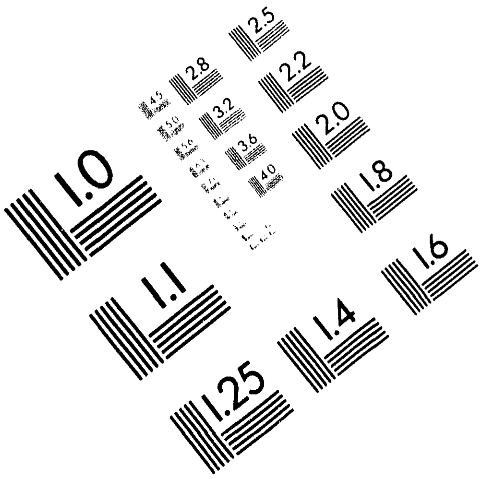

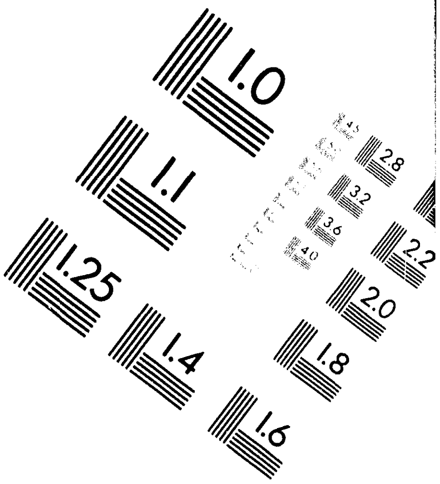

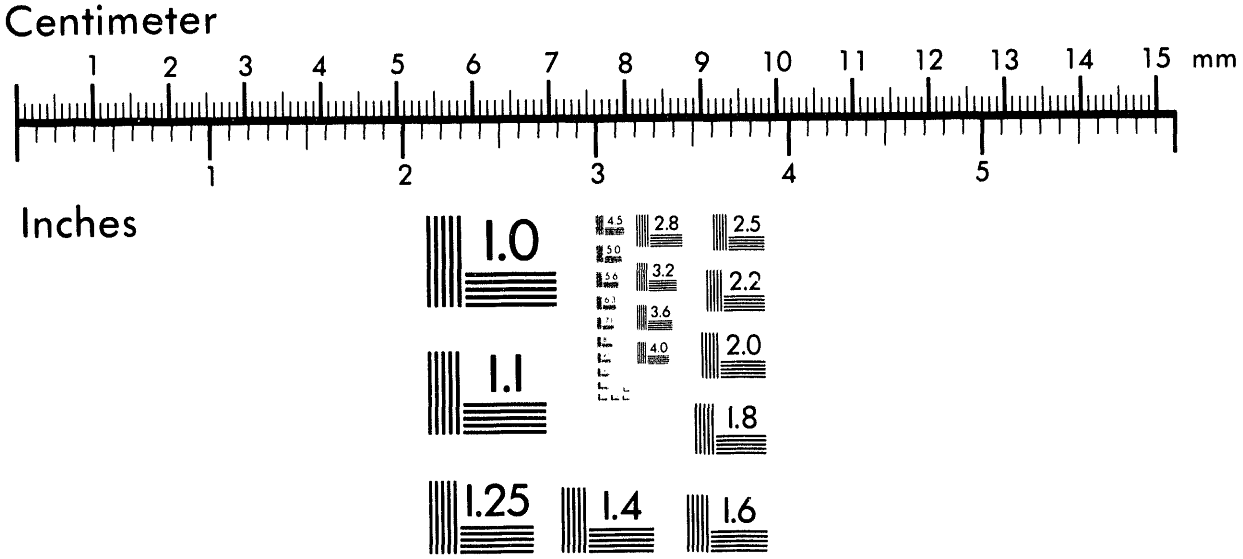
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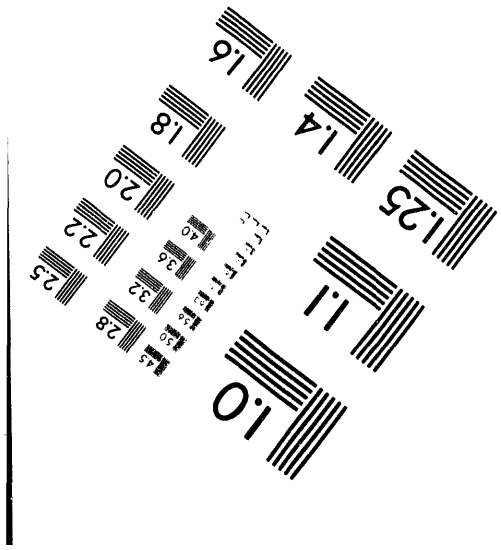

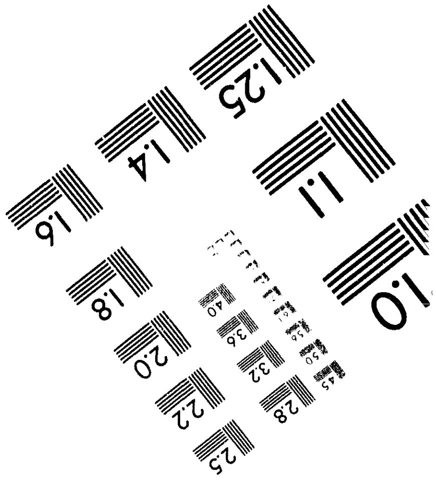

1 of 1

DOE/PC/88654--T10

COMBUSTION CHARACTERIZATION OF BENEFICIATED COAL-BASED FUELS

QUARTERLY REPORT NO. 10 FOR THE PERIOD JULY TO SEPTEMBER 1991

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NOVEMBER 1991

PREPARED FOR

U.S. DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER
UNDER CONTRACT NO. DE-AC 22-89 PC 88654

MASTER

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DISCLAIMER

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QUARTERLYREPORT

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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 third quarter of 1991, the following technical progress was made.

- Continued analyses of drop tube furnace samples to determine devolatilization kinetics.
- Completed analyses of the samples from the pilot-scale ash deposition tests of three Upper Freeport fuels.
- Completed editing of the first three quarterly reports and sent them to the publishing office.
- Presented the project results at the Annual Contractors' Conference.

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.

A fresh 20-ton sample of Upper Freeport parent coal was obtained for testing during the next quarter. The next BCFs for testing are scheduled to be produced during the first quarter of 1992.

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 and have been reported in previous quarterly reports and in the paper by Barta, et alia, 1991.

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. Results were reported in the Quarterly Report for the period January to March, 1991.

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, and (5) combustion kinetics. All these data have been reduced and reported in the Quarterly Reports for July to September, 1990, and January to March 1991, as well as in papers by Nsakala, et alia, 1990 and 1991, and the draft Topical Report issued in June, 1991.

Work during this quarter focused on completing the CE Drop Tube Furnace System-1 (DTFS-1) devolatization testing of the BCFs. The analysis of the samples collected during the tests also continued.

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:

- Illinois #6 high volatile C bituminous (hvCb) coal
  - Feed Coal
  - Microbubble Flotation Product (MFP)
  - Spherical Oil Agglomeration Product (SOAP)

- Pittsburgh #8 high volatile A bituminous (hvAb) coal
  - Feed Coal
  - MFP
  - SOAP

- 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:

- 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.
- 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.
- 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.

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,

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_2O_3	20.7	19.3	20.2	22.3	24.2	25.1
Fe_2O_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_2O	0.5	2.3	0.5	2.2	0.3	1.6
K_2O	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_2O_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

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* 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_2O_3	19.7	19.9	19.6	24.1	21.1	24.5
Fe_2O_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_2O	0.8	1.6	0.7	1.1	0.3	1.6
K_2O	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_2O_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

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

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.

The particles of both microbubble flotation and spherical oil agglomeration products are very fine compared to coals commercially suspension-fired. 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.

2.2 Bench-Scale Combustion Tests

Devolatization of three MFPs and three SOAPs in CE's Drop Tube Furnace System-1 (DTFS-1) have been completed. The BCFs were devolatilized in a nitrogen atmosphere at 1900, 2150, 2400, and 2650°F with residence time varying up to approximately 0.8 seconds. Chemical analysis of the resulting solids has been completed. Results of the analyses are being used to derive the devolatization kinetic parameters-apparent activation energy and frequency factor.

TASK 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 in the CE Fireside Performance Test Facility (FPTF) 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 in the MIT Combustion Research Facility (CRF) 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. The pilot-scale results were reported in three previous quarterly reports: May to June, 1990, October to December, 1990, and January to March, 1991. Results are also included in the papers by Barta, et alia, 1991, and Chow, et alia, 1991, as well as the draft Topical Report issued in June, 1991.

The next test will be firing Upper Freeport fresh parent coal in the CE FPTF in October, 1991. More BCFs will be available for testing in the first half of 1992. UNDEERC completed the analyses of the samples taken during testing of the first three Upper Freeport fuels in the FPTF. The results are shown in Appendix.

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.

TASK 6 - TECHNICAL REPORTING

Final editing of the first, second, and third quarterly reports was completed. The final originals were sent to the PETC Office of Technology Transfer.

A technical paper was also written and presented at the Annual Contractors' Conference in Pittsburgh on July 16, 1991.

WORK PLANNED FOR NEXT QUARTER

- Continue standard bench-scale tests.
- Analyze data from pilot-scale combustion tests and ash deposition tests.
- Run pilot-scale performance tests of the Upper Freeport parent coal in the CE FPTF.
- Continue preparations for the scale-up tests.

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APPENDIX

COMBUSTION CHARACTERIZATION OF BENEFICIATED COAL-BASED FUELS

Quarterly Technical Progress Report
for the Period July through September 1991

by

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Work Performed Under Subcontract to

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November 1991

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COMBUSTION CHARACTERIZATION OF BENEFICIATED COAL-BASED FUELS

1.0 INTRODUCTION

The University of North Dakota Energy and Environmental Research Center (EERC) is providing analytical and data interpretation support for the beneficiated coal-based fuels (BCF) project. All solid fuels are being analyzed by computer-controlled scanning electron microscopy (CCSEM) under Task 2 to determine the types and size distributions of the discrete mineral particles present in each fuel. The fuels are also being fractionated by specific gravity into four fractions: <1.4, 1.4-2.5, 2.5-2.9, and >2.9. Ash content, ash composition, and fusion temperatures for each specific gravity fraction will be determined. In addition, fly ash from each solid fuel will be generated in a drop-tube furnace system. Each fly ash sample will be sized by Malvern (laser diffraction), analyzed by ESCA-Auger for surface composition, x-ray fluorescence (XRF) for composition, x-ray diffraction (XRD) for crystalline phases and quantitative quartz determinations, and CCSEM to quantitatively determine the types and size distributions of the inorganic particles in the ash. Also included under Task 2 is analytical support for the PSI drop-tube work. This support will include CCSEM, ESCA-Auger, and SEM-EDX analyses of three fly ashes and several submicron fume substrates.

The EERC involvement in Task 3 consists of a number of different analyses of samples produced during combustion testing of the parent and beneficiated fuels in the Combustion Engineering Fireside Performance Test Facility (FPTF). The specific analyses are summarized in Table 1.

2.0 TASK 2 RESULTS AND DISCUSSION

2.1 Fuel Analyses

2.1.1 Specific Gravity Fractionation

Tables 2, 3, and 4 list the yield, ash contents, and normalized ash compositions of the specific gravity fractions of the Upper Freeport parent, microbubble flotation product (MFP), and spherical oil agglomeration product (SOAP) fuels. Although the parent and beneficiated coals were collected from the same mine, they are not from the same lot of coal, nor were they treated to the same level of conventional precleaning. Therefore, it is not possible to determine unambiguously the effect of MFP and SOAP processing on the fuels. Hence, discussion will be limited to the differences between the fuels, with causes for the differences mentioned only as possibilities.

As was true for the Illinois No. 6 fuels, the Upper Freeport MFP had a much higher 1.4 float yield, while the SOAP 1.4 yield was similar to that of the coal. This suggests that MFP processing may liberate the mineral matter from the coal, leaving the remaining coal particles with a lower overall density. In contrast, during SOAP processing, much of the liberated mineral matter is recaptured in the fuel agglomerates. However, the SOAP 1.4 float has the lowest ash content of the three fuels, indicating that SOAP processing

TABLE 1

EERC Analyses of FPTF Samples

Sample	Composition	Fusion	SEMPC	CCSEM	XRD	ESCA
In-Flame Solids						
Waterwall	X			X	X	X
Furnace Outlet	X			X	X	X
Waterwall Deposits						
T1						
Inner Layer	X	X	X		X	X
Outer Layer	X	X	X		X	X
Waterwall Deposits						
T2						
Inner Layer	X	X			X	
Outer Layer	X	X			X	
Superheater Deposits						
T1						
Inner Layer	X	X	X		X	X
Outer Layer	X	X	X		X	X
Superheater Deposits						
T2						
Inner Layer	X	X			X	
Outer Layer	X	X			X	
Fly Ash	X	X		X	X	X
Bottom Ash	X	X				

TABLE 2

Analyses of Specific Gravity Fractions of the Upper Freeport Parent Coal

Specific Gravity Fraction	<1.4	1.4-2.5	2.5-2.9	>2.9
Yield (wt%)	88.0	10.33	0.87	0.80
Ash (wt%, MF[1])	5.1	5.1	53.7	67.6
Ash Composition (wt%)[2]				
SiO_2	43.6	44.8	55.4	3.9
Al_2O_3	27.0	26.9	20.8	5.1
Fe_2O_3	18.0	20.3	13.4	88.0
TiO_2	2.1	1.4	0.9	0.4
P_2O_5	0.2	0.1	0.1	<0.1
CaO	2.7	2.4	2.2	0.7
MgO	1.6	1.7	1.2	1.8
Na_2O	<0.5	<0.5	<0.5	<0.5
K_2O	3.0	<0.5	2.5	<0.5
SO_3	1.7	2.4	3.5	0.5
Closure	100.1	94.8	96.7	107.9
Ash Fusion (°F[3])				
IDT	2098	1902	ND[4]	2046
ST	2245	1952		2122
HT	2301	2181		2239
FT	2335	2288		2379

[1] Moisture-free.
[2] ASTM ash composition (normalized wt%).
[3] Reducing atmosphere.
[4] Not determined - insufficient sample.

TABLE 3

Analyses of Specific Gravity Fractions of the Upper Freeport MFP Fuel

Specific Gravity Fraction	<1.4	1.4-2.5	2.5-2.9	>2.9
Yield (wt%)	95.26	4.60	0.14	ND[4]
Ash (wt%, MF[1])	4.8	23.1	76.7	ND[4]
Ash Composition (wt%)[2]				
SiO_2	40.0	43.3	44.8	ND[4]
Al_2O_3	25.4	24.1	14.1	
Fe_2O_3	15.6	6.1	36.9	
TiO_2	2.4	0.8	0.4	
P_2O_5	0.5	0.4	<0.1	
CaO	5.3	10.6	1.7	
MgO	1.9	1.5	0.7	
Na_2O	1.1	0.8	<0.5	
K_2O	3.8	3.1	<0.5	
SO_3	4.1	9.3	1.5	
Closure	100.6	99.0	92.9	
Ash Fusion (°F[3])				
IDT	2058	2224	ND[4]	ND[4]
ST	2095	2242		
HT	2130	2274		
FT	2295	2337		

[1] Moisture-free.
[2] ASTM ash composition (normalized wt%).
[3] Reducing atmosphere.
[4] Not determined - insufficient sample.

TABLE 4

Analyses of Specific Gravity Fractions of the Upper Freeport SOAP Fuel

Specific Gravity Fraction	<1.4	1.4-2.5	2.5-2.9	>2.9
Yield (wt%)	84.13	14.86	0.61	0.40
Ash (wt%, MF[1])	3.7	18.6	46.9	55.4
Ash Composition (wt%)[2]				
SiO_2	43.3	44.3	36.8	10.8
Al_2O_3	28.3	25.5	21.4	9.9
Fe_2O_3	12.7	18.6	38.3	78.2
TiO_2	2.2	1.0	0.2	0.2
P_2O_5	0.8	0.2	<0.1	<0.1
CaO	2.9	2.2	1.2	<0.5
MgO	2.4	2.2	1.4	0.5
Na_2O	0.3	0.6	<0.5	<0.5
K_2O	3.5	3.7	<0.5	<0.5
SO_3	3.5	1.9	0.8	0.4
Closure	107.5	100.7	98.8	114.1
Ash Fusion (°F[3])				
IDT	2121	1973	1860	2064
ST	2265	1999	1901	2160
HT	2305	2285	2070	2468
FT	2358	2310	2193	2542

[1] Moisture-free.
[2] ASTM ash composition (normalized wt%).
[3] Reducing atmosphere.
[4] Not determined - insufficient sample.

may have initially been more successful than MFP processing in liberating minerals from the coal, but that a fraction of the fuel agglomerates then recaptured some of the mineral matter. In general, the ash contents of the fractions increase as density increases to the 2.5-2.9 fraction, but may then decrease. The increase occurs because the proportion of high density, ash-forming inorganic matter in a fuel particle increases as density increases. The decrease at 2.9 occurs because pyrite, which concentrates in the 2.9 sink fraction, is combustible, but has approximately 2/3 ash by weight.

It is difficult to draw conclusions about the effects of cleaning processes on the distribution or concentrations of ash-forming constituents based on comparisons of the ash compositions of the fractions because of the variability in initial coals. Comparisons of the ash compositions for the specific gravity fractions can indicate the relative degree to which certain minerals are liberated from or locked within the fuel particles. In general, mineral grains that are locked within a coal particle collect in the gravity fraction that encompasses the average specific gravity of the particle. Mineral grains that are liberated from coal particles tend to concentrate in the gravity fraction that encompasses the specific gravity of the mineral. If the composition of the fraction shows an increase in the concentration of the elements that occur in a major mineral as compared to the whole coal ash (reported in the July to September 1990 quarterly technical progress report), then the minerals must have been liberated, but not removed, from the coal by processing. However, if there is a reduced concentration of the elements that make up a mineral that has a specific gravity encompassed by the fraction, then the liberated minerals were preferentially removed from the coal. For example, gypsum ($CaSO_4 \cdot 2H_2O$) is a commonly occurring coal mineral. It has a specific gravity of 2.3. The relatively high concentrations of calcium and sulfur in the MFP 1.4 x 2.5 fraction indicate that a portion of the gypsum is liberated, but not removed, from that fuel. This same effect of MFP processing was seen in the Illinois No. 6 samples. The parent and SOAP fuels for both the Illinois No. 6 and the Upper Freeport samples do not show this trend. By parallel reasoning, the liberation of pyrite from coal particles and subsequent recapture in SOAP fuel agglomerates is indicated in the low iron content of the SOAP 1.4 float and high iron content of the 2.5 x 2.9 fraction.

2.1.2 CCSEM Analyses of Upper Freeport Fuels

The cumulative size distributions of the mineral particles in the Upper Freeport fuels are illustrated in Figure 1. The data were determined by CCSEM analysis of polished coal/wax pellets. Therefore, the data are for mineral particles with cross-sectioned diameters between 1 and 100 microns. The mass median diameters of the 1-100 micron diameter mineral grains in the parent coal lie between 4.6 and 10 microns, whereas they lie between 2.2 and 4.6 microns in the beneficiated fuels. Because the initial coals for each beneficiation process had undergone different levels of conventional cleaning, the effects of beneficiation on the mineral size distribution are ambiguous. However, the decreased size distribution in the beneficiated fuels also occurred in the beneficiation of the Illinois No. 6 fuels. The decrease is most likely due to preferential removal and comminution of mineral grains with particle diameters of over 10 microns. The SOAP particle-size distribution is smaller as a whole than the MFP mineral particle-size distribution. The difference between the MFP and SOAP particle-size distributions is larger than was seen in the Illinois No. 6 fuels.

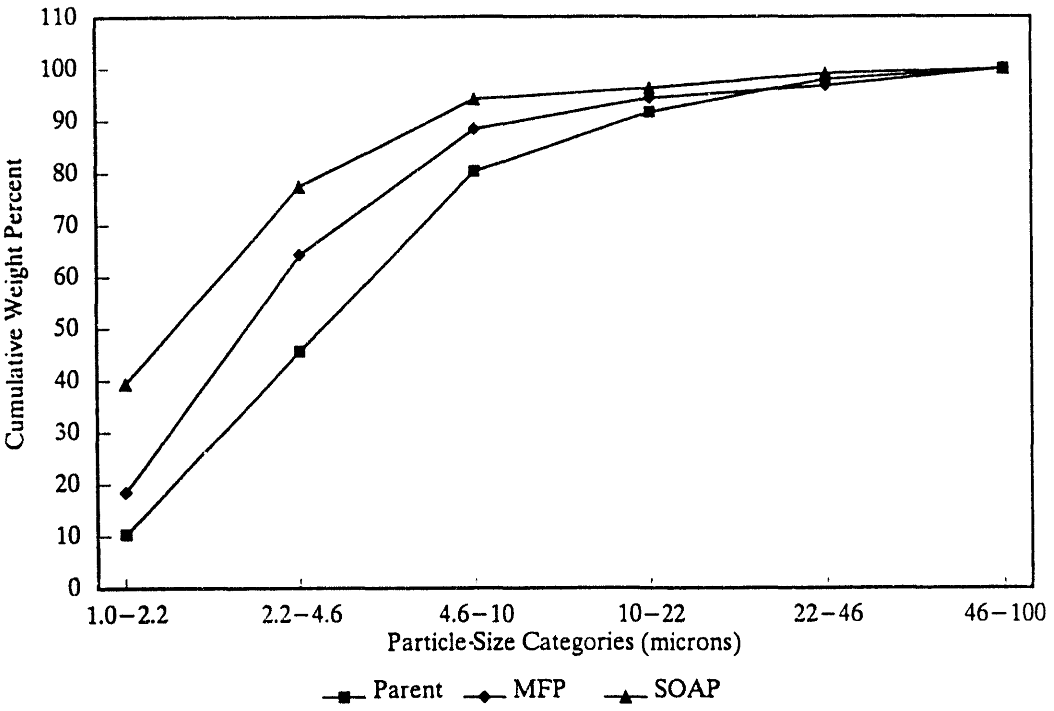


Figure 1. Cumulative size distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated fuels.

Figure 2 shows the relative quantities of the different types of mineral particles detected by CCSEM in the three fuels. The unbeneficiated or parent fuel contains primarily aluminosilicate and pyrite as the majority of the mineral particles with diameters between 1 and 100 microns. The large amount of mineral matter in the parent fuel labeled "unknown" in composition appears to be mixtures of quartz, aluminosilicates, and pyrite with overall compositions that lie outside any of the more pure mineral categories. Most of those particles had sectioned diameters of between 2 and 10 microns. In contrast, the MFP fuel contains mostly aluminosilicate with very little pyrite in the 1- to 100-micron diameter range. However, the silicon, aluminum, and iron contents of the MFP fuel ash are similar to that of the parent coal, indicating that the iron-containing species have not been preferentially removed. Therefore, instead of preferential removal of pyrite during conventional cleaning or beneficiation, it is likely that the pyrite fragmented into particles with diameters of less than one micron that could not be detected by CCSEM. In contrast to the MFP fuel, the SOAP fuel shows a much higher relative concentration of pyrite than the parent coal. Again, the concentrations of silicon, aluminum, and iron in the SOAP ash is similar to the parent fuel. This indicates that it was the aluminosilicate material in the SOAP fuel that was reduced in size to less than one micron rather than the pyrite. A similar change occurred in the Illinois No. 6 samples.

Both MFP and SOAP beneficiation processes depend on the differences in surface properties of the mineral matter, as compared to the fuel, to clean the coal. Mineral particles that are not surrounded by a matrix of fuel but

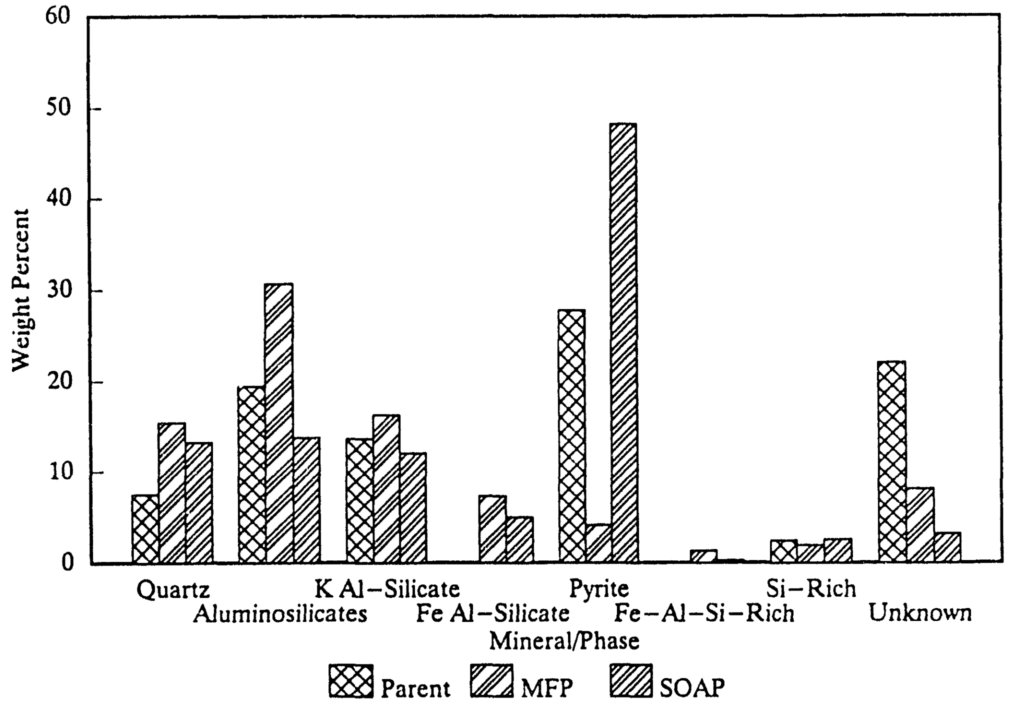


Figure 2. The composition distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated fuels.

are instead liberated from fuel particles should be more easily removed from the coal during beneficiation. In order to determine the propensity of the mineral matter to be removed, it is helpful to determine the proportion that is locked within fuel particles versus liberated from them. Similar information about the beneficiated fuels can be used to determine the efficiency with which a beneficiation process has removed the mineral matter, although this is more ambiguous with the Upper Freeport fuels because the feed coals for each process had undergone different amounts of conventional cleaning and the individual fuels varied in mineral matter content. Finally, whether mineral grains are locked within or liberated from fuel particles will determine the possible amount of interaction with other mineral grains during combustion. This is possible since most of the interaction comes between mineral grains within a given fuel particle and not between ash particles suspended in the boiler gas. Therefore, if a mineral particle is liberated from fuel particles, it will undergo little interaction with other ash particles.

Figure 3 shows the overall mass distribution of the major minerals in the three fuels as to whether they are locked or liberated from fuel particles. Since the feed coals for each beneficiation process were not analyzed, it is not possible to determine the efficiency with which each process removed the liberated minerals. The data can still be used to estimate the possible level of interaction between mineral types. In the parent coal, most of the quartz, Fe-Al-silicate, and gypsum are excluded from fuel particles and so would not interact strongly with other mineral grains during combustion. However, the major aluminosilicate types could be expected

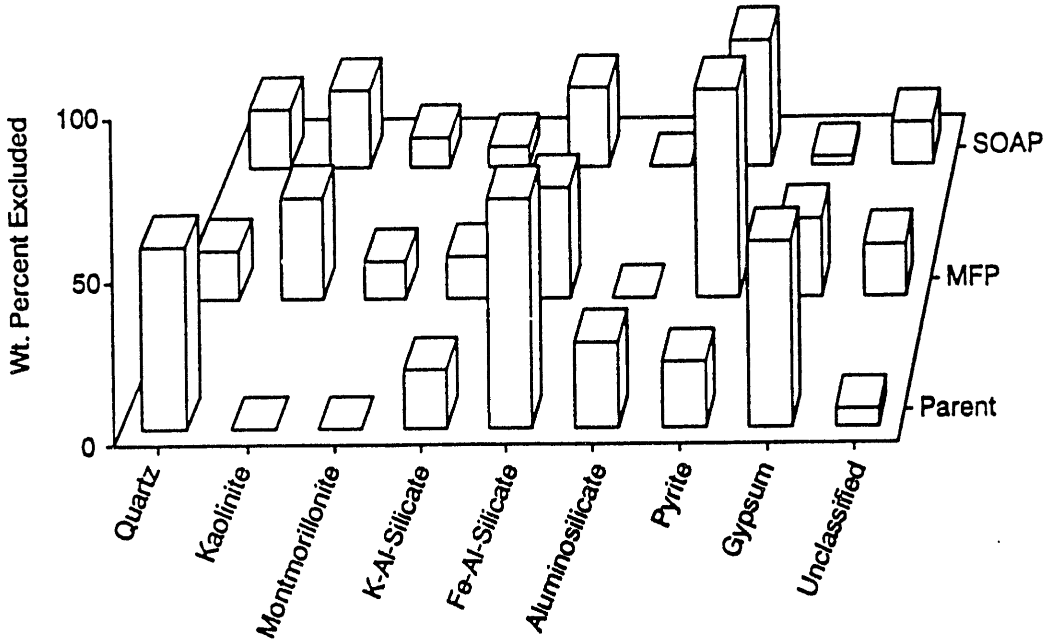


Figure 3. The relative weight percents of inorganic particles detected by CCSEM that are excluded from fuel particles.

to interact well with pyrite since the majority of those types is included within coal matrices. The general associations of the minerals in the beneficiated fuels are similar to each other, but different from the associations in the parent fuel. In both the MFP and SOAP fuels, most of the minerals except pyrite are included within fuel particles, indicating they may interact strongly. The excluded pyrite would not interact as strongly with other minerals during combustion. However, significant amounts of included pyrite still remain in the SOAP sample. Also, the composition of the MFP ash shows that there may be a significant amount of submicron pyrite in that fuel that would probably stick electrostatically to coal particles and so may still interact strongly with the other minerals during combustion.

2.2 Drop-Tube Furnace Fly Ash Characteristics

Each of the Upper Freeport 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 5. They were essentially the same for tests of the Illinois No. 6 and Pittsburgh No. 8 fuels. The conditions were chosen to be similar to the time and temperature conditions under which the coals were burned in the FPTF. However, in order to achieve the highest levels of burnout, excess air levels were maintained above one hundred percent. The ash was collected at the bottom of the DTF with a high efficiency cyclone followed by a nylon filter. Large carbonaceous char particles were excluded from analysis.

TABLE 5

Typical Combustion Conditions Used in the UNDEERC Drop-Tube Furnace System

Coal Feed	0.15 g/min
Primary Air	0.8 L/min
Secondary Air	3.2 L/min
Secondary Air Preheat	1130°C
Upper Furnace	1500°C
Lower Furnace	1490°C
Residence Time	1.2 sec

The chemical and crystalline phase compositions of the Upper Freeport DTF ashes are given in Table 6. The crystalline phases were determined by XRF and included quantitative crystalline quartz values for use in determining the possible erosivity of the ash. The XRD quartz values were determined by comparing quartz peak heights with those of rutile, which was added as an internal standard. The concentrations of major elements in the DTF ashes are within experimental error of the concentrations in the respective ASTM fuel ashes reported in the January to March 1991 quarterly technical progress report, with the exception of silicon which is much higher in the SOAP DTF ash. The concentrations of the more minor elements do not follow their concentrations in the fuel ASTM ashes as well. Sulfur is always reduced in the DTF ashes, most likely because it is initially vaporized during coal combustion, and less sulfur is captured by the ash while entrained in a gas stream rather than in a fixed bed, such as during ASTM ashing. There is also less sodium in the MFP and SOAP DTF ashes, most likely for the same reason. The reasons for the calcium variations are not clear.

The variations in crystalline phases are caused by variations in the degree of interactions of the mineral particles during combustion of the fuel. If the minerals interact strongly, then glass phases often form that do not crystallize upon quenching. Such phases do not provide an XRD pattern. For the most part, the only phases that will show up by XRD are those that do not interact strongly with other mineral phases. For the Upper Freeport parent, quartz showed up as a minor unreacted phase. The peaks for maghemite (gamma Fe_2O_3) show that some of the pyrite for each of those coals had oxidized and not interacted with other minerals. The mullite in the parent coal ash most likely originated as kaolin clay in the coal. The lack of crystalline phases in the MFP fly ash indicates that the minerals interacted more than in the other two fuels. The high level of interaction is understandable for most of the minerals because they are mostly included within coal particles. The interaction would not be as strong for the 1- to 100-micron diameter pyrite because it is primarily liberated from fuel particles (Figure 3), although very little of the larger pyrite is present in the MFP. Most of it is likely present as submicron particles that may stick to the surface of the fuel particles through electrostatic forces and interact with the mineral grains in the coal as if it were included.

TABLE 6

Compositions of Upper Freeport Drop-Tube Furnace Ashes
(Normalized Weight Percent)

Oxide	Parent	MFP	SOAP
SiO_2	44.8	44.6	47.2
Al_2O_3	24.8	26.4	25.1
Fe_2O_3	18.0	18.6	19.5
TiO_2	1.8	2.3	1.6
P_2O_5	0.1	0.7	0.3
CaO	4.3	2.9	2.0
MgO	1.5	1.2	1.3
Na_2O	<0.5	0.6	0.3
K_2O	3.3	1.2	1.7
SO_3	1.5	1.5	0.8
Closure	85.4	99.9	99.9

CRYSTALLINE PHASES

Fuel	Major	Minor	% Quartz
Parent	Maghemite Mullite	Quartz	2.3
MFP	None		<0.8
SOAP	Maghemite	Quartz	<0.5

Figure 4 shows the cumulative size distributions of the 1- to 100-micron diameter DTF ash particles as determined by CCSEM. As compared to the mineral particles in the fuels, the parent and MFP ashes are slightly smaller, indicating a minor amount of fragmentation. In contrast, the SOAP fuel ash is shifted to much larger sizes than the fuel mineral matter. The size increase most likely occurred through coalescence of the <10-micron minerals that were trapped inside the fuel particle agglomerates.

Figure 5 shows the composition distributions of the DTF fly ashes. Pyrite has been oxidized or reacted with the aluminosilicate material to form iron aluminosilicate and iron aluminosilicate-rich material. Approximately 4% remained as pure iron oxide (not shown) in the parent and SOAP samples, with less than 1% in the MFP DTF ash. The CCSEM quartz concentrations differ from the XRD values because the CCSEM definition does not take into account the crystal structure of the material, only the composition. Therefore, some of the material that was termed quartz in the CCSEM analyses may actually have melted or slightly reacted with other materials so that it lost its crystalline structure, but kept close to its original composition.

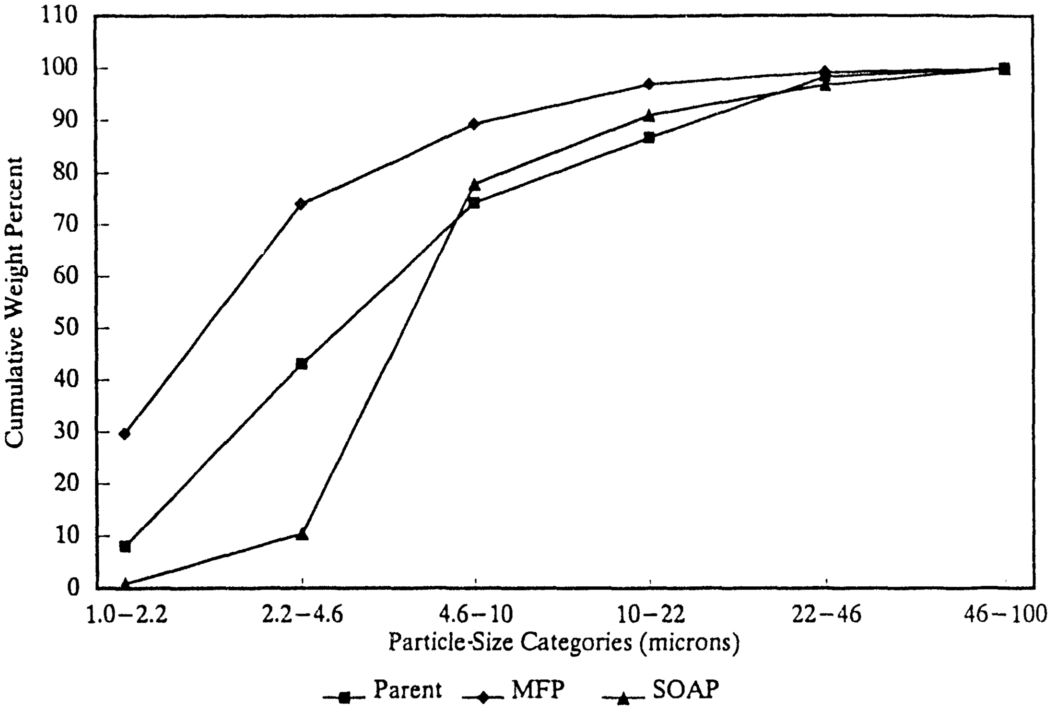


Figure 4. Cumulative size distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated drop-tube furnace ashes.

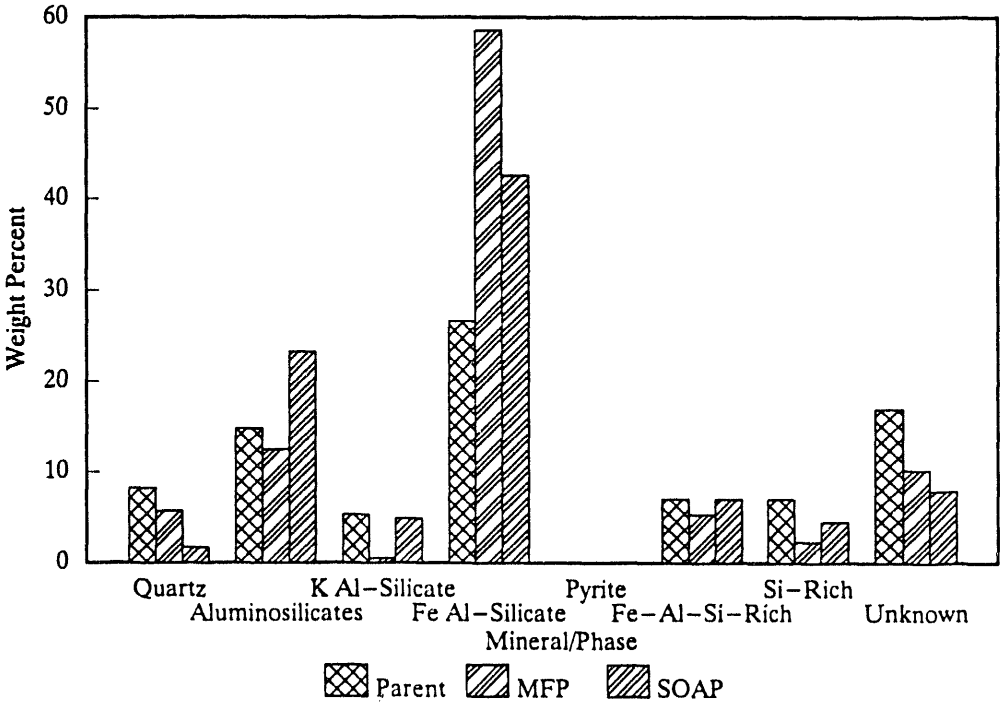


Figure 5. The composition distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated drop-tube furnace ashes.

2.3 FPTF Samples

2.3.1 In-Flame Particulates--Waterwall

The data from the CCSEM analyses of the in-flame particulate samples collected near the waterwall during testing of the Upper Freeport parent, MFP, and SOAP fuels is shown in Figures 6 and 7. The cumulative size distribution shown in Figure 6 indicates that the particulates collected from the FPTF are much finer than the ash collected from the drop-tube furnace. This was also true for the Illinois No. 6 samples and has been experienced with other bituminous coals. The larger size of the DTF ash is most likely caused by more agglomeration of thermoplastic coal particles during the early stages of combustion in the DTF than in the larger pilot-scale system. The agglomeration in the DTF leads to greater numbers of ash particles coalescing during burnout of the char, creating larger ash particles than in the FPTF. As compared to the coal minerals, the in-flame particulate ash has a size distribution shifted to slightly smaller sizes, indicating fragmentation of the minerals during burnout. As was true for the coal minerals, the SOAP fuel produced the smallest ash, followed by the MFP, with the parent producing the biggest ash particles.

The composition distributions of the ash particulates collected at the level of the waterwall are similar to those for the DTF ash, except that the aluminosilicate material for the MFP has undergone more interaction with pyrite-derived and other ash to make more complex iron aluminosilicate-rich and unclassified material rather than more pure iron aluminosilicate. Like the DTF ash, the pyrite has completely oxidized, and most of the iron oxide has reacted with aluminosilicate material to form iron aluminosilicate material. Similar reactions were observed for the Illinois No. 6 ash.

2.3.2 Waterwall Panel Slag Deposits

Figure 8 illustrates the differences in the concentrations of the major elements in the coal ash, in-flame particulates, deposits, and fly ash that were caused by beneficiation of the fuels. The lines in the figure connect the coal ash and deposit data, while the particulate samples are not connected. They are arranged in order of distance from the FPTF burner and, therefore, in decreasing gas temperatures. The data was determined by x-ray fluorescence analysis. The figures show that the concentrations of the major elements and sum of alkali elements remain the same in the deposits as in the coal ash. The only exceptions are that the SOAP deposits do show slightly less aluminum and slightly more iron, as distance from the burner increases (and temperatures drop). Those shifts may be related to the viscosities of the particles, since lower aluminum and higher ferrous iron concentrations usually lower the melting point of glasses.

The differences in deposit composition due to beneficiation are much less than were seen for the Illinois No. 6 samples and reflect the smaller differences seen in the coal ashes. The biggest difference is the silicon concentrations, which are lower in the beneficiated fuel deposits than in the parent fuel deposits. The MFP deposits had the lowest silicon and slightly higher alkaline contents than the deposits from the other fuels. Both MFP and SOAP fuel deposits had slightly higher iron concentrations than the parent fuel deposits.

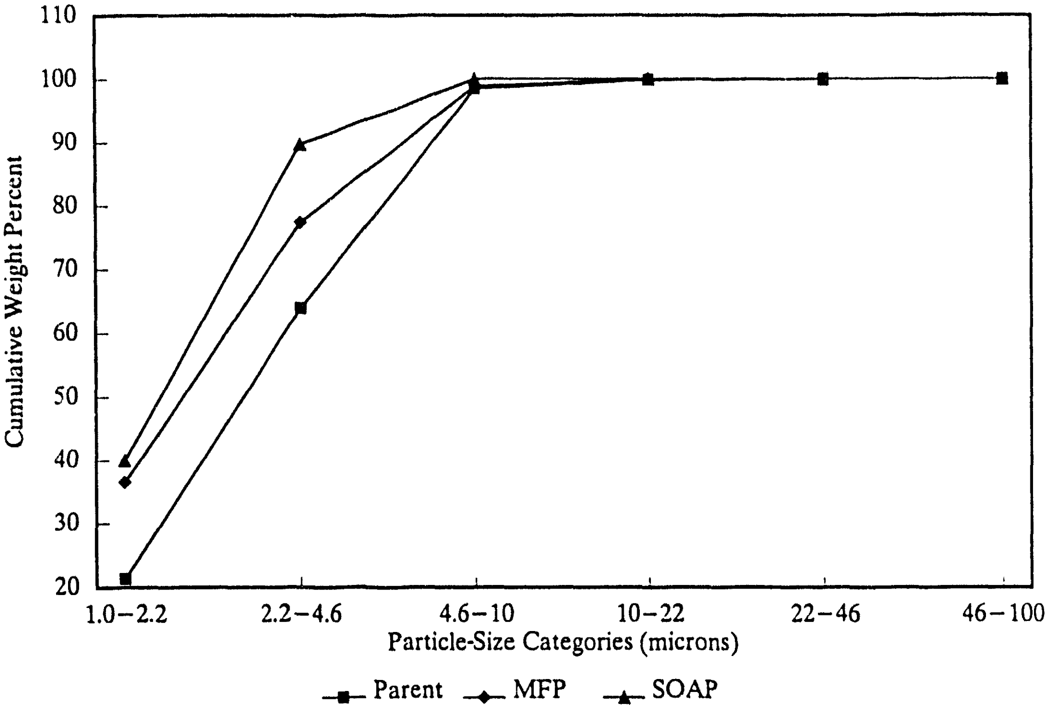


Figure 6. Cumulative size distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated particulate ashes collected in the FPTF near the waterwall.

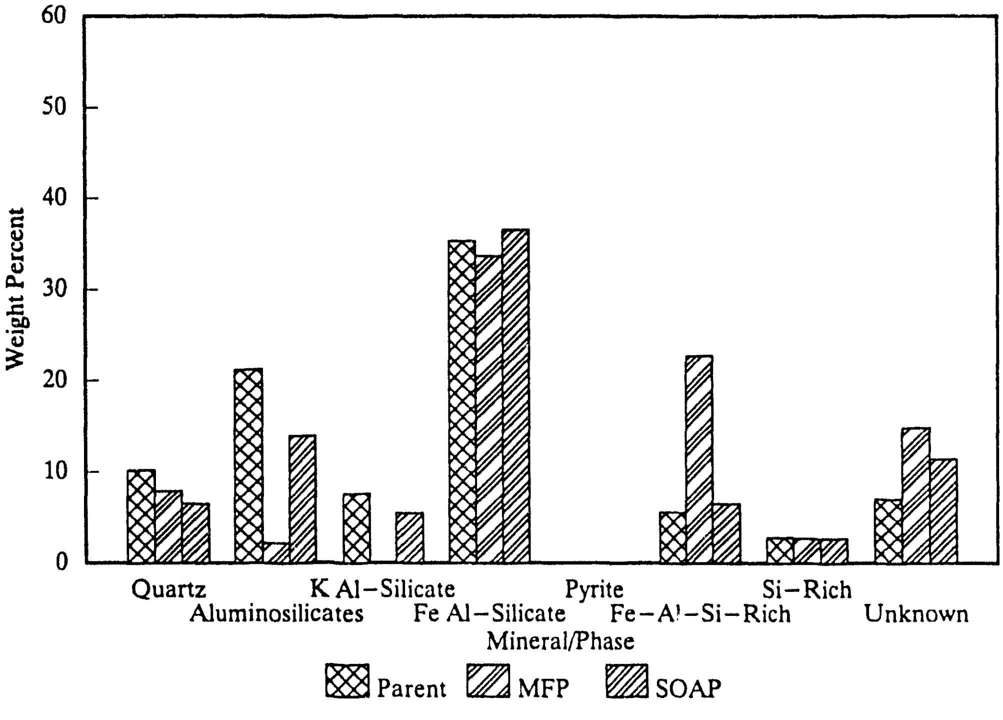
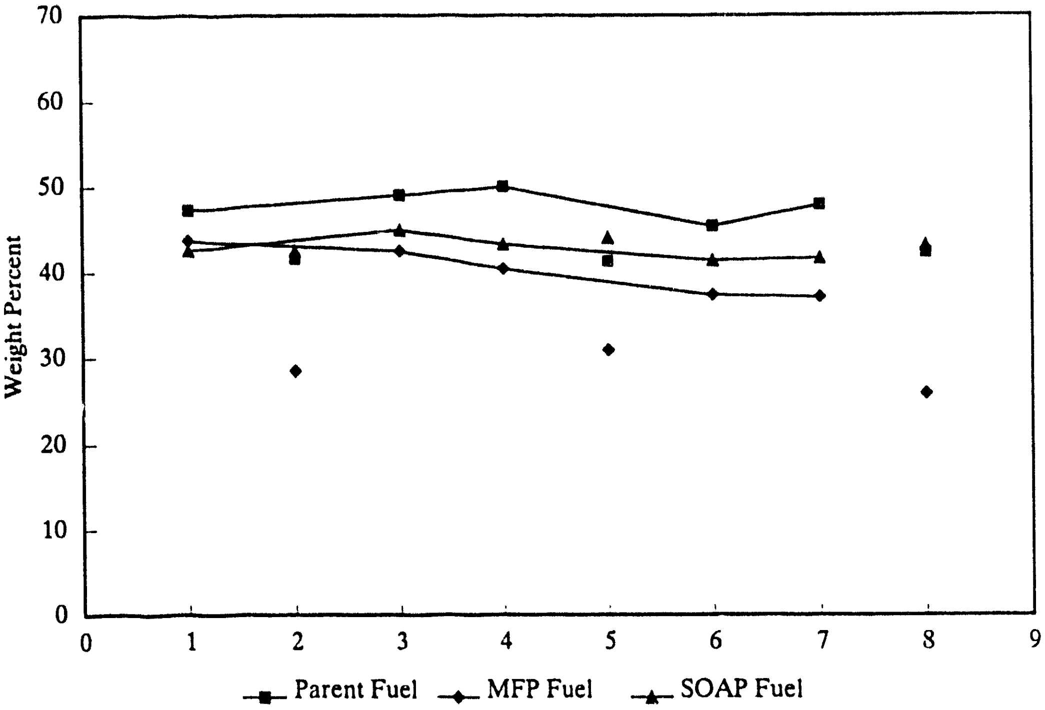
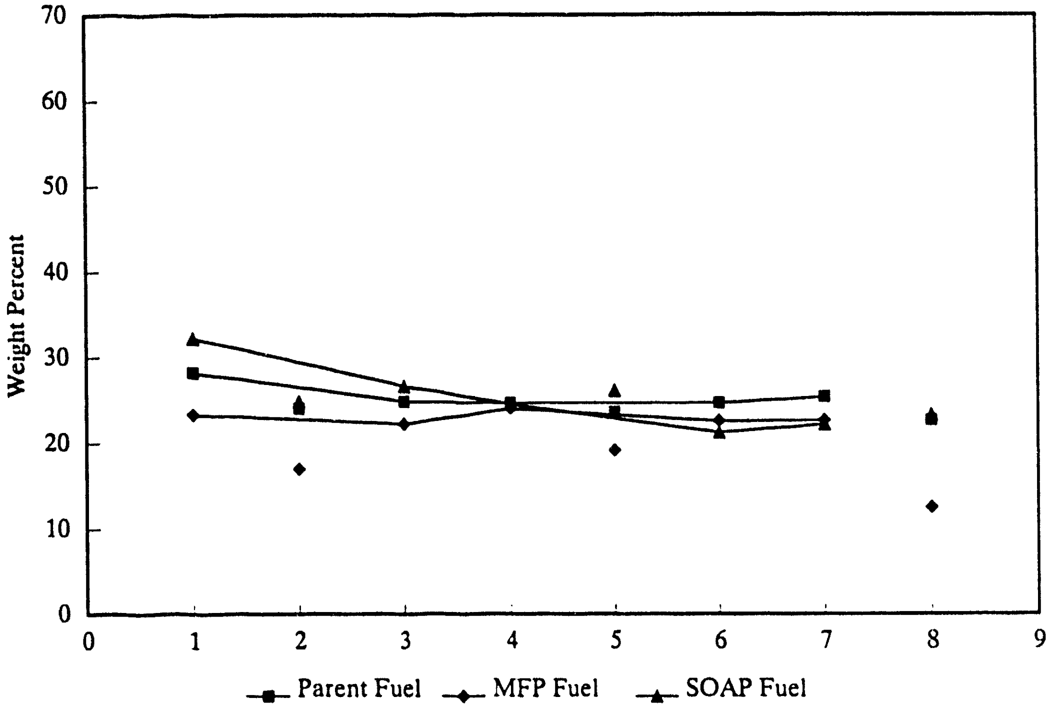


Figure 7. The composition distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated particulate ashes collected in the FPTF near the waterwall.

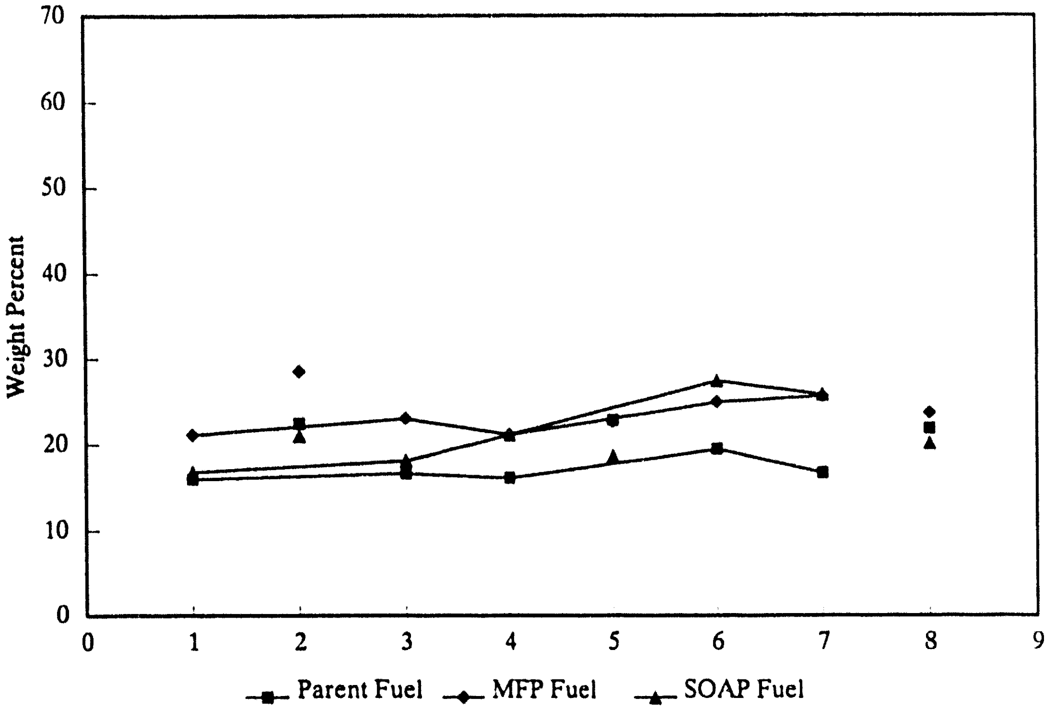


(a) SiO_2 concentrations

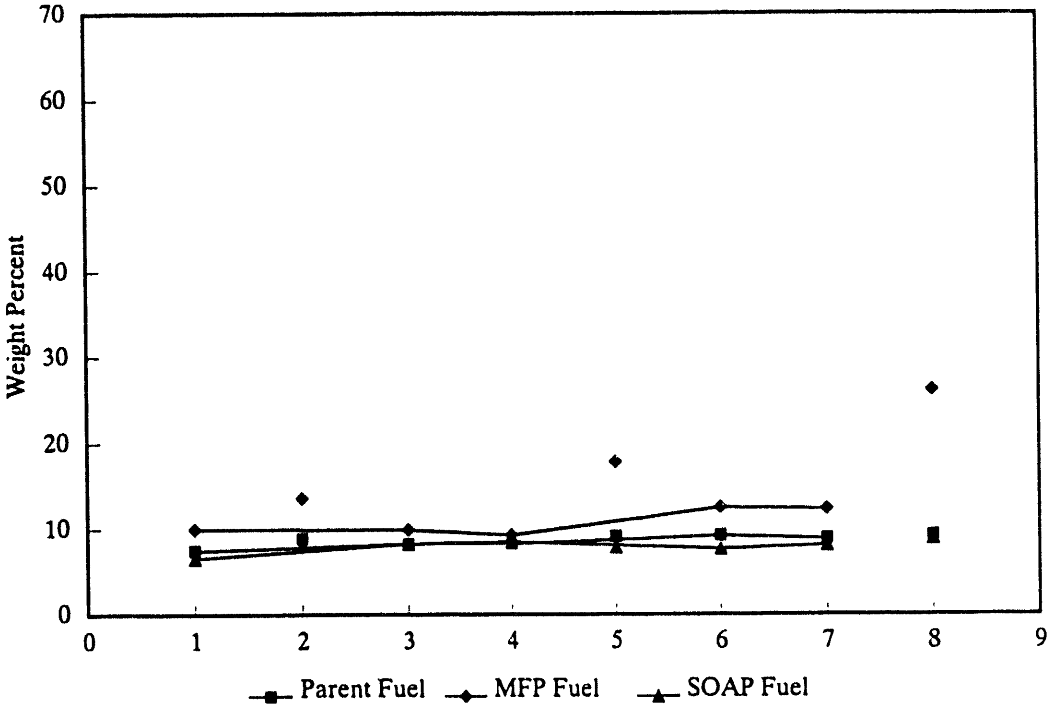


(b) Al_2O_3 concentrations

Figure 8. Changes in composition of Upper Freeport parent, MFP, and SOAP fuel ash, in-flame particulate, deposits, and fly ash due to beneficiation: (a) SiO_2, (b) Al_2O_3. Point designations are 1 = fuel ash, 2 = waterwall particulates, 3 = panel 1 slag outer layer, 4 = panel 4 slag outer layer, 5 = furnace outlet particulates, 6 = tube 1a outer deposit, 7 = tube 2c outer deposit, 8 = fly ash.



(c) Fe_2O_3 concentrations



(d) sum of alkali and alkaline earth elements

Figure 8. Changes in composition of Upper Freeport parent, MFP, and SOAP fuel ash, in-flame particulate, deposits, and fly ash due to beneficiation: (c) Fe_2O_3, and (d) sum of alkali and alkaline earth elements. Point designations are 1 = fuel ash, 2 = waterwall particulates, 3 = panel 1 slag outer layer, 4 = panel 4 slag outer layer, 5 = furnace outlet particulates, 6 = tube 1a outer deposit, 7 = tube 2c outer deposit, 8 = fly ash.

Much greater differences between parent and beneficiated ash are seen in the compositions of the in-flame particulate samples. The compositions of the parent and SOAP particulates are very similar to the deposits, but the MFP particulates have much lower silicon and aluminum contents, and much higher total alkali than the MFP deposits. The differences in composition indicate that smaller particles may have been favored in the MFP particulate samples, since silicon often concentrates in bigger ash particles and alkali in smaller. The higher concentrations of smaller particles are either caused by greater settling of large particles during the MFP test, or sampling at a greater than isokinetic rate during MFP testing.

The small differences in composition are somewhat reflected in the reducing atmosphere softening temperatures, shown for the deposits in Figure 9. The slightly higher iron and lower silicon contents of the beneficiated fuel deposits have lowered the softening temperatures of the deposit material relative to the parent coal deposits. The one exception is the relatively high softening temperature of the Upper Freeport SOAP panel 1 deposit which may be due to the lower iron concentration in that deposit.

In addition to overall softening temperatures, it is important to determine the distribution of viscosities in the deposits so that the relative amounts of material that are flowing and binding the deposits can be determined. The data can also be used to differentiate the more fluid phases from those that are drier. Determination of the distribution is especially important when the ash has not completely fused, as will be true in the cooler regions of the combustor.

Figure 10 shows the viscosity distributions for the outer deposits that formed on panel 1. The data was derived from scanning electron microscope point count (SEMPC) analyses which were used to determine the composition distributions in the deposits. The composition distribution data were then used to calculate a viscosity distribution using an algorithm developed by Kalmanovitch and Frank (1988). The temperature used in the calculations is an average gas temperature at the level of panel 1 during many FPTF runs. The Figure 10 data reflect the softening temperature data in that the parent and SOAP deposits have similar viscosity distributions whereas the MFP distribution is lower. Since sintering rate is directly proportional to viscosity, the MFP deposit would be expected to sinter and harden more rapidly than the parent or SOAP deposits at this location.

Figures 11a and 11b show the major element compositions of the points in the MFP panel 1 deposits that have calculated viscosities of greater than 250 poise and less than 250 poise, respectively, at 1650°C. The value of 250 poise was chosen because that is a standard value for determining the flow characteristics of a slag. Slags with higher viscosities cannot be tapped from a furnace, whereas those that have lower viscosities can. Areas in the deposits that have these compositions sinter and create strength more rapidly than areas with higher viscosities. The graphs show that the low viscosity points tend to have more calcium and iron associated with them than the high viscosity points. In addition, at this relatively high temperature, there are many more points that tend to have viscosities below 250 poise than above it. The diagrams for the parent and SOAP fuel deposits were similar.

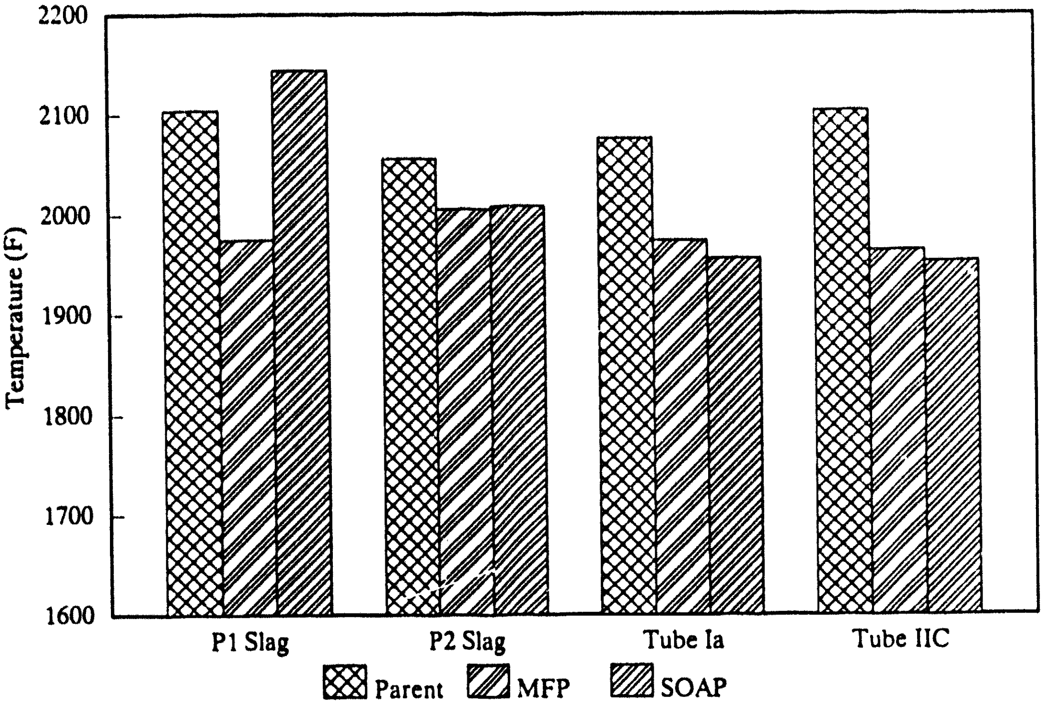


Figure 9. Reducing atmosphere ash fusion softening temperatures for the outer waterwall panel and steam-tube deposits.

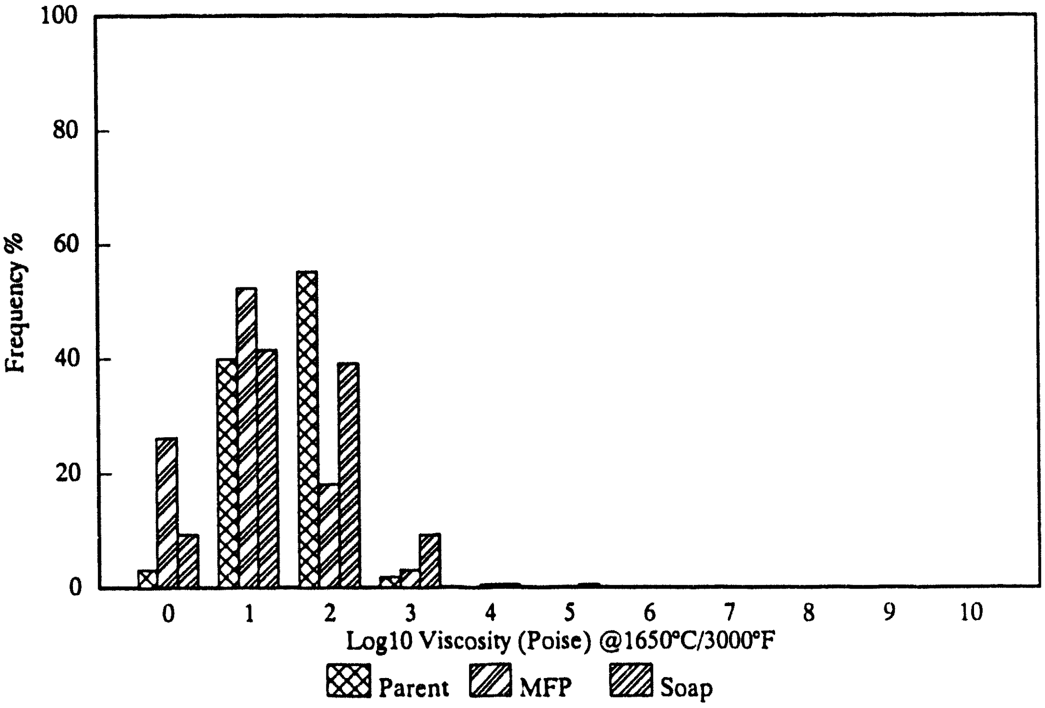
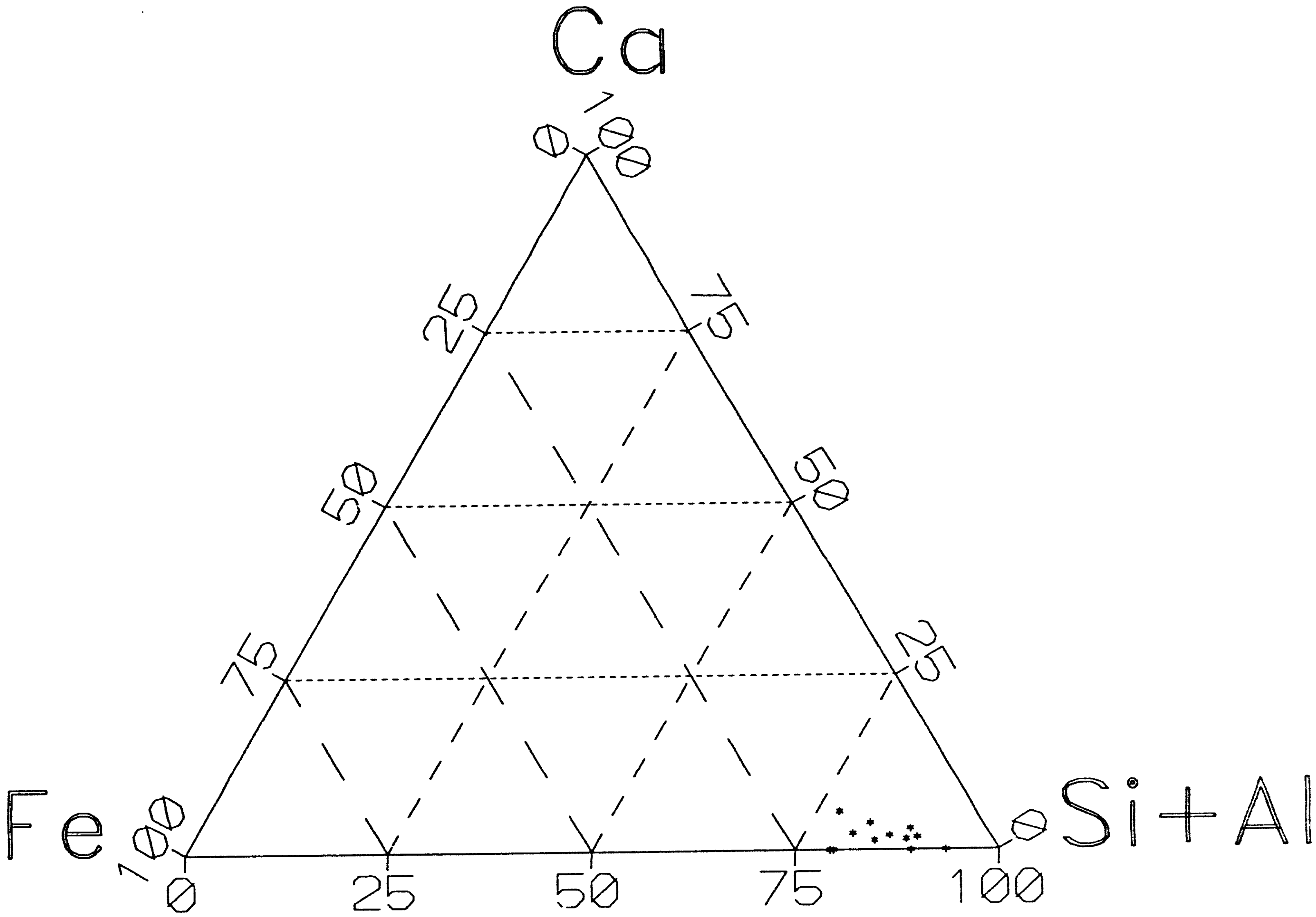
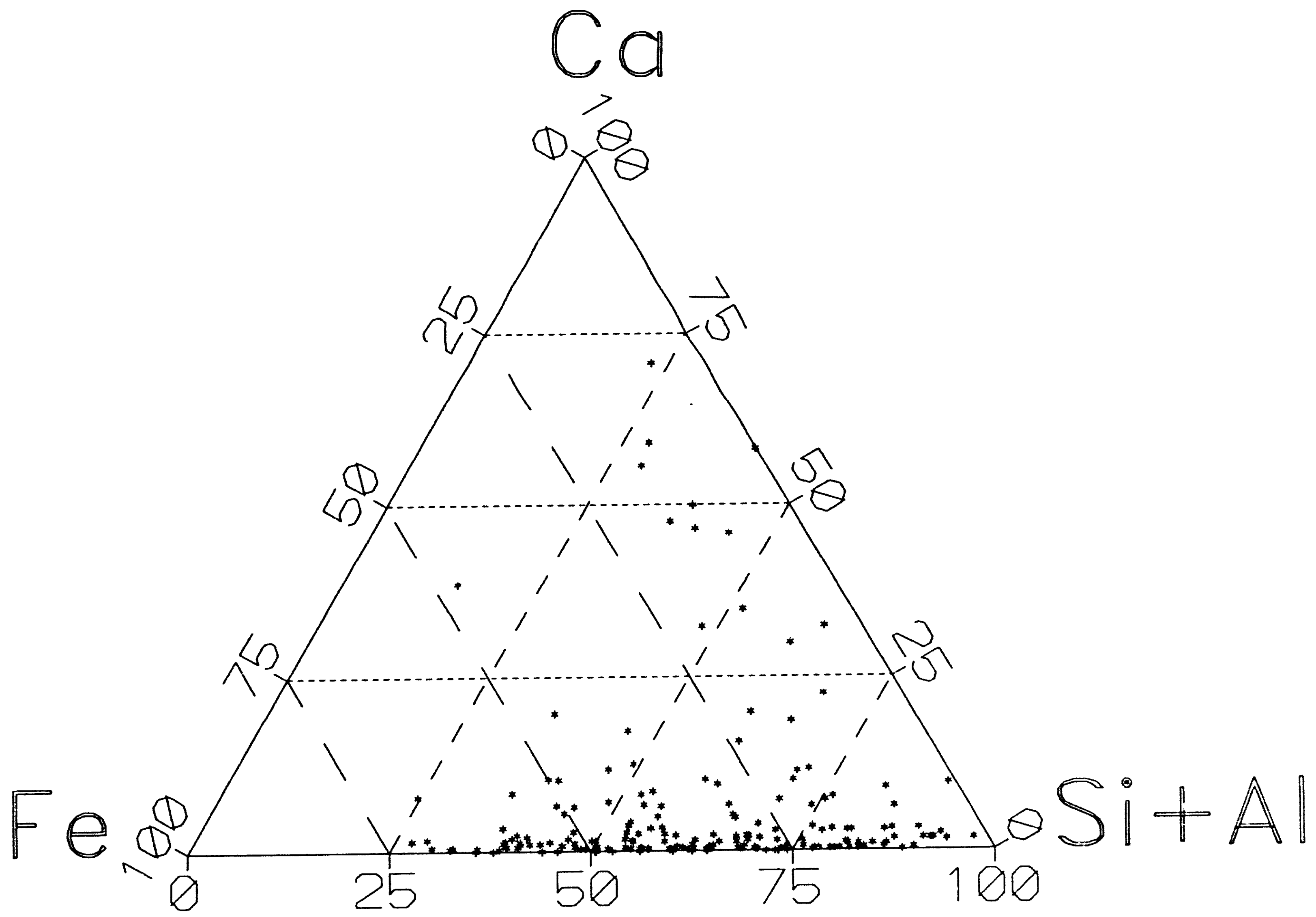


Figure 10. Calculated viscosity distributions in the waterwall panel 1 outer deposits.



(a) greater than 250 poise

Figure 11a. The major element compositions of the points in the MFP waterwall panel 1 outer deposits that have calculated viscosities at 1650°C of greater than 250 poise.



(b) less than 250 poise

Figure 11b. The major element compositions of the points in the MFP waterwall panel 1 outer deposits that have calculated viscosities at 1650°C of less than 250 poise.

2.3.3 In-Flame Particulates--Furnace Outlet

Figures 12 and 13 show the cumulative size distributions and composition distributions of the in-flame particulate ash collected at the furnace outlet. The data apply to ash particles with sectioned diameters between 1 and 100 µm and were produced by CCSEM analysis. As the particulates pass from the waterwall region to the furnace outlet, the particle-size distribution of the SOAP remains approximately the same, MFP ash increases slightly, but the parent coal ash size increases significantly. The size increase in the parent coal ash is probably not due to cenosphere growth, as that would have been complete at the level of the waterwall, or to coalescence, as the increase in size implies much more coalescence than would likely have occurred during this stage of combustion. The increase in size is more likely due to sample collection errors, or, more likely, to agglomeration during sample preparation.

Figure 13 shows the composition distributions of the in-flame particulate samples collected at the furnace outlet. The data is very similar to that for the particulates collected at the level of the waterwall. The only significant difference is an increase in the concentration of an iron aluminosilicate-rich phase and subsequent decreases in aluminosilicates and quartz in the MFP ash, indicating a limited amount of coalescence between the level of the waterwall and the outlet.

2.3.4 Convective Pass Fouling Deposits

The bulk composition and reducing atmosphere fusion temperatures for the fouling deposits that formed on the simulated steam tubes in the convective pass of the FPTF were shown in figures in previous sections of this report. As was true for the waterwall deposits, the compositions of the fouling deposits are very similar to the fuel ashes. The compositions are also similar to the in-flame particulates collected at the furnace outlet, except for the MFP samples. The MFP particulates were enriched in alkali elements, but depleted in silicon as compared to the deposits. Such differences indicate that the sample was enriched in the smallest particles, either because of large particles settling in the bottom ash or collection of particulates at a rate significantly greater than the isokinetic rate.

Like the waterwall deposits, the differences in fouling deposit composition due to beneficiation are much less than were seen for the Illinois No. 6 samples and reflect the smaller differences seen in the coal ashes. The biggest difference is the silicon concentrations which are lower in the beneficiated fuel deposits than in the parent fuel deposits. The MFP deposits had the lowest silicon content and slightly higher alkaline contents than the deposits from the other fuels. Both MFP and SOAP fuel deposits had slightly higher iron concentrations than the parent fuel deposits. As shown in Figure 9, these differences caused the beneficiated fuel deposits to have lower reducing atmosphere softening temperatures than the parent coal deposits.

The calculated viscosity distributions of the outer deposits that formed on steam tube 1a are shown in Figure 14. The temperature used in the calculations, 1250°C, is an average gas temperature in the region of the tubes during a typical fuel test. The distributions show that the parent and SOAP fuel deposits have similar viscosity distributions, whereas the MFP deposit has a

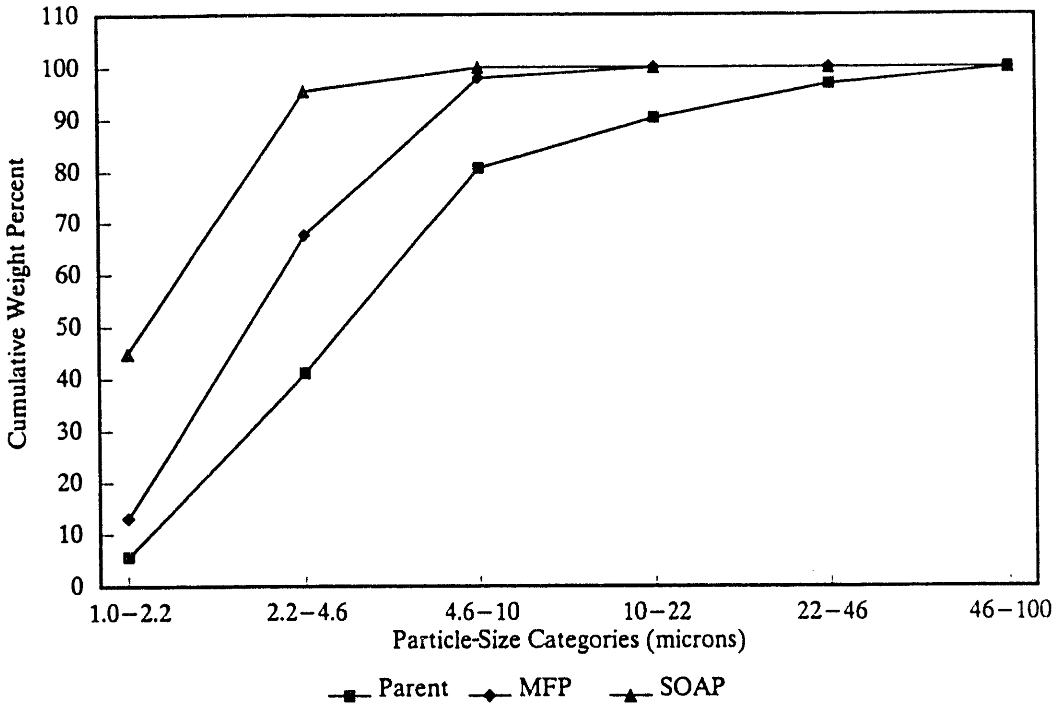


Figure 12. Cumulative size distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated particulate ashes collected in the FPTF at the furnace outlet.

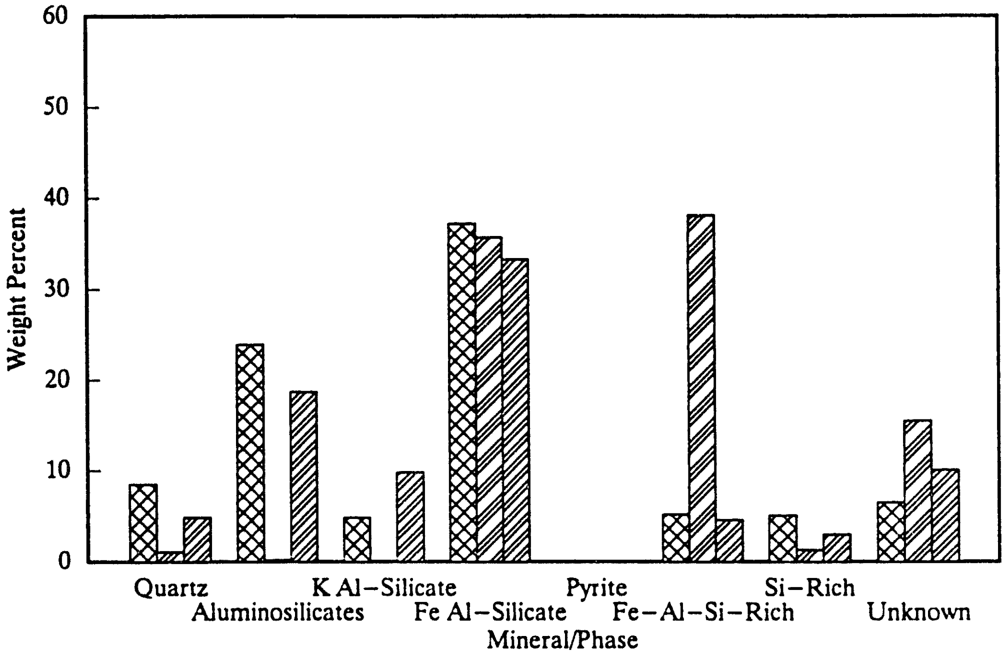


Figure 13. The composition distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated particulate ashes collected in the FPTF at the furnace outlet.

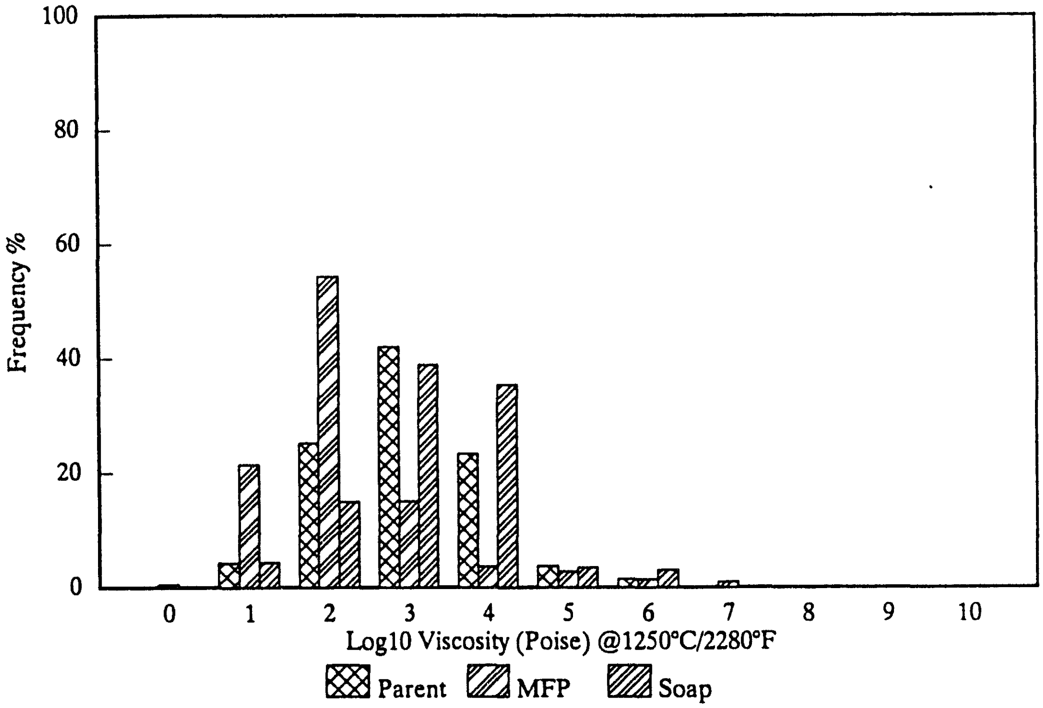


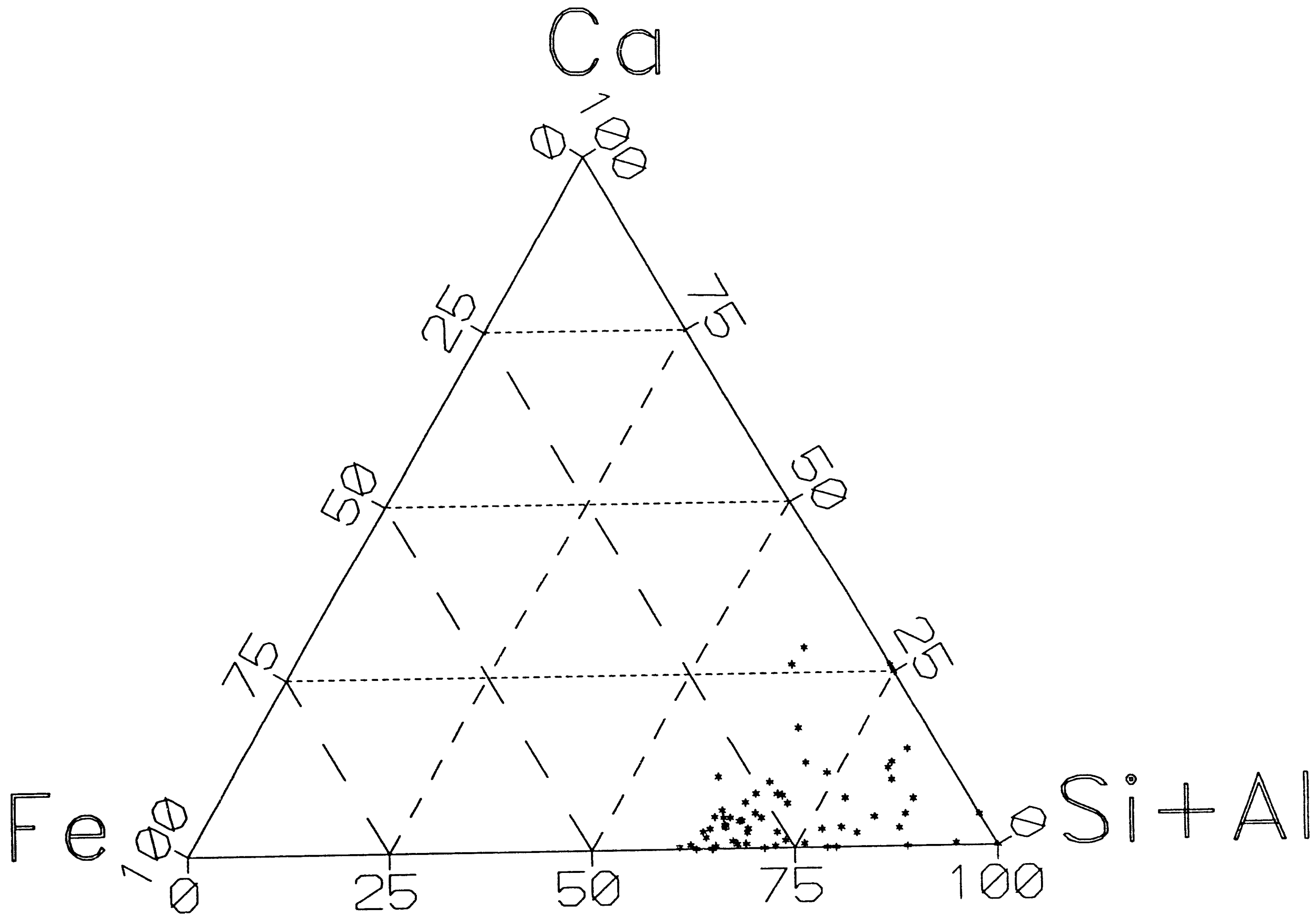
Figure 14. Calculated viscosity distributions in steam-tube 1a outer deposits.

viscosity distribution shifted lower by an order of magnitude. The lower distribution for the MFP deposits is likely due to the higher alkali content of the MFP deposit. The lower viscosity distributions for the MFP deposits imply that they will harden more quickly than the parent and SOAP deposits, because sintering rate is inversely proportional to the viscosity.

Figure 15 shows the normalized major element compositions of the points in the MFP tube 1a outer deposit that had calculated viscosities of less than 250 poise at 1250°C. The graphs show that, like the waterwall panel deposits, those areas that contain higher levels of calcium and iron tend to have lower viscosities than those that contain lower levels. The parent and SOAP deposit diagrams showed the same trends.

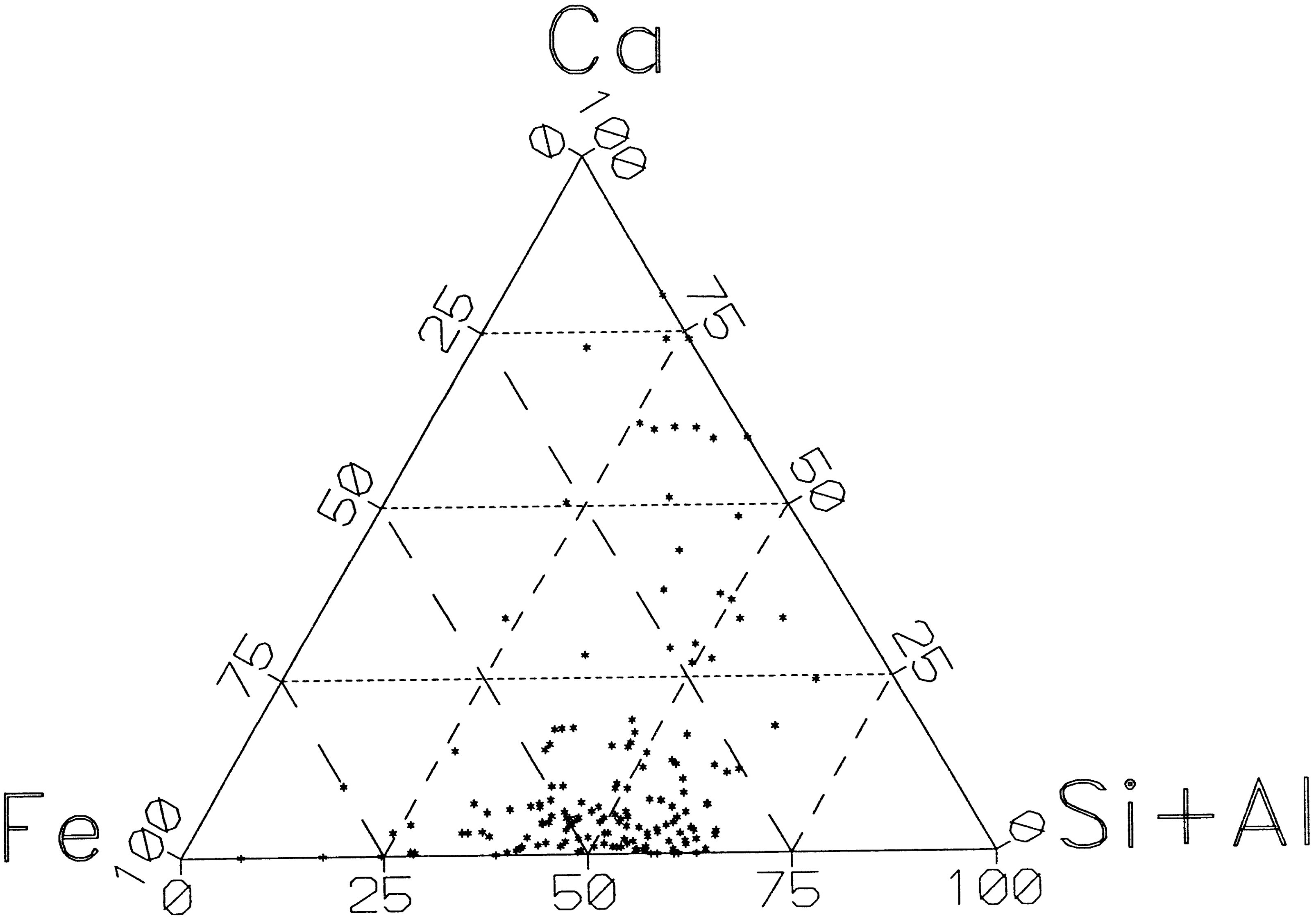
2.3.5 Fly Ash

Figure 16 shows the cumulative size distribution of the fly ash collected from the convective pass near the erosion test equipment. The size distribution for the parent coal ash is essentially the same as for the particulate ash collected at the furnace outlet. However, the MFP and SOAP fly ashes have much larger size distributions than their respective furnace outlet ashes. As was true for the furnace outlet samples, the measured size increase in the MFP and SOAP fly ash is most likely not due to ash cenosphere formation or coalescence. It is either due to sampling errors, or, more likely, to agglomeration of the fine ash so that the CCSEM mistakes an agglomerate of many ash particles for a single large particle.



(a) Greater than 250 poise

Figure 15a. The major element compositions of the points in MFP steam-tube 1a outer deposits that have calculated viscosities at 1250°C of greater than 250 poise.



(b) less than 250 poise

Figure 15b. The major element compositions of the points in MFP steam-tube 1a outer deposits that have calculated viscosities at 1250°C of less than 250 poise.

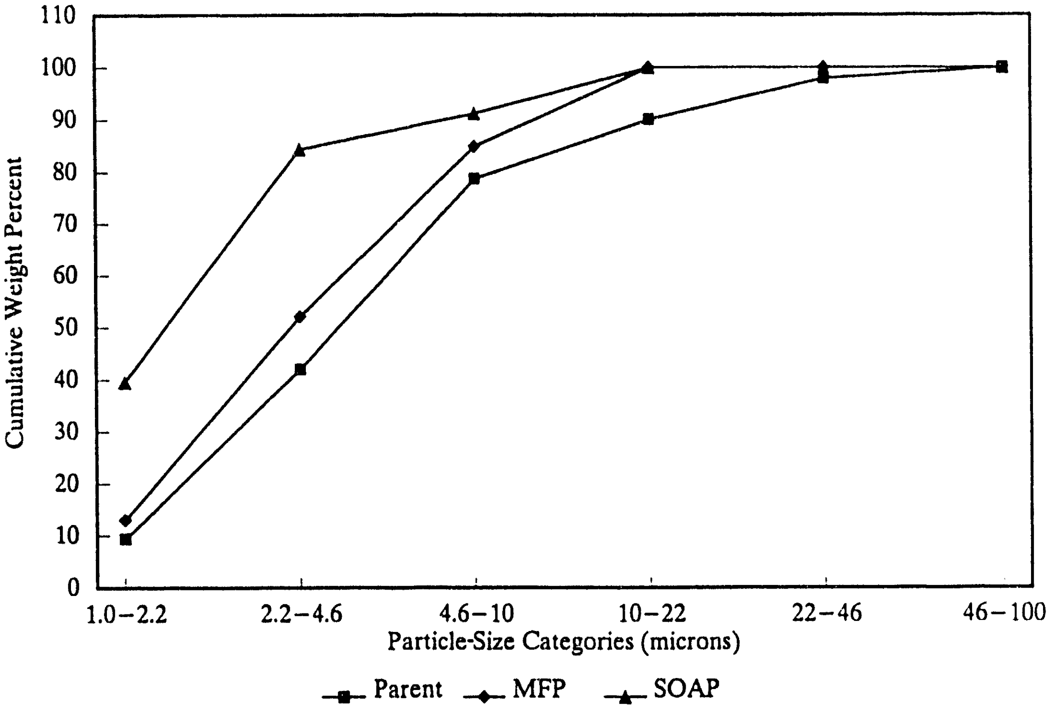


Figure 16. Cumulative size distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated fly ashes.

Figure 17 shows the composition distributions of the fly ash. The data are similar to the composition distributions of the particulate ash samples collected at the furnace outlet, except for the high quantity of unknowns in the MFP fly ash. The unknowns are primarily iron silicate or iron aluminosilicates that contain some sodium and potassium and especially sulfur. The presence of the sulfur prevents the material from being classified in one of the aluminosilicate categories. The sulfur is most likely due to sulfation of alkali metals in the ash as it cooled while passing through the convective pass.

3.0 REFERENCES

Kalmanovitch, D.P.; Frank, M. "An Effective Model of Viscosity for Ash Deposition Phenomena," in Mineral Matter and Ash Deposition from Coal; Engineering Foundation, 1988.

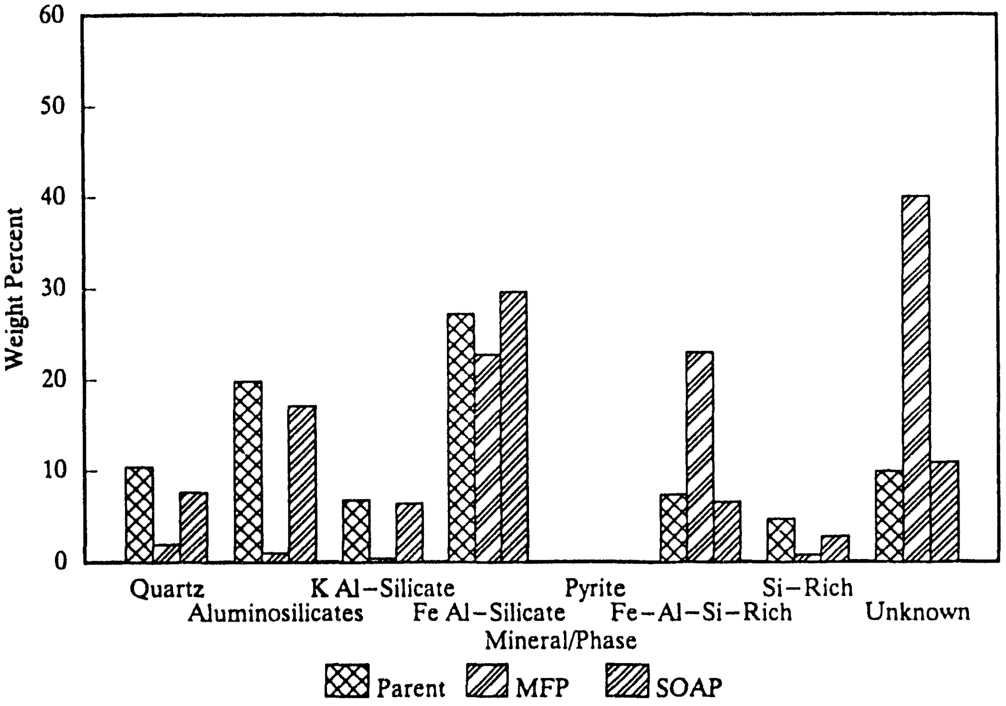


Figure 17. The composition distributions of the inorganic particles with sectioned diameters between 1 and 100 microns in the Upper Freeport parent and beneficiated fly ashes.

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