction of each fuel, indicating that quartz is liberated more readily than the clays.

The high concentrations of calcium and sulfur in the MFP 1.4Sx2.5F fraction indicate that gypsum is more highly liberated during the microbubble cleaning process. The relatively high concentrations also show that the microbubble process liberates but does not remove a significant fraction of the liberated gypsum. This conclusion is also supported by the CCSEM and image analysis data given in later sections of this report.

Table 2.1.4a

ANALYSES OF SPECIFIC GRAVITY FRACTIONS OF THE ILLINOIS #6 PARENT COAL

Specific Gravity Fraction	1.4F	1.4Sx2.5F	2.5Sx2.9F	2.9S
Yield (Wt. %)	85.25	13.92	0.54	0.30
Ash (wt. %, MF ¹)	3.5	26.0	79.1	71.2
Composition (Wt. %) ²				
SiO ₂	52.6	53.5	60.4	7.4
Al ₂ O ₃	23.9	22.0	17.4	7.1
Fe ₂ O ₃	13.9	12.5	14.8	84.0
TiO ₂	1.9	0.6	0.3	0.2
P ₂ O ₅	<0.1	<0.1	<0.1	<0.1
CaO	2.1	3.9	2.7	0.8
MgO	1.8	1.5	0.8	<0.5
Na ₂ O	<0.5	0.5	<0.5	<0.5
K ₂ O	3.0	2.6	1.5	<0.5
SO ₃	0.8	2.9	2.1	0.6

Table 2.1.4b

ANALYSES OF SPECIFIC GRAVITY FRACTIONS OF THE ILLINOIS #6 MFP FUEL

Specific Gravity Fraction	1.4F	1.4Sx2.5F	2.5Sx2.9F	2.9S
Yield (Wt. %)	96.09	3.08	0.79	0.05
Ash (wt. %, MF ¹)	4.7	8.0	7.8	64.8
Composition (Wt. %) ²				
SiO ₂	43.3	40.9	49.5	2.3
Al ₂ O ₃	21.0	17.1	15.6	2.7
Fe ₂ O ₃	20.9	12.2	21.5	94.0
TiO ₂	2.7	1.2	1.2	0.2
P ₂ O ₅	0.1	0.6	0.2	<0.1
CaO	3.2	10.2	4.0	0.7
MgO	1.7	1.1	1.3	<0.5
Na ₂ O	2.3	1.2	1.4	<0.5
K ₂ O	2.8	1.8	1.1	<0.5
SO ₃	1.9	13.5	4.3	0.5

Table 2.1.4c

ANALYSES OF SPECIFIC GRAVITY FRACTIONS OF THE ILLINOIS #6 MFP FUEL

Specific Gravity Fraction	1.4F	1.4Sx2.5F	2.5Sx2.9F	2.9S
Yield (Wt. %)	89.50	10.06	0.23	0.22
Ash (wt. %, MF ¹)	2.8	10.7	58.4	60.5
Composition (Wt. %) ²				
SiO ₂	37.7	46.4	53.3	ND ²
Al ₂ O ₃	21.6	21.4	11.7	
Fe ₂ O ₃	23.1	19.1	27.2	
TiO ₂	4.0	1.5	0.9	
P ₂ O ₅	0.1	0.1	<0.1	
CaO	4.4	5.0	2.5	
MgO	1.7	1.3	0.3	
Na ₂ O	1.2	0.4	<0.5	
K ₂ O	3.6	2.5	1.3	
SO ₃	2.6	2.1	2.8	

1. Moisture-Free
2. Not Determined

Computer Controlled Scanning Electron Microscopy. Computer Controlled Scanning Electron Microscopy (CCSEM) was carried out on each parent coal and its MFP and SOAP products to determine the sizes and compositions of their mineral grains. This information can be used to provide insights into the fundamental processes and reactions occurring during preparation and utilization of coal. Illinois #6 parent coal, MFP and SOAP data have been interpreted and are discussed in this report.

Illinois #6 Fuels Figures 2.1.2a, 2.1.2b and 2.1.2c are back-scattered electron micrographs of cross sections of Illinois #6 parent, MFP, and SOAP fuels, respectively. The back-scattered electron signal is proportional to the density of the material, so the dark areas are the mounting medium, the lighter gray areas are fuel, and the lightest areas are mineral matter. Carnauba wax was used as a mounting medium to provide maximum contrast between the fuel and the medium (Straszheim, 1986). The figures illustrate the overall size reduction of the fuel particles due to beneficiation, although some relatively large fuel agglomerates are left in the SOAP fuel. There appear to be large numbers of small mineral grains in the beneficiated fuels with diameters of less than one micron that are liberated from the coal. These particles are too small to be analyzed by CCSEM and so they could not be quantified.

The elemental chemical compositions of the Illinois #6 fuels shown in Tables 2.1.1 and 2.1.2 indicate that both the MFP and SOAP processes reduced the ash content of the parent coal by over one half. The differences in composition of the fuel ashes show that the inorganic particle removal efficiencies of the beneficiation processes were species-specific. The largest change is the decrease in silicon relative to the other elements. Except for aluminum, the concentrations of the other elements show relative increases, particularly the alkali metals and alkaline earths.

Changes caused by beneficiation in the size and relative abundance of the 1- to 100 μm diameter inorganic particles in the fuels can be seen in the CCSEM data presented in Figures 2.1.3 and 2.1.4. The data are presented on the basis of percent of total inorganic particle weight detected. The cumulative size distribution curves shown in Figure 2.1.3 show that both MFP and SOAP processing

a. Parent Coal

b. MFP

c. SOAP

FIGURE 2.1.2 BACK SCATTERED ELECTRON MICROGRAPHS OF ILLINOIS #6 FUELS

FIGURE 2.1.3 CUMULATIVE DISTRIBUTIONS OF INORGANIC PARTICLES IN ILLINOIS #6 FUELS

decreased the mass median diameter of inorganic particles from the 4.6 to 10 μm range to the 2.2 to 4.6 μm range, resulting in mean weight particle sizes of 9.7, 6.1 and 7.5 μm for the particles of the parent, MFP and SOAP, respectively. The decrease is not as significant as in the fuel particles shown in Figures 2.1.2a-2.1.2c (See Figure 2.1.1 for comparison). The shift is believed to be caused by the following: (1) the comminution of the inorganic particles produced, on average, five to 10 mineral grains in the beneficiated fuels from one mineral grain in the parent fuel; and/or (2) the mineral particles with diameters of greater than 4.6 μm were preferentially removed leaving the smaller particles to make a larger fraction of the total mineral matter.

Figure 2.1.4 shows that both beneficiation processes significantly decreased the total relative amount of alumino-silicates with diameters between 1 and 100 μm . The more silica-rich, three-layer clays, were preferentially removed.

Alumino-silicate removal may explain part of the decrease in silicon content indicated in Table 2.1.1. However, the removal is not reflected by a decrease in aluminum content. This implies that instead of removing the alumino-silicates, the processing may have reduced the size of some clay through comminution and de-agglomeration caused by slurring so that the diameters of the remaining clay particles were less than 1 μm . Such a size reduction would render the particles undetectable by the CCSEM procedure used and create the submicron inorganic particles seen in the back-scattered electron micrographs.

The quartz contents of the beneficiated fuels show a slight increase relative to the other mineral types due to processing. This relative increase in quartz can reasonably be expected to be due to the fact that less quartz is reduced in diameter to the undetectable submicron range than is the case with the other inorganic species. The differences in pyrite contents of the BCFs and feed stock indicate that the removal efficiency of this species was lower than for the other minerals. The CCSEM data show that the pyrite particles are finer in the BCF products (Figure 2.1.5). These finer particles are most likely to be highly dispersed within the fuel matrix, rendering their removal less efficient. The SOAP process also appeared to liberate some of the pyrite from the unclassified inorganics, which consist of a mixture of quartz, alumino-silicates, and pyrite

FIGURE 2.1.4 COMPOSITION DISTRIBUTIONS OF INORGANIC PARTICLES IN ILLINOIS #6 FUELS

FIGURE 2.1.5 PYRITE SIZE DISTRIBUTION IN ILLINOIS NO. 6 FUELS

or partially oxidized pyrite.

The association of the inorganic with the organic portion of the fuel is also important in determining the cleanability of the coal, as well as the fate of the inorganic materials during combustion. Both beneficiation processes depend on the differences in the surface properties of the mineral matter to permit segregation. Inorganic particles that are excluded from a fuel matrix should be more easily cleaned from the coal than those that are included. If an inorganic particle is included within a fuel particle, it has a relatively high probability of interacting during combustion with other inorganic particles present in the fuel particle. Under this circumstance, larger and more compositionally complex ash particles tend to form (Sarofim et al., 1977).

Figure 2.1.6 shows that less than 1/5 of the alumino-silicate particles, which comprise the majority of the inorganic material in the parent coal (including unknowns), are excluded from fuel particles. In addition, only about 1/3 of the quartz and pyrite are excluded from fuel particles in the parent coal. The low level of exclusion shows why fine grinding is necessary to further liberate these types of particles before cleaning. In contrast, the majorities of the oxidized pyrite and gypsum are excluded from fuel grains. In combination with the CCSEM data, the figure shows that the beneficiation processes have different efficiencies of removing the excluded inorganic particles from the fuels. The MFP process liberates relatively more quartz and pyrite than it removes, while the SOAP process more efficiently removes these types of particles. The MFP process is not effective at removing the gypsum, even though it is primarily excluded in the parent coal. The SOAP process removes approximately the same amount of gypsum as the other particle types and agglomerates the remaining gypsum with the fuel. The two processes behave similarly toward the oxidized pyrite.

FIGURE 2.1.1.6 RELATIVE WEIGHT PERCENTS OF EXCLUDED INORGANIC PARTICLES IN ILLINOIS #6 FUELS

2.2 Combustion Kinetic Parameters

CE's Drop Tube Furnace System-1 (DTFS-1) was used in this study to derive the combustion kinetic parameters of beneficiated coal-based fuels. This system (Figure 2.2.1) is comprised of a 1-inch inner diameter horizontal tube gas pre-heater and a 2-inch inner diameter vertical tube test furnace for providing controlled temperature conditions to study devolatilization, gasification and/or combustion phenomena. This entrained flow reactor, which is electrically heated with silicon carbide elements, is capable of heating reacting particles to temperatures of up to 2650°F and sustaining particle residence times of up to about one second to simulate the rapid suspension firing conditions encountered in pulverized coal-fired boilers.

The DTFS-1 testing procedure entails the following: (1) the fuel is fed at a precisely known rate through a water-cooled injector into the test furnace reaction zone; (2) the fuel and its carrier gas are allowed to rapidly mix with a pre-heated down-flowing secondary gas stream; (3) devolatilization, gasification or combustion is allowed to occur for a specific time (dictated by the transit distance); (4) reactions are rapidly quenched by aspirating the mixture into a water-cooled sampling probe; (5) the solids are separated from gaseous products in a filter medium; and; (6) an aliquot of the effluent gas stream is sent to a dedicated Gas Analysis System for on-line determination of NO_x , SO_2 , O_2 , CO_2 , CO , and THC (total hydrocarbons) concentrations. A data acquisition system records, on demand, all relevant test data for subsequent retrieval and processing.

An ash tracer technique (Nsakala, et al., 1977) is used in conjunction with the proximate analyses of feed samples and chars subsequently generated in the DTFS-1 test furnace to calculate the devolatilization, gasification or combustion efficiency as a function of operational parameters (particle temperature, particle residence time, fuel fineness, reaction medium, etc.). A software package can, alternatively, use the information on concentrations of CO_2 , CO and THC in the effluent gas streams to calculate carbon conversion rates under prevailing conditions.

Figure 2.2.1 SCHEMATIC OF DROP TUBE FURNACE SYSTEM-1 (DTFS-1)

Swelling Factors (α) of Fuels. The swelling factor of each fuel was determined. This parameter is important from a combustion modeling standpoint, because it dictates the particle size distribution of a char right after devolatilization of its parent fuel.

The procedure for measuring α entails pyrolyzing the test fuel in the DTFS-1 in nitrogen atmosphere at 2650°F, and collecting chars at 4-, 8- and 16-inch reactions zones. The swelling factor is subsequently computed as follows:

$$\alpha = [(X_4 + X_8 + X_{16})/3]/X_0 \quad (1)$$

where X_4 , X_8 , and X_{16} are the Rosin-Rammler mean weight particle sizes of chars obtained at 4-, 8- and 16-inch reactions zones, and X_0 is the mean weight particle size of the feedstock. The α values in the CE kinetic data bank range from 1.0 to 1.5. Comparatively, results from this study fall within a range of 1.0-1.67.

Combustion Kinetic Parameters of Chars. The char combustion kinetic parameters [apparent activation energies (E) and frequency factors (A)] of each BCF were determined using a two-step testing methodology (Figure 2.2.2: (1) A 325x0-mesh fuel is pyrolyzed in the DTFS-1 in nitrogen atmosphere at 2650°F; and (2) A 325x0-mesh size fraction of the resulting, virtually volatile matter-free, char is subsequently burned in the DTFS-1 in 0.03 atm O_2 (in nitrogen balance) at four temperatures (1900, 2150, 2400 and 2650°F) and particle residence times ranging up to about 0.8 sec. The rationale for this procedure is that it enables one to study the C- O_2 heterogeneous reaction without interference from burning volatile species.

It is important to note that the CE's established methodology (Nsakala, et al., 1985 and 1986) uses a regular grind fuel (about 70% -200 mesh) to generate a char, which is size-graded to 200x400-mesh size fraction before burning it under the same conditions given above. The rationale for using the 325x0-mesh size fraction in this study comes, as stated before, from the fact that the coal cleaning processes used to produce the present BCFs use, by design, very fine coal particles.

A. DTFS-1 GENERATION OF CHARS

B. DTFS-1 COMBUSTION OF CHARS

* A 70%-200 MESH GRIND IS USED IN C-E STANDARD PROCEDURE

** A 200x400 MESH SIZE GRADE IS USED IN C-E STANDARD PROCEDURE

Figure 2.2.2 **DROP TUBE FURNACE SYSTEM-1 (DTFS-1) DETERMINATION OF COAL AND BCF CHARS' COMBUSTION KINETIC PARAMETERS**

The combustion efficiency maps of the MFP and SOAP chars, expressed as a function of both temperature and time, are depicted in Figure 2.2.3. These results clearly show a number of important things: (1) both temperature and time play a major role in char combustion efficiency; (2) the combustion efficiency of a char is dependent upon its nature; and (3) DTFS-1 data reproducibility is quite good (compare T1 with T1R and T4 with T4R cases).

These combustion efficiency maps were used to determine the overall rates of carbon removal per unit external surface areas (K) assuming that: (1) the carbon-oxygen reaction proceeds by a shrinking-core mechanism and; (2) CO is the primary surface reaction product, which is oxidized to CO₂ in the boundary layer.

The values of K were used in conjunction with classically calculated corresponding diffusional reaction rate coefficients (K_D) to derive the surface reaction rate coefficients (K_s) according to the following relation:

$$1/K = 1/K_D + 1/K_s \implies K_s = KK_D/(K_D - K) \quad (2)$$

A first order, with respect to oxygen partial pressure, Arrhenius Equation is applied to the data as follows:

$$K_s = A \exp(-E/RT_p) \quad (3)$$

where E , A , R and T_p are, respectively, the apparent activation energy, frequency factor, universal gas constant and calculated particle surface temperature (Nsakala, et al., 1985). The experimental conditions are such that $K \ll K_D$ in all cases, ensuring that the external diffusion of oxygen to particle surface does not constitute a rate-determining step in the K_s derivations.

Plotting K_s vs. $1/T_p$ yields straight lines (Figure 2.2.4) from which the values of E and A can be obtained from the slopes and intercepts of the least squares fits.

Figure 2.2.3 DTFS-1 COMBUSTION EFFICIENCIES OF 325XO MESH BCF CHARs IN 3% O₂/7% N₂ MEDIUM AT VARIOUS TEMPERATURES

Figure 2.2.4 ARRHENIUS PLOTS FOR COMBUSTION OF VARIOUS 325X0 MESH BCF CHARS

Comparison to Data Base. The combustion kinetic parameters obtained from this study are summarized in Table 2.2.1 along with other relevant data (swelling factors of fuels, mercury densities and BET surface areas of chars).

Table 2.2.1*
COMBUSTION KINETIC PARAMETERS OF PARENT COALS AND BCFs

FUEL TYPE	PHYSICAL CHARACTERISTICS			KINETIC PARAMETERS	
	α	ρ (g/cm ³)	S_{BET} (g/m ²)	A (g/cm ² sec. atm)	E (kcal/ mole)
Illinois #6 hvCb	1.19	--	33.1	--	--
Illinois #6 MFP	1.00	0.66	31.0	0.47	10.9
Illinois #6 SOAP	1.30	0.66	42.0	25.8	23.2
Pittsburgh #8 hvAb	1.67	--	44.8	--	--
Pittsburgh #8 MFP	1.20	0.53	37.4	0.79	12.6
Pittsburgh #8 SOAP	1.28	0.49	31.9	5.0	18.1
Upper Freeport mvb	1.54	--	23.6	--	--
Upper Freeport MFP	1.33	0.59	17.8	2.14	14.2
Upper Freeport SOAP	1.25	0.33	35.4	17.0	24.8

* α indicates the swelling factors of the test fuels;
 ρ , S_{BET} , A, E are, respectively, mercury densities, BET surface areas, frequency factors and activation energies of 320x0 mesh chars.

The apparent activation energies of the MFP chars, in particular, are rather low. They leave one to think of them, in classical terms (Walker, Jr., et al., 1959), as falling in the Combustion Zone III (i.e., being in the oxygen diffusion-limited regime). Our experimental data show that the values of K_0 are consistently at least one order of magnitude higher than the corresponding values of K , thus ruling out a Zone-III scenario. There is a possibility that pore diffusion may be influencing the results. Also, it is not known to what extent the chemicals (heptane, asphalt, etc.) used in the coal cleaning processes may be influencing the combustion kinetic processes of the BCFs.

These combustion kinetic parameters from this study are plotted as K_s vs. $1/T_p$ in Figure 2.2.5 along with some selected literature values obtained by the present and other investigators. These results indicate that the surface reaction rates of the BCFs chars are lower than those obtained in this laboratory from high volatile bituminous coal chars. These differences are due to actual differences in reactivities and experimental conditions used.

Combustion Performance Modelling: A Case Study

The combustion kinetic parameters of fuels are determined for subsequent use in combustion performance modelling studies. An illustration of such a study is presented here. A 600-MW_e pulverized coal tangentially-fired boiler is used in the illustration. Appropriate data (Figures 2.2.6a and 2.2.6b) are input into CE's Lower Furnace Program-Slice Kinetic Model (LFP-SKM) to obtain converged solutions. While actual kinetic parameters were used for the BCFs (Table 2.2.1), surrogate kinetic parameters from the data bank had to be used for the parent coals. Particle size distributions of 78.8% -200 mesh with 4% +100 mesh and 97% -200 mesh with 1.8% +100 mesh were used for the three parent coals and six BCFs, respectively.

These choices were based on the respective screen analysis results of the composite samples of Illinois #6 hvCb coal and its microbubble flotation product obtained during their test firing in the CE's Fireside Performance Test Furnace (Chow, et al., 1991). The firing rate and excess air were maintained at full load and 20%, respectively, in each case.

Relative LFP-SKM-predicted carbon loss results are presented in Figure 2.2.7. The relative combustion performances of the parent coals are consistent with their ASTM rank-range classifications (i.e., $C_{hvCb} < C_{hvAb} < C_{mvb}$, where C stands for carbon in the fly ash). And the ultra high combustion efficiencies (i.e., > 99%) of the beneficiated coal-based fuels are mainly due to the very fine nature of these fuels. It is interesting to note that the carbon contents in the fly ashes of the BCFs remain fairly high even at such high combustion efficiencies; this

1 VARIOUS CARBONS, FIELD ET AL. (1967)

2 SANDIA, MITCHEL ET AL. (1987)

3 ANTHRACITE, BEER ET AL. (1961)

4a hvCb
4b hvAb

NSAKALA ET AL. (1983)

THIS WORK

5a U. F. MFP

6a U. F. SOAP

5b ILL. MFP

6b ILL. SOAP

5c PITTS. MFP

6c PITTS. SOAP

Figure 2.2.5

RELATIONSHIP BETWEEN SURFACE REACTIVITY COEFFICIENT AND SURFACE TEMPERATURE FOR PRESENT STUDY AND SOME LITERATURE DATA

Figure 2.2.6a

Figure 2.2.6b

FLOW DIAGRAM FOR ABB CE'S LOWER FURNACE COMBUSTION PERFORMANCE MODEL SIMULATION

Figure 2.2.7 LFP-SKM PREDICTIONS FOR A 600-MWe TANGENTIALLY-FIRED BOILER AT 20% EXCESS AIR AND FULL LOAD FIRING RATE OF 5460 MBtu/hr.

is due to the fact that carbon-to-ash ratios are very high in these fuels, compared to the ratios encountered for their parent fuels (See analyses in Table 2.1.1).

It should, finally, be borne in mind that the intent of this quick LFP-SKM study was to simply depict the general trends one would expect if these fuels were fired in a given boiler operating under given conditions. The results should, therefore, be treated strictly as such. More detailed simulation studies (involving a total of three boilers of different designs firing several BCFs under various conditions) will be conducted in conjunction with this project, similar to the studies done under a previous DOE project (Hargrove, et al., 1989).

2.3 Mineral Matter Transformation

UNDEERC Drop Tube Furnace (DTF) Fly Ash Characteristics

Each of the BCF fuels was burned in the UNDEERC drop tube furnace (DTF) system to produce fly ash under carefully controlled conditions. Typical combustion conditions are listed in Table 2.3.1. The conditions were chosen so that the combustion of the coal would occur under time and temperature conditions similar to those in the radiant zone of CE's FPTF. In order to achieve complete combustion of the coals, excess air levels were maintained above one hundred percent. The ash was collected at the bottom of the drop tube with a high efficiency cyclone followed by a nylon fiber filter. Illinois #6 parent coal, MFP and SOAP data have been interpreted and are discussed in this report.

Table 2.3.1

TYPICAL COMBUSTION CONDITIONS USED
IN UNDEERC DROP TUBE FURNACE

Coal Feed Rate	0.15 g/min
Primary Air Flow Rate	0.8 l/min
Sec. Air Flow Rate	3.2 l/min
Sec. Air Preheat	1130°C
Upper Furnace Temp.	1500°C
Lower Furnace Temp.	1490°C
Residence Time	1.2 sec

Illinois #6 Fuels. Figure 2.3.1 shows the cumulative particle size distributions of the 1-100 μm diameter inorganic particles in the DTF fly ashes as determined by CCSEM. As compared to the fuel inorganic particles, the parent ash is about the same size, the MFP ash is larger, and the SOAP ash is smaller. As was true for the fuel minerals, the beneficiated DTF ash size distributions are smaller than the parent coal ash. These similar trends were also observed with the in-flame particulate collected from the FPTF furnace as discussed in Section 3.

The elemental chemical compositions of the DTF ashes are given in Table 2.3.2. The bulk chemical compositions were similar to the respective fuel ashes, with the exceptions of some enrichment in silicate and depletion in iron minerals for the SOAP DTF fly ash. The composition of the parent and MFP DTF ashes are essentially the same as the respective ASTM fuel ashes indicating no segregation during combustion in the DTF. The SOAP DTF ash shows a slight enrichment in silicon and aluminum, and depletion in iron compared to its ASTM ash.

A comparison with the fuel mineral data shown in Figure 2.3.2 indicates that almost all the pyrite was oxidized and reacted to form iron-alumino-silicate and iron-alumino-silicate-rich ash particles during combustion. The MFP was slightly more reactive than the SOAP in this respect, with nearly all of the original alumino-silicate being converted; and both BCFs are more reactive than the parent coal. The large concentration of unclassified material in the MFP DTF ash is primarily silica-rich iron-alumino-silicate material that contains either slightly more sulfur or slightly less aluminum than allowed for classification. These results are in agreement with the FPTF data discussed in Section 3.

FIGURE 2.3.1 CUMULATIVE DISTRIBUTIONS OF INORGANIC PARTICLES IN ILLINOIS #6 DTF FLY ASHES

FIGURE 2.3.2 COMPOSITION DISTRIBUTIONS OF INORGANIC PARTICLES IN ILLINOIS #6 DTF FLY ASHES

Table 2.3.2

CHEMICAL COMPOSITIONS OF ILLINOIS #6 FUEL
AND DROP-TUBE FURNACE ASHES

Quantity (Wt.%)	Parent Coal		MFP		SOAP	
	Fuel	DTF	Fuel	DTF	Fuel	DTF
SiO ₂	51.7	50.9	42.0	43.2	40.2	45.7
Al ₂ O ₃	20.7	22.1	19.3	19.8	19.9	24.3
Fe ₂ O ₃	16.9	18.3	21.2	21.8	25.6	20.0
CaO	2.2	2.8	3.7	3.7	2.4	4.3
MgO	0.9	1.0	1.4	1.6	1.4	1.2
Na ₂ O	0.5	<0.5	2.3	1.6	1.6	0.6
K ₂ O	2.0	2.2	2.3	2.4	2.4	1.4
TiO ₂	0.8	1.3	2.2	2.9	2.5	2.4
P ₂ O ₅	0.0	<0.2	0.1	0.3	0.2	0.2
SO ₃	2.1	1.4	2.4	2.7	2.0	0.9

PSIT Drop-Tube Reactor Tests. Combustion experiments were conducted in the PSIT resistance-heated laminar flow drop-tube reactor shown schematically in Figure 2.3.3a. A methane-fired swirl stabilized reactor assembly was mounted at the inlet of the drop-tube section. This provided increased residence time for complete combustion of the large particles present in utility grind coal samples and simulated, on a small-scale, particle concentrations present in an actual combustor. Samples of the test fuels were mechanically fed to the swirl stabilized reactor at feed rates of 0.2 to 2.5 g/min, utilizing a syringe pump feeder system (Figure 2.3.3b). Oxygen levels in this region were maintained at 21 percent, corresponding to an air/fuel ratio of 10. At the exit of the swirl-stabilized section, particles entered the isothermal zone of the drop-tube furnace. Gas temperatures in this region were maintained between 1400 and 1750°K.

a. Reactor

b. Feeder System

c. Particle Stickiness Probe

Figure 2.3.3

PSIT LABORATORY REACTOR AND ANCILLARY EQUIPMENT

Upon completion of the combustion, ash particles were sampled by one of the following two techniques: (1) Isokinetic sampling through a water-cooled nitrogen-quenched probe; or (2) Deposition of a small portion of the ash articles on a "stickiness" probe (Figure 2.3.3c). Ash was collected at the furnace exit on a filter or by a cascade impactor. Analysis of the total filter ash was performed by UNDEERC, either by embedding the ash sample in epoxy, cross-sectioning, and determining the size and composition using a CCSEM, or by examining the un-sectioned ash particles.

The cascade impactor data for the ash size distribution are presented in Figure 2.3.4. It provides the mass fraction of ash for any given median particle diameter (d_{50}). About 6 percent of the total ash is smaller than $1\text{ }\mu\text{m}$ for both fuels, i.e., the fraction vaporized does not increase significantly for the beneficiated fuel. Enhanced vaporization would be expected for the beneficiated fuel if the mineral content had been reduced substantially and if the fraction of minerals that was extremely fine and highly dispersed. It would seem that the SOAP fuel was not significantly different from the parent coal to alter the mineral vaporization characteristics. Also, there is only a slightly larger proportion of the ash in the 1 to $10\text{ }\mu\text{m}$ range for the SOAP than for the ash from the parent coal. The increased extent to which mineral coalescence would be limited due to the larger distance between inclusions in the lower ash-bearing fuel was therefore not significant.

Each combustion-generated ash was also analyzed by CCSEM for size distribution and composition. The main change in the size distribution of the inorganic fraction of the parent coal was created by coalescence of minerals to form larger ash particles (Figure 2.3.5a). This occurs primarily for all particles smaller than $20\text{ }\mu\text{m}$. While the size distribution data are quite similar for ash obtained from combustion of the parent coal at 1175 and 1300°C and indicate limited coalescence for sizes larger than $20\text{ }\mu\text{m}$, the data for 1500°C do not exhibit increased degree of mineral coalescence.

a. Parent Coal Ash (Multiple Measurements)

b. SOAP Ash (Multiple Measurements)

Figure 2.3.4 CASCADE IMPACTOR RESULTS FROM UPPER FREEPORT PARENT COAL AND SOAP COMBUSTION AT 1500 °C

B-7557

a. From Parent Coal

B-7556

b. From SOAP

Figure 2.3.5 SIZE DISTRIBUTIONS OF UPPER FREEPORT PARENT COAL AND SOAP ASH PARTICLES

The main changes in the size distribution during combustion of the SOAP fuel were created by agglomeration of the mineral inclusions (Figure 2.3.5b). In this case, the behavior is more consistent with respect to combustion temperature, i.e., more coalescence occurs at higher temperature. Note that the ash size distributions for 1300 and 1500°C are similar. Despite the significant differences in the parent coal and SOAP mineral size distributions, the resulting ash particle size distributions are quite similar, with the beneficiated fuel ash being only slightly finer. This indicates that the aerodynamic properties of the fly ash produced by the two fuels will also be similar.

In the experiments with the beneficiated fuel, unburnt char particles much larger than the feed fuel size were sometimes observed on the collection filter. This is attributed to agglomeration, due to the thermo-plastic behavior of the parent coal.

The CCSEM analysis of the ash also provided the elemental composition of the individual ash particles and, for the total ash sample, a broad classification among the different composition groups (Table 2.3.3). For the parent coal, the concentration of the iron-containing mineral in the coal (classified as pyrite) dropped from 28 percent to 0 percent in the ash. On the other hand, the concentration of iron alumino-silicates as well as other mixed alumino-silicates increased in the ash compared to that present in the parent coal. The effect of combustion temperature on the ash composition is mainly the diminishing of illite concentration and formation of a greater proportion of iron alumino-silicate particles. Similar behavior to the parent coal is noted for the SOAP fuel with respect to compositional changes resulting from combustion.

Overall, the data indicate that iron-containing minerals and clays in the coal interact during combustion to form iron alumino-silicate and other clay-derived ash particles. In addition, pure iron oxide particles were also formed for both fuels.

Table 2.3.3

OVERALL COMPOSITIONS OF UPPER FREEPORT PARENT
COAL AND SOAP ASHES BY CCSEM ANALYSIS

Mineral	Parent			SOAP		
	Coal	1175°C	1500°C	Coal	1175°C	1500°C
Quartz	7.5	6.5	5.8	13.2	2.4	3.3
Pyrite	27.7	0.0	0.0	48.2	0.0	0.0
Iron Oxide	0.4	2.7	1.6	0.0	3.6	4.4
Kaolinite	12.6	19.2	18.4	4.8	10.4	9.7
K-Al-Si	13.6	15.8	5.1	12.0	12.7	8.1
Fe-Al-Si	0.2	16.8	31.3	5.0	20.5	34.8
Other Al-Si	8.1	26.5	21.5	9.7	37.5	37.5
Gypsum	4.9	1.2	0.2	1.0	0.0	0.0
Minor Others	3.1	5.3	7.0	2.8	3.5	3.5
Unclassified	22.0	5.8	8.9	3.2	9.2	7.6
Totals	100.1	100.0	100.0	100.0	99.8	100.0

The behavior indicated by the mineralogical analysis is supported by the Fe-Al-Si ternary plots of the CCSEM data (Figures 2.3.6a and b). Particles with diameters between 1 and 80 μm and containing greater than 80 percent of Fe, Al, and Si are displayed. The height of the bars represents a normalized area percent of the particles of a given composition. Although there are some Si-rich particles, the vast majority of particles lie along a line originating at 100 percent Fe to a point corresponding to 40 percent Si and 60 percent Al. This behavior is indicative of intimate mixing of the clays and pyrites to form alumino-silicate ash particles which are higher in Fe than those present in the coal.

The Fe-Al-Si ternary plots for the ash generated from the combustion of the SOAP fuel are shown in Figures 2.3.6c and d. These are seen to be similar to those of the ash of the parent coal. Perhaps the only difference in the ashes obtained at 1500°C from the parent and SOAP fuels is a slightly lesser extent of interaction between the iron minerals and alumino-silicates for the SOAP fuel. This might arise because the starting minerals for the parent coal contain some pyrite, which is expected to melt and interact strongly with the clay minerals. For the SOAP fuel, one might expect the iron sulfates and oxyhydroxides to decompose to form refractory iron oxides, which would interact to a lesser extent

a. Parent Coal Ash at 1175 °C

b. Parent Coal Ash at 1500 °C

c. SOAP Ash at 1175 °C

d. SOAP at 1500 °C

Figure 2.3.6 Fe-Al-Si CCSEM TERNARY DIAGRAMS OF UPPER FREEPORT PARENT COAL AND SOAP ASH SAMPLES AT VARIOUS TEMPERATURES

with clay minerals than the molten iron sulfide (product of pyrite decomposition) in the parent coal. For the most part, the resemblance in the Fe-Al-Si ternary diagrams and in other analyses of the CCSEM data for ash obtained from combustion of the parent and SOAP fuels suggests that, despite significant reduction in ash by the SOAP process, the beneficiation technique was non-selective in mineral removal.

The high degree of interaction of the pyrite and clays can be seen by contrasting the ternary plots in Figures 2.3.6a-d to those in Figures 2.3.7a-d, which show the corresponding Ca-Al-Si ternary plots (1-80 μm , and greater than 80 percent Ca+Al+Si). The Ca-Al-Si plots are all similar. There is some indication of Si rich minerals (mainly quartz) and Ca-rich material (mainly calcium oxide), but the vast majority of particles are very low in Ca and are located near the Si/Al ratio found most often for clays.

The data found in the mineralogical composition and ternary plots are supported by the elemental composition data presented in Table 2.3.4. The elemental analyses of the minerals in the raw fuels were performed by ASTM analyses while the data for the combustion-generated ashes were derived from the CCSEM data.

Ash deposition tests were carried out for the two fuels to determine differences in the deposition propensity using the experimental procedure discussed previously. Un-cooled mullite substrates were used as the deposition surface. Furnace gas temperature and the corresponding ash particle temperature at the substrate were varied and the deposition efficiency measured.

As shown in Figure 2.3.8, the deposition efficiency decreased with temperature for both the fuels. The higher deposition efficiency for the lower tube is due to a higher impaction velocity at this location. Therefore, a larger fraction of the smaller ash particles impact the lower tube. Visual and photographic observations of the morphology of the deposit at the highest temperature indicated a molten slag for each fuel.

a. Parent Coal Ash at 1175 °C

b. Parent Coal Ash at 1500 °C

c. SOAP Ash at 1175 °C

d. SOAP at 1500 °C

Figure 2.3.7 Ca-Al-Si CCSEM TERNARY DIAGRAMS OF UPPER FREEPORT PARENT COAL AND SOAP ASH SAMPLES AT VARIOUS TEMPERATURES

B-4795a

Figure 2.3.8

DEPOSITION EFFICIENCIES (η_p) FOR ASHES
FROM COMBUSTION OF UPPER FREEPORT FUELS
AT VARIOUS TEMPERATURES

Table 2.3.4

ELEMENTAL COMPOSITIONS OF UPPER FREEPORT
COMBUSTION-GENERATED ASHES

Oxide	Parent	SOAP	Combustion-Generated Ash			
			P-1175	P-1500	S-1175	S-1500
SiO ₂	43.8	41.2	51.2	51.3	47.6	50.6
Al ₂ O ₃	24.2	24.5	24.4	23.3	22.3	21.6
Fe ₂ O ₃	18.8	19.2	11.9	12.2	16.4	17.0
CaO	3.1	3.3	3.7	5.2	2.0	2.0
MgO	0.9	1.2	0.1	0.1	0.2	0.1
Na ₂ O	0.3	1.6	0.1	0.1	0.1	0.1
K ₂ O	2.2	2.5	0.2	2.4	3.1	2.9
TiO ₂	0.9	1.9	1.5	1.6	2.7	1.8
P ₂ O ₅	0.2	0.3	0.0	0.0	0.0	0.0
SO ₃	3.9	2.7	1.5	1.1	0.9	0.7
TOTAL	98.3	98.4	94.6	97.3	95.3	96.8
NOTE: 3% Ba in ash samples.						

At the lower temperatures, some difference was observed in the level of sintering in the deposit between the two coals (SOAP fuel was slightly less sintered), although the amount of deposit for the beneficiated coal was appreciably smaller.

The deposition efficiency is the product of the impaction effectiveness (aerodynamics) and the fraction that sticks (adhesion efficiency). Based on the ash size distributions at 1300°C, the impaction efficiencies [for the lower substrate (4 m/s)] are 0.63 and 0.58 for the parent coal and SOAP ashes, respectively. This implies that there is a lower fraction of the ash from the beneficiated fuel that is depositing compared to that from the parent coal. This is difficult to rationalize given that the compositions of the ashes were similar. One of the reasons for this difference could be more oxidized iron minerals in the SOAP fuel resulting in iron alumino-silicate particles that had Fe³⁺ rather than Fe²⁺ in the silicate glass matrix.

Table 2.3.5 contains information concerning the elemental compositions of the parent coal and SOAP fuels and the deposits obtained at 1300 and 1500°C. The parent coal deposit compositions display significant changes with temperature rise. The two largest changes are: (1) the SiO₂ concentration drops from 48 to 22 percent; and (2) the Fe₂O₃ concentration rises from 14 to 49 percent.

Once again, the composition of the deposits from the SOAP are similar to those from its parent coal, both in terms of the absolute values and the changes occurring. The two largest changes in the elemental composition as temperature rises are: (1) the SiO₂ concentration drops from 46 to 22 percent; and (2) the Fe₂O₃ concentration increases from 17 to 50 percent.

Table 2.3.5
ELEMENTAL COMPOSITIONS OF UPPER FREEPORT PARENT
COAL AND SOAP ASH DEPOSITS

Oxide	Parent	SOAP	Deposits			
			P-1300	P-1500	S-1300	S-1500
SiO ₂	43.8	41.2	47.6	22.1	46.0	22.3
Al ₂ O ₃	24.2	24.5	29.6	21.3	28.7	20.7
Fe ₂ O ₃	18.8	19.2	14.3	49.3	16.8	50.2
CaO	3.1	3.3	2.8	1.8	2.0	0.9
MgO	0.9	1.2	1.2	1.0	1.4	1.0
Na ₂ O	0.3	1.6	0.6	0.9	0.6	0.8
K ₂ O	2.2	2.5	2.5	1.4	3.0	1.8
TiO ₂	0.9	1.9	1.1	2.1	1.2	2.0
P ₂ O ₅	0.2	0.3	0.0	0.0	0.0	0.0
SO ₃	3.9	2.7	0.1	0.1	0.1	0.1
TOTAL	98.3	98.4	99.8	100.0	99.8	99.8

Figures 2.3.9a-d contain the ternary plots for the deposits of the parent coal and SOAP fuels collected at furnace temperatures of 1300 and 1500°C. The plots represent all points with Fe+Al+Si content of greater than 10 percent which corresponds to all the SEMPC points studied. The two 1300°C plots are similar to each other and qualitatively similar to the fly ash ternary plots. Most of the points lie around a line from 100 percent Fe to a point at 60 percent Si and 40 percent Al.

The data for the 1500°C parent coal and SOAP deposits are similar to each other and different from the 1300°C data. The region where the majority of points are located shifts from low to high Fe concentrations as the temperature is raised. Additionally, the data seem to intercept the 0 percent Si line at 90 percent Fe as opposed to 100 percent in all previous plots. The shift in concentration and the high Fe contents suggest that crystallization has occurred on the surface of the 1500°C deposit, and that the surface concentration is not indicative of the bulk deposit concentration.

a. Parent Coal Ash Deposit
at 1300 °C

b. Parent Coal Ash Deposit
at 1500 °C

c. SOAP Ash Deposit
at 1300 °C

d. SOAP Ash Deposit
at 1500 °C

Figure 2.3.9

Fe-Al-Si CCSEM TERNARY DIAGRAMS OF UPPER FREEPORT
PARENT COAL AND SOAP ASH DEPOSIT SAMPLES AT
VARIOUS TEMPERATURES

3. PILOT-SCALE TESTING

The pilot-scale studies were designed to provide key information for the technical and economic assessment of the BCFs for commercial applications. Comprehensive tests were conducted to evaluate the combustion, furnace slagging, convective pass fouling and fly ash erosion characteristics of the BCFs prepared in both dry (micro-fine) and wet (micro-fine coal-water fuel) forms. Studies were also carried out to evaluate the effect of BCF fly ashes on electrostatic precipitator (ESP) collection performance. Additionally, representative in-flame solids and ash deposit samples collected were analyzed in detail to enhance the understanding of mineral matter transformation and ash deposition and to relate these to fuel mineral distributions and combustion conditions. Also, complementary experiments were carried out to provide more detailed information on the combustion and emission characteristics of selected BCFs. These experiments focused on application of the coal-water fuel form.

Nine test fuels were evaluated for combustion and performance testing. These fuels included Illinois No.6, Upper Freeport, Pittsburgh No.8 microbubble flotation products (MFPs), spherical oil agglomeration products (SOAPs), and the MFP parent coals. Most of the pilot-scale results were reported in two previous quarterly reports: May to June, 1990, and October to December, 1990. This report includes the analyses of particulates and deposits collected in the CE test facility and a discussion of the ESP collection performance.

3.1 Performance Test Sample Analyses

Analyses of In-Flame Particulate and Waterwall Deposit Samples. In-flame solids, waterwall deposits, convection tube deposits and fly ash samples collected from the FPTF were analyzed by the University of North Dakota Energy and Environmental Research Center (UNDEERC). Scanning electron microscope, Mossbauer, x-ray diffraction, x-ray fluorescence, Auger and ESCA techniques were used to determine the distribution of amorphous and crystalline phases, chemical compositions and surface chemistry of the ash components. These analytical data were related to performance characteristics and fuel properties in order to enhance the understanding of the effects of coal beneficiation on ash formation and

deposition mechanisms. Illinois #6 parent coal, MFP and SOAP data have been interpreted and are discussed below.

Illinois No. 6 Fuels The particle size distributions of the in-flame solids samples collected at waterwall P1 are shown in Figure 3.1.1. The results indicate that the overall particle size distributions of the parent and SOAP ashes shifted to a slightly smaller range than the mineral matters in the parent fuels. The decreases in sizes were probably caused by the fragmentation of the char and mineral particles during combustion, particularly the pyrite and possibly some of the alumino-silicate material in these two fuels. By contrast, the particle size distribution of the MFP ash was shifted to larger sizes than the minerals in the coal. The size increase was due to coalescence of the mineral matter and formation of ash cenospheres.

The chemical composition distributions of the in-flame particulate are shown in Figure 3.1.2. A comparison with the mineral data indicates that all three fuel samples show considerable interaction of pyrite and alumino-silicate to form iron-alumino-silicate particles. The iron-alumino-silicate rich material in the two BCF samples is less pure compared to that of the parent sample, indicating greater interaction with particles containing other elements due to the high dispersion of the submicron alumino-silicate particles, as discussed in Section 2. The larger proportion of included pyrite and alumino-silicates in the SOAP fuel contributed to the formation of a greater concentration of iron-alumino-silicate rich material.

The elemental compositions of the waterwall deposits collected from the three test fuels are shown in Table 3.1.1. Differences in composition between the deposits reflect the differences observed in the respective fuel ashes. The MFP and SOAP deposits showed depletion in silicon and enrichment in iron and alkali and alkaline earth elements compared to those of the parent coal deposits. These changes resulted in lower overall melting temperatures and viscosities, which are consistent with the formation of more sintered and fused deposits from the two BCF fuels.

Figure 3.1.1 Cumulative size distributions of the inorganic particles collected at the level of FPTF waterwall panel P1 from Illinois No. 6 fuels

Figure 3.1.2 The composition distribution of the inorganic particles collected at the level of FPTF waterwall panel P1 from Illinois No. 6 fuels

Table 3.1.1

**ELEMENTAL CHEMICAL COMPOSITION OF WATERWALL DEPOSITS
FROM ILLINOIS NO. 6 FUELS**

ILLINOIS NO. 6 PARENT

ASH FUS. TEMP. DEG F	AS-FIRED FUEL ASH	WATERWALL PARTIC.	PANEL 1 DEPOSITS	FURN. OUT PARTIC.	PANEL 4 DEPOSITS
IDT	2000	ND	2012	ND	2034
ST	2260	ND	2068	ND	2057
HT	2420	ND	2189	ND	2191
FT	2530	ND	2216	ND	2303
ASH COMP. WT. %					
SiO ₂	51.7	50.2	54.2	51.7	54.2
Al ₂ O ₃	20.7	21.7	20.6	21.7	20.2
Fe ₂ O ₃	16.9	18.5	17.9	17.1	16.3
CaO	2.2	2.7	2.3	2.4	2.3
MgO	0.9	1.2	1.1	1.2	1.1
Na ₂ O	0.5	0.0	0.0	0.0	0.0
K ₂ O	2.0	2.9	2.7	3.1	2.7
TiO ₂	0.8	1.5	1.2	1.4	1.2
P ₂ O ₅	0.0	0.0	0.0	0.0	0.0
SO ₃	2.1	1.4	0.0	1.2	0.0
TOTAL	97.8	100.1	100.0	99.8	100.0

ILLINOIS NO. 6 MFP

ASH FUS. TEMP. DEG F	AS-FIRED FUEL ASH	WATERWALL PARTIC.	PANEL 1 DEPOSITS	FURN. OUT PARTIC.	PANEL 4 DEPOSITS
IDT	2020	ND	1923	ND	2026
ST	2160	ND	1977	ND	2051
HT	2230	ND	2072	ND	2076
FT	2260	ND	2125	ND	2088
ASH COMP. WT. %					
SiO ₂	42.0	41.3	40.0	43.7	40.0
Al ₂ O ₃	19.3	19.7	18.1	20.4	18.4
Fe ₂ O ₃	21.2	22.6	23.2	21.5	24.7
CaO	3.7	3.9	4.0	3.9	3.5
MgO	1.4	1.4	1.3	1.4	1.4
Na ₂ O	2.3	2.2	2.0	2.0	1.6
K ₂ O	2.3	2.5	4.1	2.4	3.3
TiO ₂	2.2	2.8	2.4	2.7	2.7
P ₂ O ₅	0.1	0.2	0.3	0.2	0.3
SO ₃	3.4	3.0	4.6	1.7	4.1
TOTAL	97.8	99.8	100.0	99.9	100.0

ILLINOIS NO. 6 SOAP

ASH FUS. TEMP. DEG F	AS-FIRED FUEL ASH	WATERWALL PARTIC.	PANEL 1 DEPOSITS	FURN. OUT PARTIC.	PANEL 4 DEPOSITS
IDT	1850	ND	1883	ND	1894
ST	1910	ND	1928	ND	1915
HT	1950	ND	2031	ND	2062
FT	2000	ND	2172	ND	2153
ASH COMP. WT. %					
SiO ₂	40.2	43.2	36.9	41.7	40.4
Al ₂ O ₃	19.9	20.2	17.9	20.5	24.1
Fe ₂ O ₃	25.6	23.9	29.9	24.8	21.1
CaO	3.4	3.7	3.5	3.7	4.2
MgO	1.4	1.3	0.9	1.4	1.5
Na ₂ O	1.6	1.3	0.8	1.3	0.9
K ₂ O	2.4	2.1	4.9	2.2	2.7
TiO ₂	2.5	2.4	2.6	2.6	2.1
P ₂ O ₅	0.2	0.2	0.4	0.3	0.7
SO ₃	2.0	1.6	1.9	1.6	2.3
TOTAL	99.2	99.9	99.9	100.1	100.0

The waterwall deposits were analyzed by scanning electron microscope point count (SEMP) technique to provide information on the composition distributions within the deposits. This data was used in conjunction with an algorithm proposed by Kalmanovitch and Frank (1988) to calculate viscosity distributions within the waterwall deposits.

As shown in Figure 3.1.3, while the calculated viscosity distributions of the MFP and SOAP deposits were relatively similar, both were considerably lower than those in the parent coal deposits. Since sintering rate is inversely proportional to viscosity, the BCF deposits sinter more rapidly, and at lower temperatures than the parent coal deposits. The more rapid sintering of the deposits causes strength to develop more rapidly in the BCF deposits than in the parent coal deposits. Therefore, although the beneficiated fuel deposits are thinner than the parent coal deposits, they are more difficult to remove.

Analyses of Particulates and Convective Pass Deposits - Illinois #6 Fuels. The cumulative size distributions of the inorganic particles in the in-flame samples are shown in Figure 3.1.4. As the particulate pass from the waterwall region of the FPTF to the furnace outlet, the particle size distributions of the parent and SOAP ashes change little. However, the concentration of greater than 10 micron diameter MFP inorganic particles significantly decreased, possibly through fragmentation of ash cenospheres formed in the waterwall region.

The chemical composition distributions in the particles as determined by CCSEM are shown in Figure 3.1.5. The only significant change in compositions between the waterwall and furnace outlet samples is the decrease in alumino-silicate and increase in iron-alumino-silicate in the parent coal particulate, indicating some coalescence of the alumino-silicates with submicron iron oxides left from the oxidation and fragmentation of the pyrite, particularly in the 2.2 microns to 10 microns range.

The bulk elemental chemical compositions and reducing atmosphere fusibility temperatures for the fouling deposits are shown in Table 3.1.2. As was true for the waterwall deposits, the compositions of the fouling deposits are very similar to their respective fuel ashes and in-flame particulates. The differences

Figure 3.1.3 Calculated viscosity distributions of the waterwall deposits from Illinois No. 6 fuels

Figure 3.1.4 Cumulative size distributions of the inorganic particles collected at the level of FPTF furnace outlet from Illinois No. 6 fuels

Figure 3.1.5 The composition distribution of the inorganic particles collected at the level of FPTF furnace outlet from Illinois No. 6 fuels

Table 3.1.2

**ELEMENTAL CHEMICAL COMPOSITION OF CONVECTIVE
PASS DEPOSITS FROM ILLINOIS NO. 6 FUELS**

ILLINOIS NO. 6 PARENT

ASH FUS. TEMP. DEG F	AS-FIRED FUEL ASH	LA SUP. DEPOSITS	MC SUP. DEPOSITS	FLYASH
IDT	2000	2012	2036	1962
ST	2260	2069	2100	2027
HT	2420	2193	2246	2214
FT	2530	2271	2309	2256
ASH COMP. WT. %				
SiO ₂	51.7	55.7	53.3	52.5
Al ₂ O ₃	20.7	21.3	21.0	20.9
Fe ₂ O ₃	16.9	15.5	17.4	16.9
CaO	2.2	2.5	2.7	2.7
MgO	0.9	1.2	1.1	1.3
Na ₂ O	0.5	0.0	0.0	0.0
K ₂ O	2.0	2.6	3.0	2.6
TiO ₂	0.6	1.2	1.4	1.3
P ₂ O ₅	0.0	0.0	0.0	0.0
SO ₃	2.1	0.0	0.0	1.6
TOTAL	97.6	100.0	99.0	100.0

ILLINOIS NO. 6 MFP

ASH FUS. TEMP. DEG F	AS-FIRED FUEL ASH	LA SUP. DEPOSITS	MC SUP. DEPOSITS	FLYASH
IDT	2020	1811	2020	1861
ST	2180	2076	2038	1959
HT	2230	2124	2200	2031
FT	2260	2223	2245	2251
ASH COMP. WT. %				
SiO ₂	42.0	46.9	44.6	42.1
Al ₂ O ₃	19.3	20.6	20.9	18.0
Fe ₂ O ₃	21.2	19.7	21.5	23.6
CaO	3.7	5.6	5.0	3.6
MgO	1.4	1.0	1.4	1.7
Na ₂ O	2.3	1.0	1.1	1.9
K ₂ O	2.3	2.7	2.7	2.6
TiO ₂	2.2	2.3	2.5	2.6
P ₂ O ₅	0.1	0.0	0.0	0.2
SO ₃	3.4	0.0	0.0	3.4
TOTAL	97.6	100.0	99.7	99.9

ILLINOIS NO. 6 SOAP

ASH FUS. TEMP. DEG F	AS-FIRED FUEL ASH	LA SUP. DEPOSITS	MC SUP. DEPOSITS	FLYASH
IDT	1850	1814	1834	1903
ST	1910	1836	1949	1930
HT	1950	1979	2064	1947
FT	2000	2146	2149	2122
ASH COMP. WT. %				
SiO ₂	40.2	40.0	41.9	36.7
Al ₂ O ₃	19.9	20.9	22.3	17.7
Fe ₂ O ₃	25.6	27.2	25.2	26.9
CaO	3.4	4.2	3.9	3.9
MgO	1.4	1.1	1.2	1.6
Na ₂ O	1.6	0.5	0.0	1.2
K ₂ O	2.4	3.0	2.6	2.9
TiO ₂	2.5	3.1	2.7	3.1
P ₂ O ₅	0.2	0.1	0.0	0.3
SO ₃	2.0	0.0	0.0	3.7
TOTAL	99.2	100.1	99.6	100.0

between the parent and beneficiated fuels fouling deposits were also the same as seen in the waterwall deposits. The beneficiated fuels contained relatively less silicon and more iron, alkali and alkaline earth elements than the parent coal deposits. In addition, the ash fusibility temperatures of the BCF deposits were lower than those of the parent coal deposits. The lower fusibility temperatures in the beneficiated fuel deposits are reflected in the calculated viscosity distributions shown in Figure 3.1.6. The BCF deposits have lower viscosity distributions which can lead to more rapid sintering and strength development than the parent coal deposits.

3.2 Fly Ash Collectibility

Fly ash collectibility tests were conducted in a four-field pilot-scale electrostatic precipitator (ESP) connected through a heat exchanger to the flue gas discharge of the FPTF. Isokinetic samples of the flue gases and fly ashes were taken at the inlet and outlet of the ESP to determine dust loadings, gas flow rates, gas temperatures and gas moisture contents. Fly ash resistivity, flue gas SO_3 concentration and ESP electric power consumption were also measured during each test operation to determine the overall ESP fly ash collection efficiencies.

In general, test results indicate that the ESP operation with the BCFs will not be significantly different from that with the parent coals. The reduced ash loadings due to the beneficiation processes reduced particulate entering the ESP. However, this benefit may be partially offset by the lower collection efficiencies with the BCF fly ashes.

A summary of the ESP test data from the nine fuels tested is shown in Table 3.2.1. The flue gas moisture contents ranged from 4% to 7% during these tests. The highest concentration was for the Upper Freeport MFP as it was fired as micro-fine coal-water fuel. The other values were lower than would expected for a field unit because of the indirect firing method of the FPTF, which does not exhaust coal drying air into the combustion chamber.

Figure 3.1.6 Calculated viscosity distributions of the superheater deposits from Illinois No. 6 fuels

Table 3.2.1

PILOT-SCALE ELECTROSTATIC PRECIPITATOR PERFORMANCE

FLY ASH TYPE	MOIST. CONC. (%)	SO ₃ CONC. (ppm)	FLY ASH LOADINGS (G/FT ³ , DRY)		FLY ASH RESISTIVITY (10 ¹¹ ohm-cm)	COLLECT. EFFIC. (%)	MIGRAT. VEL. (cm/s)	SPECIFIC COLLECTION AREA (min/ft)	TOTAL POWER (watt/10 ³ ACFM)	FIELD VOLTAGE				
			IN	OUT						No. 1 (kV)	No. 2 (kV)	No. 3 (kV)	No. 4 (kV)	
=====														
ILLINOIS No. 6														
Parent	4.0	3.5	0.96	0.07	6.0	91	8.2	147	3.0	9	11	9	12	
MFP	5.8	4.3	0.38	0.20	0.01	21	0.9	125	7.0	7	10	10	10	
SOAP	4.5	-	0.43	0.15	2.0	64	3.6	146	8.0	8	10	11	11	
=====														
PITTSBURGH No. 8														
Parent	4.3	3.0	0.75	0.03	0.7	95	12.6	123	9.0	11	11	12	12	
MFP	4.1	4.8	0.30	0.12	0.2	53	2.7	141	9.0	10	10	10	10	
SOAP	4.3	-	0.35	0.21	0.4	29	1.4	123	11.0	8	9	9	10	
=====														
UPPER FREEPORT														
Parent	4.1	3.0	1.08	0.34	1.2	55	2.9	142	3.0	9	11	11	11	
MFP	7.0	3.4	0.18	0.03	0.5	70	4.4	149	25.0	13	11	13	15	
SOAP	3.2	2.4	0.54	0.35	1.5	38	2.1	116	6.0	10	10	10	9	
=====														

The SO₃ concentrations in the flue gases were low, ranging from 2.4 ppm to 4.8 ppm. Variations of these levels are not expected to be significant for ESP performance.

Fly ash resistivities were affected by the beneficiation processes. The results shown in Figure 3.2.1 indicate that the fly ash from the parent coals had the highest resistivities, followed by the SOAP and MFP fuels. The values ranged from 7×10^{10} to 6×10^{11} ohm-cm, 4×10^{10} to 2×10^{11} ohm-cm, and 1.2×10^9 to 5×10^{10} ohm-cm for the parent, MFP, and SOAP fly ashes, respectively. With other variables being equal, all these resistivity values are considered within the desirable range for ESP operations (Katz, 1980).

The ESP power consumption during these tests was low because of voltage limit settings on the power supplies for each field (3 to 25 versus 50 to 150 and 200 to 700 watts/1000 ft³/min for low and high efficiency ESP). As a result, the collection efficiencies were lower than expected for conventional ESP units.

The ESP collection efficiencies of the fly ashes from the nine test fuels varied significantly (Figure 3.2.2). The variations in ash conditions, gas conditions, and power consumption accounted for a good part of the efficiency differences. Variation in operating conditions from fuel to fuel also significantly affect ESP performance. In order to account for these variabilities, a modified migration velocity incorporating these variations was used to provide a uniform basis for determining the ESP collection efficiencies.

The use of the migration velocity has been proposed (White, 1977) to express ESP collection efficiency as the velocity of ash particles migrating to the collecting electrode surface. The migration velocity was originally used by White to compare data from several commercial ESP units:

$$n = 1 - \exp(-SCA We/508)$$

where:

n = ash collection efficiency
SCA = specific collection area
We = ash particle migration velocity

FIGURE 3.2.1 ESP BCF FUELS INLET ASH RESISTIVITY

FIGURE 3.2.2

Migration velocities of ash particles are significantly affected by fly ash resistivity, fly ash particle size, flue gas temperature, moisture and power supply voltage. The migration velocities from these tests were modified to reflect an empirical fit with operating variables to account for differences in test conditions. The results are shown in Figure 3.3.3.

The differences in migration velocities are not as significant as differences in the collection efficiencies shown in Table 3.2.1. Overall, the parent coal and SOAP fly ashes performed as expected. However, the MFP fly ashes performed significantly lower than expected. These results indicate that the ESP can be operated with BCFs in the same manner as for parent coals. The reduction in ash content with the BCFs could reduce the particulate emissions, but the associated benefit may be offset by the lower collection efficiencies, particularly with the MFPs.

TASK 4 - SCALE-UP TESTS

The purpose of the scale-up tests is to verify that the results obtained from tests done at bench- and pilot-scales in Tasks 2 and 3 can be used to provide reasonable estimates of the performance effects when firing BCFs in commercial-scale boilers. Two beneficiated fuels will be fired in either a small utility boiler or a full-scale test furnace.

The only activities in this task were discussions on fuel procurement, alternative test facility selection, and scheduling. Recommendations have been submitted to the DOE to run the tests in CE's Boiler Simulation Furnace, a 50×10^6 Btu/hr unit that models full-scale boilers.

TASK 5 - TECHNICAL-ECONOMIC EVALUATIONS

The results of bench-scale, pilot-scale, and scale-up tests (Tasks 2, 3, and 4) will be used to predict the performance of three commercial boilers. The boilers include: a 560MW coal-designed utility unit; a 600MW oil-designed utility unit; and an 80,000 lb/hr oil designed, shop assembled industrial unit. Eight of the base project BCFs will be used in models of each unit to calculate performance.

No activity was scheduled for Task 5 during this quarter.

WORK PLANNED FOR NEXT QUARTER

- Continue standard bench-scale tests.
- Continue drop tube furnace tests at CE.
- Analyze data from pilot-scale combustion tests and ash deposition tests.
- Continue preparations for the scale-up tests.
- Issue draft topical report including results to date from the testing of the nine fuels.

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