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COMBUSTION CHARACTERIZATION OF BENEFICIATED COAL-BASED FUELS

QUARTERLY REPORT NO. 6 FOR THE PERIOD JULY 1990 TO SEPTEMBER 1990

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MASTER

DISCLAIMER

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QUARTERLY REPORT

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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 being run at the cleaning facility in Homer City, Pennsylvania, 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 microfine coal (DMPC) 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 1990, the following technical progress was made.

- Evaluated the ignitibility and reactivity characteristics of the Pittsburgh No. 8 microbubble flotation and spherical oil agglomeration beneficiated products, including flammability indices, TGA, and BET surface areas.
- Continued drop tube combustion tests of the beneficiated products.
- Analyzed the data from three (MIT) pilot-scale combustion tests of the Upper Freeport feed coal.
- Continued analyses of the data from the CE pilot-scale tests of nine fuels.
- Completed the draft report describing the boilers selected for the techno-economic analysis.

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 during the previous four quarters. Approximately fifty barrels of each spherical oil agglomeration product (SOAP) were unused and remain 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.

Nine fuels are being characterized. These include: (1) Upper Freeport mvb, Pittsburgh #8 hvAb and Illinois #6 hvCb; (2) three microbubble flotation products (MFPs) prepared from the above parent coals; and (3) three spherical oil agglomeration products (SOAPs) prepared from the same parent coals. The overall objective of this task is to derive a technical data base to be used in conjunction with Task 5 to predict the performance and economic impacts of firing the BCFs in commercial boilers of various designs.

2.1 UNDEERC FUEL ANALYSES

CCSEM, in conjunction with image analysis of the Illinois No. 6 spherical oil agglomeration product (SOAP), Pittsburgh No. 8 microbubble flotation product (MFP), and Upper Freeport MFP and SOAP fuels, was completed during this quarter. Also, the FORTRAN program used to reduce the raw CCSEM data was rewritten to add new particle types, tighten up the definitions of the existing particle types, and to make the program more flexible in dealing with nonroutine CCSEM analyses. The new program has been named PARTCHAR for PARTicle CHARacterization program. PARTCHAR will be used on all future CCSEM data, and so, for consistency, it has been run on all of the CCSEM data reported previously. In this report, PARTCHAR will be described, and summaries of the PARTCHAR output for the Illinois No. 6 parent, MFP, and SOAP, as well as the Upper Freeport parent, MFP, and SOAP fuels will be listed and discussed.

The new inorganic particle-type definitions used in PARTCHAR are listed in Table 2.1.1. The values given are percentages of x-ray counts normalized to total 100% for the 12 elements measured. Those elements are Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe, Ba, and Ti. Care must be taken in interpreting CCSEM data because the SEM

TABLE 2.1.1

COMPOSITIONS (Normalized X-ray Count Percent) AND DENSITIES (g/cm^3) USED TO DEFINE CCSEM PARTICLE TYPES AND CONVERT AREA PERCENT TO WEIGHT PERCENT

Quartz		Al≤5, Si≥80
Density	2.65	
Iron Oxide		Si<10, S≤5, Mg≤5, Al≤5, Fe≥80
Density	5.3	
Periclase		Mg≥80, Ca≤5
Density	3.61	
Rutile		S≤5, Ti+Ba≥80
Density	4.9	
Alumina		Al≥80
Density	4.0	
Calcite		S<10, Mg≤5, Si≤5, P≤5, Ti≤5, Ba≤5, Ca≥80
Density	2.8	
Dolomite		Mg≥5, Ca>10, Ca+Mg≥80
Density	2.86	
Ankerite		S<15, Mg<Fe, Fe>20, Ca>20, Ca+Mg+Fe≥80
Density	3.0	
Kaolinite		Al+Si≥80, 0.8<Si/Al<1.5, Fe≤5, K≤5, Ca≤5
Density	2.65	
Montmorillonite		Al+Si≥80, 1.5<Si/Al<2.5, Fe≤5, K≤5, Ca≤5
Density	2.5	
K-Al-Silicate		Na≤5, Ca≤5, Fe≤5, K≥5, Si>20, Al≥15, K+Al+Si≥80
Density	2.6	
Fe-Al-Silicate		Fe≥5, Al≥15, Si>20, S≤5, Ca≤5, K≤5, Na≤5, Fe+Al+Si≥80
Density	2.8	
Ca-Al-Silicate		S≤5, K≤5, Fe≤5, Na≤5, Ca≥5, Al≥15, Si>20, Ca+Al+Si≥80
Density	2.65	
Na-Al-Silicate		S≤5, K≤5, Fe≤5, Ca≤5, Na≥5, Al≥15, Si>20, Na+Al+Si≥80
Density	2.6	
Aluminosilicate		K≤5, Ca≤5, Fe≤5, Na≤5, Si>20, Al>20, Si+Al≥80
Density	2.65	

(continued)

(Table 2 continued)

Mixed Silicates		Na<10, Fe<10, Ca<10, K<10, S≤5, Si>20, Al>20, Si+Al+Fe+Ca+K+Na≥80
Density	2.65	
Fe-Silicate		Fe>10, Na≤5, K≤5, Ca≤5, Al≤5, S≤5, Si>20, Fe+Si≥80
Density	4.4	
Ca-Silicate		Na≤5, K≤5, Fe≤5, Al≤5, S≤5, Ca>10, Si>20, Ca+Si≥80
Density	3.09	
Ca-Aluminate		P≤5, S≤5, Si≤5, Al>15, Ca>20, Ca+Al≥80
Density	2.8	
Pyrite		Ca<10, 10≤ Fe ≤40, S>40, Fe+S≥80
Density	5.0	
Pyrrhotite		10≤S<40, Fe<40, Fe+S≥80
Density	4.6	
Gypsum		Ti<10, Ba<10, Si<10, S>20, Ca>20, Ca+S≥80
Density	2.5	
Barite		Fe<10, Ca≤5, S>20, Ba+Ti>20, Ba+S+Ti≥80
Density	4.5	
Apatite		P≥20, Ca≥20, Al≤5, S≤5, Ca+P≥80
Density	3.2	
Ca-Al-P		Al>10, P>10, Ca>10, S≤5, Si≤5, Al+Ca+P≥80
Density	2.8	
KCl		K≥30, Cl≥30, K+Cl≥80
Density	1.99	
Gypsum/Barite		Fe≤5, Ca≥5, Ba≥5, Ti≥5, S>20, Ca+Ba+S+Ti≥80
Density	3.5	
Gypsum/Al-Silicate		Al≥5, Si≥5, S≥5, Ca≥5, Ca+Al+Si+S≥80
Density	2.6	
Si-Rich		65≤Si<80
Density	2.65	
Ca-Rich		65≤Ca<80, Al<15
Density	2.6	
Unknown		All Other Compositions
Density	2.7	

provides only elemental composition data and not crystallographic data. Therefore, although the inorganic particle types have compositions similar to the defined mineral types and the defined mineral types are known to commonly exist in coal, the particles analyzed by CCSEM may not have the same crystallographic properties as the defined mineral type for which it is named.

Because no atomic number, absorbance, or fluorescence (ZAF) corrections were used, it was necessary to make some definitions relatively broad. In all cases, the sum of the concentrations of the constituent elements in a given particle type was constrained to equal 80% or greater if the particle was to be defined as a particular mineral. Particle types in which the sum of the constituent elements was allowed to be less than 80% were designated as element-rich types, rather than as specific minerals. Some overlap appears in the definitions of the Ca-rich and Si-rich inorganic types and other inorganic types that contain high levels of Ca or Si. The overlap does not pose a difficulty in assigning types because the Ca-rich and Si-rich categories appear at the end of the program. Since the program checks the composition of a particle against the definitions in a sequential manner, the Ca-rich and Si-rich categories are assigned only if the composition of the particle does not first meet the criteria of the other inorganic types in the list. The categories of gypsum/barite and gypsum/aluminosilicate were defined because gypsum has been found through experience to occur, at times, intergrown with barite and aluminosilicate particles.

In general, limits on the concentrations of elements not normally occurring in a given mineral type were defined because gypsum has been found through experience to occur, at times, intergrown with barite and aluminosilicate particles.

In general, limits on the concentrations of elements not normally occurring in a given mineral type were imposed to prevent classification of a particle as a pure mineral when in fact the particle might be composed of two different mineral types. For example, a limit of 5% was placed on the concentration of aluminum in the quartz particle type, even though quartz does not normally contain aluminum, because the greater than or equal to 80% constraint on the concentration of silicon in the quartz would allow up to 19% aluminum to exist in the particle and still allow a classification as quartz. Since such a particle is more likely composed of both quartz and clay, the 5% maximum concentration constraint on the aluminum content would force such a particle to be classified as unknown. Although arguments can always be made for small changes in the definitions or for numerous new particle types to be defined, the relatively limited concentration of particles having elemental compositions not fitting a defined category illustrates the effectiveness of the definitions listed in Table 2.1.1.

The bin sizes used in the PARTCHAR for size classifying the particles were not changed from those used previously. The size ranges that the particles are listed in are a geometric progression differing by a factor of the cube root of ten. A geometric progression of cube root ten was used for several reasons. Since the range in average particle diameters measured is 1 to 100 μm, a whole number of bins that are the cube root of ten μm wide will fit into the range. the minimum in the range was adopted because, although particles smaller than 1μm in diameter can be imaged, the composition of the particle is usually rather ambiguous because the volume of the sample that is excited by the electron beam to emit x-rays is slightly larger than 1 μm in diameter. Therefore, interference effects from adjacent particles become large as the diameter of the particles analyzed drops below approximately 1μm in average diameter. Particles larger and 100 microns in diameter are not analyzed because the counting statistics for those particles is very poor.

A geometric size distribution was used in reporting the CCSEM data to lessen sectioning effects that cause the exposed cross section of the particles to be less than or equal to the maximum diameter of the particles[1]. In effect, the use of a geometrical size distribution makes the errors related to sectioning constant between categories, and small compared to the errors related to the counting statistics. Therefore, no corrections for shifting of particle diameters to smaller size ranges caused by sectioning are applied to the data.

Another reason that the factor of cube root of ten is used between bins is to allow quick comparison of actual numbers of particles between bins. Such comparisons can be easily made with use of two relationships. First, the area fraction of an inorganic particle type exposed at the surface of a random cross section through the coal-epoxy SEM plug can be assumed to equal the volume fraction of that particle type within the volume of the SEM plug[2]. Second, for spheres, the volume of the particle equals a constant times the cube of the diameter. By using a geometric factor of cube root ten, the relationship between the relative number of particles present in the total volume of the SEM plug that belong in two adjacent size categories is given by

$$\text{\# in A/\# in B} = 10 \times (\text{Volume in A/Volume in B}) \qquad \text{[Eq 1]}$$

where:

in A = the number of particles in size range A

in B = the number of particles in the next size range larger than A

In other words, if the volume fraction in each of two adjacent size categories is equal, then , on average, there are about ten times as many of the smaller particles in the coal as there are larger particles.

CCSEM Analyses of Illinois No. 6 and Upper Freeport Fuels

Tables 2.1.2, 2.1.3, and 2.1.4 list summaries of the PARTCHAR output for the CCSEM analyses of the Illinois No. 6 parent, MFP, and SOAP fuels. The information listed in the tables is similar to that listed in previous reports except that more detail about the analysis parameters is now given. Also, the order of the types has been grouped by composition. Oxides are listed first, followed by aluminosilicates, silicates, sulfates-sulfides, phosphate-chlorides, mixed minerals, and finally, element-rich types and unknowns.

A comparison of Tables 2.1.2 and 2.1.3 with data previously reported shows that the size distribution of the mineral matter has shifted by a few tenths of a percent because of differences in the way the numbers are rounded. The biggest differences in quantities of the different types of mineral matter between the output of PARTCHAR and the old program are in the amounts of aluminosilicate material. PARTCHAR defines several new categories of aluminosilicate material and also tightens up definitions. The tightened definitions cause somewhat less mineral matter to be classified as a type of aluminosilicate, so they fall into the unknown category. Most of the unknowns tended to have higher concentrations (~20% each) of Al, Si, and S, with smaller levels of K, Ca and Fe. We believe that these types of particles are essentially small aluminosilicate particles that have high levels of interference due to nearby or intergrown pyrite particles or because of the organically associated S. The high levels of interference were caused by the small size of most of these particles which permitted x-rays to be emitted from a larger volume within the coal than the volume of the particle.

Comparisons between the data for the Illinois No. 6 parent and MFP fuels show that the MFP cleaning appears to preferentially remove aluminosilicates, and somewhat preferentially remove pyrite, leaving quartz and the dominant mineral type. However, the composition of the ASTM ash of the parent and MFP fuels shows that Si is preferentially reduced, indicating that quartz may be preferentially removed. These discrepancies indicate that instead of preferential removal, the continuation and slurrying (deaggregation) used in pyrite particles to less than one micron in diameter, so they were not picked up in the CCSEM analysis. This would leave quartz as the dominant mineral type in the 1 to 100-μm size range even though overall it was preferentially removed, thereby decreasing the Si content of the ASTM ash.

In contrast to the MFP process, CCSEM analysis indicates that the SOAP cleaning process appears to somewhat preferentially remove quartz and aluminosilicates from the Illinois No. 6 coal which causes a relative increase in the amount of pyrite. The higher iron and relatively small reduction in the pyritic S content of the SOAP as compared to the Illinois No. 6 parent indicate that the preferential reductions are real and not artifacts of size reduction of quartz and aluminosilicates.

TABLE 2.1.2

PARTCHAR SUMMARY OF THE CCSEM DATA FOR THE ILLINOIS NO. 6 PARENT COAL

Summary of Parameters

Total Mineral Area Analyzed at High Mag. = 5,367.8 μm^2
Normalized Area Analyzed at High Mag. = 149,035.2 μm^2
Total Mineral Area Analyzed at Low Mag. = 8,365.1 μm^2
Number of Frames at High Mag. = 14.0
Number of Frames at Low Mag. = 18.0
Total Number of Points Analyzed = 1,076.0
Number of Points under Threshold = 7.0

	Weight Percent on a Mineral Basis						
	1.0 - 2.2	2.2 - 4.6	4.6 - 10.0	10.0 - 22.0	22.0 - 46.0	46.0 - 100.0	TOTAL
Quartz	3.8	7.3	5.5	.5	.0	.0	17.1
Iron Oxide	.0	.7	.0	.0	.0	.0	.7
Periclase	.0	.0	.0	.0	.0	.0	.0
Rutile	.0	.0	.0	.0	.0	.0	.0
Alumina	.0	.0	.0	.0	.0	.0	.0
Calcite	.0	.0	.0	.0	.0	.0	.0
Dolomite	.0	.0	.0	.0	.0	.0	.0
Ankerite	.0	.0	.0	.0	.0	.0	.0
Kaolinite	1.6	5.5	5.8	.4	.2	.0	13.5
Montmorillonite	1.9	4.9	.8	.1	.0	.0	7.7
K-Al-Silicate	2.4	6.4	2.9	.5	1.0	.0	13.2
Fe-Al-Silicate	.1	.7	.0	.0	.0	.0	.7
Ca-Al-Silicate	.0	.2	1.3	.0	.0	.0	1.5
Na-Al-Silicate	.0	.0	.0	.0	.0	.0	.0
Aluminosilicate	.1	.3	.4	.1	.0	.0	.9
Mixed Al-Silica	.2	.4	.0	.1	.0	.0	.7
Fe-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Aluminate	.0	.0	.0	.0	.0	.0	.0
Pyrite	2.0	4.1	8.2	1.8	.0	.0	16.0
Pyrrhotite	1.7	.4	.0	.1	.0	.0	2.1
Oxidized Pyrrho	.0	.4	.0	.1	.0	.0	.5
Gypsum	.2	.3	.8	.3	.0	.0	1.5
Barite	.0	.0	.0	.0	.0	.0	.0
Apatite	.0	.0	.0	.0	.0	.0	.0
Ca-Al-P	.0	.0	.0	.0	.0	.0	.0
KCl	.0	.0	.0	.0	.0	.0	.0
Gypsum/Barite	.0	.0	.0	.0	.0	.0	.0
Gypsum/Al-Silic	.2	.2	.0	.0	.0	.0	.4
Si-Rich	.4	1.2	.0	.0	.0	.0	1.7
Ca-Rich	.0	.0	.0	.0	.0	.0	.0
Ca-Si-Rich	.0	.0	.0	.0	.0	.0	.0
Unknown	10.2	7.2	4.0	.5	.0	.0	21.9
TOTAL	24.8	39.9	29.6	4.5	1.3	.0	100.0

TABLE 2.1.3

PARTCHAR SUMMARY OF THE CCSEM DATA FOR THE ILLINOIS NO. 6 MFP FUEL

Summary of Parameters

Total Mineral Area Analyzed = 5,527.5 μm^2
Number of Frames (240x Only) = 27.0
Total Number of Points Analyzed = 1,016.0
Number of Points under threshold = 35.0

	Weight Percent on a Mineral Basis						
	1.0 - 2.2	2.2 - 4.6	4.6 - 10.0	10.0 - 22.0	22.0 - 46.0	46.0 - 100.0	TOTAL
Quartz	7.5	21.1	8.0	3.9	9.8	.0	50.4
Iron Oxide	.4	.6	.0	.0	.0	.0	1.0
Periclase	.0	.0	.0	.0	.0	.0	.0
Rutile	.0	.0	.0	.0	.0	.0	.0
Alumina	.2	.5	.6	.0	.0	.0	1.3
Calcite	.6	.1	.0	.0	.0	.0	.6
Dolomite	.7	.3	.0	.0	.0	.0	1.0
Ankerite	.0	.0	.0	.0	.0	.0	.0
Kaolinite	.4	2.0	.0	.0	.0	.0	2.5
Montmorillonite	.7	.8	.0	.0	.0	.0	1.5
K-Al-Silicate	.9	.6	.7	.0	.0	.0	2.1
Fe-Al-Silicate	.1	.0	.0	.0	.0	.0	.1
Ca-Al-Silicate	.2	.4	.0	.0	.0	.0	.6
Na-Al-Silicate	.0	.0	.0	.0	.0	.0	.0
Aluminosilicate	.1	.0	.0	.0	.0	.0	.1
Mixed Al-Silica	.1	.3	.0	.0	.0	.0	.4
Fe-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Aluminate	.0	.1	.0	.0	.0	.0	.1
Pyrite	6.7	6.6	5.4	.0	.0	.0	18.7
Pyrrhotite	.8	.0	.0	.0	.0	.0	.8
Oxidized Pyrrho	.5	.5	.0	.0	.0	.0	.9
Gypsum	.4	.4	1.1	.0	.0	.0	2.0
Barite	.0	.2	.0	.0	.0	.0	.2
Apatite	.0	.0	.0	.0	.0	.0	.0
Ca-Al-P	.0	.0	.0	.0	.0	.0	.0
KCl	.0	.0	.0	.0	.0	.0	.0
Gypsum/Barite	.0	.0	.0	.0	.0	.0	.0
Gypsum/Al-Silic	.3	.1	.0	.0	.0	.0	.4
Si-Rich	.5	.3	.3	.0	.0	.0	1.1
Ca-Rich	.1	.0	.0	.0	.0	.0	.1
Ca-Si-Rich	.0	.0	.0	.0	.0	.0	.0
Unknown	6.4	4.7	.9	2.2	.0	.0	14.2
TOTAL	27.5	39.5	17.1	6.1	9.8	.0	100.0

TABLE 2.1.4

PARTCHAR SUMMARY OF THE CCSEM DATA FOR THE ILLINOIS NO. 6 SOAP FUEL

Summary of Parameters

Total Mineral Area Analyzed at High Mag. = 7,499.7 μm^2
Normalized Area Analyzed at High Mag. = 323,908.7 μm^2
Total Mineral Area Analyzed at Low Mag. = 32,773.9 μm^2
Number of Frames at High Mag. = 8.0
Number of Frames at Low Mag. = 16.0
Total Number of Points Analyzed = 1,113.0
Number of Points under Threshold = 16.0

	Weight Percent on a Mineral Basis						
	1.0 - 2.2	2.2 - 4.6	4.6 - 10.0	10.0 - 22.0	22.0 - 46.0	46.0 - 100.0	TOTAL
Quartz	1.0	5.6	3.6	1.3	.3	1.5	13.2
Iron Oxide	.0	.7	1.5	.0	.0	.0	2.2
Periclase	.0	.0	.0	.0	.0	.0	.0
Rutile	.1	.0	.0	.0	.0	.0	.1
Alumina	.0	.0	.0	.0	.0	.0	.0
Calcite	.0	.2	.0	.1	.0	.0	.3
Dolomite	.0	.0	.0	.0	.0	.0	.0
Ankerite	.0	.0	.0	.0	.0	.0	.0
Kaolinite	.3	3.1	6.0	.6	.5	.0	10.5
Montmorillonite	.5	2.7	5.9	.2	.0	.0	9.3
K-Al-Silicate	.3	2.4	3.1	.6	.5	.0	6.9
Fe-Al-Silicate	.1	1.6	.7	.1	.0	.0	2.4
Ca-Al-Silicate	.0	.3	.0	.0	.0	.0	.3
Na-Al-Silicate	.0	.0	.0	.0	.0	.0	.0
Aluminosilicate	.2	.1	1.0	.1	.0	.0	1.5
Mixed Al-Silica	.2	1.0	.0	.0	.0	.0	1.2
Fe-Silicate	.0	.0	.3	.0	.0	.0	.3
Ca-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Aluminate	.0	.0	.0	.0	.0	.0	.0
Pyrite	3.6	16.9	5.1	1.3	.7	.0	27.7
Pyrrhotite	.1	.2	.4	.2	.0	.0	.9
Oxidized Pyrrho	.1	.9	.0	.0	.0	.0	1.0
Gypsum	.1	.6	1.1	.3	.0	.0	2.1
Barite	.0	.0	.0	.0	.0	.0	.0
Apatite	.0	.0	.0	.0	.0	.0	.0
Ca-Al-P	.0	.0	.0	.0	.0	.0	.0
KCl	.0	.0	.0	.0	.0	.0	.0
Gypsum/Barite	.0	.0	.0	.0	.0	.0	.0
Gypsum/Al-Silic	.3	.3	.0	.0	.0	.0	.6
Si-Rich	.5	.7	.5	.2	.0	.0	1.9
Ca-Rich	.1	.0	.0	.0	.0	.0	.1
Ca-Si-Rich	.0	.0	.0	.0	.0	.0	.0
Unknown	5.6	8.2	3.2	.3	.0	.0	17.3
TOTAL	13.2	45.7	32.3	5.3	2.0	1.5	100.0

Tables 2.1.5, 2.1.6, and 2.1.7 list the results of the CCSEM analyses of the Upper Freeport parent, MFP, and SOAP fuels. The overall size of the mineral grains was reduced by both cleaning processes. Both processes reduced the concentration of mineral grains larger than 4.6 μm in diameter. The MFP process increased the concentration of particles in the 1.0- to 4.6-μm range, whereas the SOAP process increased the concentration in only the 1.0- to 2.2-μm range. However, it is unknown by how much the concentrations of inorganic particles less than 1 μm in diameter were increased.

As seen in the Illinois No. 6 CCSEM data, apparent changes in the concentrations of minerals in the products are not supported by the changes in the composition of the ASTM ashes of the fuels. The discrepancies occur for several reasons. The first is that reduction in size of a mineral type to less than 1.0 μm in diameter makes it appear, in the CCSEM data, that the mineral was removed during the cleaning process. Such is the case for pyrite. Its concentration appears, from the CCSEM data, to have been dramatically reduced relative to the other minerals by the MFP process (sulfur forms data supports this observation), but the concentration of iron in the ash has not decreased relative to the other elements. The discrepancy may imply that the size of the pyrite particles was reduced to below 1.0 μm in diameter, probably through deagglomeration of framboidal pyrite (pyrite framboids are raspberry-like agglomerations of smaller pyrite particles that occur commonly in coal). A second reason that such discrepancies occur is that the data is presented on a percent of mineral matter basis so that preferential removal of one mineral type will cause the concentrations of other mineral types to increase. If only one mineral type is preferentially removed, the effect can usually be easily corrected for. However, such corrections are difficult for the Upper Freeport coal because of a third cause of the discrepancies. That is, the relatively large change in the amount of mineral matter falling into the unknown category in the parent coal. The unknowns in the parent are predominantly concentrated in the less than 10-μm range and usually exhibit high levels of S, with somewhat less Fe, Al, and Si. This mixture of elements implies masses of intergrown pyrite and clay. During cleaning, the purer minerals in these masses may have separated from each other to contribute to the concentrations of that mineral type in the cleaned fuel and reduce the level of unknowns, or they may have been preferentially removed during cleaning. In general, the reasons for the discrepancies between the changes in CCSEM data, elemental concentrations in the coal ash, and sulfur forms data are complex and so will be investigated further, and the results reported in a future report.

2.2 CE TEST RESULTS

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

TABLE 2.1.5

PARTCHAR SUMMARY OF THE CCSEM DATA FOR THE UPPER FREEPORT PARENT COAL

Summary of Parameters

Total Mineral Area Analyzed at High Mag. = 8,031.3 μm^2
Normalized Area Analyzed at High Mag. = 315,331.5 μm^2
Total Mineral Area Analyzed at Low Mag. = 67,219.0 μm^2
Number of Frames at High Mag. = 11.0
Number of Frames at Low Mag. = 20.0
Total Number of Points Analyzed = 1,210.0
Number of Points under Threshold = 27.0

	Weight Percent on a Mineral Basis						
	1.0 - 2.2	2.2 - 4.6	4.6 - 10.0	10.0 - 22.0	22.0 - 46.0	46.0 - 100.0	TOTAL
Quartz	.6	3.2	3.2	.4	.0	.0	7.5
Iron Oxide	.0	.2	.0	.2	.0	0	.4
Periclase	.0	.0	.0	.0	.0	.0	.0
Rutile	.1	.0	.0	.0	.0	.0	.1
Alumina	.0	.0	.0	.0	.0	.0	.0
Calcite	.0	.0	.0	.0	.0	.0	.0
Dolomite	.0	.0	.0	.0	.0	.0	.0
Ankerite	.0	.0	.0	.0	.0	.0	.0
Kaolinite	1.2	4.2	5.3	1.0	.1	.0	11.8
Montmorillonite	.5	1.9	.7	.3	.5	.0	3.9
K-Al-Silicate	1.0	3.5	6.9	1.2	.2	.0	12.7
Fe-Al-Silicate	.0	.2	.0	.0	.0	.0	.2
Ca-Al-Silicate	.3	.6	.2	.0	.0	.0	1.1
Na-Al-Silicate	.0	.0	.0	.0	.0	.0	.0
Aluminosilicate	.1	.3	.0	.0	.0	.0	.4
Mixed Al-Silica	.2	.2	.0	.0	.1	.0	.6
Fe-Silicate	.0	.0	.0	.1	.0	.0	.1
Ca-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Aluminate	.0	.0	.0	.0	.0	.0	.0
Pyrite	2.2	8.0	7.8	6.5	3.2	.0	27.7
Pyrrhotite	.0	.1	.0	.0	.0	.0	.2
Oxidized Pyrrho	.0	.1	.0	.0	.0	.0	.1
Gypsum	.1	.3	1.0	.5	1.1	2.0	4.9
Barite	.0	.0	.0	.0	.0	.0	.0
Apatite	.0	.0	.0	.0	.0	.0	.0
Ca-Al-P	.0	.0	.0	.0	.0	.0	.0
KCl	.0	.0	.0	.0	.0	.0	.0
Gypsum/Barite	.0	.0	.0	.0	.0	.0	.0
Gypsum/Al-Silic	.0	.1	.0	.1	.0	.0	.2
Si-Rich	.2	.6	.4	.0	.2	.0	1.4
Ca-Rich	.0	.0	.0	.0	.0	.0	.0
Ca-Si-Rich	.0	.1	.0	.0	.0	.0	.1
Unknown	3.9	11.7	8.9	1.2	1.0	.0	26.7
TOTAL	10.4	35.2	34.6	11.5	6.3	2.0	100.0

TABLE 2.1.6

PARTCHAR SUMMARY OF THE CCSEM DATA FOR THE UPPER FREEPORT MFP FUEL

Summary of Parameters

Total Mineral Area Analyzed at High mag. = 6,566.1 μm^2
Normalized Area Analyzed at High Mag. = 232,025.2 μm^2
Total Mineral Area Analyzed at Low Mag. = 32,169.4 μm^2
Number of Frames at High Mag. = 11.0
Number of Frames at Low Mag. = 18.0
Total Number of Points Analyzed = 1221.0
Number of Points under Threshold = 3.0

	Weight Percent on a Mineral Basis						
	1.0 - 2.2	2.2 - 4.6	4.6 - 10.0	10.0 - 22.0	22.0 - 46.0	46.0 - 100.0	TOTAL
Quartz	1.7	5.9	4.5	3.0	.4	.0	15.4
Iron Oxide	.1	.2	1.5	.0	.0	.0	1.7
Periclase	.0	.0	.0	.0	.0	.0	.0
Rutile	.1	.1	.0	.0	.0	.0	.2
Alumina	.1	.0	.0	.1	.0	.0	.2
Calcite	.1	.2	.0	.0	.0	.0	.2
Dolomite	.0	.0	.0	.0	.0	.0	.0
Ankerite	.0	.0	.0	.0	.0	.0	.0
Kaolinite	1.8	8.5	4.7	.2	.2	.0	15.4
Montmorillonite	1.4	6.0	2.5	.1	.0	.0	10.1
K-Al-Silicate	2.4	8.5	3.5	.3	.4	.0	15.2
Fe-Al-Silicate	1.3	4.2	1.6	.2	.0	.0	7.3
Ca-Al-Silicate	.0	.4	.0	.0	.0	.0	.4
Na-Al-Silicate	.0	.1	.0	.0	.0	.0	.1
Aluminosilicate	.1	.1	.2	.0	.0	.0	.5
Mixed Al-Silica	.9	1.8	.3	.1	.0	.0	3.1
Fe-Silicate	.1	.1	.0	.0	.0	.0	.2
Ca-Silicate	.0	.1	.0	.0	.0	.0	.2
Ca-Aluminate	.0	.0	.0	.0	.0	.0	.0
Pyrite	1.9	1.6	.5	.1	.0	.0	4.1
Pyrrhotite	.3	.2	.0	.0	.0	.0	.4
Oxidized Pyrrho	.0	.1	.0	.0	.0	.0	.1
Gypsum	.1	1.2	2.7	1.6	1.4	3.2	10.2
Barite	.0	.0	.0	.0	.0	.0	.0
Apatite	.0	.0	.0	.0	.0	.0	.0
Ca-Al-P	.0	.0	.0	.0	.0	.0	.0
KCl	.0	.0	.0	.0	.0	.0	.0
Gypsum/Barite	.0	.0	.0	.0	.0	.0	.0
Gypsum/Al-Silic	.2	.1	.3	.0	.0	.0	.6
Si-Rich	.4	1.2	.2	.1	.0	.0	2.0
Ca-Rich	.0	.0	.0	.0	.0	.0	.0
Ca-Si-Rich	.0	.0	.0	.0	.0	.0	.0
Unknown	5.5	5.0	1.7	.3	.0	.0	12.4
TOTAL	18.6	45.7	24.2	6.0	2.4	3.2	100.0

TABLE 2.1.7

PARTCHAR SUMMARY OF THE CCSEM DATA FOR THE UPPER FREEPORT SOAP FUEL

Summary of Parameters

Total Mineral Area Analyzed at High Mag. = 3,872.4 μm^2
Normalized Area Analyzed at High Mag. = 445,993.7 μm^2
Total Mineral Area Analyzed at Low Mag. = 31,539.3 μm^2
Number of Frames at High Mag. = 3.0
Number of Frames at Low Mag. = 16.0
Total Number of Points Analyzed = 1,127.0
Number of Points under Threshold = 0.0

	Weight Percent on a Mineral Basis						
	1.0 - 2.2	2.2 - 4.6	4.6 - 10.0	10.0 - 22.0	22.0 - 46.0	46.0 - 100.0	TOTAL
Quartz	2.9	5.5	3.3	.2	1.2	.0	13.2
Iron Oxide	.0	.0	.0	.0	.0	.0	.0
Periclase	.0	.0	.0	.0	.0	.0	.0
Rutile	.0	.0	.0	.0	.0	.0	.0
Alumina	.0	.0	.0	.0	.1	.0	.1
Calcite	.1	.0	.0	.0	.0	.0	.1
Dolomite	.0	.0	.0	.0	.0	.0	.0
Ankerite	.0	.0	.0	.0	.0	.0	.0
Kaolinite	1.3	3.3	.0	.0	.1	.0	4.8
Montmorillonite	1.9	1.9	.9	.2	.0	.0	5.0
K-Al-Silicate	5.4	5.9	.0	.3	.2	.0	11.8
Fe-Al-Silicate	2.0	3.0	.0	.0	.0	.0	5.0
Ca-Al-Silicate	.1	.1	.0	.0	.0	.0	.2
Na-Al-Silicate	.0	.0	.0	.0	.0	.0	.0
Aluminosilicate	.3	1.2	.0	.0	.0	.0	1.5
Mixed Al-Silica	.6	.6	.4	.0	.0	.0	1.6
Fe-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Silicate	.0	.0	.0	.0	.0	.0	.0
Ca-Aluminate	.0	.0	.0	.0	.0	.0	.0
Pyrite	21.2	13.8	11.7	.8	.7	.0	48.2
Pyrrhotite	.0	.0	.0	.0	.0	.0	.0
Oxidized Pyrrho	.1	.0	.0	.0	.0	.0	.1
Gypsum	.2	.2	.5	.1	.1	.0	1.0
Barite	.0	.0	.0	.0	.0	.0	.0
Apatite	.1	.0	.0	.0	.0	.0	.1
Ca-Al-P	.0	.0	.0	.0	.0	.0	.0
KCl	.0	.0	.0	.0	.0	.0	.0
Gypsum/Barite	.0	.0	.0	.0	.0	.0	.0
Gypsum/Al-Silic	.1	.3	.0	.0	.0	.0	.4
Si-Rich	.4	.7	.0	.1	.4	.9	2.4
Ca-Rich	.0	.0	.0	.0	.0	.0	.0
Ca-Si-Rich	.0	.0	.0	.0	.0	.0	.0
Unknown	2.6	1.5	.0	.2	.2	.0	4.5
TOTAL	39.4	38.0	16.8	2.1	2.9	.9	100.0

areas of chars produced in the DTFS-1. All the data have been reduced and are reported herein. Work on CE's DTFS-1 combustion testing continued. All three MFPs have been combusted in the DTFS-1 and the data are being reduced to determine their combustion kinetic parameters. Results are illustrated here with the Upper Freeport microbubble flotation product.

The chemical analyses of the test fuels are given in Tables 2.2.1 and 2.2.2 (the SOAP feed coal data are from Huettenhain and Schaal, 1990). The microbubble flotation process (MFP) and spherical oil agglomeration process (SOAP) performed on Illinois #6, Pittsburgh #8, and Upper Freeport coals have the following characteristics: ash contents reduced by more than 50%; pyritic sulfur contents reduced by more than 80%; calorific values increased by more than 4%. However, these two coal cleaning processes did not appear to materially improve the qualities of the BCF ashes, due perhaps to selective removal of certain mineral species (e.g., silicates) and enrichment of others (e.g., alkali metals and alkaline earths).

Ignitibility Characteristics of Test Fuels

The Flammability Index (FI) was used as a measure of the ignitibility characteristic of each test fuel. This test entails feeding 0.2 gram of sized fuel in an oxygen atmosphere heated until the fuel ignites. Two fuel sizes were tested: 200x0 mesh, standard for pulverized coal, and 325x0 mesh, more representative of the finer BCFs. Results are presented below:

Fuel	Flammability Index °F (200x0mesh)	(325x0mesh)
Upper Freeport mvb Coal	1060	1060
Upper Freeport MFP	850	840
Upper Freeport SOAP	895	865
Pittsburgh #8 hvAb Coal	940	920
Pittsburgh #8 MFP	850	850
Pittsburgh #8 SOAP	910	805
Illinois #6 hvCb Coal	950	950
Illinois #6 MFP	850	840
Illinois #6 SOAP	850	840

Comparatively, the FI results in the CE data bank show 800-950°F for lignites, 900-1050°F for subbituminous coals, 1050-1250°F for bituminous coals and $1450\text{-}1700^{+}$ °F for anthracites. These results indicate that each of

TABLE 2.2.1

ASTM STANDARD ANALYSES OF FEED COALS AND THEIR MFPs*

	ILLINOIS #6 hvCb		PITTSBURGH #8 hvAb		UPPER FREEPORT mvb	
QUANTITY	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 2.2.2

ASTM STANDARD ANALYSES OF FEED COALS AND THEIR SOAPs*

	ILLINOIS #6 hvCb		PITTSBURGH #8 hvAb		UPPER FREEPORT mvb	
QUANTITY	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

---

* All analyses are reported on dry basis

SOAP = Spherical Oil Agglomeration Product the feed coals and BCFs has good ignitibility characteristics and should not cause ignitibility/flame turndown problems under normal pulverized-fuel firing conditions.

Weak Acid Leaching (WAL)

This test is designed to determine the concentrations of alkali metals in an ash sample, which are leachable by a weak acid. Results are indicative of volatilizable alkali metals, which are known to initiate ash fouling phenomenon. Results obtained from this study are as follows:

Fuel	Alkali Metals in Ash, Wt.%				Volatilizable	
	ASTM Method		WAL Method		Alkali Metals, Wt.%	
	(Na_2O)	(K_2O)	(Na_2O)	(K_2O)	(Na_2O)	(K_2O)
U.F. mvb	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
Pitts. #8 hvAb	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
Ill. #6 hvCb	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

These results show enrichments of alkali metals in the BCF products, compared with their respective coal feed stocks. Thus they support the conclusion that the microbubble flotation and spherical oil agglomeration coal cleaning processes do not improve the fouling qualities of the subject BCF ash samples. The BCF ash fouling may, however, be tempered by the fact that these BCFs have much lower ash contents than their feed stock counterparts.

TGA Reactivities and Physical Characteristics of Test Fuel Chars

The TGA results from this study are summarized in Figures 2.2.1, 2.2.2 and 2.2.3 and the BET data are shown below:

DOE Fuels	BET Surface Area of Char, $m^2/g(daf)$	
	(200x400 mesh)	(325x0 mesh)
Upper Freeport Coal	23.6	28.8
Upper Freeport MFP	17.8	32.1
Upper Freeport SOAP	35.4	55.0
Pittsburgh #8 Coal	44.8	49.8
Pittsburgh #8 MFP	37.4	60.0
Pittsburgh #8 SOAP	31.8	52.2
Illinois #6 Coal	33.1	32.5
Illinois #6 MFP	31.0	39.4
Illinois #6 SOAP	42.0	55.0

The TGA burn-off curves indicate that: (1) the microbubble flotation and spherical oil agglomeration coal cleaning processes did not adversely affect the reactivities compared to the parent coal chars; (2) the impact of particle size on reactivity is more pronounced for the least reactive coal char (i.e., the one prepared from the Upper Freeport coal); and (3) all the chars studied to date are considered to have good combustion reactivities. The BET specific pore surface areas given above are generally in support of the TGA burn-off curve results.

In summary, the microbubble flotation and spherical oil agglomeration cleaning processes led to significant reductions in ash and pyritic contents and increases in calorific values of Illinois #6, Pittsburgh #8 and Upper Freeport coals. However, these processes did not appear to materially improve the qualities of the BCF ashes, due perhaps to selective removal of certain mineral species and enrichment of others. Neither cleaning process appears to have adversely affected the ignitibility/flame turndown and reactivity characteristics of the beneficiated coal-based products studied to-date.

Combustion Kinetic Parameters of Upper Freeport MFP Char

The effects of temperature and time on the combustion efficiency of the Upper Freeport MFP char in the DTFS-1 (Figure 2.2.4) in the 1900-2650 ^{O}F temperature range and time ranging up to approximately 0.8 sec. are

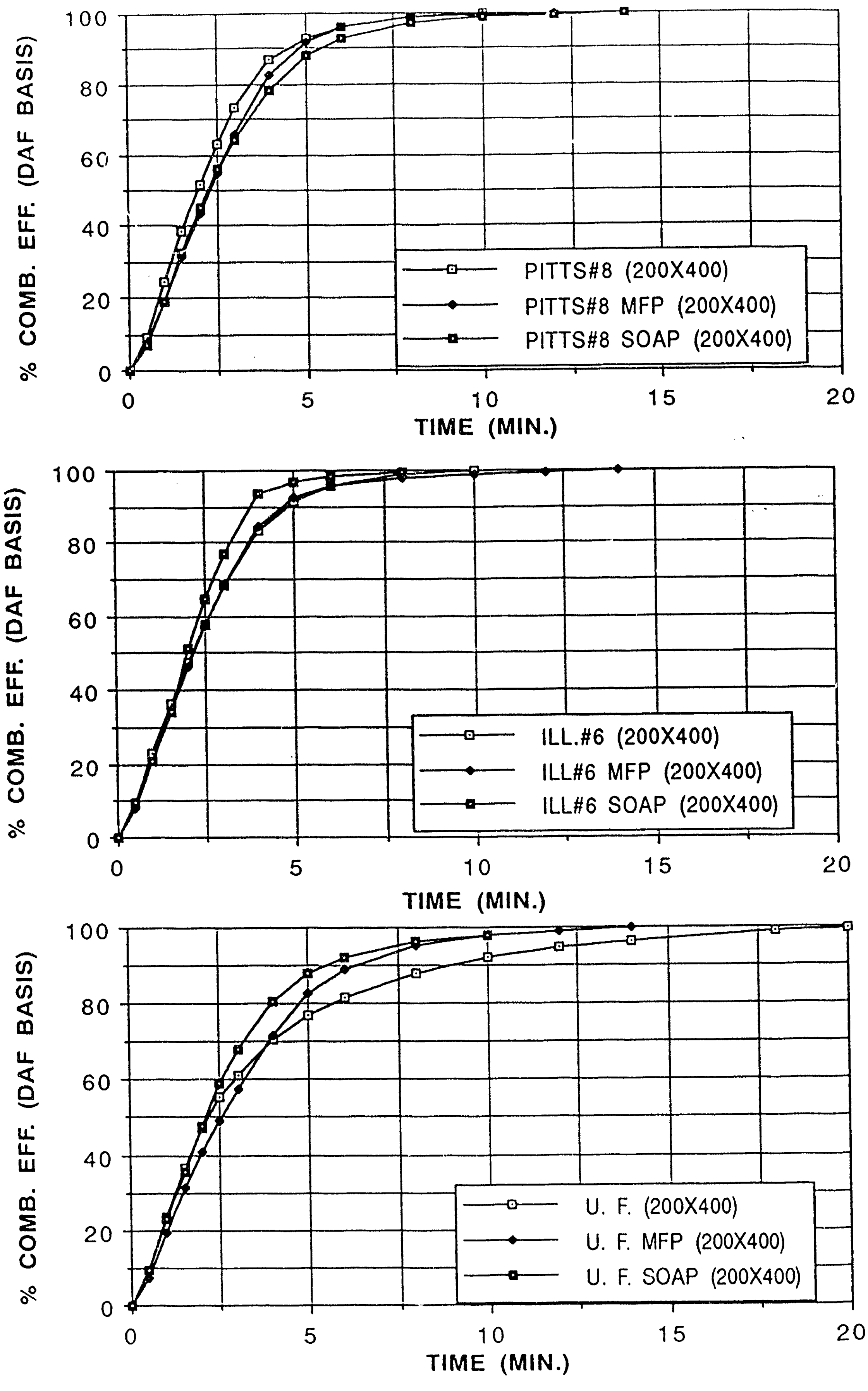


FIGURE 2.2.1 TGA BURN-OFF CURVES IN AIR AT 700 °C

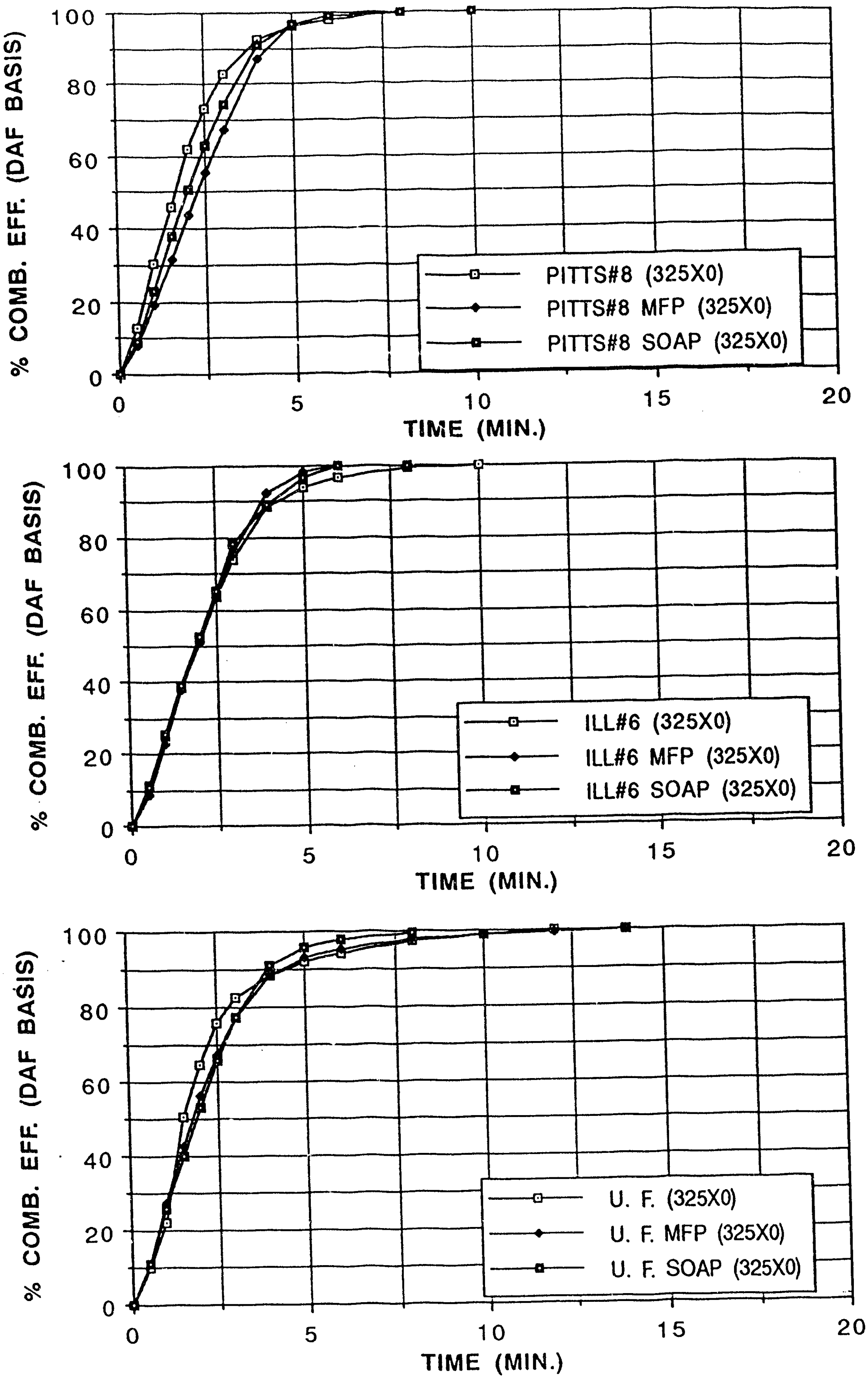


FIGURE 2.2.2 TGA BURN-OFF CURVES IN AIR AT 700 °C

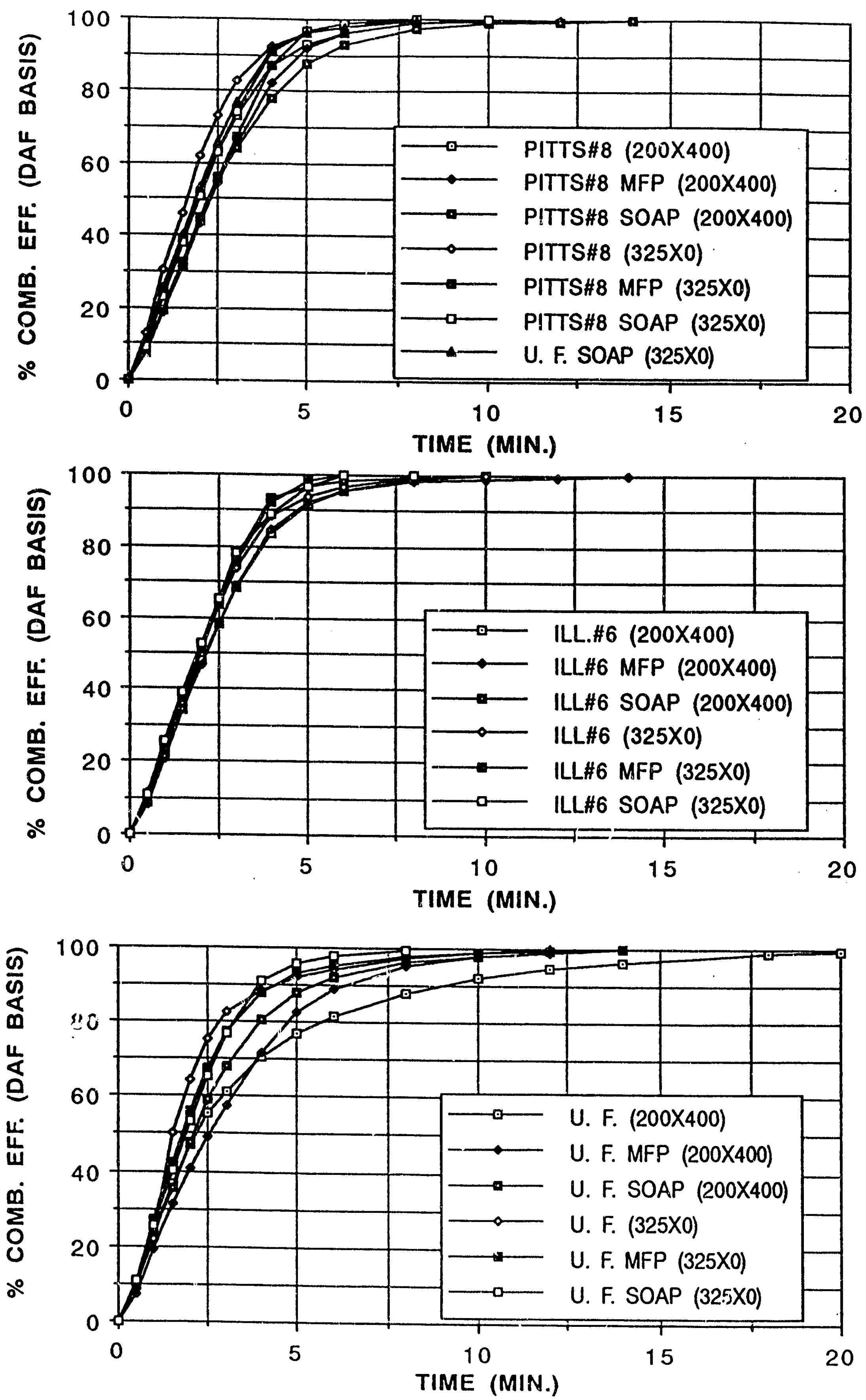


FIGURE 2.2.3 TGA BURN-OFF CURVES IN AIR AT 700 °C

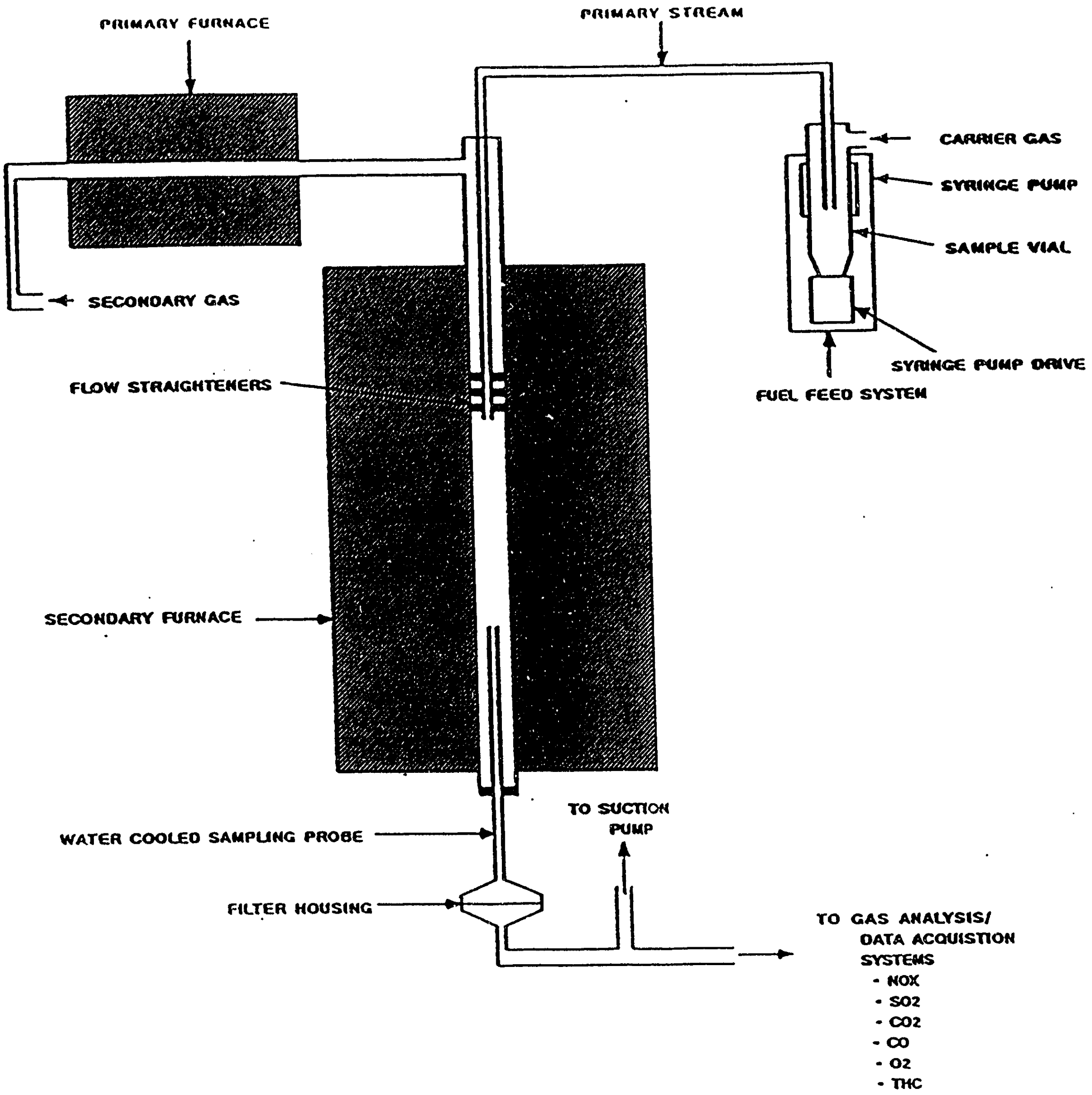


FIGURE 2.2.4

Schematic of Combustion engineering's
Drop Tube Furnace System-1 (DTFS-1)

depicted in Figure 2.2.5a. These results clearly show two important things: (1) both temperature and time play a major role in char combustion efficiency; and (2) DTFS-1 data reproductibility is quite good (compare T1 with T1R and T4 with T4R cases).

The combustion efficiency maps given in Figure 2.2.5a were used to derive the Arrhenius plot shown in Figure 2.2.5b. A least squares fit of the data in Figure 2.2.5b was used to derive the apparent activation energy (E) and frequency factor (A) from the slope and intercept, respectively, of the ln K_s vs. 1/T (where K_s is the surface reaction rate coefficient and T is the temperature) plot. Two methods were used in this calculation. One used the bulk gas temperatures and the other used calculated particle temperatures (Table 2.2.3).

The E and A values obtained from this statistical analysis were fairly insensitive to the calculation method used, due to the fact that the particle temperatures were only slightly higher than the bulk gas temperatures. These values are comparable to those found in the CE Data bank and in the open literature.

Analysis of the samples collected from the MIT drop tube furnace was performed using the computer-controlled scanning electron microscopy technique. The data generated from this analysis is being processed.

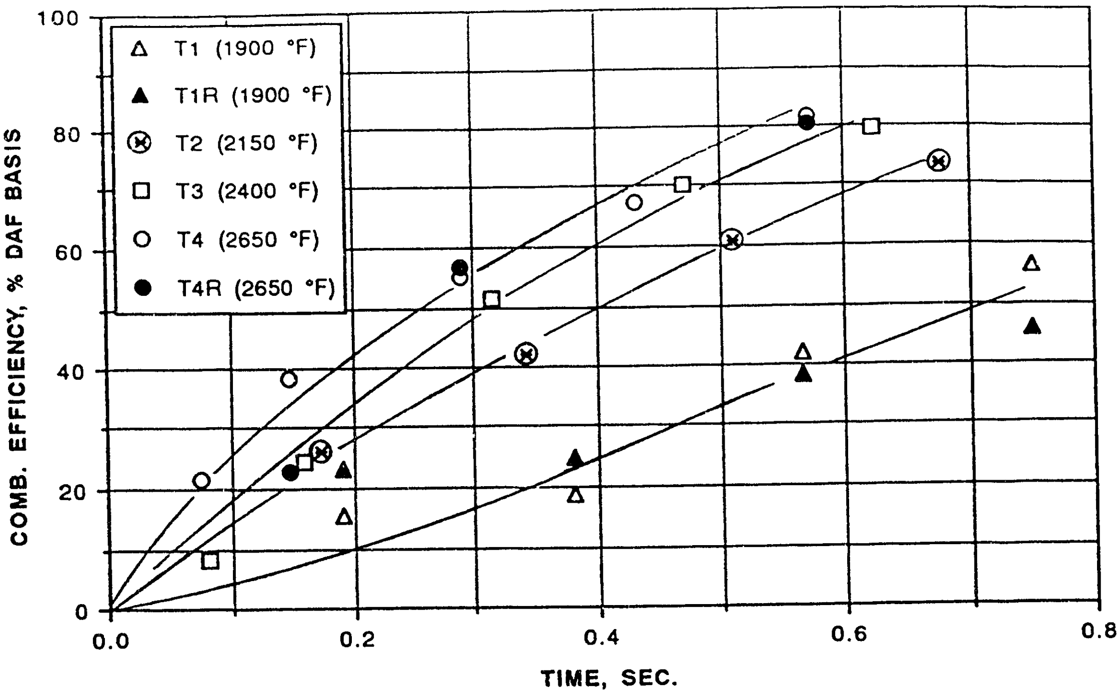


FIGURE 2.2.5a **DTFS COMBUSTION EFFICIENCY PLOTS OF 325X0 MESH UPPER FREEPORT MICROBUBBLE PRODUCT CHAR**

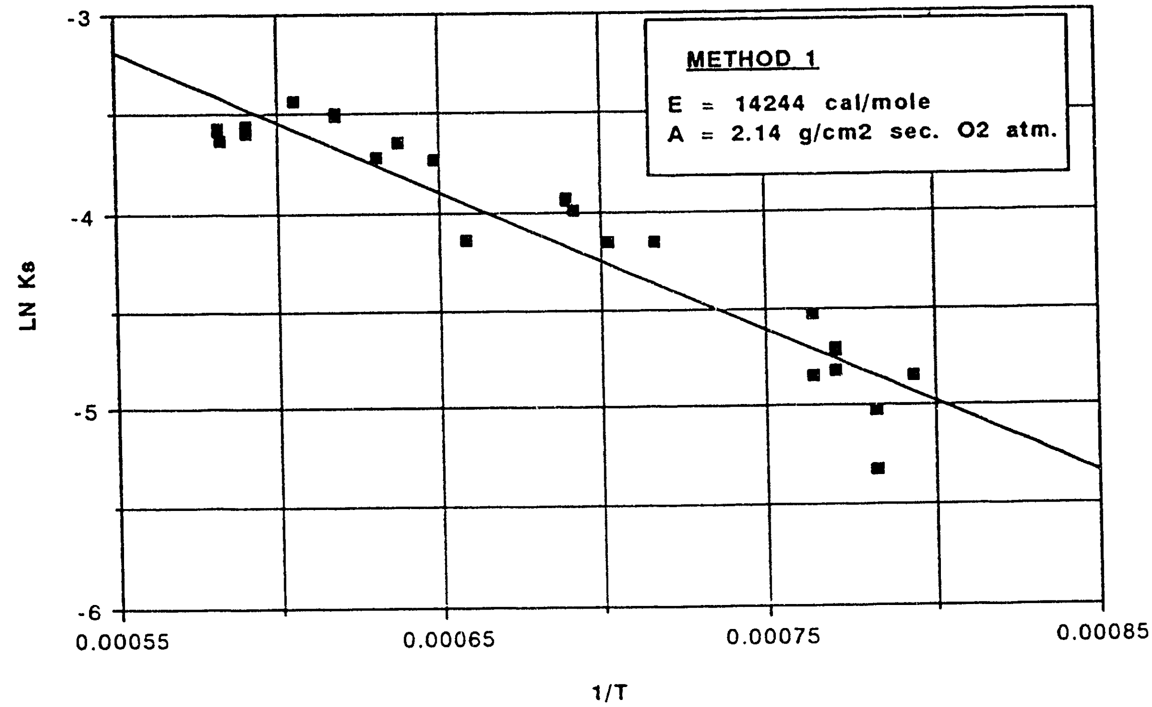


FIGURE 2.2.5b **ARRHENIUS PLOTS FOR 325X0 MESH UPPER FREEPORT MICROBUBBLE PRODUCT CHAR COMBUSTION IN THE DTFS**

TABLE 2.2.3

KINETIC DATA FROM COMBUSTION OF 325X0 MESH UPPER FREEPORT MICROBUBBLE BENEFICIATED PRODUCT (U. F. MFP) CHAR IN 0.03 OXYGEN ATMOSPHERE AND 1250-1750 DEG. K TEMPERATURE RANGE

U. F. MFP			
METHOD 1		METHOD 2	
TEMPERATURE	KS	TEMPERATURE	KS
1261	0.0079	1276	0.0079
1278	0.0049	1292	0.0049
1299	0.0090	1313	0.0090
1310	0.0108	1322	0.0109
1278	0.0066	1293	0.0066
1299	0.0082	1312	0.0082
1310	0.0079	1321	0.0079
1396	0.0156	1418	0.0157
1424	0.0157	1445	0.0158
1446	0.0185	1465	0.0187
1451	0.0194	1469	0.0198
1518	0.0158	1540	0.0158
1541	0.0240	1564	0.0243
1568	0.0261	1589	0.0267
1584	0.0243	1601	0.0249
1619	0.0303	1648	0.0305
1652	0.0323	1684	0.0327
1694	0.0276	1723	0.0281
1716	0.0267	1740	0.0272
1720	0.0277	1740	0.0285
1694	0.0288	1724	0.0293
1720	0.0283	1739	0.0291

Kinetic Parameters	Kinetic Parameters
E = 14245	E = 14415
A = 2.14	A = 2.15
R = -0.948	R = -0.951

Method 1 - Using Measured Bulk Gas Temperature (Tg)
Method 2 - Using Calculated Particle Surface Temperature (Tp)
E = Activation Energy, cal/mole
A = Frequency Factor, g/cm2-sec. O2 atm.
R = Correlation Coefficient of ln Ks vs. 1/T Plot
Temperature = deg. K

TASK 3 - PILOT SCALE TESTING

Combustion experiments are conducted with selected fuels in MIT's Combustion Research Facility (CRF) to characterize the effects of fuel type, beneficiation process, and firing mode upon flame stability, carbon conversion, and gaseous emissions. Combustion tests are also run in CE's Fireside Performance Tests Facility (FPTF) with most of the base project fuels, to evaluate combustion performance, furnace wall slagging, convection pass fouling, fly ash erosion, electrostatic precipitator performance, and emissions.

3.1 MIT COMBUSTION TEST RESULTS

Analysis and reduction of the data from the three combustion tests listed below on the raw Upper Freeport coal in the pilot-scale furnace was performed during this quarter:

Case 1	Base flame with 222°C air preheat & 3.5% oxygen in flue
Case 2	Flame with 215C air preheat and 2.5% oxygen in flue
Case 3	Internally staged low NOx flame with 209°C air preheat and 4.5% oxygen in the flue

The solids samples from the pilot-scale combustion tests were removed from the filter sampling apparatus, dried, and weighed for solids flux and solids concentration. The Malvern Particle Sizer was then used to measure the particle size of the samples from all three cases. This data is included as Figures 3.1.1, 3.1.2, and 3.1.3. The data for each sample are presented as a bar, with the bottom point representing the size where 10 percent of the sample volume is smaller than that size. The top of the bar represents the size where 90 percent of the sample volume is smaller and the point in the center is the mean size based on volume. For Case 1, Figure 3.1.1 shows the progression of the particle size found in the solids samples. Typically, as a pulverized coal burns out, the particle size initially increases as the smaller particles are consumed faster than the larger particles. Then, as all the carbon particles are completely reacted, the solids sample size decreases to the final fly ash size.

The solids samples collected along the axis of the three investigated flames were also analyzed for carbon burnout. The results obtained are shown in Figure 3.1.4. Temperature, oxygen, and NOx concentration data collected for the same flames are shown in Figure 3.1.5, 3.1.6, and 3.1.7.

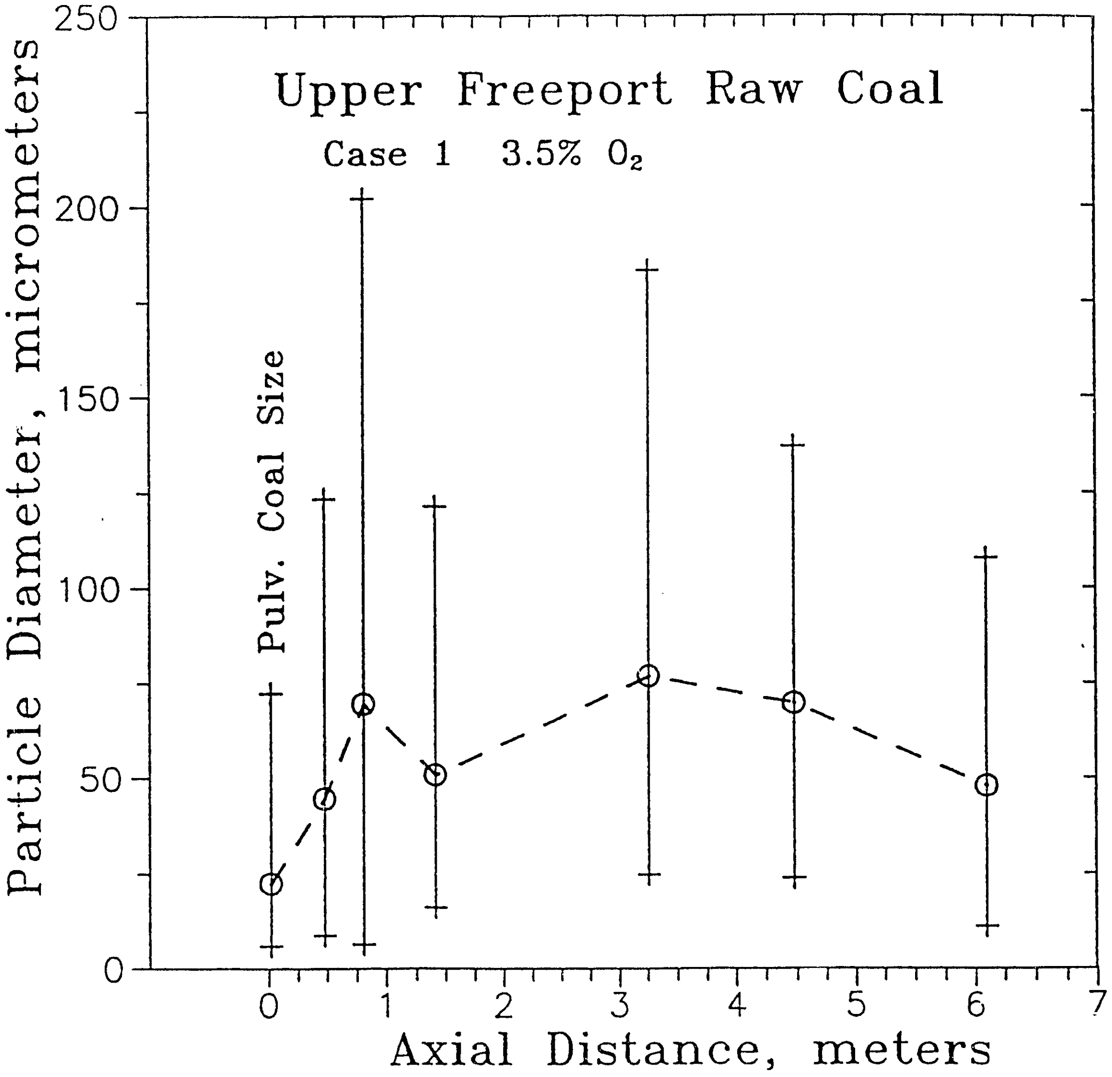


FIGURE 3.1.1
PARTICLE SIZE DISTRIBUTION OF SOLIDS SAMPLES COLLECTED
ALONG THE FLAME FOR CASE 1

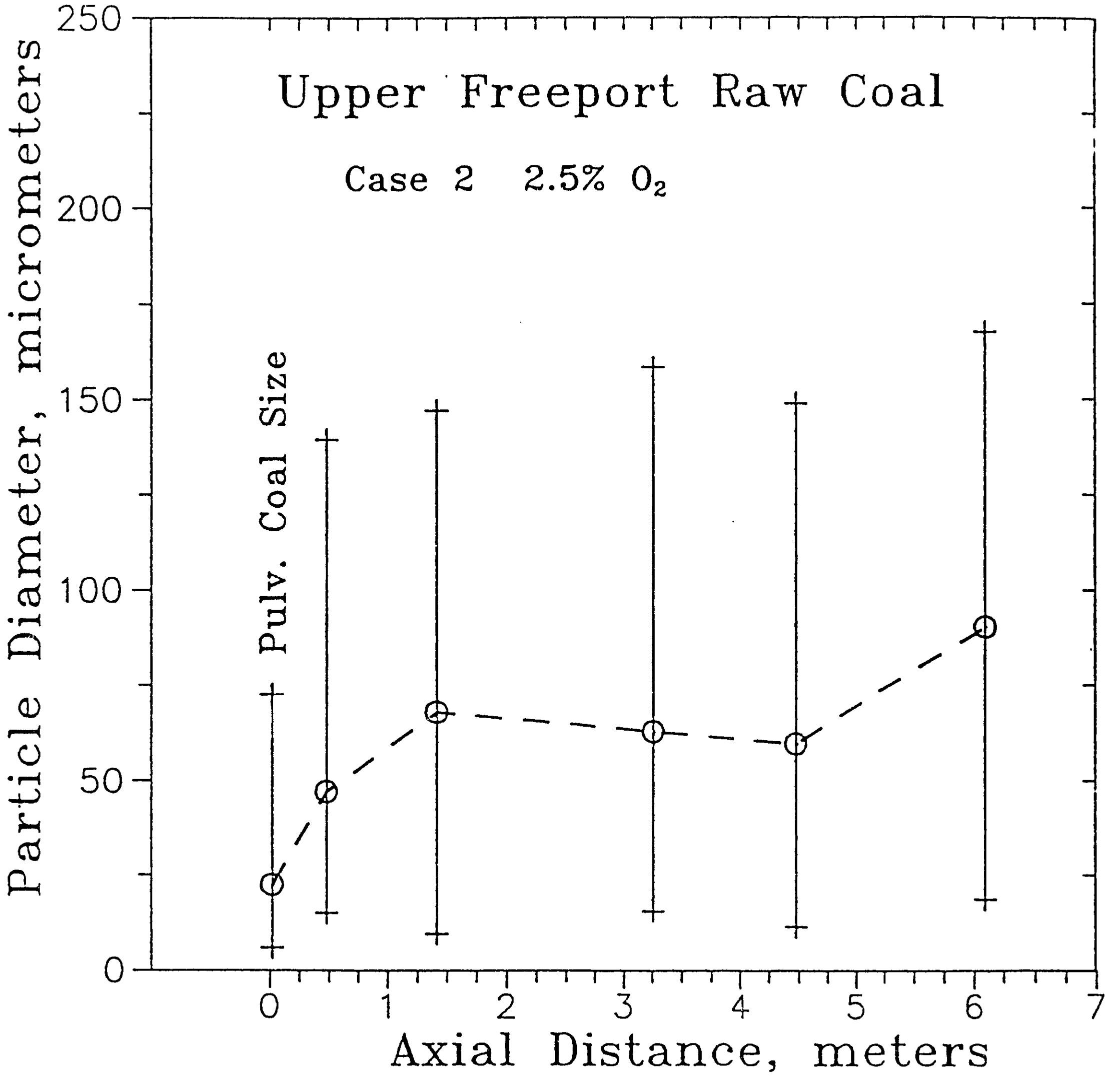


FIGURE 3.1.2

PARTICLE SIZE DISTRIBUTION OF SOLIDS SAMPLES COLLECTED ALONG THE FLAME FOR CASE 2

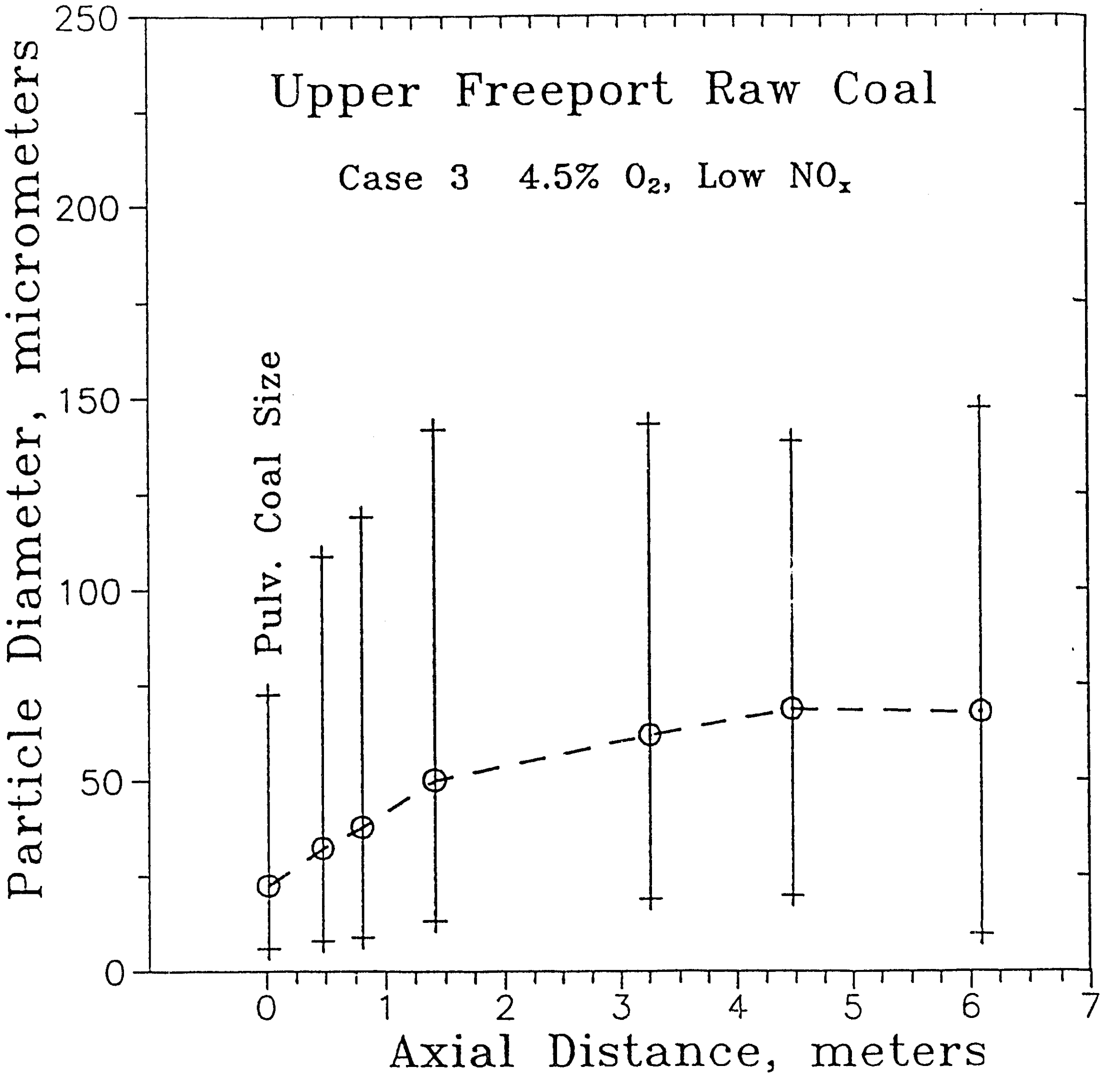


FIGURE 3.1.3

PARTICLE SIZE DISTRIBUTION OF SOLIDS SAMPLES

COLLECTED ALONG THE FLAME FOR CASE 3

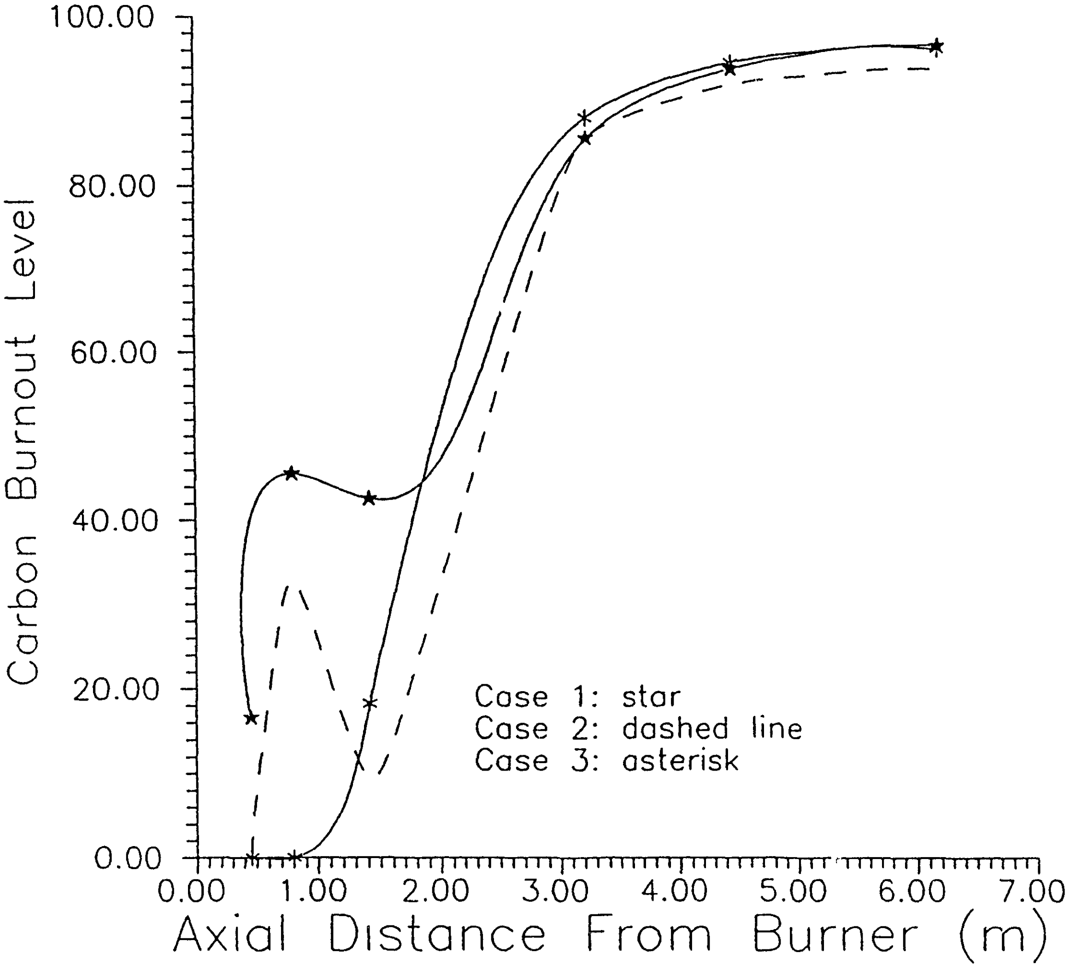


FIGURE 3.1.4

CARBON BURNOUT LEVELS ALONG THE FLAME AXIS

FOR CASES 1, 2, AND 3

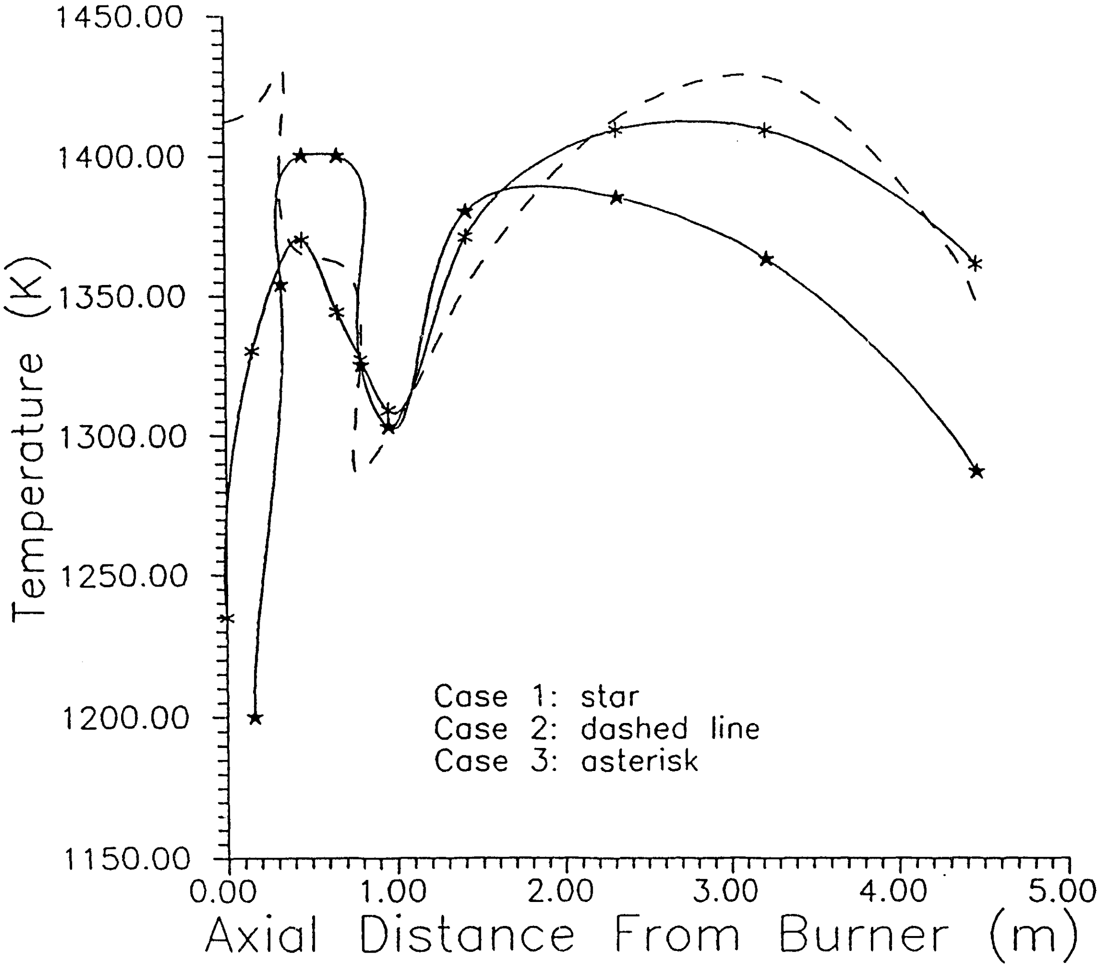


FIGURE 3.1.5

AXIAL TEMPERATURE PROFILES

FOR CASES 1, 2, AND 3

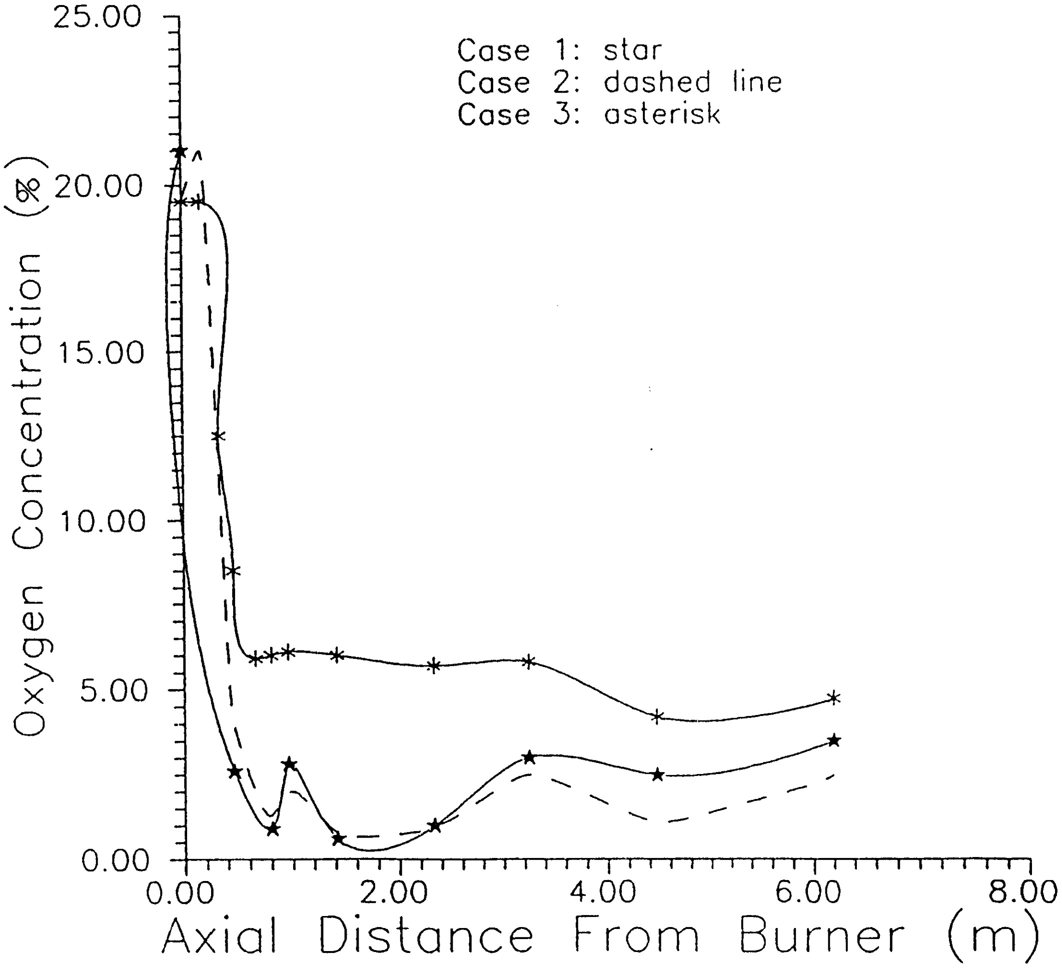


FIGURE 3.1.6

OXYGEN CONCENTRATION ALONG THE FLAME AXIS

FOR CASES 1, 2, AND 3

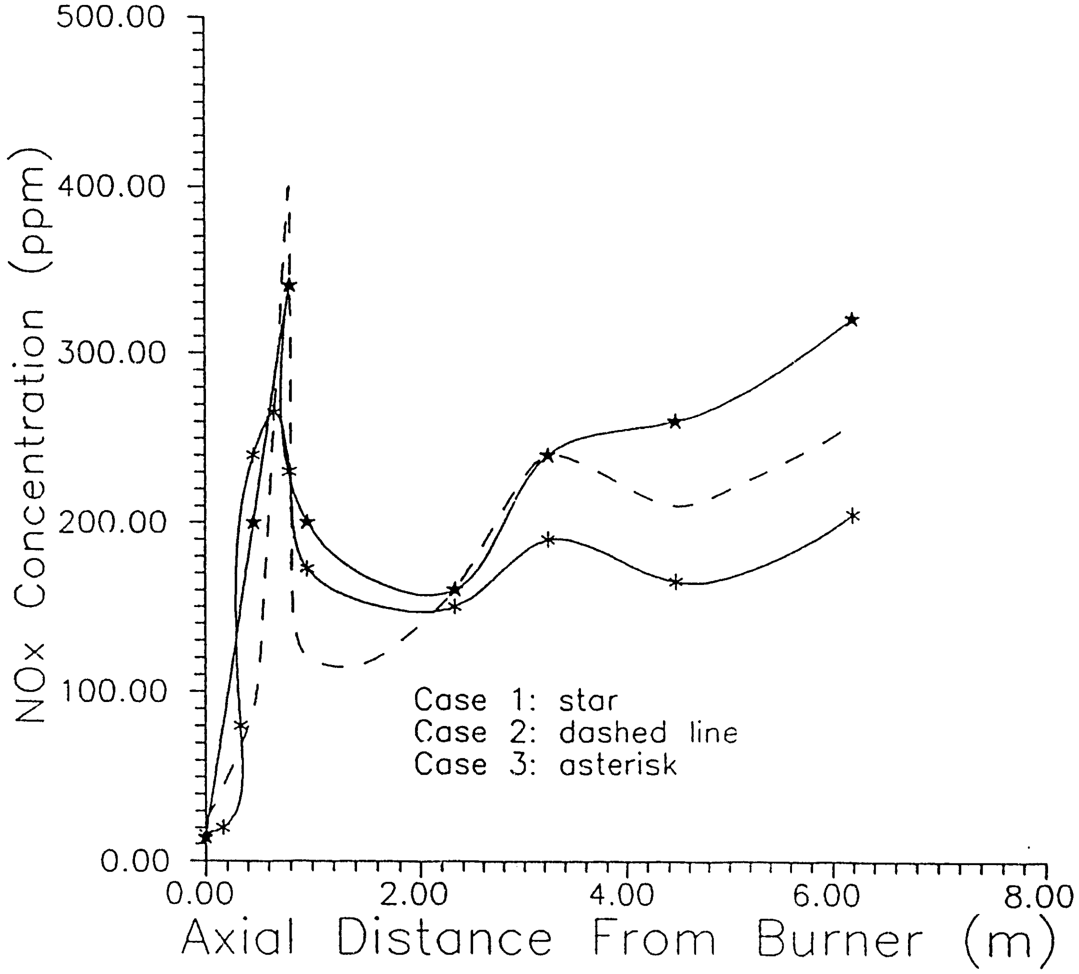


FIGURE 3.1.7

NOx CONCENTRATION ALONG THE FLAME AXIS

FOR CASES 1, 2, AND 3

The measurements of the carbon burnout levels, temperature, and gas composition illustrate that the rate of consumption of oxygen in Cases 1 & 2 is faster than that of Case 3 (internally staged low NOx flame). Therefore, the carbon burnout levels measured close to the burner for those two cases are higher than for Case 3. However, at larger distances, the burnout achieved in Case 3 is similar to that of Case 1. Moreover, NOx concentrations measured for that case are for the most part lower than the other two cases. These results indicate that with proper burner adjustments, it is possible to achieve high carbon burnout levels as well as low NOx emissions.

3.2 COMBUSTION PERFORMANCE TESTS - CE

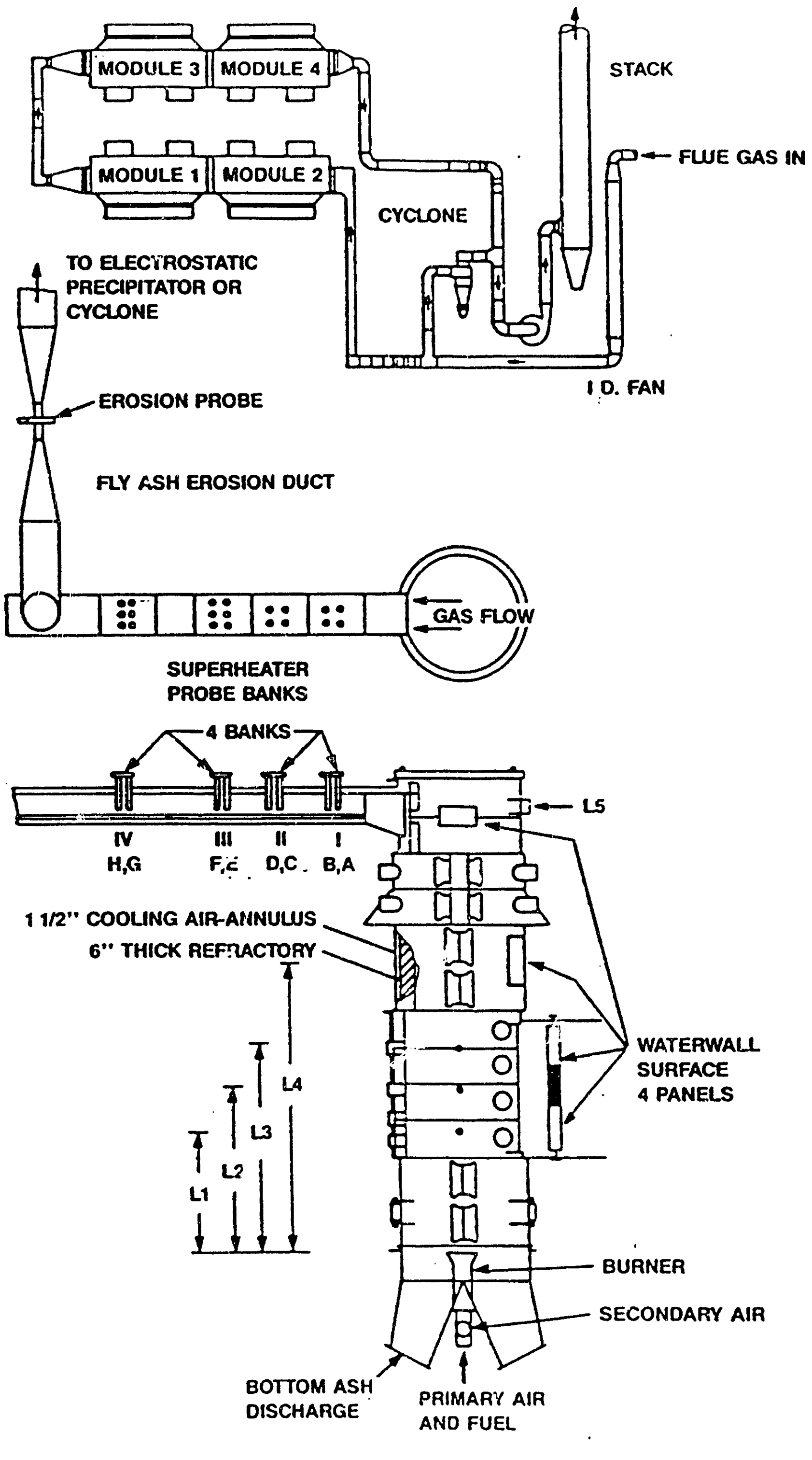
Analysis and data reduction from the nine fuel tests to date in the Fireside Performance Test Facility (FPTF) continued during this period. Waterwall deposit samples collected from these fuels were prepared for radiative properties measurements. The initial and outer layers of the waterwall deposits will be evaluated. The total normal emissivity and absorptivity will be determined at wavelengths of 1.5 to 10 microns and at three different surface temperatures. This data will provide necessary input to the computer model for commercial performance prediction.

The FPTF combustion performance results for the nine test fuels are summarized below. A schematic of the FPTF test facility is shown in Figure 3.2.1.

Relative Handling Characteristics

Since the as-received BCF products had very high moisture content, air drying was required to facilitate handling. The Upper Freeport MFP was then formulated into a microfine coal-water fuel. The remainder of the BCFs were further dried into a dry microfine pulverized coal form using a CE size 271 bowl mill. The parent coals were prepared as standard grind pulverized coals (70% through 200 mesh). The chemical analyses of the as-fired test fuels are shown in Table 3.2.1.

In general, the BCFs were successfully fed through the FPTF pulverizer system without compaction or pasting inside the bowl mill. However, the BCFs, in particular the three SOAPs, exhibited some unusual handling characteristics which were not observed with the parent coals and other fuels previously tested in the FPTF. The SOAPs have a high tendency of adhering to the surfaces of the transition chute and feed line wall. The peculiar behavior of these fuels would indicate a potential for plugging problems in commercial coal handling systems.



FIRESIDE PERFORMANCE TEST FURNACE

FIGURE 3.2.1

TABLE 3.2.1

ANALYSES OF AS-FIRED FUELS FOR FPTF COMBUSTION PERFORMANCE TESTS

	ILLINOIS NO. 6			UPPER FREEPORT			PITTSBURGH NO. 8		
QUANTITY	PARENT	MFP DMPC	SOAP DMPC	PARENT	MFP MCWF	SOAP DMPC	PARENT	MFP DMPC	SOAP DMPC
Proximate, wt.%									
Moisture	4.5	7.0	5.1	1.4	38.7	2.2	1.9	2.9	2.0
Volatile Matter	36.9	37.6	40.7	27.7	18.6	29.9	38.2	40.4	40.8
Fixed Carbon	50.0	51.5	50.1	60.3	39.3	62.8	50.5	53.5	52.9
Ash	8.6	3.9	4.1	10.6	3.4	5.1	9.4	3.2	4.3
Higher Heating Value, Btu/lb									
	12100	12265	13180	13420	8500	14078	12775	13629	14429
Ultimate, dry, wt.%									
Hydrogen	5.0	4.8	5.8	4.7	5.3	4.7	5.0	5.7	5.6
Carbon	69.3	75.5	75.7	76.9	79.6	81.2	71.4	77.5	79.1
Sulfur	3.0	2.7	2.8	1.8	1.4	1.5	4.5	3.3	1.9
Nitrogen	1.3	1.0	1.5	1.3	2.2	1.4	1.2	1.3	1.6
Oxygen	12.4	11.8	9.9	4.6	6.0	6.0	8.4	8.9	7.4
Forms of Sulfur, dry, wt.%									
Pyritic	0.53	0.09	0.37	0.49	0.05	0.08	1.34	0.03	0.31
Sulfate	0.35	0.41	0.02	0.55	0.56	0.51	0.44	0.60	0.17
Organic	2.12	2.20	2.41	0.76	0.79	0.91	2.72	2.67	1.40
Ash Fus. Temps., RED. ATM, ^{o}F									
IDT	2000	2020	1850	2010	1900	2100	2130	1900	2004
ST	2280	2180	1910	2380	2000	2150	2390	1980	2160
HT	2420	2230	1950	2450	2080	2190	2440	2020	2200
FT	2530	2280	2000	2400	2120	2300	2490	2119	2447
Ash Composition, wt. %									
SiO_2	51.7	42.0	40.2	43.8	38.3	41.2	39.3	34.1	38.7
Al_2O_3	20.7	19.3	19.9	24.2	24.7	24.5	20.2	22.3	24.1
Fe_2O_3	16.9	21.2	25.6	18.8	17.0	19.2	31.4	27.7	19.7
CaO	2.2	3.7	3.4	3.1	3.1	3.3	3.0	4.6	5.3
MgO	0.9	1.4	1.4	0.9	1.2	1.2	0.8	1.3	1.4
Na_2O	0.5	2.3	1.6	0.9	7.0	1.6	0.5	2.2	1.1
K_2O	2.0	2.3	2.4	2.2	2.5	1.6	1.5	1.6	1.6
TiO_2	0.8	2.2	2.5	0.2	1.8	1.9	1.0	1.8	1.7
P_2O_5	0.0	0.1	0.2	0.2	0.2	0.3	0.1	0.2	0.4
SO_3	2.1	3.4	2.0	3.9	2.8	2.7	2.1	3.2	3.9

Although it is beyond the work scope of this project, further investigation is needed to address the handling characteristics of the BCFs. One possible explanation for the adhering tendency of the BCFs is the high percentage of fines, which are more susceptible to static forces and tend to collect and retain moisture. In the case of the SOAPs, the presence of low melting asphalt which was used as a binding agent in the agglomeration process may have also contributed to their tendency to adhere.

Test Conditions

The test conditions for the nine fuels are summarized in Table 3.2.2. Firing rates between 3.5 x 10^6 Btu/h and 4.0 x 10^6 Btu/h were performed at different furnace flame temperatures by varying the secondary preheat. Each test was conducted with approximately 20% excess air. The Upper Freeport MFP MCWF was preheated to 230°F fuel temperature to improve atomization during testing. Furnace residence times varied from 1.01 sec. to 1.25 sec. The FPTF furnace gas temperature profiles during these tests are illustrated in Figures 3.2.2 to 3.2.4.

Overall, the combustion characteristics of all six BCFs were good and comparable to their respective parent coals. Good, stable flames were obtained and very few sparklers were observed. Chemical analyses of the fly ash samples indicated that in every case the carbon contents were very low, and the carbon conversion efficiencies calculated from the isokinetically collected dust loadings were greater than 99.9% for all test fuels (Table 3.2.3).

Furnace Slagging

The FPTF test results indicate that firing the BCFs improved waterwall heat transfer characteristics. However, there was no improvement in deposit cleanability compared to their respective parent coals.

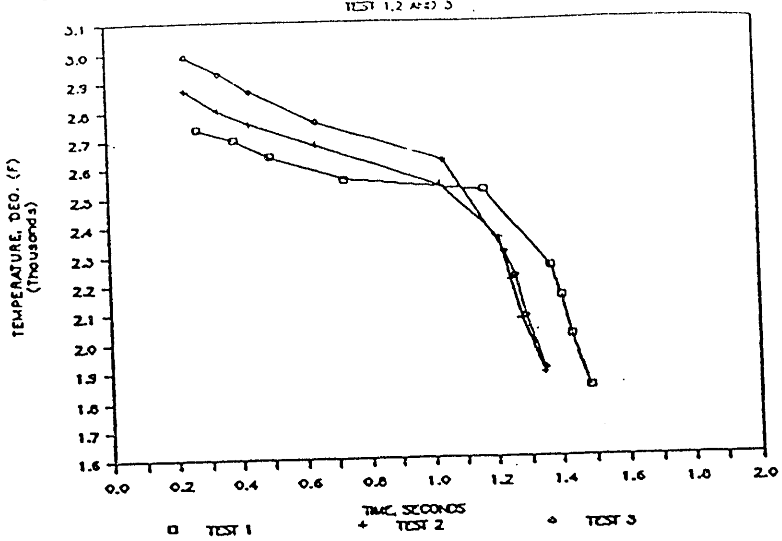
The effects of ash deposition on furnace heat transfer can be illustrated by comparing the heat fluxes from the four waterwall panels located at different elevations of the FPTF furnace. These four panels are used to represent ash deposition that occurred at different local gas temperatures for a given firing rate. In all cases, at the same 4 x 10^6 Btu/h firing rate and similar flame temperatures, waterwall heat transfer was higher with the BCFs than with their respective parent coals (Figures 3.2.5 to 3.2.7).

TABLE 3.2.2

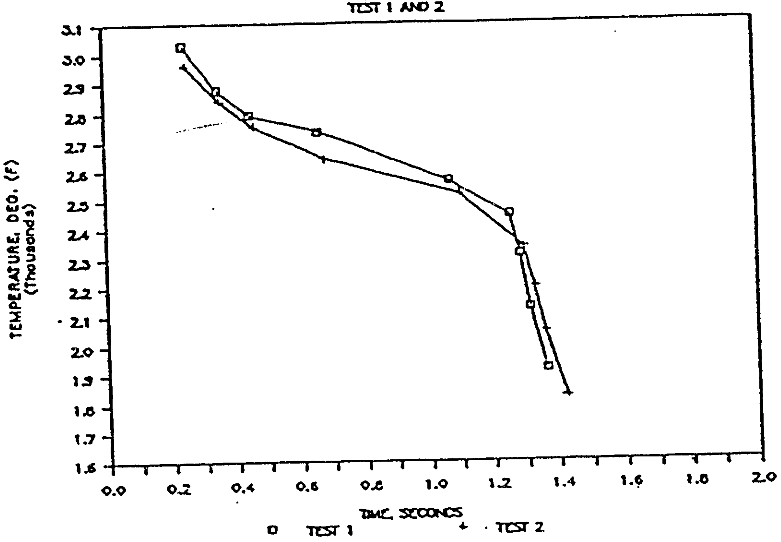
COMBUSTION PERFORMANCE TEST MATRIX WITH 20% EXCESS AIR

FUEL TYPE	FIRING MODE	FIRING RATE (10^6 Btu/h)	AVG. FLAME TEMPERATURE (°F)	GAS TEMP. ENTERING CONVECTIVE PASS (°F)	TEST DURATION (h)
ILLINOIS NO. 6					
Parent	PC	3.75	2740	2250	12
		4.00	2870	2320	24
		4.00	2980	2350	22
MFP	DMPC	4.00	3030	2450	24
		4.00	2960	2340	24
SOAP	DMPC	3.75	2940	2340	12
		3.50	2900	2320	12
		4.00	3030	2380	21
UPPER FREEPORT					
Parent	PC	3.75	2910	2290	12
		4.00	2990	2340	24
MFP	MCWF	4.00	2970	2270	19
SOAP	DMPC	4.00	3010	2430	24
		3.75	2930	2380	24
PITTSBURGH NO. 8					
Parent	PC	3.75	2920	2290	12
		4.00	2990	2360	12
		3.50	2860	2230	12
MFP	DMPC	3.75	2920	2260	24
		4.00	2980	2360	24
SOAP	DMPC	3.75	2920	2340	12
		4.00	2980	2410	21

IL6 PARENT COAL TEMPERATURE -RES. TIME



IL6 MFP TEMPERATURE - RESIDENCE TIME



IL6 SOAP TEMPERATURE - RESIDENCE TIME

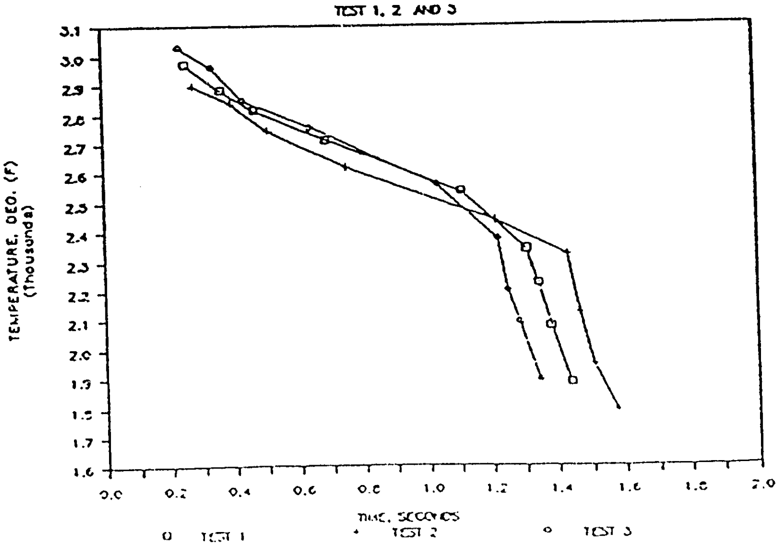
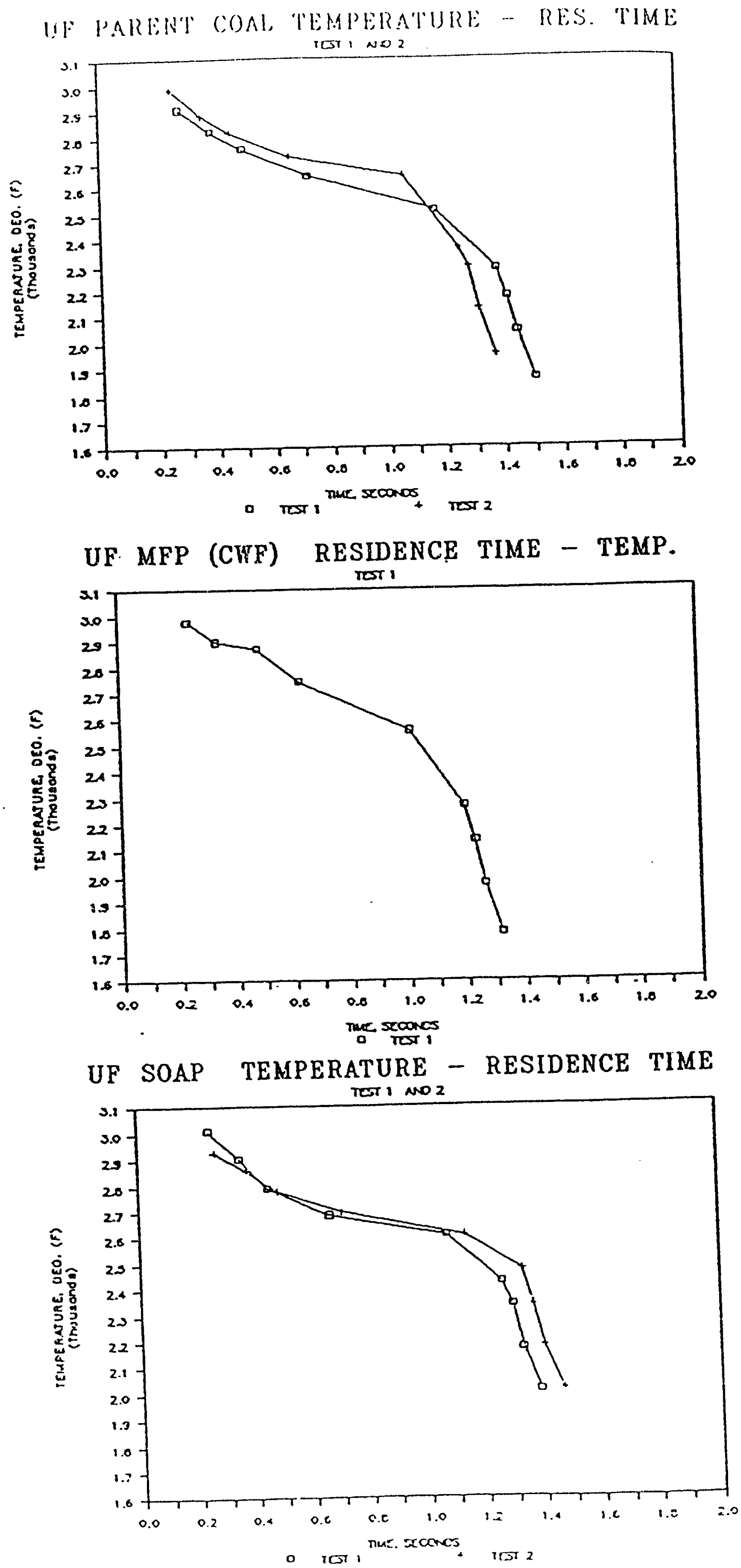


FIGURE 3.2.2



UF PARENT COAL TEMPERATURE - RES. TIME

TEST 1 AND 2

UF MFP (CWF) RESIDENCE TIME - TEMP.

TEST 1

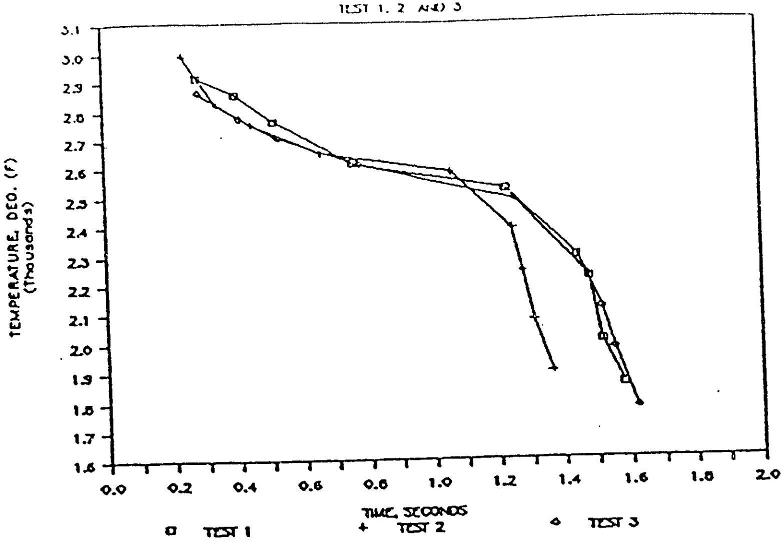
UF SOAP TEMPERATURE - RESIDENCE TIME

TEST 1 AND 2

FIGURE 3.2.3

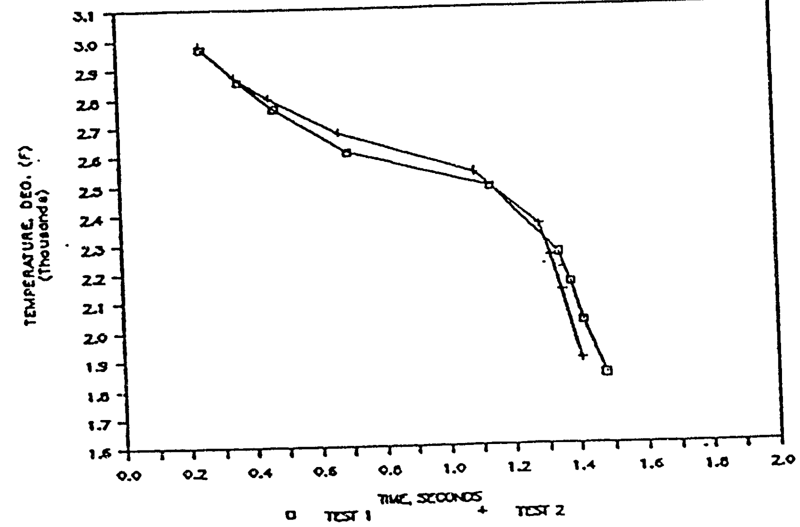
PT8 PARENT COAL TEMPERATURE - RES. TIME

TEST 1, 2 AND 3



PT8 MFP TEMPERATURE - RESIDENCE TIME

TEST 1 AND 2



PT8 SOAP TEMPERATURE - RESIDENCE TIME

TEST 1 AND 2

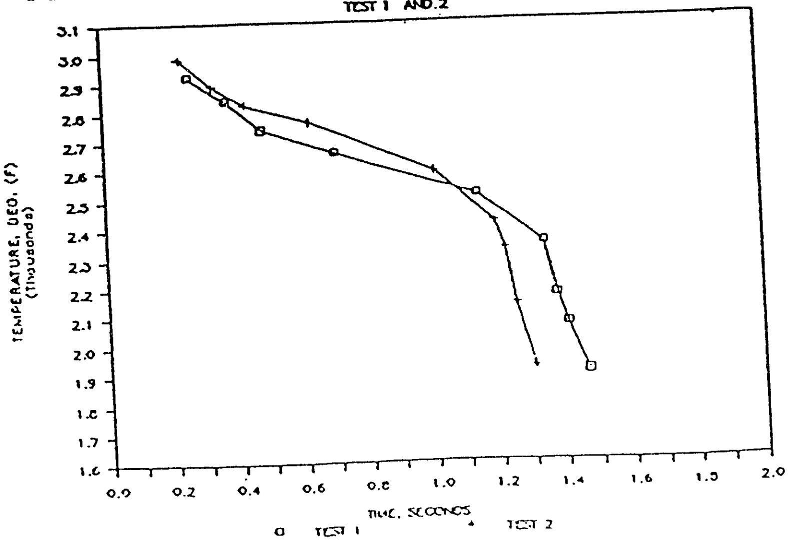
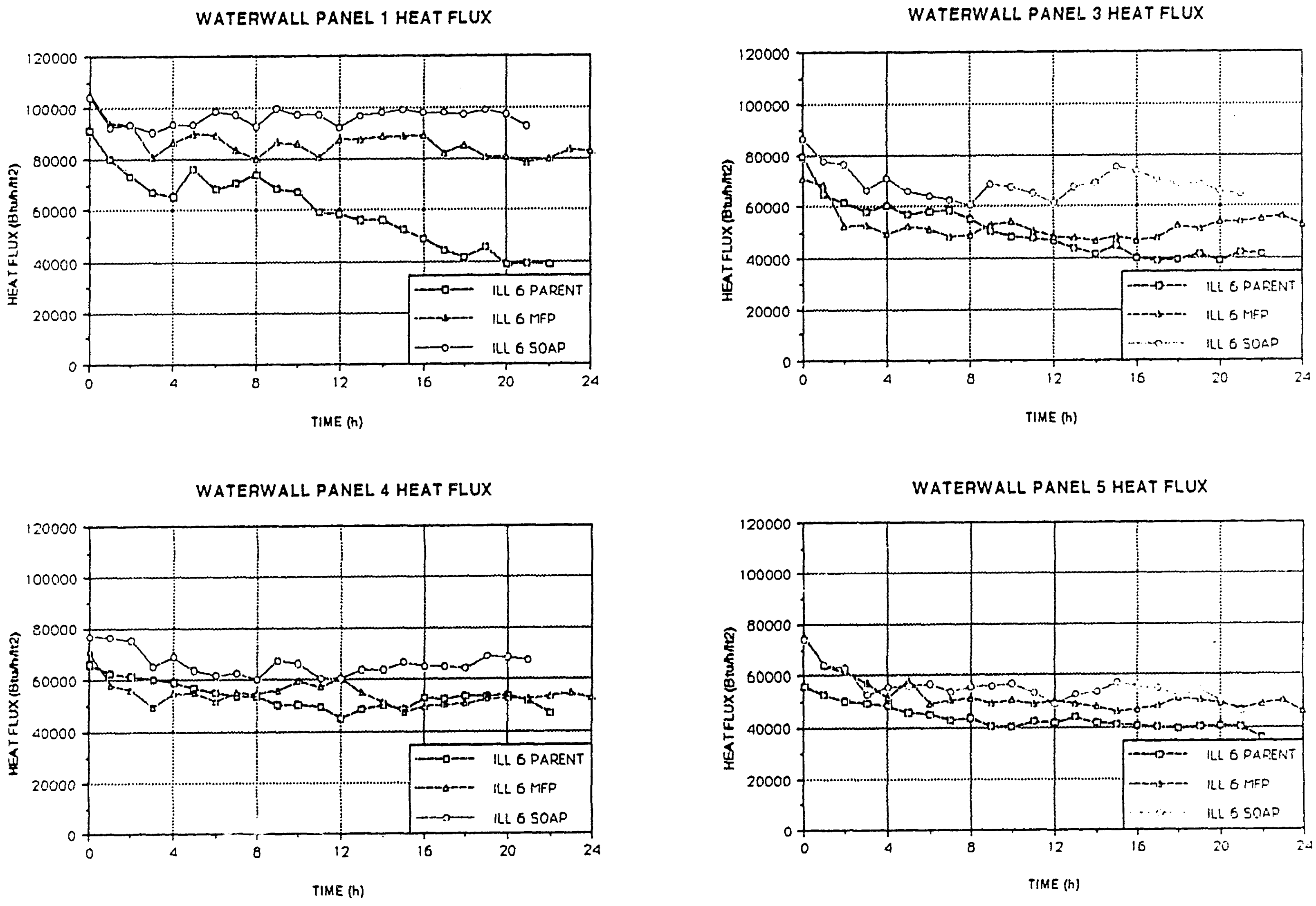


FIGURE 3.2.4

TABLE 3.2.3

CARBON CONVERSION EFFICIENCIES OF BCFS

Fuel Type	Firing Firing Mode	Fuel Mass Mean Diameter (microns)	Fly Ash Mass Mean Diameter (microns)	Fly Ash Carbon Content (wt. %)	Carbon Conversion (%)
ILLINOIS NO. 6					
Parent	PC	42.2	7.7	0.1	99.9
MFP	DMPC	17.9	3.2	1.0	99.9
SOAP	DMPC	18.2	6.6	1.3	99.9
UPPER FREEPORT					
Parent	PC	48.9	10.2	0.7	99.9
MFP	MCWF	20.3	17.6	2.1	99.9
SOAP	DMPC	20.0	12.5	0.9	99.9
PITTSBURGH NO. 8					
Parent	PC	43.8	12.8	1.0	99.9
MFP	DMPC	21.4	13.6	0.6	99.9
SOAP	DMPC		3.7	1.1	99.9

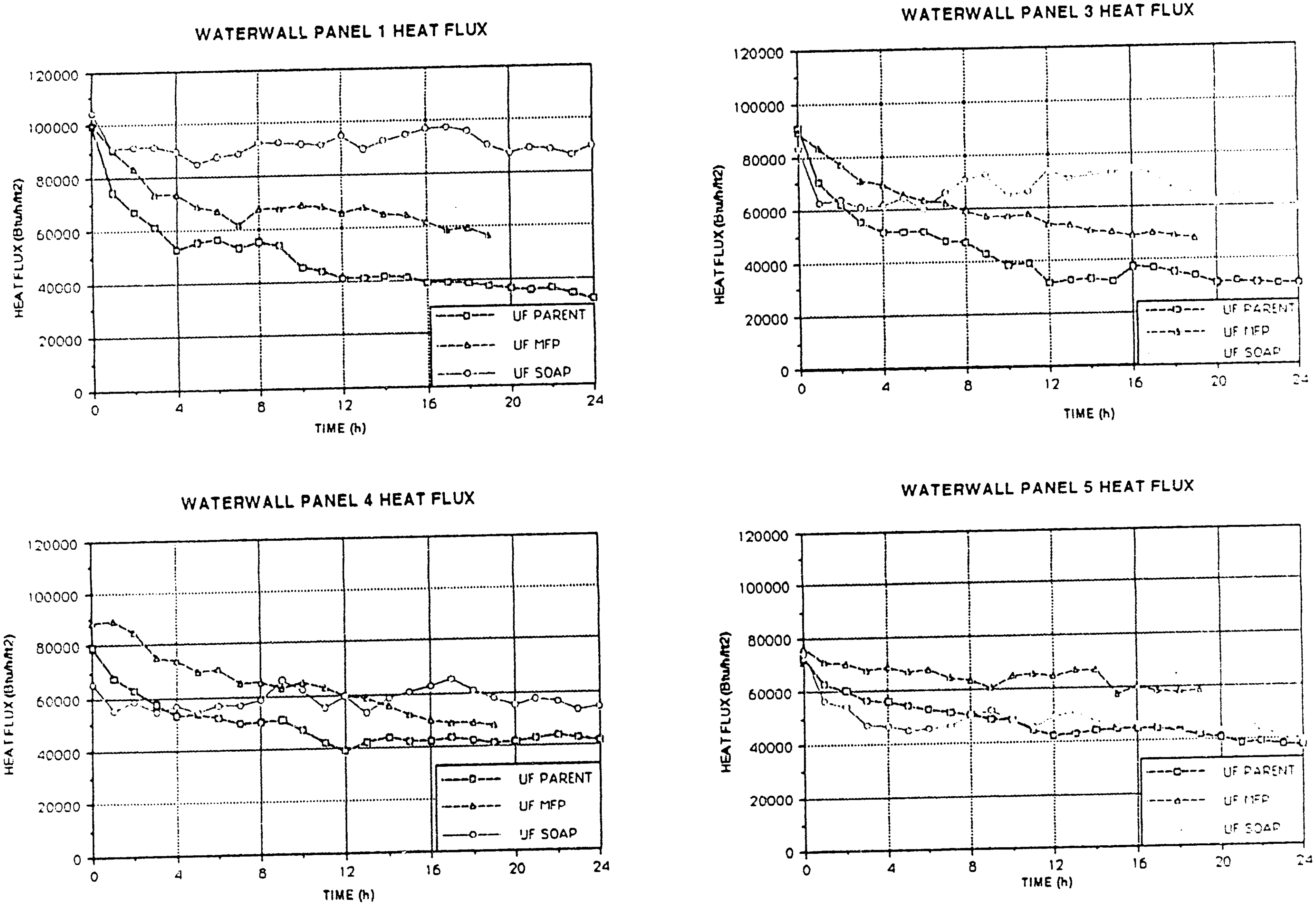

WATERWALL PANEL 1 HEAT FLUX

WATERWALL PANEL 3 HEAT FLUX

WATERWALL PANEL 4 HEAT FLUX

WATERWALL PANEL 5 HEAT FLUX

FIGURE 3.2.5



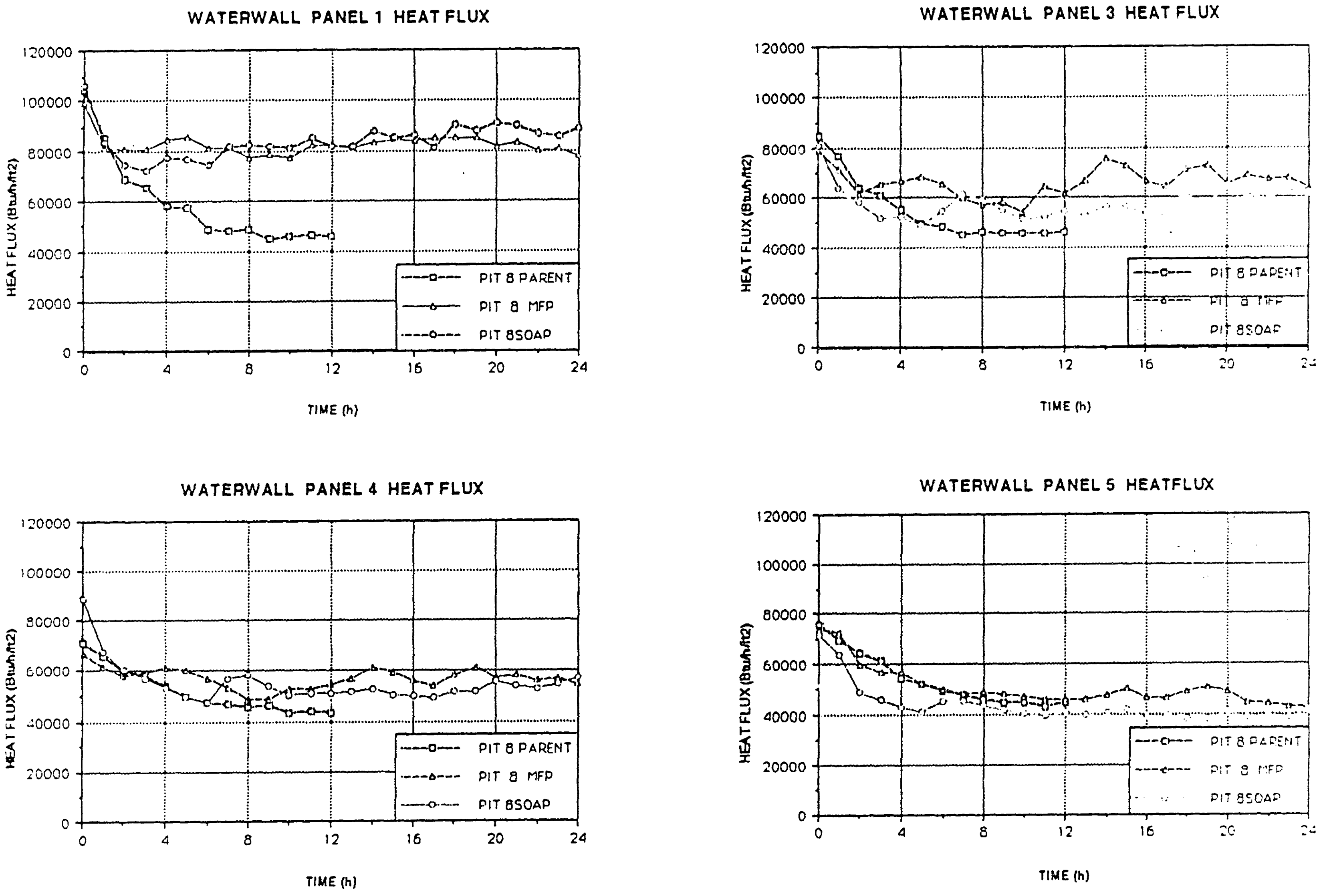
WATERWALL PANEL 1 HEAT FLUX

WATERWALL PANEL 3 HEAT FLUX

WATERWALL PANEL 4 HEAT FLUX

WATERWALL PANEL 5 HEAT FLUX

FIGURE 3.2.6


WATERWALL PANEL 1 HEAT FLUX

WATERWALL PANEL 3 HEAT FLUX

WATERWALL PANEL 4 HEAT FLUX

WATERWALL PANEL 5 HEATFLUX

FIGURE 3.2.7

The higher heat absorption rates of the BCFs appeared to be related to their thinner deposits, compared to those of the parent coals under the same firing conditions (Table 3.2.4). Deposits developed from the parent coals were highly sintered with a molten outer layer, whereas deposits from most of the BCFs were fluid and formed a thin fused scale. The thicker deposits developed from the parent coals have a more shielding effect, either by scattering or absorption, to decrease radiation transfer.

On-line soot blowing was conducted at the end of each test run to evaluate furnace deposit cleanability. Sufficient time was allowed when possible for the waterwall deposits to approach long term characteristics. The results indicate that, under similar firing conditions and flame temperatures, waterwall deposit cleanability did not improved with the BCFs and remained comparable to that of the parent coal deposits (Table 3.2.4).

The slagging characteristics of the BCFs can be generally explained by the lower ash fusibility temperatures compared to those of the corresponding parent coals. The lower melting temperatures appeared to be caused by the changes in the ash constituents of each fuel. Ash composition of the BCFs showed reductions in silicate, which was probably preferentially removed during the beneficiation process, coupled with a relative enrichment in the alkali and alkaline earth constituents which can act as fluxes to reduce ash melting temperatures. Lower fusibility temperature ashes tend to form more fluid deposits on the furnace walls.

Fouling Characteristics

Overall, at similar gas temperatures, firing the MFPs produced more tightly bonded deposits, whereas the SOAPs produced deposits with bonding strengths comparable to their respective parent coals. Convection tube deposit buildup rates were reduced with most of the BCFs due to their lower ash contents resulting from the beneficiation processes.

The fouling characteristics of the nine test fuels are summarized in Table 3.2.5. The ash deposit build-up rates were generally reduced with the BCFs due to their lower ash contents resulted from cleaning. However, this benefit was partially offset by the more tenaciously bonded deposits produced from the MFPs. This was primarily attributed to the increases in sodium related to the cleaning process, and, for the Upper Freeport MFP, a commercially established process which included a sodium based additive was used to formulate a heatable microfine coal-water fuel. Active alkalis such as sodium are very instrumental in ash fouling due to their propensity to form very low temperature melting compounds and to act as a bonding medium cementing deposits together.

TABLE 3.2.4

WATERWALL DEPOSIT PHYSICAL CHARACTERISTICS

FUEL TYPE	FIRING MODE	FIRING RATE (10^6 Btu/h)	AVG FLAME TEMPERATURE (°F)	DEPOSIT PHYSICAL STATE	DEPOSIT THICKNESS (mil)	DEPOSIT CLEANABILITY
ILLINOIS NO. 6						
Parent	PC	3.75	2740	sintered		good
		4.00	2870	sintered		good
		4.00	2980	molten	169	poor
MFP	DMPC	4.00	3030	fused		poor
		4.00	2960	scale	19	poor
SOAP	DMPC	3.75	2940	fused		poor
		3.50	2900	scale		poor
		4.00	3030		21	poor
UPPER FREEPORT						
Parent	PC	3.75	2910	molten		good
		4.00	2990	molten	320	poor
MFP	MCWF	4.00	2970	molten	234	poor
SOAP	DMPC	4.00	3010	molten		poor
		3.75	2930	molten	154	good
PITTSBURGH NO. 8						
Parent	PC	3.75	2920	molten		good
		4.00	2990	molten	125	poor
		3.50	2860	molten		good
MFP	DMPC	3.75	2960	fused		poor
		4.00	2980	scale	21	poor
SOAP	DMPC	3.75	2920	fused		good
		4.00	2980	scale	43	poor

TABLE 3.2.5

CONVECTION TUBE FOULING CHARACTERISTICS

FUEL TYPE	FIRING MODE	FIRING RATE (10^6 Btu/h)	GAS TEMP ENTERING (°F)	DEPOSIT PHYSICAL STATE	AVERAGE DEPOSIT BONDING STRENGTH	SOOTBLOWING FREQUENCY (h)
ILLINOIS #6						
Parent	PC	3.75	2250	sintered	5	6
		4.00	2320	sintered	7	4
		4.00	2350	sintered	9	4
MFP	DMPC	4.00	2440	sintered	13	8
		4.00	2340	sintered	10	8
SOAP	DMPC	3.75	2340	sintered	11	8
		3.50	2320	sintered	11	8
		4.00	2380	sintered	12	8
UPPER FREEPORT						
Parent	PC	3.75	2290	sintered	< 1	6
		4.00	2340	sintered	4	2
MFP	MCWF	4.00	2320	sintered	15	3
SOAP	DMPC	4.00	2420	sintered	10	8
		3.75	2380	sintered	7	8
PITTSBURGH #8						
Parent	PC	3.75	2290	sintered	5	8
		4.00	2360	sintered	7	8
		3.50	2230	sintered	5	8
MFP	DMPC	3.75	2260	sintered	15	12
		4.00	2360	sintered	16	12
SOAP	DMPC	3.75	2340	sintered	2	12
		4.00	2410	sintered	4	12

Fly Ash Erosion

The FPTF results indicate that firing the BCFs produced significantly less erosion than the parent coals. These results were anticipated due to the reduction in ash loadings from the beneficiation process. A comparison of the erosion rates between test fuels is shown in Table 3.2.6. Reductions in ash loadings by approximately 40% to 70% resulted in 60% to 90% decreases in erosion rates for the BCFs.

Generally, erosion is expected to increase exponentially with velocity and linearly with ash loading. The improvement in erosion rates beyond that projected for the reduction in ash loadings is attributed to changes in erosiveness of the ashes. The cleaning process may have reduced the concentrations of more erosive constituents in the ashes of the BCFs.

Fly Ash Collectability

Results of the collection of BCF fly ash are given in Table 3.2.7 and in Figure 3.2.8. The collection efficiency of the ESP is expressed as a function of migration velocity:

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

where:

n = ash collection efficiency
SCA = specific collection area
SCA = A_s/Q_a
A_s = collector electrode surface area
Q_a = actual gas flow rate
W_e = ash particle migration velocity

The migration velocities for the ashes from the parent, microbubble flotation products (MFP), and spherical oil agglomerated products (SOAP) are given in Figure 3.2.8 as a function of ash resistivity. Also given for reference are migration velocities from commercial units reported by H. J. White. The resistivity vs migration velocity is generally the way that ash is characterized to evaluate its collectability. However, additional terms such as gas temperature, moisture, particle size, and power supply voltage also affect the migration velocity.

TABLE 3.2.6

FLY ASH EROSION CHARACTERISTICS

FLY ASH SAMPLE	ASH LOADING (lb/h)	FLY ASH[1] size (microns)	QUARTZ CONTENT (wt %)	EROSION FACTOR (10^{-10})	NORMALIZED[2] WEAR RATE (mil/10^4h)	CRITICAL[3] VELOCITY (ft/s)
ILLINOIS NO. 6						
Parent	16.2	7.5	17.8	4.5	2.4	76
MFP	7.7	3.2	5.0	1.7	0.4	95
SOAP	7.5	6.6		3.0	0.8	77
UPPER FREEPORT						
Parent	18.3	10.2		5.0	3.0	53
MFP	9.0	17.6		1.6	0.5	91
SOAP	8.4	12.5		2.9	0.9	76
PITTSBURGH NO. 8						
Parent	16.7	12.8		5.5	3.4	51
MFP	5.4	13.6		1.1	0.2	114
SOAP	7.2	3.7		2.0	0.5	89

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[1] Mass mean diameter
[2] Normalized to 60 ft/s and 10000 h
[3] Projected to 2 mil/10000 h erosion rate

TABLE 3.2.7

PILOT-SCALE ELECTROSTATIC PRECIPITATOR PERFORMANCE

	ILLINOIS NO. 6			UPPER FREEPORT			PITTSBURGH NO. 8		
	Parent	MFP	SOAP	Parent	MFP	SOAP	Parent	MFP	SOAP
Flue Gas Moisture, %									
	4.0	5.8	4.5	4.1	7.0	3.2	4.3	4.1	4.3
SO_3 Concentration, ppm									
	3.5	4.3		3.0	3.4	2.4	3.0	4.8	
Fly Ash Loadings, gr/dscf									
Inlet	0.96	0.38	0.43	1.08	0.18	0.54	0.75	0.30	0.35
Outlet	0.07	0.20	0.15	0.34	0.03	0.35	0.03	0.12	0.21
Fly Ash Mass Mean Dia., microns									
	7.5	3.2	6.6	10.2	17.6	12.5	12.8	13.6	3.7
Fly Ash Resistivity, 10^{-11} ohm-cm									
	6.0	.01	2.0	1.2	0.5	1.5	0.7	0.2	0.4
ESP Collection Efficiency, %									
	91	21	64	55	72	38	95	53	29
Migration Velocity, cm/s									
	8.3	0.9	3.6	2.9	4.4	2.1	12.6	2.7	1.4
Specific Collection Area, ft^2/1000 acfm									
	147	125	146	139	149	116	123	141	123

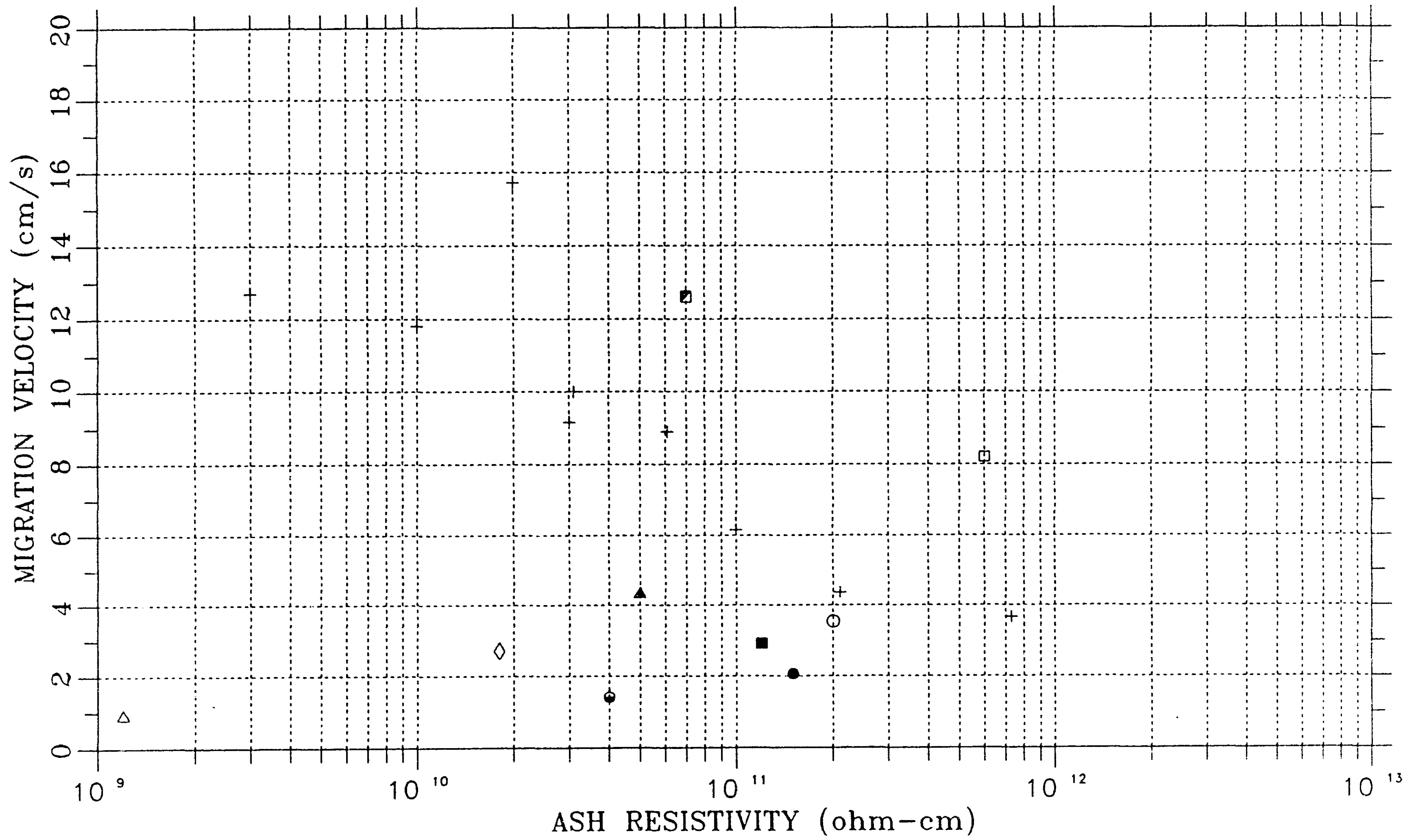

FIGURE 3.2.8 ESP ASH MIGRATION VELOCITY (CLASSICAL ALGORITHM)

Migration velocities obtained from previous CE pilot ESP programs have been correlated with these additional variables to reduce variability of the results. Such analysis of the data from the BCF program is planned for the next quarter.

The Illinois and Pittsburgh parent coals had ash migration velocities higher than expected. However, the Upper Freeport parent coal had a low migration velocity. Also, all of the beneficiated coals had lower than expected migration velocities. It should be noted, as indicated above, that this reduction may be partially accounted for by the gas temperatures, particle size, and other variables. Therefore, it is too soon to state that BCF ashes have low collecting rates compared to parent coals.

The pilot facility is being inspected and modified to verify and improve the data obtained from the facility. Power supply measurement capabilities are being implemented to more accurately measure the true power supplied to the charging electrodes, as opposed to the power measured from the power supplies. In addition, the sampling system is being revised. These modifications will improve the accuracy of future test results.

Sample Analysis

All of the UNDEERC analyses of the FPTF samples from testing of the Illinois No. 6 Pittsburgh No. 8, and Upper Freeport parent, MFP, and SOAP fuels were completed this quarter. However, data reduction is not complete, so discussion of the results of those analyses will be done in future reports.

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 were 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) are used to predict the performance of three commercial boilers. The boilers include: a 560 MW coal-designed utility unit; a 600 MW 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.

The writing of a report describing the commercial boilers which will be evaluated was completed in draft form. The draft report is included as Appendix A.

TASK 6 - TECHNICAL REPORTING

In addition to issuing the quarterly technical report, two technical papers were prepared and presented:

1. "Combustion Characterization of Coal-Based Fuels," by O. K. Chow, N. Y. Nsakala, and M. J. Hargrove, DOE Contractors' Conference, August 6-9, 1990, Pittsburgh, PA.

2. "Combustion Characteristics of Beneficiated Coal-Based Fuels as Measured in Bench- and Pilot-Scale Tests," by O. K. Chow, N. Y. Nsakala, and M. J. Hargrove, EPRI Coal Quality Conference, September 19-21, 1990, St. Louis, MO.

WORK PLANNED FOR NEXT QUARTER

- Continue standard bench-scale tests.
- Continue drop tube furnace tests at CE and UNDEERC.
- Analyze data from pilot-scale combustion tests and ash deposition tests.
- Continue preparations for the scale-up tests.

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3. Huettenhain, H., and Schaal, A. M., "Advanced Physical Fine Coal Cleaning by Spherical Agglomeration," Final Report for U.S. DOE, PETC under Contract DE-AC 22-87 PC 79867, September, 1990.
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APPENDIX A

COMBUSTION CHARACTERIZATION OF BENEFICIATED COAL-BASED FUELS

SELECTION OF BOILERS FOR TECHNO-ECONOMIC ANALYSIS

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AUGUST 1990

PREPARED FOR

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

SELECTION AND DESCRIPTION OF THE STUDY UNITS

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 being run at the DOE/EPRI cleaning facility in Homer City, Pennsylvania, 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 to 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.

Three major fuel burning installations designed for coal or oil firing were selected for BCF performance and economic evaluation. The study units were selected to be representative of a large portion of the current boiler population: a 560 MW coal-designed boiler purchased in 1973 and used in Environmental Protection Agency (EPA) Research and Development studies (1) as a typical unit; a 600 MW oil-designed boiler purchased in 1970 and selected for the Department of Energy (DOE) Coal Water Fuels (CWF) evaluations (2) as being both representative of utility units and challenging to convert to coal-based fuels; and an 85,000 lb/hr industrial unit purchased in 1983, similar to a unit used in a performance analysis study sponsored by the DOE (3). All three of these units were built by CE, but the fuel-related design parameters are similar to those used by other manufacturers.

DESCRIPTION OF THE STUDY UNITS

The three units selected represent a wide range of boiler operating conditions. The coal unit has a relatively low furnace heat release rate and wide convection pass tube spacings typical of a large utility coal-fired boiler. The oil-designed utility boiler has significantly higher furnace heat release rates and closer convection tube spacing. The industrial boiler has even higher heat release rates and tighter tube spacings. See Table 1. Design data is described for each unit in the following text:

Coal-Fired Boiler Design. The coal-fired utility unit chosen is a balanced draft unit designed to fire midwestern bituminous coal through six elevations of tilting tangential fuel nozzles. It has a maximum continuous rating (MCR) of 4,150,000 lb/hr of main steam flow and 3,709,000 lb/hr reheat steam flow; main and reheat outlet conditions are 1005°F/2620 psig and 1005°F/570 psig, respectively. Superheater outlet steam temperature is controlled from 2,490,000 to 4,150,000 lb/hr by means of desuperheater spray. Reheat outlet steam temperature is controlled from 2,240,000 to 3,709,000 lb/hr by means of fuel nozzle tilt and reheat spray. Outlet conditions at control load are 1005°F/2440 psig for the main steam and 1005°F/356 psig for reheat steam. The unit provides steam to a turbine for a 560 MW generator. A side elevation of the unit is shown in Figure 1.

The radiant furnace is of single cell design 60.83 feet wide and 51.38 feet deep. The volume of the lower furnace is 400,000 cubic feet. One hundred and eight wall blowers are located in the lower furnace to control slag build-up, with a concentration of blowers immediately above the burner windbox.

Table 1
Unit Design Parameters

Main Steam Flow, lb/hr	4,150,000	4,200,000	85,000
Reheater Steam Flow, lb/hr	3,709,000	3,881,000	-
Superheater Outlet Steam			
Pressure, psig	2620	2600	500
Temperature, °F	1005	1005	650
Reheater Outlet Steam			
Pressure, psig	570	607	-
Temperature, °F	1005	1005	-
Excess Air, %	25	3	20
Gas Recirculation, %	-	15	-
Efficiency, %	87	89	77
Firing Rate, MBtu/hr	5485	5460	100
Lower Furnace Volume, ft^3	400,000	278,000	1,470
Lower Furnace Release Rate, $10^3 Btu/hr\text{-}ft^3$	14	20	68
Tube Spacing at Horizontal Furnace Outlet Plane	10 feet	10 inches	4 inches
End Product	560 MW Electricity	600 MW Electricity	Process Steam

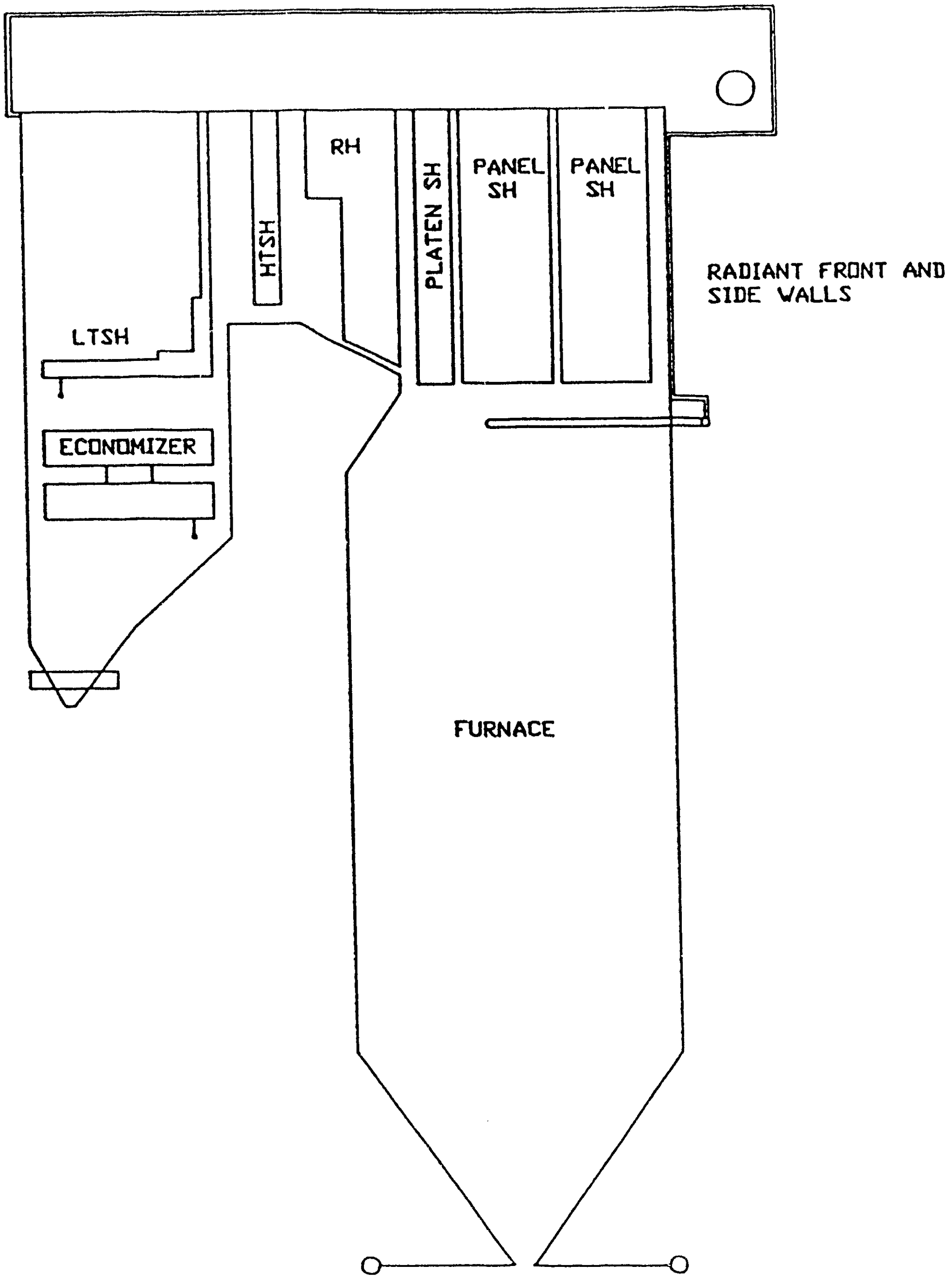

FIGURE 1

COAL FIRED UTILITY STEAM GENERATOR

The superheater train (steam side) consists of, in order, (1) radiant roof, (2) low temperature horizontal, (3) low temperature pendant, (4) division panels, (5) desuperheater, (6) pendant platen assemblies and (7) pendant finishing sections. The reheater arrangement utilizes radiant sections on the front and side walls in the upper furnace followed by pendant convective finishing sections at the furnace outlet. The economizer is of continuous spiral fin design providing 282,000 square feet of installed surface.

Two Ljungstrom model 30 1/2 VI 60 regenerative type air heaters are provided to cool the flue gas to approximately 290°F when the boiler is operating at MCR. Coal is pulverized in six CE Raymond RP-903 mills. These pulverizers are rated for a maximum capacity of 119,000 lb/hr when grinding a 55 HGI coal to a fineness of 70% through 200 mesh sieve. The contract analysis for the design fuel is listed in Table 2. The analysis for the average of several fuels typically fired is also listed. While the ultimate analyses and higher heating value are fairly close, the high iron content and low ash fusibility temperatures have severely influenced the furnace's potential to operate in a slagging limited mode.

Oil-Fired Utility Unit. This steam utility generating unit is a radiant reheat, single cell, balanced draft boiler. It is designed to fire No. 6 fuel oil through five elevations of tilting tangential fuel nozzles. It has a maximum continuous rating of 4,200,000 lb/hr of main steam flow at 1005°F/2600 psig and 3,881,000 lb/hr of reheat steam flow at 1005°F/607 psig. Superheat outlet steam temperature is controlled from 2,820,000 to 4,200,000 lb/hr by means of desuperheat spray. Reheat outlet steam temperature is controlled from 2,570,000 to 3,881,000 lb/hr by means of burner tilt and gas recirculation flow rate. The steam is supplied to a 600 MW turbine generator set. The general arrangement is shown in a side elevational view in Figure 2.

The radiant furnace is 56.66 feet wide by 44.38 feet deep. The furnace volume is 278,000 cubic feet. There are no wall blowers in the lower furnace due to the low slagging potential when firing oil. The superheater (steam side)consists of, in order, (1) horizontal platen and (2) horizontal spaced sections. The reheater arrangement utilizes three convective sections, two horizontal and one vertical cross-over. The economizer is of continuous spiral fin design providing 205,000 square feet of heating surface.

Two Ljungstrom model 28 VI 39 1/2 regenerative air heaters are provided to cool the flue gas to approximately 350°F when the boiler is operating at MCR. The original contract analysis for the design fuel is listed below in Table 3.

Table 3
Oil-Fired Units Design Fuel

Oil-Fired	Utility Unit	Industrial Unit
Ultimate Analysis, Wt.%		
Moisture	0.39	0.30
Hydrogen	9.84	13.16
Carbon	86.01	85.23
Sulfur	2.80	0.47
Nitrogen	0.39	0.84
Oxygen	0.39	--
Ash	0.09	--
Unacc.	0.09	
HHV,Btu/lb	18200	19285

Table 2

Coal-Fired Utility Unit Fuel Analysis

	Contract Design Analysis	Typical Field Analysis
Proximate Analysis, Wt %		
Moisture		12.73
Volatile Matter		35.07
Fixed Carbon		41.32
Ash		10.88
HHV, Btu/lb	10750	10820
Ultimate Analysis, Wt. %		
Moisture	13.52	12.73
Hydrogen	4.27	4.23
Carbon	61.50	59.73
Sulfur	2.55	4.32
Nitrogen	1.27	1.13
Oxygen	7.27	6.98
Ash	10.00	10.88
Ash Fusibility, °F		
Initial Deformation		1910
Softening		2030
Hemispherical		2150
Fluid		2290
Ash Composition, Wt. %		
SiO_2		37.3
Al_2O_3		16.8
Fe_2O_3		34.9
CaO		3.9
MgO		0.7
Na_2O		0.5
K_2O		1.4
TiO_2		0.9
SO_3		2.7
TOTAL		99.1

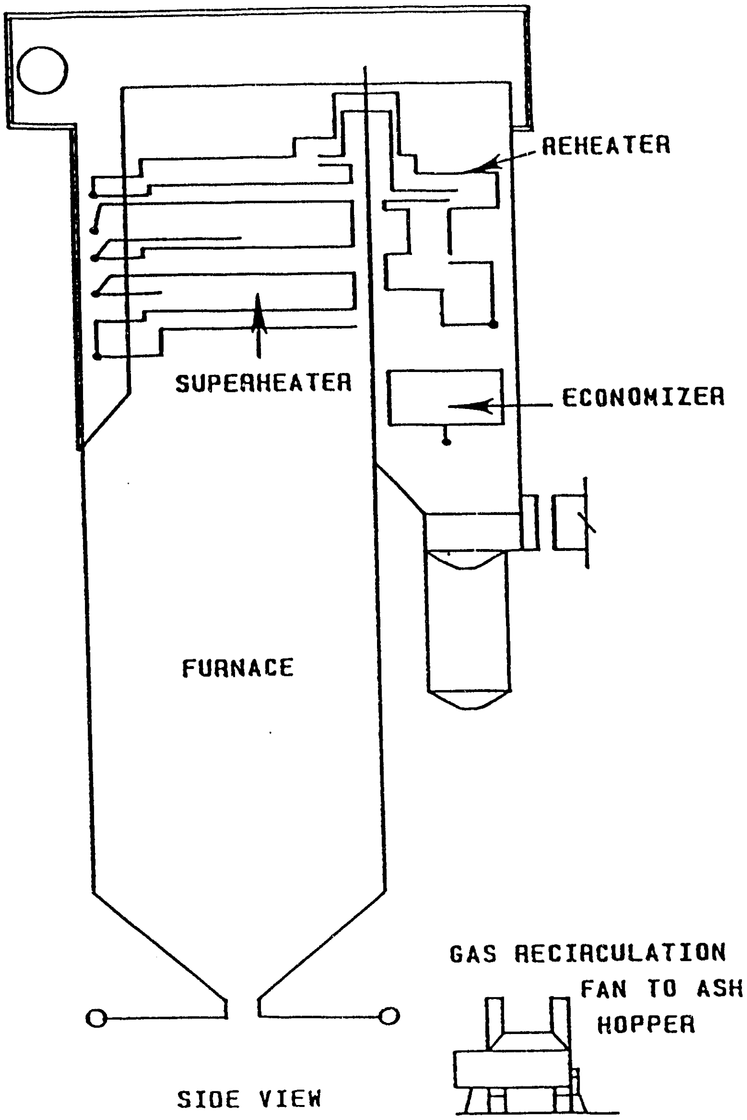

FIGURE 2

OIL-FIRED UTILITY STEAM GENERATOR

CLOSE-COUPLED SCREEN DESIGN

Oil-Fired Industrial Unit. The industrial unit chosen for this study is a "D-type" shop-assembled boiler. Several different designs are available for shop-assembled boilers with the designation based on the location of the steam and water drums. In the "D-type" boiler the steam and water drums are located on one side of the boiler. The fuel and combustion gas path originates at a single burner on the front wall of the unit. The combustion gases move through the furnace and are diverted 90° at the rear wall to a vertical superheater assembly. The gases then turn another 90° into a single convective pass located between the two drums. This boiler bank is comprised of simple tube circuits starting at the lower drum and terminating at the steam drum. Combustion gases then flow back toward the front wall in the convective pass and exit the unit. A diagram illustrating the gas flow pattern is shown in Figure 3.

The furnace dimensions are 23.96 feet long, 9.75 feet high and 7.02 feet wide. Furnace volume is 1470 cubic feet. The boiler is equipped with three soot blowers. One is a retractable soot blower located between superheater and boiler bank sections. The other two are rotary soot blowers located in the boiler bank.

The steam supply is used exclusively for auxiliary steam usage as the sootblowing medium on four utility units. The boiler has a maximum continuous rating of 85,000 lb/hr of main steam flow at 650°F/500 psig. Due to the usage and typical superheat outlet temperature of 650°F, steam from the unit is not desuperheated.

The unit was originally equipped with burners firing steam atomized No. 6 fuel oil as primary fuel and steam atomized No. 2 fuel oil as backup. Recently these burners were removed and replaced with burners that fire natural gas as primary fuel and steam atomized No. 2 fuel oil as backup. Data from oil firing will be used in the unit calibration for this study. The original contract analysis for the design fuel is listed in Table 3.

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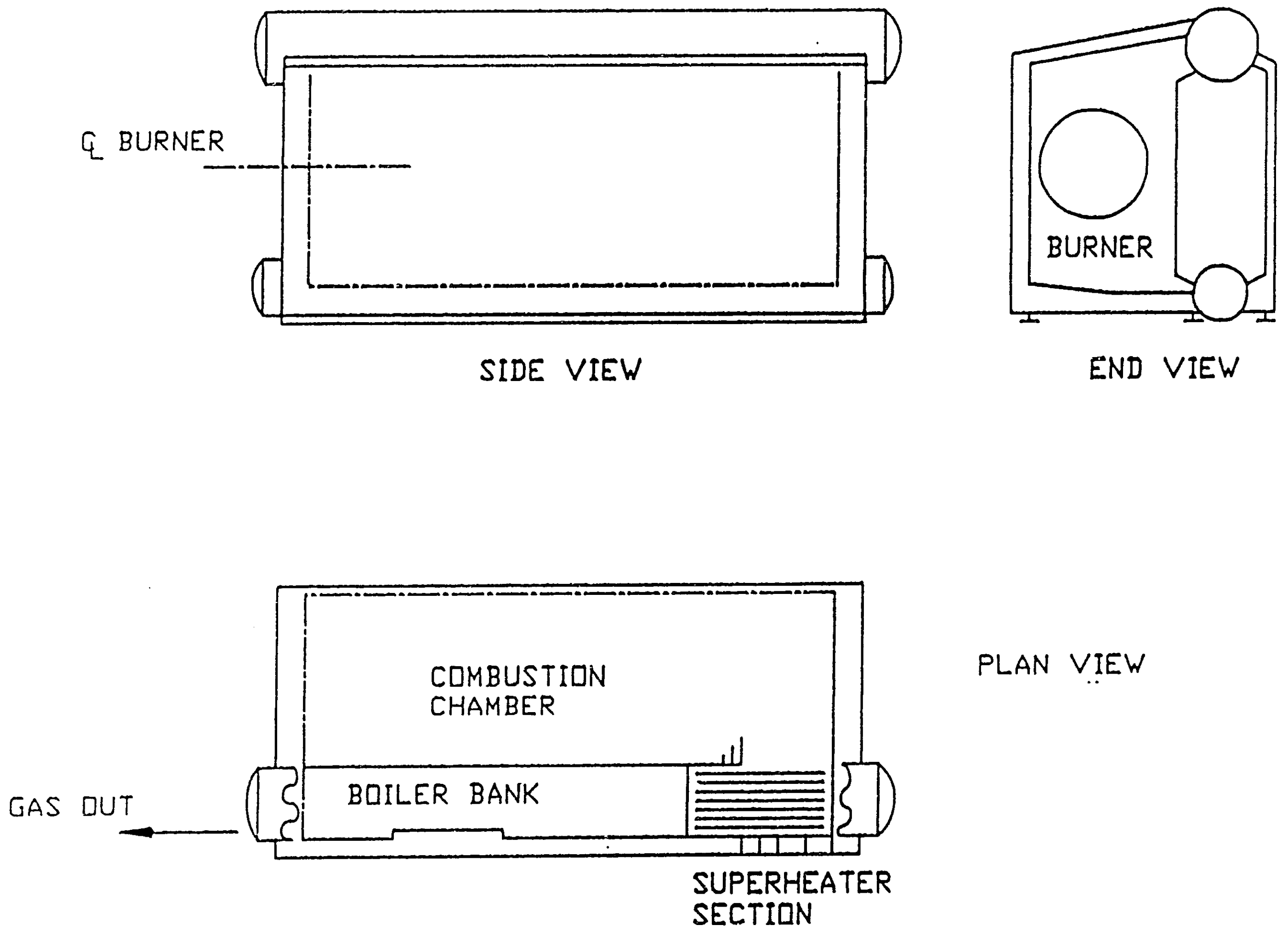

FIGURE 3

GENERAL ARRANGEMENT OF D-TYPE BOILER

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