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EDS COAL LIQUEFACTION PROCESS DEVELOPMENT. PHASE V

Interim Report: Laboratory Evaluation of the Characteristics of
EDS Illinois Bottoms

By
T. C. Lao
A. A. Levasseur

February 1984

Work Performed Under Contract No. FC05-77ET10069

Kreisinger Development Laboratory
Combustion Engineering, Inc.
Windsor, Connecticut

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EDS COAL LIQUEFACTION PROCESS DEVELOPMENT

PHASE V

Laboratory Evaluation of the Characteristics of
EDS Illinois Bottoms

Interim Report

Project 900347

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Report Prepared by

T. C. Lao

A. A. Levasseur

Fuels Technology
KREISINGER DEVELOPMENT LABORATORY
COMBUSTION ENGINEERING, INC.

February 1984

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W. R. Epperly - Project Director

Exxon Research and Engineering Company
P. O. Box 101
Florham Park, New Jersey 07932

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EDS COAL LIQUEFACTION PROCESS DEVELOPMENT - PHASE V
LABORATORY EVALUATION OF THE CHARACTERISTICS
OF EDS ILLINOIS BOTTOMS

ABSTRACT

This is an interim technical progress report for U.S. Department of Energy Cooperative Agreement No. DE-FC05-77ET10069, EDS Coal Liquefaction Process Development - Phase V. Funding is shared by U.S. Department of Energy, Exxon Company, U.S.A. (a division of Exxon Corporation), Electric Power Research Institute, Japan Coal Liquefaction Development Company, Phillips Coal Company, Anaconda Minerals Company, Ruhrkohle A.G., and ENI. This agreement covers the period January 1, 1977 through December 31, 1985.

This interim report documents work carried out by Combustion Engineering, Inc. under a contract to Exxon Research and Engineering Company to develop a conceptual Hybrid Boiler design fueled by the vacuum distillation residue (vacuum bottoms) derived from Illinois No. 6 coal in the EDS Coal Liquefaction Process. This report was prepared by Combustion Engineering, Inc., and is the first of two reports on the predevelopment phase of the Hybrid Boiler program. This report covers the results of a laboratory investigation to assess the fuel and ash properties of EDS vacuum bottoms. The results of the laboratory testing reported here were used in conjunction with Combustion Engineering's design experience to predict fuel performance and to develop appropriate boiler design parameters. These boiler design parameters were used to prepare the engineering design study reported in EDS Interim Report FE-2893-113, the second of the two reports on the predevelopment phase of the Hybrid Boiler program.

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1. INTRODUCTION

A comprehensive laboratory investigation was conducted to assess the fuel and ash properties of the residue (vacuum bottoms) produced by the EDS Coal Liquefaction Process. This effort was part of Combustion Engineering's contract with Exxon Research and Engineering Co. to develop a conceptual hybrid boiler design fueled by Illinois #6 coal derived EDS residue. The results of the laboratory testing were used in conjunction with C-E's design experience to predict fuel performance and to develop appropriate boiler design parameters.

The laboratory investigation examined both the combustion and the ash deposition characteristics of the Illinois coal derived EDS residue. The test work was comprised of the following phases.

- Task I: Bench-Scale Characterization
- Task II: Combustion Evaluation in C-E's Drop Tube Furnace System (DTFS)
- Task III: Pulverization Testing
- Task IV: Ash Deposition/Performance Evaluation in C-E's Fireside Performance Test Facility (FPTF).

During Tasks I, II, and III, two different EDS residues, "low ash" and "high ash" samples, were tested. The sample of low ash residue consisted of once through vacuum bottoms and the high ash sample was recycled vacuum bottoms. During Task IV, FPTF testing, only the low ash residue was evaluated. This investigation represents the first phase of study and detailed testing was primarily conducted on non-commercial low ash residue. More definitive information will be obtained during the second phase of the study when more commercially representative (high ash) residue is subjected to comprehensive large-scale testing.

This section contains the results of the laboratory investigation. Included is the detailed discussion of the results obtained during testing in all four tasks.

2. OBJECTIVES

The overall goal of this test program was to provide the detailed fuel characterization data necessary for the development of the Illinois #6 coal derived bottoms based conceptual hybrid boiler design. In order to meet this overall objective, determination of the pulverization, combustion, and ash properties of the EDS residue were addressed through bench-scale and pilot-scale testing. Specific objectives included:

I. Bench-Scale Characteristics

Determination of the analytical properties of EDS low and high ash residue to assess grinding characteristics, ignition stability and fuel reactivity properties, and the ash fouling and slagging tendencies.

II. Combustion and Burnout Characteristics

- a) Assessment of the combustion and burnout characteristics of both high ash and low ash residues by comparing the overall combustion efficiencies with that of a marginal reactivity bench mark coal obtained similarly in the DTFS.
- b) Characterization of DTFS chars through determination of char combustion kinetic parameters, microscopic characteristics and BET pore surface areas of each char.

III. Pulverization Testing

Determination of the grinding characteristics of the EDS residue under actual pulverizing conditions.

IV. Performance Characterization

- a) Characterization of relative ash fouling behavior through determination of convection pass deposit buildup rates, relative deposit bonding strengths, and the physical and analytical properties of convection pass deposits generated by the low ash residue.

- b) Characterization of the relative ash slagging behavior of low ash residue through determination of waterwall panel heat absorption rates, and the physical and analytical properties of waterwall deposits.
- c) Assessment of the relative combustion characteristics of low ash residue through evaluation of flame stability, and the determination of carbon burnout in the FPTF.

3. SUMMARY AND CONCLUSIONS

Samples of Illinois #6 coal derived EDS residues representing low ash (once through vacuum bottoms) and high ash (recycled vacuum bottoms) residues were assessed during a series of bench-scale tests and during comprehensive DTFS testing. Larger quantities of these two residue were evaluated during pulverization tests, and the low ash residue studied during test firing in the FPTF.

Overall, results indicate that the combustion characteristics of the EDS residues have many similarities to high volatile bituminous coals and some subtle differences. A Kentucky high volatile bituminous coal was tested along with the EDS residues under similar (highly oxidizing) conditions in the DTFS in order to provide reference points for comparison. Test results indicate that volatiles from the high ash residue evolve, ignite, and burn more slowly than the coal volatiles at lower temperatures but are comparable at typical flame temperatures encountered under high load boiler operation. Unlike that of the high ash sample, volatiles from the low ash sample have evolution, ignition, and burn-off properties very similar to that of the high volatile bituminous coal. From a char reactivity standpoint, the high ash char is the most reactive followed by low ash char and the Kentucky high volatile bituminous coal char, respectively. Bench scale TGS-II results also indicate this same order of char reactivity.

Overall, results indicate that both the low and high ash residues have high ash slagging potentials similar to those of Illinois #6 coals. Ash composition and ash fusibility temperatures indicate high slagging potentials for each residue and FPTF results for the low ash residue show high slagging characteristics. Ash fouling potentials of both residues appear relatively low based upon bench scale results and was confirmed for the low ash residue by FPTF results. The ash deposit characteristics of the Illinois #6 feed coal did not appear to be greatly altered by the EDS process when producing low ash residue. However, the rate of deposit buildup would be expected to increase with the increase in ash content of the residue.

Both the low and high ash residues were successfully pulverized in a C-E #271 bowl mill. Problems associated with compaction or pasting were not observed during pulverization under normal mill operating conditions.

Based upon the testing conducted in this investigation several specific conclusions were drawn. Since much of the testing involved non-commercial low ash residue, these conclusions are subject to refinement based upon more detailed testing on commercially representative residues during the second phase of study. Specific conclusions from each task follow:

I. Bench Scale Tests

Ash Properties

1. The high iron content in the ash of each residue is the most important ash characteristic. This high iron content coupled with significant quantities of calcium (which has fluxing properties) indicate the potential for low melting deposits. The relatively low ash fusibility temperatures and the narrow spread between fusibility temperatures also indicate low melting deposits and a high potential for thin fluid slag deposits. Overall, a high slagging potential is indicated for both the low and high ash residues.
2. The relatively low alkali and alkaline earth contents in the residue ashes indicate low fouling tendencies. This is substantiated by acetic acid leaching results which show very low concentrations of active sodium.
3. The high ash loading ($22.9 \text{ lb}/10^6 \text{ Btu}$ fired) resulting from high ash residue is not unusual and can be easily designed for, however, it must be considered from the standpoint of bottom ash and fly ash removal capacity. In addition, the high ash loadings would tend to increase deposit buildup rates and dictate the need for greater sootblowing capacity. Fuel and fly ash erosion rates also generally increase with ash loading (for a given mineral content and grain size).

Grinding Properties

1. Minor pasting/compaction of residue was observed in the Hardgrove grindability apparatus during grinding of both the low ash and high ash residues. The high ash sample exhibited a slightly greater pasting tendency than the low ash sample. The low melting characteristics of the residue coupled with the heat buildup in this apparatus are the likely reasons for pasting. Addition of small quantities of moisture (1% of the residue) alleviated pasting for both residues. Similar pasting behavior and control with small additions of moisture were previously experienced with other solvent derived fuels. Results of the bench-scale tests indicate the potential for residue buildup in the mill during pulverization. However, during actual pulverizing of both low and high ash residues in a bowl mill (see III-Pulverization Tests) pasting did not occur.

Combustion Properties

1. The Flammability Index determined for both residues (1270°F) was higher than typical bituminous coals. However, the melting characteristics of these fuels, specifically the endothermic reaction accompanying the solid-to-liquid phase change, may have influenced these results toward the high side.
2. The burnout characteristics of the chars from these residues appear similar to those from high volatile bituminous coals. Char reactivity of both the low and high ash samples are similar to those from high volatile bituminous coals. TGA and surface area analysis indicate the high ash char is more reactive than that of the low ash sample. This is likely due to the increased catalytic effect of the mineral matter. High carbon losses are not indicated by the bench scale results for either fuel.

3. The low melting characteristics (300-400°F) of the residues indicate the fuel will undergo a phase change during passage through burner assemblies and present the potential for residue buildup and cause interference with burner performance. Properly designed water-cooled burners appear necessary.

II. DTFS Combustion Characteristics

1. From an overall combustion standpoint, at commercial/high temperatures the low ash residue is the most reactive fuel followed by the high ash residue and the Kentucky high volatile bituminous coal, respectively. Both EDS residues should burnout adequately under high temperatures encountered in conventional pulverized coal fired boilers.
2. The high ash residue has distinctive volatile matter evolution, ignition and volatile burnout properties which are highly temperature sensitive. At high temperatures (typically encountered under high load boiler operation) and highly oxidizing conditions the volatile evolution, and burn-off of the high ash sample is comparable to that of the low ash residue and to high volatile bituminous coal. However, at low temperatures, ignition, and burn-off takes place relatively slow constituting an ignition delay and the potential for volatile generated unburned carbon. For the high ash residue, this unique ignition property should be noted when considering flame stability at low loads, as well as possible increases in unburned carbon at low loads.
3. The low ash residue ignition characteristics are similar to high volatile bituminous coals. The high volatile content of this fuel seems to promote ignition and volatile burnout. The fuel burns very rapidly in the early stages of combustion which renders it the highest in overall combustion efficiency among the three fuels. It does not show the same sensitivity to temperature with respect to volatile combustion as the high ash residue.

4. From a char reactivity standpoint, the high ash residue is slightly more reactive than the low ash residue and both EDS residue chars are slightly more reactive than the Kentucky high volatile bituminous coal char.

III. Pulverization Tests

Both the low ash and high ash residue were successfully pulverized in a C-E #271 bowl mill under normal operating conditions. Tests were conducted with mill inlet temperatures up to 500⁰F and outlet temperatures up to 180⁰F without any evidence of significant pasting or residue build-up in the mill. A substantial quantity (20 tons) of low ash residue was pulverized without problems.

Although the high ash sample used for pulverization testing was recycled bottoms, this sample was obtained during low yield periods and had only 15.8% ash compared to the 26.5% ash in the bench-scale sample. The pasting characteristics of each high ash sample were very similar in the Hardgrove apparatus, and it is reasonable to expect that high ash residue from higher severity EDS liquefaction (with approximately 27% ash) can be successfully pulverized in a bowl mill. More definitive information will be obtained for high ash residue during subsequent testing in Phase II.

IV. FPTF Performance Tests on Low Ash Residue

Ash Fouling Characteristics

1. Overall, the low ash residue test fired had a low convection pass fouling potential. Convection probe deposits were dry and relatively friable over the entire range of conditions tested (gas temperatures up to 2100⁰F). Deposition was very light below a gas temperature of 1900⁰F; deposits were lightly sintered and friable from gas temperatures of 1900⁰ to 2100⁰F; and deposits had moderate sintered strength at gas temperatures above 2100⁰F.

2. All convection deposits were weakly bonded and could be easily removed from probes. Deposits sloughed off probes frequently, reflecting the low bonding strengths. The maximum bonding strength values measured in situ during the tests were between 5 and 6.5. These measurements categorize the deposit bonding strength as low (less than 8) and fall well below a cut-off value of 15 (considered to be highest bonding strength deposits cleanable with conventional sootblowing).
3. Relative convection pass deposit buildup rates were low. Interference from deposit carryover generated in high temperature section (2300-2400°F gas temperatures) was observed during the subject testing. Therefore, careful examination of test data coupled with visual observations were required to assess buildup and pressure drop test results. Pressure drop test results reflect low buildup rates as deposits did not require sootblowing during the test period time span (more than 12 hrs at 2190°F gas temperatures and more than 20 hrs at 2015°F gas temperatures). Buildup test data also reflects low deposition rates. Overall, results show buildup rates were highly dependent upon gas temperature. Deposition rates were minimal below 1900°F, buildup rates became more significant above 2100°F. A gas temperature of 2100°F was established as the critical temperature above which buildup rates accelerate, however deposits are still removable at this temperature level.
4. Analytical properties of convection deposits did not reflect any unusual behavior. Overall, deposits did not vary substantially from the as-fired residue ash. In general, the powdery initial deposit layer contained higher concentrations of sodium and iron than the as-fired ash. Sintered outer deposits showed slight enrichment of iron and approximately the same concentration of sodium as the as-fired ash. The initial deposits on front (leading) probes within a given bank contained higher sulfur contents than those on back probes. Outer deposits on front probes generally contained higher calcium contents than those on back probes. Although deposit composition did vary somewhat as a function of deposit layers, probe geometry, and gas temperature; the lack of substantial enrichment of particular constituents is typical of deposits from low fouling coals.

5. Overall, convection deposit characteristics of the EDS low ash residue are typical of low fouling bituminous coals. Fouling characteristics of the residue very closely resembled those of a previously tested low fouling Illinois coal. The fouling behavior of the residue ash coincides with that indicated by the bench-scale analysis.

Radiant Section Deposit Characteristics

1. The ash slagging potential of the subject residue was high. Highly fused/molten ash deposits were generated at relatively low furnace loadings/temperatures. Thin (1/8-1/2" thick), fluid waterwall deposits formed at the high and intermediate firing rates. Running slag covered approximately 80% of the panel at the high firing rate and approximately 60% at the intermediate rate. At these firing rates, waterwall deposits consisted primarily of highly fused material with a very thin (approximately 1/8" thick) sintered inner layer, and a thin (approximately 1/16" thick) powdered initial layer. At the low firing rate waterwall deposits were slightly thicker. However, highly fused outer material represented only approximately 10% of the total deposition, and the inner sintered layer was approximately 3/8" thick in this case.
2. The relative waterwall bonding strengths of EDS ash deposits were high. On-line removal of waterwall deposits during the high and intermediate firing rates was difficult. Although waterwall deposits were not removed during the low firing rate, it is reasonable to conclude that deposits had moderate bonding strengths based upon the physical properties of these deposits. The formation of tenaciously bonded slag similar to that observed during the high and intermediate firing rate tests should be minimized/controlled as a result of the low thermal loading temperatures in the hybrid boiler design.

3. Waterwall heat transfer data indicates the potential for substantial reduction in heat absorption rate due to ash deposition. However, the thermal properties of waterwall deposits do not entirely reflect the severity of slagging. Average heat absorption rates were moderate during the tests reflecting the relatively thin deposits. The insulating properties of thin, dense, highly fused slag are not as good as thick, dry deposits. Heat absorption rates decreased steadily as deposits accumulated reflecting the high bonding strengths of deposits. Minimum heat absorption rates were relatively low showing the potential for substantial (up to 75%) reduction in heat transfer if deposits are not removed with wallblowers at proper intervals.
4. The composition and fusibility temperatures of waterwall deposits did not vary substantially from the as-fired residue ash. In general, coals having similar ash compositions as the subject residue have shown greater enrichment of iron and greater reductions in fusibility temperatures than observed in the waterwall deposits from the residue.
5. Overall, slagging characteristics of the subject EDS residue are not unusual, but are typical of high iron Illinois and Ohio coals. The physical and thermal properties of waterwall deposits were very similar to those of a previously tested Illinois coal. Processing did not appear to significantly influence ash slagging characteristics even though it is evident that original iron containing compounds in the parent coal were changed. (Pyrite could not be detected in the residues.) The slagging behavior of the low ash EDS residue can be readily compared to coals with which C-E has vast design and operating experience.

Combustion Characteristics

1. Overall, observations made during testing indicate that combustion characteristics of the low ash residue were good. The residue appeared to burn very easily once properly dispersed in the furnace. However, the low melting temperature of this fuel must be carefully considered.

Although a water-cooled burner housing and water-cooled fuel line were used, residue buildup/coking occurred on the test burner refractory face. Frequent cleaning of the coked material was required to maintain good burner performance. Although this condition was specifically related to the test hardware, it indicates the importance of a properly designed fuel firing system.

2. The ignition characteristics of the low ash residue appeared to be better than typical bituminous coals. Flame stability was good at low loads and the fuel appeared to burn very rapidly. Although flame characteristics can be changed through adjustment of the burner/combustion air swirl, it appeared that the residue burned very intensely and close to the burner with relatively low swirl. Relatively high waterwall panel heat absorption rates (for particular deposit coverage and panel elevation temperatures) were observed during the testing. These may be attributed to greater radiation due to rapid, intense combustion in the space between the burner and the panel.
3. Carbon losses during testing with the low ash residue were acceptably low. Carbon content in the fly ash ranged from 1.8% to 2.6%. Considering the periodic difficulties associated with burner coking, indications are that the carbon burnout characteristics should be good.

4.0 DISCUSSION OF RESULTS

4.1 Bench-Scale Characterization

Low and high ash samples of the EDS vacuum bottoms were prepared and analyzed. Both of these samples were derived from Illinois #6 (Monterey Mine #1) coal. The primary difference between the samples was the process conditions at which they were produced. The low ash sample consisted of once through material, whereas the high ash sample consisted of recycled material. Results of the tests conducted on these samples should reflect their actual properties. The degree to which these samples represent the actual commercial product (recycled vacuum bottom residue) should be considered during application of these results.

Representative samples from the respective drums of low and high ash residue were subjected to a series of analyses. These tests included ASTM proximate and ultimate analyses, ash composition, ash fusibility temperatures, Hardgrove grindability testing as well as Thermo-Gravimetric Analysis, Flammability testing, pore surface area analysis, and Acetic Acid Leaching.

Bench-scale analyses on fuels are sometimes performed in a routine, but standard fashion. The value of these analyses are obtained through comparison with those on fuels of known behavior. Several of the analysis performed for this evaluation fall into this category, and should be considered only in a comparative fashion.

Proximate and Ultimate Analyses

Analytical data on the two subject samples are summarized in Table I. The ash contents of the low ash and high ash samples were 14.5% and 26.5%, respectively. Other than the difference in ash content, proximate and ultimate analyses of the two samples were fairly similar. Moisture contents in both samples were very low (less than 1%). Higher heating values were 13010 and 11575 Btu/lb for the low and high ash samples, respectively,

TABLE I
FUEL ANALYSIS
EDS RESIDUE

SAMPLE	LOW ASH RESIDUE		HIGH ASH RESIDUE	
	<u>AS RECEIVED</u>	<u>DRY & ASH FREE</u>	<u>AS RECEIVED</u>	<u>DRY & ASH FREE</u>
Proximate, (% Wt.)				
Moisture	0.7	--	0.4	--
Volatile Matter	45.8	54.0	39.7	54.3
Fixed Carbon	39.0	46.0	33.4	45.7
Ash	14.5	--	26.5	--
TOTAL	100.0	100.0	100.0	100.0
Ultimate (% Wt.)				
Moisture	0.7	--	0.4	--
Hydrogen	4.7	5.6	3.9	5.3
Carbon	72.0	85.0	64.3	88.0
Sulfur	2.6	3.0	2.2	3.0
Nitrogen	1.5	1.7	1.3	1.8
Oxygen	4.0	4.7	1.4	1.9
Ash	14.5	--	26.5	--
TOTAL	100.0	100.0	100.0	100.0
HHV (Btu/lb)	13010	15345	11575	15840
Pyritic Sulfur (%Wt)	0.1	--	0.1	--
lb Ash/10 ⁶ Btu	11.2	11.2	22.9	22.9
Grindability	Greater than 100		Greater than 100	
Melting Temp. (°F)	300° - 400°F		300° - 400°F	

reflecting the difference in ash content. The volatile matter contents were significantly higher (greater than 50% volatile matter on a dry-ash-free basis) than typical bituminous coals..

The high volatile content of the residue would tend to enhance ignition characteristics. However, since these are solvent derived fuels, the composition and the behavior of these volatiles during combustion may be different than that of coals. See Section 4.2 for a more detailed discussion of combustion behavior.

Results of the ultimate analyses of the two residues (on an ash-free basis) shows slightly less hydrogen and considerably less oxygen in the high ash sample. Reduction of these constituents indicates a loss of lighter hydrocarbon chains during the more extensive processing of the high ash sample. The sulfur and nitrogen contents of the two subject samples are very similar. The fuel nitrogen contents of the samples were relatively high and the sulfur contents of the samples were high. Sulfur content on an ash-free basis in both samples was approximately 3% and corresponds to 3.9 and 3.8 lbs of SO_2 per 10^6 Btu fired without removal or more than 3 times the allowed maximum.

Ash Properties

Ash composition and ash fusibility temperatures of the two samples were very similar (See Table II). The ash from the subject residues are commonly described as "eastern-type" ash because their iron contents are greater than the combined alkali and alkaline earth contents. In general, the subject ashes contain relatively high percentages of iron and low concentrations of sodium with other constituents falling within typical ranges.

The most significant characteristic of the residue ash is the high iron content (18.8% and 15.7% Fe_2O_3 in the low and high ash, respectively).

TABLE II
FUEL ASH ANALYSIS
EDS RESIDUE

Sample	Low Ash Residue	High Ash Residue
<u>ASH FUSIBILITY (% Wt.)</u>		
I.T. (°F)	2050	2000
S.T. (°F)	2090	2120
H.T. (°F)	2190	2230
F.T. (°F)	2350	2380
<u>ASH COMPOSITION (% Wt.)</u>		
SiO ₂	49.0	51.5
Al ₂ O ₃	15.7	17.0
Fe ₂ O ₃	18.8	15.7
CaO	4.9	4.6
MgO	0.8	1.2
Na ₂ O	1.1	1.2
K ₂ O	1.5	1.6
TiO ₂	1.0	0.9
SO ₃	5.4	5.8
TOTAL	98.2	99.5
1b Ash/10 ⁶ Btu	11.2	22.9
Base/Acid Ratio	0.41	0.35
Fe ₂ O ₃ /CaO Ratio	3.80	3.46
SiO ₂ /Al ₂ O ₃ Ratio	3.13	3.03

Iron containing compounds can play a very significant role in slagging behavior. High iron content often results in low melting temperature ash and the potential for troublesome fused/molten deposits. A substantial percentage of the iron contained in coals of similar analysis as the subject residues would be present in the pyritic form. However, essentially all of the pyrite in the parent coal was evidently converted during processing as pyrite could not be detected in either residue sample.

Iron in the pyritic form has historically been associated with slagging behavior. However, the fact that pyrite is often present in a segregated manner could be the primary reason for its detrimental behavior. Gravity fractionation work conducted at C-E has strongly indicated that a small percentage of iron rich particles (segregated or free iron/pyrite particles) results in high slagging behavior. Depending on the properties of the parent coal and the processing conditions, large iron rich particles could exist in the residue. Although large iron rich particles would be uniformly distributed through the solid residue, these particles could be liberated during pulverization.

Another consideration when evaluating high iron ash is the quantity of fluxing constituents. In general, calcium is the primary fluxing agent with eastern-type ashes. The iron-to-calcium ratios for the subject ashes are roughly 3.5. Iron-to-calcium ratio has been used as a slagging index, and ratios falling between 0.3 and 3.0 have been correlated to low melting ash. The ratios for the subject ashes fall very close to this range. A problem with indices which rely upon ratios is that the magnitude of key constituents is not considered. However, in the case of the subject residue ash both iron (approximately 17% Fe_2O_3) and calcium (approximately 4.7% CaO) are present in very significant quantities. Therefore, the high iron content of the residue ash coupled with the possible fluxing behavior of calcium indicates the potential for low melting furnace deposits.

The base-to-acid ratio of the residue ash was 0.41 and 0.35 for the low and high ash samples, respectively. The base-to-acid ratio, like the iron-to-calcium ratio provides an indication of the fusion characteristics of the ash. The rationale for this index is based upon the tendency of ash constituents to combine according to their acidic or basic properties to form lower melting salts. Values of this ratio between 0.4 and 0.7 have been correlated to low melting ash. The base-to-acid ratios for the subject ash fall very close to this problem range.

The iron-to-calcium and base-to-acid ratios are indices developed through correlation against ash fusibility temperatures. Fusibility temperatures are a much more direct measurement of ash behavior. The ash fusibility temperatures determined in a reducing atmosphere for the low and high ash samples are contained in Table II. Overall, ash fusibility temperatures were low. Fusibility temperatures for the low ash sample were somewhat lower than the high ash sample probably due to the higher iron content and better balance between acid and basic constituents. The spread between the initial deformation temperature (I.T.) and fluid temperature (F.T.) of the ashes were 300⁰F for both the low and high ash samples. The relatively narrow spread in ash fusibility temperatures coupled with low fluid temperatures (<2400⁰F) indicates a high potential for thin, fluid/running furnace deposits. These deposits are typically very difficult to control by sootblowing.

Overall, based upon the high iron contents of the residue ash, potential fluxing by calcium, and the low fusibility temperatures, the furnace slagging potential of both low and high ash samples should be classified as high. The low ash sample has a slightly higher slagging potential than the high ash sample based on the above factors. However, the higher ash loadings associated with the high ash sample would tend to increase the rate of deposit buildup.

The primary considerations when evaluating the fouling potential of the subject residues are the alkali and alkaline earth concentrations. Alkalies, in particular sodium, can play a major role in convection pass fouling. The sodium contents in the residue ashes were relatively low for both samples (1.1% Na₂O and 1.2% Na₂O for the low and high ash, respectively). In addition to standard analysis, each sample was analyzed through acetic acid leaching techniques. Pulverized samples were leached at pH values of 3 and 5, and the leachates were subsequently analyzed for sodium, potassium, calcium and magnesium contents. (A more detailed procedure is given in Appendix A).

Weak acid leaching provides more definitive information on the nature of the alkalies present. The technique detects alkalies which are loosely bound (organic or simple salts), and are likely to volatilize during combustion and be instrumental in ash fouling. C-E has found that the leachable or soluble sodium content in fuel correlates very well with its fouling behavior.

Table III summarizes concentrations of weak acid soluble constituents. The concentrations at pH values of 5 and 3 are presented as micrograms per gm of coal on a dry coal basis ($\mu\text{g/g} = .0001\%$). The relative percentage of the total concentration of each constituent which was solubilized is listed in column 5. The concentration of soluble constituent on an ash basis is provided in column 6.

Overall, only small concentrations of alkali and alkaline earths were soluble. The soluble sodium content of both the low and high ash samples are very low. Low concentrations of soluble sodium is typical in eastern bituminous coals with low fouling potential. Only about 20% of total sodium is solubilized by acid leaching indicating that the sodium is primarily tied up with minerals in the coal and would have little influence on deposition in the convection passes. Overall, the low sodium contents of both samples indicate low fouling potentials.

TABLE III

ACETIC ACID SOLUBLE ALKALIES AND ALKALINE EARTHS
EDS RESIDUE

Sample	Component	pH 3.0 Sol. ug/g-Dry Coal Basis	pH 5.0 Sol. ug/g-Dry Coal Basis	Relative % Sol. of Total @ pH 3	% Sol. @ pH 3 (Ash basis)
Low Ash Residue	CaO	4780	580	66	3.27
	MgO	50	7	4	0.03
	Na ₂ O	370	330	22	0.25
	K ₂ O	19	10	1	0.01
High Ash Residue	CaO	5610	1070	46	2.11
	MgO	80	13	3	0.03
	Na ₂ O	460	360	14	0.17
	K ₂ O	31	16	1	0.01

Grinding Characteristics

The subject residue samples were ground in a standard Hardgrove grindability apparatus to assess pulverization characteristics. The Hardgrove grindability index for each sample is contained in Table I, however, this index is not the primary consideration for these fuels. Although the grindability indices were very high (more than 100) indicating the residue is very easy to grind, pasting/compaction of the residue was observed on Hardgrove grinding surfaces. Pasting/compaction of the residue was not observed during actual pulverization tests. (See next section.)

Figures 1 and 2 show the grindability apparatus after grinding the low and high ash samples, respectively. Note the buildup on the balls and the removed race. The low ash residue show less pasting than the high residue. The magnitude of the pasting was not particularly severe with either sample, however, the potential for pasting during pulverization must be carefully considered. Grinding behavior in the small ball mill (grindability apparatus) does not simulate the conditions in a large, air-swept bowl mill.

Pasting/compacting behavior in the grindability apparatus has also been observed with other solvent derived fuels. These previously tested fuels showed more severe buildup than the EDS residue, however, their pasting could be very effectively controlled with small additions of water. By increasing the moisture content of these fuels by 1%, all evidence of pasting was alleviated. After increasing the moisture contents of residue samples by 1%, there was also no evidence of pasting with either the low or high ash samples.

Since solvent derived fuels contain essentially no moisture, it is believed that supplementary moisture is required during bench-scale grinding to provide a heat sink for the heat generated during grinding. The melting temperatures of these fuels are low (300⁰-400⁰F, See Table I), therefore,

FIGURE 1

EDS RESIDUE
HI ASH-VAC BOTTOM
7347-C

NORSON-15 1 2

FIGURE 2

if the heat produced in the grindability apparatus is not dispersed, particle softening and agglomeration may occur. Previously tested solvent refined fuels could be successfully pulverized in C-E's Model #271 with roughly 1% moisture addition and heated drying air. The EDS residues physical properties and grinding behavior are somewhat similar to these fuels (but less troublesome). Although no pasting of the residue was observed during pulverization testing and these problems are not anticipated, control of pasting through supplemental water addition provides an easy solution to this problem if future characteristics of the residue change.

Combustion Properties

Although combustion characteristics of the residues will be discussed in detail in the subsequent section summarizing Phase II, a number of bench-scale tests were conducted to assess their combustion properties.

Flammability testing was performed to assess ignition characteristics of the two residue samples. (See Appendix A for a description of the Flammability Test). Flammability results provide the relative ignition temperature in an oxygen atmosphere. Table IV contains the flammability indices for the subject samples and some other U.S. coals for comparison. The flammability values (1270°F) for the subject residues were relatively high indicating flame stability/ignition characteristics may be somewhat poorer than typical high volatile bituminous coals. The flammability index for the residues falls between the Kentucky coal and anthracites.

It should be noted that the flammability indices of similar magnitude were determined for other solvent derived fuels. These fuels showed better ignition characteristics during actual burning tests than indicated by their flammability indices. Flammability results for these fuels as well as the EDS residues may be significantly influenced by their melting characteristics. Visual observations indicate these solvent derived materials undergo significant melting before releasing volatiles. Since the flammability testing is conducted at relatively low temperatures and residence times are very short, relatively high temperatures (from a flammability index standpoint) may be necessary for the particles to absorb sufficient heat for a phase change prior to volatile release.

TABLE IV
COMBUSTION CHARACTERISTICS
EDS RESIDUE

Fuel	BET Char Surface Area (m ² /g)		Flammability Index (°F)
	(dry)	(dry-ash-free)	
EDS Low Ash	30.1	64.8	1270
EDS High Ash	53.3	133.0	1270
Texas Lignite	151.7	268.8	910
Wyoming Sub A	76.8	99.8	1040
Kentucky HvBb	31.8	36.9	1170
Pennsylvania Anthracite	17.6	19.5	1650

25

NOTE: BET Surface Area was determined by nitrogen gas adsorption data on ASTM volatile matter free Chars ground to minus 200 mesh particle size.

Reactivity Parameter was determined from TGA char burnoff data at 700°C.

Thermo-Gravimetric analysis was conducted to assess char burnout characteristics of the residues. (See Appendix A for description). The combustion process is believed to consist of volatile matter evolution and burnout, followed by char burnout. Char burnout requires substantially longer time, therefore char burnout is generally the rate controlling step that dictates the overall reactivity of a particular fuel. Prepared char (ASTM volatile matter-free char) from each residue samples was analyzed through thermogravimetric techniques. Figure 3A shows the relative burnoff rate of subject char samples and comparative coals. These results were obtained by measuring weight loss in air at 700°C (isothermal) as a function of time.

The burnoff curves for the EDS residue chars fall between the Wyoming sub-bituminous coal and the Kentucky bituminous coal. The Kentucky coal is our bench mark coal; it is known to yield higher than normal carbon losses in an industrial unit and is considered somewhat marginal from a combustion efficiency standpoint. Since both the low and high ash burnoff curves fall to the left of (or burnoff more rapidly than) the Kentucky coal, carbon burnout problems are not indicated. Char from the high ash sample was slightly more reactive than the low ash char, however, results for both samples fall well within the ranges of high volatile bituminous coal chars. Overall, Thermo-Gravimetric results indicate the residues should have burnout characteristics similar to typical high volatile bituminous coals.

The bench-scale pyrolysis study of the two EDS residues were conducted in the Thermo-Gravimetric apparatus in nitrogen atmosphere at heating rate of 10°C/min. Results are presented in Figure 3B. The pyrolysis curves indicate the high ash residue pyrolyzed at temperature slightly lower than the low ash residue and both residues reach a peak devolatilization rate at about 300°C (30 minutes). This temperature is surprisingly low for solvent derived bottoms since both residues were processed at higher temperatures.

The Brummer, Emmett, Teller (BET) method was used to determine pore surface areas of the ASTM volatile matter-free derived from the subject residue.

FIGURE 3A TGA CHAR BURNOFF PLOT

FIGURE 3B RELATIVE PYROLYSIS RATE FOR EDS RESIDUES

(See Appendix A for description of BET Analysis/Quantsorb Surface Area Analyses). Results are summarized in Table IV. Generally, the more reactive fuels have larger BET pore surface areas indicating the importance of the internal pore surface area during char combustion. As such, the BET pore surface area can help explain differences in fuel reactivity.

The pore surface areas of the high ash char was approximately double that of the low ash char on a dry-ash-free basis. (Pore surface area is generally compared on a dry-ash free basis because the internal area of the carbonaceous material is much greater than the area associated with the ash or the outer surface area of the particles.) The greater surface area of the high ash char coincides with the reactivity results obtained from thermo-gravimetric analysis.

The surface area of the high ash char is substantially higher than typical bituminous coal chars. On a dry-ash-free basis, this char surface area is slightly higher than that of the subbituminous coal char. Surface area of the low ash char is comparable to that of the bituminous coal chars.

Overall, the BET surface area analysis supports the Thermo-Gravimetric analysis results indicating chars from the subject residues are relatively reactive and should behave similar to typical bituminous coal chars. Carbon burnout problems are not indicated by the bench-scale testing.

4.2 Drop Tube Furnace Testing

4.2.1 Experimental Procedure

The Drop Tube Furnace System (DTFS) was used to determine the combustion and burnout characteristics of the EDS residues (once-through vacuum bottoms "low ash" and recycle bottoms "high ash"). An eastern Kentucky high volatile bituminous coal (KHB) was also tested to provide reference points for comparison. The DTFS facility is described in Appendix B. The experimental procedure consisted of the following steps: (i) pneumatically transporting pulverized fuel particles with a small amount of carrier gas; (ii) introducing the fuel particles, confined in a narrow stream along the axis of the furnace through a water cooled injector; (iii) allowing this fuel and its transport primary gas to rapidly mix with a pre-heated down-flowing secondary gas stream; (iv) allowing combustion or pyrolysis to occur for a specific time; (v) quenching all the reactions by aspirating the products through a water-cooled sampling probe; (vi) separating the solids from gaseous products through a filter assembly; and (vii) determining on-line concentrations of NO_x , O_2 , CO , and CO_2 in the effluent gas stream. The particle heating and cooling rates in the reaction zone of the DTFS were on the order of 10^4 °C/sec. This is consistent with the findings of other research teams employing similar reactors (1,2) and approximates heating rates found in commercial boilers.

4.2.2 Test Matrix

The test matrix for the DTFS testing of EDS residues is given in Table V. Nine tests were run in the DTFS on the three fuels to assess their combustion characteristics in air at three gas temperatures ($T_g = 1850, 2250, 2650^\circ\text{F}$). Regular grind* fuel samples were used for these tests.

Tests were also run on 200 x 400 mesh size graded char samples, generated individually from the three regular grind fuels in the DTFS at three gas temperature ($T_g = 1900, 2300$ and 2580°F) for the char reactivity study.

* 70% - 200 mesh, mean weight particle size of 50 μm .

TABLE V

DTFS TEST MATRIX FOR EDS RESIDUES AND REFERENCE COAL

<u>FUEL</u>	<u>TEST NUMBER</u>	<u>SIZE GRADE</u>	<u>REACTION MEDIUM</u>	<u>GAS TEMPERATURE (°F)</u>
EDS High Ash Residue	EDS HA-I-1	Regular Grind (1)	Air	1850
	(Fuel) EDS HA-I-2			2500
	EDS HA-I-3			2440
	(2) EDS HA-II-1	200 x 400 mesh	3% O ₂ /97% N ₂	1900
	(Char) EDS HA-II-2			2300
	EDS HA-II-3			2580
EDS Low Ash Residue	EDS LA-I-1	Regular Grind	Air	2250
	(Fuel) EDS LA-I-2			2440
	EDS LA-I-3			1900
	EDS LA-II-1	200 x 400 mesh	3% O ₂ /97% N ₂	2300
	(Char) EDS LA-II-2			2580
	EDS LA-II-3			
Kentucky High Volatile Bituminous Coal	KHC-I-1	Regular Grind	Air	1850
	KHC-I-2			2250
	KHC-I-3			2440
	KHCC-II-1	200 x 400 mesh	3% O ₂ /97% N ₂	1900
	(Char) KHCC-II-2			2300
	KHCC-II-3			2580

Notes: 1. 70% -200 mesh size.

2. Prepared by devolatilizing fuel in the DTFS at 2650°F in helium atmosphere.

3. Tests on 100% +200 and 100% -400 mesh sizes are not included as results were spurious in nature.

Preparation of the char samples was carried out by devolatilizing fuels in helium atmosphere at highest furnace temperature ($T_g = 2550^{\circ}\text{F}$) and maximum furnace residence time (through 16" reaction zone). Each char sample was size graded to 200 x 400 mesh, all oversize materials were ground, size graded and added to the first cut. The 200 x 400 mesh cut was chosen because it minimized the effect of particle size differences yet also simulated the mean weight size of a regular commercial grind, (i.e., about 50 μm). It was originally intended to also study the effect of particle size on the combustion characteristics by testing the 100% + 200 mesh and 100% - 400 mesh size grade chars. However, data obtained from these tests were inconclusive, therefore, the effort was abandoned.

4.2.3 Data Reduction Program

A computer program was formulated to reduce the data resulting from each test. The main facets of this program are; (1) calculate the residence time of particles as they flow down the reaction zone taking into account the reactant gas velocity and their average free-fall velocity (3,4); and (2) calculate the combustion efficiency profiles on ash tracer basis (assumes ash in the fuel is inert during combustion) from the char and feed fuel proximate analyses. The DTFS test data and computed results from each test are presented in the Appendix C.

4.2.4 Temperature Profiles

Gas temperatures at the axis of the furnace were measured by using a suction pyrometer to measure the gas temperatures at different locations of the test furnace reaction zone. Generally, the gas temperatures are fairly isothermal in the reaction zone extending from 8 to 16 inches, however, in the first 8 inches of the reaction zone the gas temperatures are lower due to the cooling effects from the water cooled fuel injection probe and the relatively cold primary air stream. The temperature profiles for this phase of the tests is presented in Figure 4. In the temperature profile plots the three curves represent the low, intermediate and high wall temperature settings.

Figure 4 CORRECTED GAS TEMPERATURE PROFILES ALONG THE AXIS OF THE DROP TUBE FURNACE SYSTEM'S REACTION ZONE WHEN AIR WAS USED AS REACTION MEDIUM

4.2.5 Fuel Combustion Characteristics

The overall combustion efficiencies of the two EDS residues and the reference coal at three furnace temperatures (plateau gas temperatures of 1850, 2250, and 2440°F) are presented as a function of residence time in Figures 5, 6, and 7. Regular grind of the fuel was used and the average furnace oxygen concentration was 20± 1%. The shapes of the curves in these figures indicate that: (1) the combustion process for these fuels is extremely rapid in the early stages where volatile release and burning predominate, but the subsequent char burn-out process is comparatively slow; (2) the temperature effect on the combustion process is discernible; that is, combustion efficiencies are generally higher at higher temperatures; (3) the temperature effect is much more pronounced in the case of the high ash residue than the low ash or reference coal and the effect is predominant in the early stages. A relative comparison of the three fuels is shown at three temperatures in Figures 8, 9 and 10. Results indicate that: (1) the low ash sample yields the highest overall combustion efficiencies at all three temperatures. (ii) the combustion process for the high ash residue is much slower than that of the other fuels in the early stages when volatile burning is the most dominant factor, but is faster in the latter stages when char burnout is important. This explains the fact that the combustion efficiency of the high ash residue catches up with that of the low ash and reference coal after some time (200-400 milliseconds) in the reaction zone. In fact, the relatively higher char reactivity of the high ash samples was confirmed later in the char reactivity study. The volatile early stage burn off rate of the three fuels are presented as a function of residence time in Figures 11, 12 and 13. The volatile matter burn off rates were determined by their original fuel volatiles subtracting the ASTM volatiles remained in the partially devolatilized chars collected along the DTFS furnace distances. For the low ash residue and Kentucky high volatile bituminous coal, temperature seems to have little influence on volatile burning rate. However, in the case of the high ash residue, volatile burning appears highly temperature sensitive. At lower furnace temperature the relatively slow burning of the volatile constitutes a substantial combustion delay in the early stages. It should be noted that the gas temperatures denoted on these Figures (1850, 2250, and 2440°F) are the plateau temperatures (see temperature profiles in Figure 4).

Figure 5 DTFS COMBUSTION EFFICIENCY OF EDS HIGH ASH IN AIR AT VARIOUS GAS TEMPERATURES

Figure 6 DTFS COMBUSTION EFFICIENCY OF EDS LOW ASH IN AIR
AT VARIOUS GAS TEMPERATURES

Figure 7 DTFS COMBUSTION EFFICIENCY OF KENTUCKY HIGH VOLATILE BITUMINOUS COAL IN AIR AT VARIOUS GAS TEMPERATURES

Figure 8. DTFS COMBUSTION EFFICIENCIES OF FUELS
IN AIR AT LOW FURNACE TEMPERATURE

Figure 9 DTFS COMBUSTION EFFICIENCIES OF FUELS IN AIR AT INTERMEDIATE FURNACE TEMPERATURE

Figure 10 DTFS COMBUSTION EFFICIENCIES OF FUELS IN AIR AT HIGH FURNACE TEMPERATURE

Figure 11 VOLATILE MATTER BURN OFF RATE OF EDS HIGH ASH
IN AIR AT VARIOUS TEMPERATURES

Figure 12 VOLTAILE MATTER BURN OFF RATE OF EDS LOW ASH IN AIR AT VARIOUS TEMPERATURES

Figure 13 VOLATILE MATTER BURN OFF RATE OF KENTUCKY HIGH VOLATILE BITUMINOUS COAL IN AIR AT VARIOUS TEMPERATURES

In fact, actual gas temperatures in the top 4 inches of the reaction zone, which corresponds to the initial 200 milliseconds of residence time in the furnace, are much lower. For instance, at the low furnace temperature testing ($T_g=1850^{\circ}\text{F}$), the top 4 inches of the furnace the gas temperature was only on the average of 1550°F . Therefore, for the high ash sample, the initial combustion time delay associated with volatile ignition/burn off may not be as significant as it appears, since plateau temperature instead of real gas temperature was denoted and actual early stage temperatures are lower.

Earlier, the bench-scale pyrolysis tests showed that the high ash sample devolatilized at temperature slightly lower than the low ash sample (Figure 3-B). Later, during the low temperature DTFS runs on the high ash sample, heavy brownish fume was evidenced by visual observations through the glass filter housing at 1" and 2" collection zone. Therefore, it is reasonable to believe that for the high ash residue, instead of devolatilization step alone, it is the ignition and subsequent gas phase volatile burn off which were highly temperature dependent constituting the combustion delay at the low temperatures.

To summarize, DTFS results indicate that the overall reactivity of the low ash and high ash residues are acceptable. The ignition and combustion of volatiles from the low ash residue are acceptable at all temperatures investigated. However, volatile ignition and combustion of the high ash residue is very temperature sensitive. At high temperatures (i.e. full load boiler operation) it is comparable to a high volatile bituminous coal. At low temperatures is significantly less than the coal indicating that boiler turndown will be more limited for this residue than with typical coals, and indicating the potential for increased unburned carbon at low loads. The degree to which turndown is limited will be addressed during the Phase 2 tests.

4.2.6 Char Burnout Characteristics

Char Burnout.

The temperature profiles for the char burnout study are presented in Figure 14.

The 200 x 400 mesh size graded chars generated from the high and low ash residues and KHB coal were tested in 3% O₂/97% N₂ gas at three temperatures. The char combustion efficiencies are presented as a function of residence time in Figures 15, 16 and 17. Results indicate the high ash char yields the highest carbon burnout followed by low ash char and KHB coal char, respectively. These results reinforce the earlier bench-scale conclusion that both EDS residue chars are relatively reactive, comparable to high volatile bituminous coal chars.

Char Combustion Kinetics.

Although not an original objective this char reactivity study has provided data on the kinetics of carbon burnout in the temperature region of 1800°F to 2600°F for pulverized fuel combustion applications. Combustion efficiency (char burnout) data have been analyzed in terms of a diffusional reaction rate coefficient (K_D) which depends on the rate of oxygen transport to the external surface of the particle and a surface reaction rate coefficient (K_s) which depends both on chemical reactivity and internal diffusion. Field's mathematical model (5) was used to calculate the overall reaction rate coefficient (K). The value of the diffusional reaction rate coefficient (K_D) was calculated assuming a mechanism factor of 2 i.e., CO is the main product transported away from the particle. The surface reaction rate coefficient (K_s) was then back calculated from K and K_D from the relationship:

$$1/K = 1/K_D + 1/K_s.$$

Details of the calculations are as shown by Field (5). Average K , K_D , and K_s values obtained in the DTFS reaction zone are given in DTFS data sheet. The surface reaction rate coefficient can be expressed as a function of temperature of the form:

$$K_s = A \exp (-E/RT).$$

where A and E denote the apparent frequency factor and the apparent activation energy. Table VI shows the gas temperature of individual points and their corresponding K_s values, all invalid (diffusional control) points were excluded. The best fit straight lines of the K_s vs. $1/T$ values of the three chars give apparent activation energies (E) of 15,600, 16,200, and 28,400

Figure 14 CORRECTED GAS TEMPERATURE PROFILES ALONG THE AXIS OF THE DROP TUBE FURNACE SYSTEM'S REACTION ZONE WHEN 3% O₂/97% N₂ WAS USED AS REACTION MEDIUM

Figure 15 DTFS COMBUSTION EFFICIENCY OF CHARs AT LOW FURNACE TEMPERATURE

Figure 16 DTFS COMBUSTION EFFICIENCY OF CHARS AT INTERMEDIATE FURNACE TEMPERATURE

Figure 17. DTFS COMBUSTION EFFICIENCY OF CHARs AT HIGH FURNACE TEMPERATURE

TABLE VI

SURFACE REACTION RATE COEFFICIENTS AND KINETIC PARAMETERS OF THE DTFS CHARS

	Temp. (°K)	(g/cm ² s atm)	Kinetic Parameters
EDS High Ash Residue	1078	.05880	E=15608 cal/mole
	1106	.02931	
	1174	.01087	
	1258	.03791	
	1300	.03157	
	1295	.03905	
	1490	.19966	A=26 g/cm ² s atm
	1517	.16952	
	1515	.12418	
	1677	.38380	* $\gamma = .831$
	1692	.27052	
EDS Low Ash Residue	1106	.02866	E=16193 cal/mole
	1174	.02116	
	1258	.01469	
	1300	.02045	
	1295	.03201	
	1428	.16321	A=22.3 g/cm ² s atm
	1442	.07839	
	1456	.13378	
	1490	.11139	
	1517	.09100	
	1515	.08331	
	1677	.21347	* $\gamma = .843$
	1692	.14434	
Kentucky High Volatile Bituminous Coal	1078	.00334	E=28365 cal/mole
	1106	.00140	
	1258	.00204	
	1300	.01275	
	1428	.02290	A=762 g/cm ² s atm
	1442	.03111	
	1456	.07133	
	1490	.06599	
	1517	.09402	
	1515	.09062	
	1593	.06431	* $\gamma = .926$
	1692	.17848	

*Where γ is correlation coefficient.

cal/mole with corresponding frequency factors of 26, 22 and 762 g/cm²s atm. for the high ash low ash and KHB coal chars, respectively. The surface reaction rate coefficients of the three chars are plotted as a function of temperature in Figure 18. The curves show that the Ks values for the high ash char are consistently larger than corresponding values for the low ash char as well as KHB coal char, depicting the overall char reactivities of the three fuels.

4.2.7 Physical Characteristics

Morphology.

To assess the physical characteristics of the fuels, selected chars from the DTFS reaction zone were observed under a Scanning Electron Microscope to show the particle structure change at various stages of combustion.

The pulverized EDS residues are shown in Figure 19 (top). The particles are angular with no internal cavities. The pyrolyzed chars are shown in Figure 19 (bottom). The particles have become rounded, full of large bubbles, and are about the same size as the raw fuels. The cavities are open but they are quite small and few in number.

Partially burned chars are shown in Figure 20 (top). The high ash sample (top left) had lost about 60% of its original weight (about 65% ash in char); for the low ash sample (top right) the weight loss was about 73% (about 54% ash in char). The particles are much more skeletal, with large holes in the outer walls. The appearance suggests that oxygen is attacking both externally and internally and there are progressively more attack on the internal structure as combustion proceeds due to the opening of large access holes in the outer skin. No cenosphere-type particle is seen in either high ash or low ash chars; this suggests the combustion most likely proceeds by the shrinking core mechanism. The highly burned chars are shown in Figure 20 (bottom). The high ash sample (bottom left) had lost about 72% of its original weight (about 95% ash in char) the mass are predominately pure ash particles spherical in shape. For the low ash sample (bottom right) the weight loss

Figure 18 RELATION BETWEEN SURFACE REACTION RATE COEFFICIENT AND GAS TEMPERATURE FOR THE DTFS CHARS

1000 x MAGNIFICATION
RAW FUEL, HIGH ASH RESIDUE

1000 x MAGNIFICATION
RAW FUEL, LOW ASH RESIDUE

500 x MAGNIFICATION
PYROLYZED CHAR, HIGH ASH RESIDUE

1000 x MAGNIFICATION
PYROLYZED CHAR, LOW ASH RESIDUE

Figure 19 SCANNING ELECTRON MICROGRAPHS OF DTFS FEED
AND PYROLYZED CHAR SAMPLES OF THE EDS RESIDUES

200 x MAGNIFICATION
HIGH ASH DTFS CHAR - 4"

200 x MAGNIFICATION
LOW ASH DTFS CHAR - 4"

200 x MAGNIFICATION
HIGH ASH DTFS CHAR - 12"

200 x MAGNIFICATION
HIGH ASH DTFS CHAR - 8"

Figure 20 SCANNING ELECTRON MICROGRAPHS OF DTFS CHARs
FROM VARIOUS REACTION ZONE

was about 83% (about 83% ash in char). Again, the same type of ash particles are observed.

Char Pore Surface Area.

The BET surface areas of the DTFS chars are presented in Table VII. The pore surface areas of ASTM chars are also presented for comparison. Results indicate the BET surface areas of the DTFS chars are consistently lower than the corresponding ASTM chars. The differences are due to the differences in how the chars were made (fixed bed VM char vs. DTFS suspension char, temperature, heating rate, devolatilization medium etc.). However, the total surface areas of the three chars still follow the order of:

High Ash > Low Ash > Kentucky HvBb coal
(48.3) (33.2) (18.6)

This coincides with the relative reactivities of the three chars and indicates that the surface area is a good indicator in explaining char reactivity trends.

4.2.8 NO_x Formation Potential in the DTFS

Nitrogen Conversion in Pyrolysis.

During the Drop Tube Furnace char making process, all three fuels were pyrolyzed in a helium atmosphere. Regular grind fuel was used and the furnace temperature was maintained at highest setting (T_g=2550°F). Fuel nitrogen evolutions during pyrolysis are presented in Table VIII. Results indicate a significant nitrogen enrichment in the volatiles for both high ash residue (70.4%) and low ash residue (68.7%) compared to KHB coal (47.3%).

This information leads to the conclusion that the EDS residues by virtue of their relatively high nitrogen content and the fact that most of it is evolved as volatiles would have a higher NO_x potential than coal under single stage combustion. This is because under these conditions the volatile nitrogen will burn in an air rich environment. However, it is well known that if nitrogen is evolved in the volatiles, the fuel is very amenable to low NO_x

TABLE VII

BET PORE SURFACE AREA OF CHARs

	<u>ASTM CHAR (M²/g)</u>		<u>+200</u>	<u>DTFS CHAR (M²/g)</u>	
				<u>200 x 400</u>	<u>-400</u>
EDS High Ash Residue	53.3	DRY	29.2	32.1	32.7
	133.0	DAF	40.6	48.3	47.3
EDS Low Ash Residue	30.1	DRY	40.8	26.3	22.8
	64.8	DAF	45.2	33.2	30.2
Kentucky HvBb Coal	32.5	DRY	20.1	16.1	15.8
	36.9	DAF	23.0	18.6	18.7

TABLE VIII
FUEL NITROGEN EVOLUTION DURING PYROLYSIS IN THE DTFS

Fuel	%N in Fuel		ASTM Volatile		DTFS Volatile ⁽¹⁾		%N Released ⁽²⁾ in DTFS volatile ($\frac{\text{N in vol.}}{\text{N in fuel}} \times 100$)
	Dry	DAF	Dry	DAF	Dry	DAF	
EDS High Ash	1.3	1.8	36.5	49.6	23.0	34.9	70.4
EDS Low Ash	1.5	1.7	42.5	49.8	33.0	42.2	68.7
Kentucky HvBb Coal	1.3	1.4	33.6	37.3	31.5	36.3	47.3

1. From DTFS char analysis, using ash as a tracer.
2. In DTFS at 2550°F gas temperature in helium atmosphere.

concepts such as staged combustion.

The DTFS results also indicate that the high ash residue yields significantly lower DTFS volatiles (35% dry-ash-free basis) compared to ASTM volatile yield (50% dry-ash-free basis). The difference in volatile yields may be due to the condensation of carbonaceous material from the volatiles that were subsequently collected with the char in the DTFS yet are not recoverable in the ASTM volatile matter determination procedure.

NO_x Emissions During Combustion. The DTFS NO_x emissions are presented in Table IX. Results indicate within 1850°F to 2600°F temperature range, both high ash and low ash residues yielded slightly lower NO_x than the KHB coal (0.6 to 1.6 lb NO₂/MMBtu for the high ash, 1.2 to 1.5 lb NO₂/MMBtu for the low ash compared to 1.1 to 2.0 lb NO₂/MMBtu for the KHB coal). Because of the ignition/volatile combustion delay at the lower temperatures, for the high ash residue, the higher numbers should be used in assessing DTFS NO_x potential. The high ash residue contained 1.3% fuel-bound nitrogen compared to 1.5% for the low ash residue and 1.3% for the KHB coal. Figure 21 shows the effect of temperature on NO_x emissions for the three fuels. Results indicate that although the high ash residue had the lowest potential in NO_x formation at low temperatures, it is more temperature sensitive than the other two fuels and gives comparable NO_x at high temperature (i.e., when it does not experience a volatile combustion delay). Thus, the EDS residues yield slightly less NO_x than the high volatile bituminous coal in the DTFS at the higher temperatures tested. It should be noted that the DTFS yields higher NO_x values than in the field because of its oxygen rich environment. The relationship between the DTFS and field NO_x is yet to be determined.

Earlier, pyrolysis results indicated that the EDS residues had significant fuel nitrogen enrichment in the volatiles, that is, more fuel-bound nitrogen would be released in the early stages of combustion. This indicates that the EDS residues would have a relatively high NO_x potential during single stage combustion but would be amenable to low NO_x measures such as staged combustion.

TABLE IX

FUEL NO_x FORMATION IN THE DTFS
FOR EDS RESIDUES AND REFERENCE COAL AT VARIOUS TEMPERATURES

Combustion Medium: Air
Low Temp. Tg = 1870°F
Intermediate Temp. Tg = 2280°F
High Temp. Tg = 2580°F

	<u>EDS HIGH ASH</u>			<u>EDS LOW ASH</u>			<u>KENTUCKY HvBb COAL</u>		
	<u>Lo</u>	<u>Int.</u>	<u>Hi</u>	<u>Lo</u>	<u>Int.</u>	<u>Hi</u>	<u>Lo</u>	<u>Int.</u>	<u>Hi</u>
Gas Feed Rate (l/min)	14.5	14.0	14.8	14.5	13.6	13.2	14.3	12.5	14.9
Fuel Feed Rate (gm/min)	.094	.11	.11	.095	.093	.085	.074	.077	.077
NO _x Measured (ppm)	23	35	70	51	61	66	36	55	68
<hr/>									
% Fuel Nitrogen* Converted to NO _x	15.2	20.0	43.1	30.7	40.7	44.0	27.7	42.3	52.3
DTFS Emissions (lb NO ₂ /MMBtu)	0.6	0.8	1.6	1.2	1.3	1.5	1.1	1.4	2.0

* Assuming no thermal NO_x formation.

Figure 21 EFFECT OF TEMPERATURE ON NO_x EMISSION
IN THE DTFS FOR THE EDS RESIDUES AND
REFERENCE COAL

4.3 Pulverization Tests

As part of the original test program a large (20 Ton) sample of EDS low ash residue was evaluated during pilot-scale testing. Pulverization tests were conducted on this sample prior to test firing, as well as longer term pulverization runs to provide fuel for subsequent test firing. In addition, based upon the results of the bench-scale tests, a sample of high ash residue was obtained and evaluated during pulverization tests. All large-scale pulverization tests were conducted in a small C-E (Model #271) bowl mill. (See Appendix D for description of the pulverization system.) This mill operates in the same fashion as commercial C-E bowl mills, and can be used to detect potential pulverization problems as well as determine relative pulverization characteristics.

Both the high ash and low ash residue were successfully pulverized in the #271 mill without special conditions. There were no significant pulverization problems observed during pulverization with either the low or high ash samples. Significant fuel compaction/pasting of mill surfaces was not evident during any of the testing.

Low Ash Residue Testing

Test conditions evaluated during the pulverization testing with the low ash sample are summarized below.

<u>Additional Moisture</u>	<u>Mill Inlet Temp.</u>	<u>Mill Outlet Temp.</u>	<u>Fuel Fineness (% <200 Mesh)</u>	<u>Pasting Compaction</u>
1%	<150°F	110°F	>75%	None
1%	300-500°F	140°F	>75%	None
0	Ambient	--	>75%	Slight*
0	<150°F	110°F	>75%	None
0	250-350°F	140°F	>75%	None
0	350-400°F	160°F	>75%	None

*Due to insufficient inlet temperature to remove the surface moisture.

Testing was initially conducted with a small percentage (1%) of additional moisture. This moisture was injected to act as a heat sink to reduce the probability of particle melting and to provide more uniform heating/temperature within the mill. After successful pulverization with addition of moisture, tests were conducted without supplemental moisture.

Mill outlet temperatures during all tests were controlled at the desired level through automatic throttling of mill inlet temperature. Fuel feed rates were run between 50% and 100% of normal maximum capacity; the typical feed rate was approximately 1500 lb/hr. Fuel fineness was controlled through adjustment of classifier vanes, however, during preliminary mill setup it was found that even when set for the coarsest grind, the size distribution of the pulverized fuel was finer than 75% minus 200 mesh.

The primary result of the low ash residue pulverization tests is a demonstration of the ability to successfully pulverize this material in a bowl mill at typical operating temperatures without any supplemental moisture. There was no evidence of residue melting within the mill nor observation of significant pasting/compaction of residue which may interfere with grinding at any of the conditions tested. The residue was very easy to grind, and mill power requirements were relatively low. Pulverization of the residue resulted in unusually fine particle size distributions. Minimum classifier settings resulted in more than 75% of the pulverized fuel smaller than 200 mesh (75 microns). These pulverization characteristics did not vary during pulverization of more than 20 Tons (approximately 30 hrs) and no pulverizing problems were experienced over the entire test period.

High Ash Residue Testing

The high ash sample of EDS residue was tested under a similar matrix as the low ash sample. Test conditions during the evaluation are summarized on the following page.

<u>Additional Moisture</u>	<u>Mill Inlet Temp., °F</u>	<u>Mill Outlet Temp., °F</u>	<u>Fuel Fineness (% <200 Mesh)</u>	<u>Pasting/ Compaction</u>
0	Ambient	--	>70%	Slight*
0	<150	110	>70%	None
0	≈325	140	>70%	None
0	≈425	160	>70%	None
0	≈500	180	>70%	None

Tests with the high ash sample were conducted without supplemental moisture, because initial tests (without moisture addition) did not reveal potential pasting problems. Pulverization characteristics of the high ash sample were very similar to those of the low ash sample. The residue was very easy to grind as reflected by the low relative mill power requirements, and was very easily reduced to fine particle size distribution. Fuel pasting/compaction was not evident with mill temperatures up to 500°F inlet drying air and 180°F mill outlet temperature.

Analytical data on the low and high ash samples used during the pulverization tests are summarized in Table X. The low ash sample varied little from the low ash sample (once through bottoms) used during the bench-scale tests, however, the high ash (recycle vacuum bottoms) used during the pulverization tests contained only 15.8% ash. This high ash sample was obtained during low yield periods, and how well the grinding characteristics of this sample represent those of the commercial bottoms must be considered. The behavior of the high ash (15.8% ash) pulverization test sample and the high ash (26.5%) bench test sample were very similar in the Hardgrove apparatus. In each case, the high ash (recycled bottoms) samples indicated slightly higher tendencies to paste than the low ash samples. Although not totally conclusive, results of pulverization tests coupled with the bench-scale tests indicate (with a relatively high level of confidence) that high ash EDS residues with similar properties as the bench test sample (26.5% ash) can be successfully pulverized in a C-E bowl mill without use of any special conditions.

*Due to insufficient inlet temperature to remove the surface moisture.

TABLE X

FUEL ANALYSIS FROM
PULVERIZATION TESTS
EDS RESIDUE

SAMPLE	LOW ASH RESIDUE	HIGH ASH RESIDUE
Proximate, Wt. %		
Moisture	0.1	0.1
Volatile Matter	45.9	50.7
Fixed Carbon	39.1	33.4
Ash	15.0	15.8
HH, Btu/lb	13050	12860
Ultimate, Wt. %		
Moisture	0.1	0.1
Hydrogen	4.7	4.6
Carbon	72.2	71.0
Sulfur	2.6	2.5
Nitrogen	1.4	1.4
Oxygen (Dif.)	4.1	4.6
Ash	15.0	15.8
Ash Composition, Wt. %		
SiO ₂	40.3	53.0
Al ₂ O ₃	15.3	17.7
Fe ₂ O ₃	19.0	17.5
CaO	5.3	4.8
MgO	0.9	0.9
Na ₂ O	1.7	1.5
K ₂ O	1.6	1.7
TiO ₂	1.0	0.9
SO ₃	<u>4.6</u>	<u>3.6</u>
TOTAL	97.7	101.6

4.4 Fireside Performance Testing

4.4.1 Test Conditions

EDS low ash residue was evaluated during a series of three test runs conducted at different firing rates in C-E's Fireside Performance Test Facility. (See Appendix D for detailed facility description.) The span of each test run was approximately 60 hrs during which time more than 40 consecutive hours of coal firing was conducted. Typical furnace operating data for each run is summarized in Table XI. The high, intermediate and low firing rates correspond to total heat inputs of 3.67×10^6 , 2.95×10^6 , and 2.25×10^6 Btu/Hr, respectively. Fuel feed rates ranged from 254 to 154 lb/Hrs of pulverized residue. No supplementary fuel was burned during any of the testing periods. (See Appendix E for detailed description of Test Procedures.)

Testing at three different firing rates allows evaluations of deposit characteristics over a broad range of important design/operating parameters such as gas temperature, gas velocity, heat release rate, etc. Gas temperatures present in various elevations of the furnace and convection sections are shown in Figures 22 thru 24, for respective runs. Convective section gas temperatures entering test probe banks ranged from 2190° to 1390° F during the series of evaluations. Values in Table VI represent the average gas temperatures during the deposit buildup test segment of each run. The range of gas temperatures from Probe Bank I to IV was roughly 500° F within a particular firing rate. Convection section gas temperatures were fairly uniform as temperatures generally fluctuated less than 100° F at a given location during each firing rate. The pulsating nature of the coal flame produced momentary fluctuations in gas temperatures as high as 50° F. The gas velocity in the superheater duct is a function of mass flow rate and gas temperature. The calculated gas velocities entering the convection probe bank in each respective duct are listed in Table XI. The overall range

TABLE XI
TYPICAL OPERATING DATA
EDS RESIDUE
FPTF RESULTS

Test Run Firing Rate	1	2	3
	High	Inter	Low
<u>COMBUSTION DATA</u>			
Total Heat Input(Btu/hr)	3.67X10 ⁶	2.95X10 ⁶	2.25X10 ⁶
Coal Feed Rate (lb/Hr)	254	200	154
Primary Air Flow (lb/Hr)	297	329	247
Secondary Air Flow(lb/Hr)	2,580	2,010	1,470
Furnace Pressure ("H ₂ O)	-0.35	-0.35	-0.35
Furnace Residence Time(Sec.)	1.5	1.8	2.8
Flue Gas Analysis(% Vol.)			
O ₂	4.8	3.7	2.8
CO ₂	13.0	13.8	12.3
H ₂ O	7.0	7.3	6.7
SO ₂	0.2	0.2	0.2
N ₂	75.0	75.0	75.2
<u>WATERWALL TEST PANEL</u>			
Metal Temp. (°F)	700	700	700
Coolant Inlet Temp.(°F)	421	394	444
Coolant Outlet Temp.(°F)	444	430	464
Coolant Flow(gpm)	8.0	7.1	9.0
Furnace Gas Temp.(°F)	2530	2480	2200
NHI/PA(Btu/Hr-Ft ³)	.46X10 ⁶	.36X10 ⁶	.28X10 ⁶
Vol. Heat Release(Btu/Hr-Ft ³)	33.3X10 ³	26.2X10 ³	20.2X10 ³
<u>CONVECTION PROBES</u>			
Metal Temp.(All Banks,°F)	1100	1100	1100
Gas Temperature			
Duct I	2190	2160	1810
Duct II	2080	1940	1680
Duct III	1800	1700	1550
Duct IV	1620	1510	1380
Gas Velocity			
Duct I	57	46	29
Duct II	55	42	28
Duct III	49	38	26
Duct IV	45	35	24

FURNACE GAS TEMPERATURE PROFILE
EDS RESIDUE
FPTF TEST RESULTS
HIGH FIRING RATE: RUN 1

Figure 22

FURNACE GAS TEMPERATURE PROFILE
EDS RESIDUE
FPTF RESULTS
INTERMEDIATE FIRING RATE: RUN 2

Figure 23

FURNACE GAS TEMPERATURE PROFILE
EDS RESIDUE
FPTF RESULTS
LOW FIRING RATE: RUN 3

Figure 24

in gas velocities was 57 to 24 ft/sec.

Furnace gas temperatures varied with firing rate. The typical flame temperatures measured at the level of the waterwall panel (3 ft. above the burner) were 2530⁰, 2480⁰, and 2290⁰F during the representative standard firing rates. Typical furnace refractory wall temperatures ranged from 1500⁰ to 2000⁰F. Fluid, molten slag was generated on furnace refractory walls during each firing rate. The thickness of refractory deposits varied with firing rate and location. In general, deposits varied from 1 to 3 inches thick, with the greatest thickness occurring at the lower gas temperatures. The estimated lower furnace residence time ranged from 1.5 to 2.8 seconds. Calculated values for the Volumetric Heat Release Rate and the Net Heat Input/Plan Area are listed in Table XI. The size and geometry of the test furnace must be taken into account when viewing these values. The Volumetric Heat Release Rate was calculated for the entire furnace chamber. These values are expected to be considerably lower than the actual heat release rate seen by the waterwall panel, since the panel is located at the intense portion of the flame. The flame front was maintained between 6 to 12 inches above the burner during all evaluations, and a luminous flame typically filled between 40 and 70 percent of the furnace cavity.

Flame stability was generally good throughout the tests. A water-cooled burner and fuel transport line was used during the tests, however, the burner face was refractory material. EDS residue built up on this refractory face and required cleaning frequently (roughly every 30 mins.) to maintain proper flame stability. Residue buildup on the burner consisted of a friable coke/carbon deposit. This material built up more rapidly at the higher temperatures associated with the high firing rate, but was more of an interfering factor during low firing rate where flame stability is much more sensitive. Based upon visual observations the

EDS residue appeared to ignite easily and burn rapidly once properly dispersed into the furnace. The coking problems encountered during these tests are specific to the test hardware, however, they do indicate the need to properly cool surfaces in commercial burner arrangements. The coking of fuel on the burner face occurred during previous testing of other low melting temperature solvent derived fuels.

Figures 25 through 27 summarize the mass and energy balances for the FPTF during each run. These calculations include all furnace mass flows, and account for heat flows from the burner to the first probe bank in the convection section. The distribution of heat leaving the furnace varied with firing rate. The heat loss through the lower furnace refractory wall accounted for between 4% and 6% of the heat input. The percentage of heat absorbed in the lower furnace remained relatively constant with firing rate. The quantity of heat absorbed by the waterwall panel was also approximately 4% to 6% the total heat input. The water-cooled burner and other water-cooled sections in the lower furnace accounted for between 10% and 20% of the heat. The heat absorbed by the water-cooled sections of the upper furnace represented between 11% and 13% of the total heat input. The heat remaining in the flue gas varied from 51% to 38% of the heat input as total heat input increased from 3.67×10^6 to 2.25×10^6 Btu/hr. The furnace heat flow distributions during these runs were similar to those typically obtained with coal at similar rates, however, slightly more heat was absorbed in the lower furnace.

The ratio of fly ash-to-bottom ash varied significantly with firing rate. The percentage of fly ash increased with firing rate as the split between fly ash and bottom ash varied from 43% fly ash/57% bottom ash at the low rate to 54% fly ash/46% bottom ash at the high rate. These values are based on dust loadings isokinetically sampled from the furnace outlet duct, and the weight of bottom ash collect during the

FURNACE MASS AND ENERGY BALANCES

FPTF RESULTS

EDS RESIDUE

Figure 25

FURNACE MASS AND ENERGY BALANCES

FPTF RESULTS

EDS RESIDUE

Figure 26

FURNACE MASS AND ENERGY BALANCES

FPTF RESULTS

EDS RESIDUE

Figure 27

respective test. The ratio of fly ash-to-bottom ash obtained in the FPTF does not directly correspond to those obtained in commercial boilers, since both surface-to-volume ratios and wall temperatures differ widely between this test furnace and a boiler. In general, a relatively high percentage of bottom ash was produced during the subject FPTF tests. Explanation for this is the high rate of ash deposition in the lower furnace due to low melting slag produced. Since similar quantities of slag were generated on refractory walls at each firing rate, the percent removed in this manner was greater at the low inputs.

Tables XII through XIV show computer printouts of furnace mass and energy balances corresponding to Figures 25 through 27 respectively. Two methods of calculations are shown. The primary difference between the two methods is the manner in which the total combustion air is calculated. Method 1 is based on measured secondary and primary air flow rates. Values from Method 2 are calculated based on the measured oxygen concentration in the flue gas and the coal input. Method 2 is normally used as a check.

The overall variation between the methods can be seen by comparing the percentages of heat unaccounted for. Heat unaccounted for ranged from 7 to 23 percent of the total heat input. Differences in the percentage of heat unaccounted for (within a test) was less than 8%. The primary difference occurred in the heat remaining in the flue gas. Heat losses unaccounted for are generally associated with radiation losses from the furnace exterior. Heat unaccounted for during the subject tests were higher than typically observed. Calculations (both methods) are based on 100% carbon consumption. Carbon content of the fly ash was measured at approximately 2.0%. However, this quantity of unburned carbon represented a very small heat loss (less than 5400 Btu/hr), which

TABLE XII
FPTF Mass and Energy Balances
at High Firing Rate

METHOD 1-----	EDS Residue		
FLUE GAS FLOW RATE LB/HR		.251E+04	
COMPOSITION IN MOLES/HR			
OXYGEN	.276E+01		3.27
CARBON DIOXIDE	.120E+02		14.19
WATER	.632E+01		7.47
SULFUR DIOXIDE	.163E+00		.19
NITROGEN	.633E+02		74.88
METHOD 1-----			
HEAT LOSS FROM REFRACTORY BTU/HR	.180E+06		6.12
HEAT LOSS FROM PANEL	.574E+05		1.95
HEAT LOSS FROM WATER COOLED FRAME	.861E+05		2.92
HEAT LOSS FROM W.W. COIL	.119E+06		4.03
HEAT LOSS FROM FLY ASH	.731E+04		.25
HEAT LOSS FROM FLUE GAS	.149E+07		50.59
HEAT LOSS FROM ROOF	.478E+05		1.62
HEAT LOSS FROM S.H. TRANSITION	.120E+06		4.09
HEAT LOSS FROM S.H. FRAME	.796E+05		2.70
HEAT LOSS FROM S.H. DUCT	.138E+06		4.68
HEAT LOSS FROM OBS. PORT	.528E+05		1.79
HEAT LOSS FROM BURNER	.979E+05		3.32
HEAT LOSS FROM FURNACE BOTTOM LEFT	.664E+05		2.25
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.541E+05		1.83
METHOD 2-----			
FLUE GAS FLOW RATE LB/HR	.257E+04		
COMPOSITION IN MOLES/HR			
OXYGEN	.321E+01		3.70
CARBON DIOXIDE	.120E+02		13.84
WATER	.636E+01		7.33
SULFUR DIOXIDE	.163E+00		.19
NITROGEN	.650E+02		74.94
METHOD 2-----			
HEAT LOSS FROM REFRACTORY BTU/HR	.180E+06		6.12
HEAT LOSS FROM PANEL	.574E+05		1.95
HEAT LOSS FROM WATER COOLED FRAME	.861E+05		2.92
HEAT LOSS FROM W.W. COIL	.119E+06		4.03
HEAT LOSS FROM FLY ASH	.731E+04		.25
HEAT LOSS FROM FLUE GAS	.153E+07		51.84
HEAT LOSS FROM ROOF	.478E+05		1.62
HEAT LOSS FROM S.H. TRANSITION	.120E+06		4.09
HEAT LOSS FROM S.H. FRAME	.796E+05		2.70
HEAT LOSS FROM S.H. DUCT	.138E+06		4.68
HEAT LOSS FROM OBS. PORT	.528E+05		1.79
HEAT LOSS FROM BURNER	.979E+05		3.32
HEAT LOSS FROM FURNACE BOTTOM LEFT	.664E+05		2.25
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.541E+05		1.83
METHOD 1-----	TOTAL HEAT INPUT BTU/HR	.295E+07	
	TOTAL HEAT OUTPUT BTU/HR	.268E+07	
	HEAT UNACCOUNTED FOR	9.03	
METHOD 2-----	TOTAL HEAT INPUT ,BTU/HR	.295E+07	
	TOTAL HEAT OUTPUT ,BTU/HR	.272E+07	
	HEAT UNACCOUNTED FOR	7.78	
METHOD 1-----	TOTAL MATERIAL INPUT LB/HR	.254E+04	
	TOTAL MATERIAL OUTPUT LB/HR	.254E+04	
	MATERIAL UNACCOUNTED FOR	-.02	
METHOD 2-----	TOTAL MATERIAL INPUT LB/HR	.260E+04	
	TOTAL MATERIAL OUTPUT LB/HR	.260E+04	
	MATERIAL UNACCOUNTED FOR	.00	
.257 CP SECONDS EXECUTION TIME			76

TABLE XIII
FPTF Mass and Energy Balances
at Intermediate Firing Rate
EDS Residue

METHOD 1-----		
FLUE GAS FLOW RATE LB/HR	.309E+04	
COMPOSITION IN MOLES/HR		
OXYGEN	.278E+01	2.67
CARBON DIOXIDE	.152E+02	14.67
WATER	.796E+01	7.66
SULFUR DIOXIDE	.206E+00	.20
NITROGEN	.777E+02	74.80
METHOD 1-----		
HEAT LOSS FROM REFRACTORY BTU/HR	.146E+06	3.97
HEAT LOSS FROM PANEL	.434E+05	1.18
HEAT LOSS FROM WATER COOLED FRAME	.112E+06	3.05
HEAT LOSS FROM W.W. COIL	.103E+06	2.80
HEAT LOSS FROM FLY ASH	.102E+05	.28
HEAT LOSS FROM FLUE GAS	.186E+07	50.83
HEAT LOSS FROM ROOF	.464E+05	1.26
HEAT LOSS FROM S.H. TRANSITION	.139E+06	3.79
HEAT LOSS FROM S.H. FRAME	.100E+06	2.73
HEAT LOSS FROM S.H. DUCT	.169E+06	4.62
HEAT LOSS FROM OBS. PORT	.410E+05	1.12
HEAT LOSS FROM BURNER	.907E+05	2.47
HEAT LOSS FROM FURNACE BOTTOM LEFT	.621E+05	1.69
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.506E+05	1.38
METHOD 2-----		
FLUE GAS FLOW RATE LB/HR	.349E+04	
COMPOSITION IN MOLES/HR		
OXYGEN	.565E+01	4.80
CARBON DIOXIDE	.152E+02	12.95
WATER	.822E+01	6.98
SULFUR DIOXIDE	.206E+00	.18
NITROGEN	.884E+02	75.09
METHOD 2-----		
HEAT LOSS FROM REFRACTORY BTU/HR	.146E+06	3.97
HEAT LOSS FROM PANEL	.434E+05	1.18
HEAT LOSS FROM WATER COOLED FRAME	.112E+06	3.05
HEAT LOSS FROM W.W. COIL	.103E+06	2.80
HEAT LOSS FROM FLY ASH	.102E+05	.28
HEAT LOSS FROM FLUE GAS	.211E+07	57.44
HEAT LOSS FROM ROOF	.464E+05	1.26
HEAT LOSS FROM S.H. TRANSITION	.139E+06	3.79
HEAT LOSS FROM S.H. FRAME	.100E+06	2.73
HEAT LOSS FROM S.H. DUCT	.169E+06	4.62
HEAT LOSS FROM OBS. PORT	.410E+05	1.12
HEAT LOSS FROM BURNER	.907E+05	2.47
HEAT LOSS FROM FURNACE BOTTOM LEFT	.621E+05	1.69
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.506E+05	1.38
METHOD 1-----		
TOTAL HEAT INPUT BTU/HR	.367E+07	
TOTAL HEAT OUTPUT BTU/HR	.308E+07	
HEAT UNACCOUNTED FOR	15.93	
METHOD 2-----		
TOTAL HEAT INPUT ,BTU/HR	.367E+07	
TOTAL HEAT OUTPUT ,BTU/HR	.333E+07	
HEAT UNACCOUNTED FOR	9.32	
METHOD 1-----		
TOTAL MATERIAL INPUT LB/HR	.313E+04	
TOTAL MATERIAL OUTPUT LB/HR	.313E+04	
MATERIAL UNACCOUNTED FOR	-.02	
METHOD 2-----		
TOTAL MATERIAL INPUT LB/HR	.352E+04	
TOTAL MATERIAL OUTPUT LB/HR	.352E+04	
MATERIAL UNACCOUNTED FOR	.00	
.252 CP SECONDS EXECUTION TIME		

TABLE XIV
FPTF Mass and Energy Balances
at Low Rating Rate

METHOD 1-----	EDS Residue	
FLUE GAS FLOW RATE LB/HR	.185E+04	
COMPOSITION IN MOLES/HR		
OXYGEN	.151E+01	2.43
CARBON DIOXIDE	.924E+01	14.87
WATER	.481E+01	7.74
SULFUR DIOXIDE	.125E+00	.20
NITROGEN	.465E+02	74.76
METHOD 1-----		
HEAT LOSS FROM REFRACTORY BTU/HR	.124E+06	5.52
HEAT LOSS FROM PANEL	.424E+05	1.88
HEAT LOSS FROM WATER COOLED FRAME	.847E+05	3.76
HEAT LOSS FROM W.W. COIL	.110E+06	4.87
HEAT LOSS FROM FLY ASH	.193E+04	.09
HEAT LOSS FROM FLUE GAS	.873E+06	38.82
HEAT LOSS FROM ROOF	.356E+05	1.58
HEAT LOSS FROM S.H. TRANSITION	.715E+05	3.18
HEAT LOSS FROM S.H. FRAME	.645E+05	2.87
HEAT LOSS FROM S.H. DUCT	.833E+05	3.70
HEAT LOSS FROM OBS. PORT	.304E+05	1.35
HEAT LOSS FROM BURNER	.810E+05	3.60
HEAT LOSS FROM FURNACE BOTTOM LEFT	.506E+05	2.25
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.419E+05	1.86
METHOD 2-----		
FLUE GAS FLOW RATE LB/HR	.222E+04	
COMPOSITION IN MOLES/HR		
OXYGEN	.421E+01	5.60
CARBON DIOXIDE	.924E+01	12.30
WATER	.505E+01	6.73
SULFUR DIOXIDE	.125E+00	.17
NITROGEN	.565E+02	75.20
METHOD 2-----		
HEAT LOSS FROM REFRACTORY BTU/HR	.124E+06	5.52
HEAT LOSS FROM PANEL	.424E+05	1.88
HEAT LOSS FROM WATER COOLED FRAME	.847E+05	3.76
HEAT LOSS FROM W.W. COIL	.110E+06	4.87
HEAT LOSS FROM FLY ASH	.193E+04	.09
HEAT LOSS FROM FLUE GAS	.105E+07	46.61
HEAT LOSS FROM ROOF	.356E+05	1.58
HEAT LOSS FROM S.H. TRANSITION	.715E+05	3.18
HEAT LOSS FROM S.H. FRAME	.645E+05	2.87
HEAT LOSS FROM S.H. DUCT	.833E+05	3.70
HEAT LOSS FROM OBS. PORT	.304E+05	1.35
HEAT LOSS FROM BURNER	.810E+05	3.60
HEAT LOSS FROM FURNACE BOTTOM LEFT	.506E+05	2.25
HEAT LOSS FROM FURNACE BOTTOM RIGHT	.419E+05	1.86
METHOD 1-----	TOTAL HEAT INPUT BTU/HR	.225E+07
	TOTAL HEAT OUTPUT BTU/HR	.176E+07
	HEAT UNACCOUNTED FOR	21.81
METHOD 2-----	TOTAL HEAT INPUT ,BTU/HR	.225E+07
	TOTAL HEAT OUTPUT ,BTU/HR	.193E+07
	HEAT UNACCOUNTED FOR	14.01
METHOD 1-----	TOTAL MATERIAL INPUT LB/HR	.187E+04
	TOTAL MATERIAL OUTPUT LB/HR	.187E+04
	MATERIAL UNACCOUNTED FOR	-.02
METHOD 2-----	TOTAL MATERIAL INPUT LB/HR	.224E+04
	TOTAL MATERIAL OUTPUT LB/HR	.224E+04
	MATERIAL UNACCOUNTED FOR	.00

.249 CP SECONDS EXECUTION TIME

is equivalent to less than 0.2% of the total heat input for each firing rate.

4.4.2 Test Fuel

The EDS residue which was pulverized and test fired in the FPTF represents the vacuum bottoms from the once-through process using Illinois #6 - Monterey feed coal. As-fired pulverized residue analyses of feeder samples for the three runs are given in Table XV. Each sample consisted of a composite of samples taken hourly during the respective test run. Proximate and ultimate analyses of the feed was very consistent through all tests, and were essentially the same as that of the bench-scale sample discussed earlier. Overall, the most significant characteristics reflected by this data is the low moisture and high volatile matter content which would tend to promote ignition and flame stability.

Screen analyses of the feed samples show approximately 78% of the fuel was less than 200 mesh. The pulverized residue was slightly finer than typically fired bituminous coals, however, this grind is expected to be representative because of the pulverization characteristics (easy grinding) of the residue.

Table XVI summarize as-fired ash analyses for the three runs. Ash compositions were similar during the runs. The Run 3 (Low Firing Rate) sample had slightly higher alumina content and slightly lower sodium and calcium contents than the samples from Runs 1 and 2. This variation in ash composition is the apparent reason for the difference in ash fusibility temperatures in the Run 3 feed. Ash softening temperatures of the ash samples from Run 3 were higher than those for Run 1 and 2, and fluid temperatures were lower. The increase in softening

TABLE XV
AS-FIRED PULVERIZED FUEL ANALYSES
EDS RESIDUE
FPTF RESULTS

SAMPLE Run Firing Rate	1	2	3
	High	Inter.	Low
<u>PROXIMATE, WT. %</u>			
Moisture	< 0.1	< 0.1	< 0.1
Volatile Matter	46.1	45.9	45.5
Fixed Carbon	39.2	39.1	39.5
Ash	14.7	15.0	14.9
Total	100.0	100.0	100.0
HHV, Btu/lb.	13010	12990	1300
Lb. Ash/mm Btu	11.3	11.5	11.5
<u>ULTIMATE</u>			
Moisture	< 0.1	< 0.1	< 0.1
Hydrogen	4.6	4.7	4.7
Carbon	72.2	72.2	71.8
Sulfur	2.6	2.6	2.5
Nitrogen	1.4	1.4	1.4
Oxygen (dif.)	4.5	4.1	4.8
Ash	14.7	15.0	14.9
Total	100.0	100.0	100.0
<u>SCREEN ANALYSIS</u>			
±50 Mesh	1.0	0.8	0.8
50 x 100 Mesh	6.2	6.4	6.5
100 x 200 Mesh	14.3	15.6	14.8
-200 Mesh	78.5	77.2	77.9

TABLE XVI
AS-FIRED FUEL ASH ANALYSES
EDS RESIDUE
FPTF RESULTS

SAMPLE	1	2	3
Run			
Firing Rate	High	Inter.	Low

ASH FUSIBILITY

I.T.(°F)	1900	1980	2130
S.T.(°F)	2010	2010	2170
H.T.(°F)	2120	2120	2310
F.T.(°F)	2500	2520	2390

ASH COMPOSITION

SiO ₂	48.8	48.3	47.3
Al ₂ O ₃	15.5	15.3	17.7
Fe ₂ O ₃	19.4	19.0	19.5
CaO	5.3	5.3	4.8
MgO	1.0	0.9	0.9
Na ₂ O	1.8	1.7	1.4
K ₂ O	1.8	1.6	1.5
TiO ₂	1.0	1.0	1.3
SO ₃	4.5	4.6	4.4
Base/Acid Ratio	0.45	0.44	0.42
Fe ₂ O ₃ /CaO Ratio	3.66	3.58	4.06
SiO ₂ /Al ₂ O ₃ Ratio	3.15	3.16	2.67

temperatures in Run 3 could be somewhat explained by the reduction of fluxing constituents (Na, Ca); however, the reduction of fluid temperature is difficult to explain.

- ④ Overall, ash analyses of the as-fired fuel vary little from the bench-scale sample discussed earlier. The low fusibility temperatures and the high iron content of the ash indicates high slagging potential. The low alkali and alkaline earth contents indicate low fouling potential.

4.4.3 Convection Section Deposition

Overall, the ash fouling characteristics of the subject residue can be classified as low. The rate of convection probe deposit buildup was relatively low. Deposits were generally friable and weakly bonded to tube surfaces over the entire range in gas temperatures studied (2190^o to 1380^oF). Convection probe deposition was very light below gas temperatures of 1900^oF. The observed ash fouling characteristics of the EDS low ash residue were less severe than the vast majority of coals tested under similar conditions, and were comparable to those of the low fouling eastern bituminous coal tested. Fouling characteristics of the residue were very similar to those of a previously tested low fouling Illinois coal.

Convection probe deposition was evaluated by determining deposit buildup rates, measuring deposit bonding strengths coupled with observations depicting the physical characteristics of the deposits. Ash deposit buildup rates on convection probes were quantified by two methods: (1) - Deposit buildup tests; (2) - Pressure drop tests. See Appendix E for a detailed description of these tests.

Deposit Buildup Tests

Deposit buildup tests consisted of a standard eight hour period during

which time superheater deposits were allowed to grow undisturbed. At the conclusion of this test, the furnace was shut down and deposits from all four probe banks were quantitatively collected and weighed. The mass of deposits collected during this standard period was the prime concern.

Table XVII summarizes results of deposit buildup tests conducted at each firing rate. Photographs in Figures 28 through 30 illustrate the corresponding deposits accumulated in ducts containing each probe bank at the completion of the buildup test. The deposits present in the duct do not in all cases express the actual quantity of deposit generated on that probe bank during the eight hour collection period. In some cases, deposits which were generated on upstream surfaces sloughed off and were carried downstream with the gas flow to lodge against the probe bank. The reason for this interference is related to the ash fouling characteristics of the fuel. Upper furnace deposits had relatively low bonding strengths. As a deposit builds out from the tube surface, the shear force at the surface increases due to the increased weight. When the bond between the deposit and the surface is not strong enough to support the increasing weight, the deposit will then slough off.

Also observed during the tests, was an unusually high amount of deposit carryover from the entrance to the convection sections. This condition has only been observed with a few of the many fuels tested in the facility. The reason it occurred during this test was again related to the nature of the deposits generated. Although the ash fouling (convection section) deposition of the residue was low, the ash slagging (radiant section) tendencies were relatively high. Deposits built up rapidly in the higher gas temperature transition sections between the furnace and the convection ducts. This rapid and potentially massive deposit growth had to be frequently cleaned back into the furnace to reduce interference with the downstream convection test probes. This condition was most severe during the intermediate firing rate run which was chronologically conducted first. Based upon the results of this run, additional provisions were made to reduce interference during the subsequent tests.

TABLE XVII
CONVECTION DEPOSIT BUILDUP TESTS
EDS RESIDUE
FPTF RESULTS

Run	Firing Rate	Heat Input (Btu/Hr)	Ash Input (Lb/Hr)	Time Collected Hours	Probe Bank	Gas Temp. (°F)	Gas Vel. (ft/sec.)	Deposits Collected (gm)	Normalized Buildup Rate (Lb/Hr-ft ²)
1	High	3.67X10 ⁶	36.8	8.0	I	2190	57	1656	0.654
					II	2080	55	948	0.374
					III	1800	49	104	0.027
					IV	1620	45	113	0.029
2	Inter	2.95X10 ⁶	29.0	8.0	I	2160	46	10,433*	*
					II	1940	42	5,443*	*
					III	1700	38	4,536*	*
					IV	1510	35	3,175*	*
3	Low	2.25X10 ⁶	22.3	8.0	I	1810	29	<150*	*
					II	1680	28	<150*	*
					III	1550	26	<150*	*
					IV	1380	24	<150*	*

* Deposit weights include material from upstream section of the test furnace; actual deposit accumulation significantly less.

SUPERHEATER PROBE DEPOSITS AFTER SHUTDOWN - EDS RESIDUE
HIGH FIRING RATE

Probe Bank I

Front

Probe Bank II

Front

Probe Bank III

Front

Probe Bank IV

Front

Side

Side

Side

Side

Duct

Duct

Duct

Duct

FIGURE 28

SUPERHEATER PROBE DEPOSITS AFTER SHUTDOWN - EDS RESIDUE

INTERMEDIATE FIRING RATE

FIGURE 29

SUPERHEATER PROBE DEPOSITS AFTER SHUTDOWN - EDS RESIDUE

LOW FIRING RATE

Probe Bank I

Front

Probe Bank II

Front

Probe Bank III

Front

Probe Bank IV

Front

Side

Side

Side

Side

Duct

Duct

Duct

Duct

FIGURE 30

Sloughing of weakly bonded convection deposits and carryover of deposits from the furnace outlet also occurred during the testing of Illinois Old Ben #21 coal. This coal has many similar characteristics as the Monterey coal used to produce the residue and, in particular, it would be expected to exhibit similar ash fouling behavior. (See Table XVIII for comparative analysis.)

Due to deposit accumulation on the probes from the carryover of upstream deposits, visual observations of deposit growth on probe surfaces are very important. Comparisons between deposit buildup tests data and visual deposit growth can be drawn from the time-sequence photographs taken during the tests. Photographs depicting deposit buildup during the high firing rate are shown in Figures 31 through 34 and the intermediate firing rate in Figures 35 through 37. Very little deposit buildup occurred during the low firing rate.

Convection deposit growth overall increased as the firing rate increased. Key operating variables affecting ash deposition are gas temperature, gas velocity and ash loading. Varying the firing rate results in changes in all these parameters. The effect of gas temperature (and also the interdependent variable of gas velocity) is illustrated by the variation in deposit buildup on the different probe banks at a particular firing rate (see Figures 31, 32, 33 and 34). During each firing rate, convection probe deposit growth generally decreased from Banks I to IV as the gas temperature decreased. The effect of ash loading (lbs/hr of ash input) requires more interpretation. Comparing deposit growth on convection probes at similar gas temperatures reflects the effects of ash loading. When making comparisons between different firing rates, the variation in gas flow rate, and other possible factors must be considered. In general, probe deposition appeared to increase as ash loading increased with all other factors remaining constant. However, the relatively low deposit buildup rate coupled with less quantitative data from the buildup tests due to upstream interference does not allow definitive conclusions.

TABLE XVIII
COMPARATIVE FUEL ANALYSES
ILLINOIS #6 COAL AND EDS RESIDUE
(AS-FIRED IN FPTF)

SAMPLE	ILLINOIS #6 OLD BEN	EDS RESIDUE LOW ASH
Rank	hV8b	- - -
Moisture (%)	2.6	0.1
Volatile	32.2	46.1
Fixed C	48.1	39.2
Ash	17.1	14.7
HHV (Btu/lb)	11480	13100
Ash Fusibility Temp.		
I.D. (°F)	2030	1980
S.T.	2120	2010
H.T.	2380	2120
F.T.	2670	2500
Ash Composition		
SiO ₂ (% wt.)	54.6	48.8
Al ₂ O ₃	21.4	15.5
Fe ₂ O ₃	9.0	19.4
CaO	4.8	5.3
MgO	1.0	1.0
Na ₂ O	1.1	1.8
K ₂ O	2.3	1.8
TiO	0.9	1.0
SO ₃	4.5	4.5
TOTAL	99.6	99.1

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST
EDS RESIDUE

HIGH FIRING RATE
GAS TEMPERATURE = 1915°F
PROBE BANK II

After 30 Min.

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 31

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST

EDS RESIDUE

HIGH FIRING RATE

GAS TEMPERATURE = 2160°F

PROBE BANK I

After 30 Min.

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 32

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST

EDS RESIDUE

HIGH FIRING RATE
GAS TEMPERATURE = 1740°F
BANK III

After 30 Mins.

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 33

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST

EDS RESIDUE

HIGH FIRING RATE
GAS TEMPERATURE = 1580°F
PROBE BANK IV

After 30 Mins.

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 34

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST

EDS RESIDUE

INTERMEDIATE FIRING RATE
GAS TEMPERATURE = 2120°F
PROBE BANK I

After 1 Hour

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 35

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST

EDS RESIDUE

INTERMEDIATE FIRING RATE
GAS TEMPERATURE = 1710°F
PROBE BANK II

After 1 Hour

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 36

SUPERHEATER PROBE DEPOSITS
DURING BUILD UP TEST

EDS RESIDUE

INTERMEDIATE FIRING RATE
GAS TEMPERATURE = 1630°F
PROBE BANK III

After 1 Hour

After 2 Hours

After 6 Hours

After 8 Hours

FIGURE 37

Gas temperature appeared to have the most predominant influence on convection deposit buildup both in terms of deposit friability and rate of growth. Figure 38 illustrates relative deposit buildup rates as a function of gas temperature for the EDS residues and three previously tested coals. The curve for convection deposit buildup rate during residue firing is based both upon visual observations of deposit growth during the tests and data from the deposit buildup tests. (Plots for the other three coals are based upon quantitative data from the 8 hr buildup tests.) The weight of the deposit collected during the buildup tests were normalized for ash loading and probe collection area. Convection probe deposit buildup has generally shown an exponential relationship with gas temperature (exponentially increased with increasing gas temperature). For most test coals there has been a particular gas temperature region above which deposit growth accelerated rapidly. This temperature has been referred to as the critical gas temperature.

The relative buildup rate of deposit generated from the EDS residue can be classified as low. Deposits generated from the residue did not build up significantly until reaching gas temperatures of approximately 2100°F. Comparing the residue to Coals I and II, its buildup curve falls far to the right reflecting less severe fouling. Coal I is a high fouling subbituminous coal and its curve is representative of a high buildup rate. Coal II is a moderate fouling bituminous coal, and Coal III a low fouling lignite and their plots are representative of moderate and low buildup rates. A plot for Old Ben coal was not presented because of the lack of quantitative data, however, the estimate buildup curve was very similar to that of the residue. Although the curve for the subject residue was estimated, its comparatively low rate of convection deposit buildup and "critical" gas temperature of approximately 2100°F can be established with a fairly high level of confidence based upon both the buildup test data and visual observations.

COMPARATIVE FPTF RESULTS:
RELATIVE CONVECTION DEPOSIT BUILDUP RATES

Figure 38

Pressure Drop Tests

Another method used to determine convection deposit buildup rate was pressure drop tests. The goal of the pressure drop tests is to establish the relative soot blowing frequency of convection deposits in the FPTF. Soot blowing of ash deposits is determined by the increase in pressure drop across the leading probe bank. The shorter the period between soot blowings, the more rapid the deposit growth. Overall, results of the pressure drop tests are in agreement with the buildup tests results previously discussed (both reflecting the low rate of deposit buildup). Table XIX summarizes the results of the pressure drop tests. These results indicate that ash deposits generated from the residue are generally self-cleaning. Deposits tended to slough off after a moderate amount of buildup (maximum observed deposit thickness was approximately 4 inches).

As previously mentioned, deposits generated upstream sometimes interfered with testing on the probe banks. Interference was greatest during the intermediate firing rate run, and necessitated soot blowing after 10-12 hrs (See Figure 39.) However, without deposit interference, probe banks did not require soot blowing to maintain the pressure drop across the probes below the "standard" value over the duration of each testing period (including high firing run).

Bonding Strength Measurements

The relative bonding strength of convection probe deposits was low over the entire range of gas temperatures (1380⁰ through 2190⁰F) studied. Convection deposits bonding strength was evaluated based on the behavior of the deposits during the tests. As discussed, deposits sloughed off at irregular intervals continuously during all tests. Normally deposit bonding strength is measured during the pressure drop tests. The technique

TABLE XIX

CONVECTION DEPOSITS PRESSURE DROP TESTS
 EDS RESIDUE
 FPTF RESULTS

Run	Firing Rate	Heat Input (Btu/Hr)	Ash Input (Lb/Hr)	ΔP Test	Probe Bank	Increase (In. H ₂ O)	Avg. Gas Temp.	Avg. Gas Vel.	Soot Blowing Frequency
1	High	3.67×10^6	36.8	1	II	<0.18	1915	51	>20 Hrs
				2	I	<0.25	2160	57	>12 Hrs
2	Inter	2.95×10^6	29.0	1	II	0.40	1710	38	12
				1	II	0.40	1820	41	10
				2	I	<0.40	2120	44	>12
3	Low	2.25×10^6	22.3	1	II	<0.15	1660	28	>20 Hrs
				2	I	<0.10	1800	29	>12 Hrs

SUPERHEATER PROBE DEPOSITS
DURING PRESSURE DROP TEST
EDS RESIDUE

INTERMEDIATE FIRING RATE

After 10 Hours

Bank I

Bank II

Bank III

Bank IV

After 12 Hours

Bank I

Bank II

Bank III

Bank IV

quantifies the force required to push a deposit off the probe surface. (A detailed description of the determination is given in Appendix E.) Since deposits did not always have a sufficient bonding strength to support their own weight, the external force to remove these deposits was small. The fact that the deposits sloughed off by themselves characterized the relative bonding strength as low. The maximum bonding strength measured in situ with our penetrometer probe during the three runs was 6.5, a low value. Criteria used to assess bonding strength are as follows:

Severe: Greater than 30

High: 15-30

Moderate: 8-15

Low: Less than 8

These values were established based upon the corresponding ease of deposit removal during soot blowing and upon experience with similar coal/deposit behavior in the field. The highest measurements obtained during the tests with EDS residue were well below the cutoff point considered for low bonding strength. Normally, deposits yielding bonding strength measurements up to 15 are considered controllable through conventional sootblowing techniques.

Past test results have indicated that the physical characteristics of convection probe deposits such as bonding strength show a direct relationship to gas temperature. This behavior was also observed during the subject tests. The thickness which deposits build up to before sloughing was greater at higher gas temperatures. Maximum bonding strength (5.0 to 6.5) was measured at gas temperatures above 1900°F. Below 1900°F deposits were too weakly bonded to allow measurements to be taken.

Bonding strength, as discussed in FPTF test results, refers to the strength which the outer deposit is attached. Generally, when the outer deposit is removed, a very thin layer of deposit (initial deposit) remains on the tube surface. This behavior can also be safely assumed to occur in the field.

The effect of time on the initial deposit cannot be fully determined during the (40 hours) pilot-scale testing. However, coals of similar ash composition to the residue which have shown similar behavior during FPTF testing have not exhibited high fouling behavior in the field. Tests with the Old Ben Illinois coal (having ash characteristics similar to EDS residue ash) also did not exhibit increases in fouling behavior during a longer term (300 hour) run.

Tables XX through XXII summarize the physical characteristics of the deposits generated on convection probes during the three test runs. Convection deposit formation during these tests with the subject residue was typical of that with most coals as two distinct deposit layers accumulated on the probes. A thin, powdered layer of fine particulate material first accumulated on the tube metal surface. This layer, designated "initial" deposit, varied from 1/16" to 1/8" thick, and ranged from light gray to tan in color. Initial deposits accumulating on front (leading/upstream) probes within a particular probe bank generally were more compacted and comprised of coarser material than initial deposits on back (downstream) probes. This has been typical with coals previously studied. Frequently coals having high iron contents similar to the subject residue form a very hard, iron-rich scale which is tightly bonded to tube surfaces. This hard scale can then provide a base for tenaciously bonded bulk or outer deposits. Lack of this hard scale formation is addition data supporting the formation of weakly bonded/easily removable deposits.

Outer deposit formation was very dependent on gas temperature. Deposits accumulated at higher gas temperatures had higher densities and were less friable. All convection probe outer deposits were dry and relatively friable, however, at gas temperatures above 2100°F deposits had a moderate

PHYSICAL CHARACTERISTICS OF CONVECTION DEPOSITS

HIGH FIRING RATE

EDS RESIDUE

FPTF RESULTS

Probe Bank	Probe Row	Gas Temp. (°F)	Deposit Layer	Thickness (Inches)	Physical State	Deposit Strength	Overall Deposit-to-Tube Bonding Strength
I	A	2190	Outer	2-4	Sintered	Moderate	Low (<5.0)*
			Initial	1/16	Powder	---	
	B	2190	Outer	2-3	Sintered	Friable/Moderate	Low
			Initial	1/8	Powder	---	
II	C	2080	Outer	1-2	Sintered	Friable	Low (<5.0)*
			Initial	1/16	Powder	---	
	D	2080	Outer	2-3	Sintered	Very Friable	Very Low
			Initial	1/8	Powder	---	
III	E	1800	Outer	1/2	Sintered	Very Friable	Very Low
			Initial	1/8	Powder		
	F	1300	Outer	1/2-1"	Sintered	Very Friable	Very Low
			Initial	1/8	Powder		
IV	G	1620	Outer	---	---	---	---
			Initial	1/16	Powder	---	
	H	1620	Outer	1/2	Sintered	Friable	Low
			Initial	1/8	Powder	---	

*In Situ Bonding Strength Measurements with Penetrometer Probe.

TABLE XXI
PHYSICAL CHARACTERISTICS OF CONVECTION DEPOSITS
INTERMEDIATE FIRING RATE
EDS RESIDUE
FPTF RESULTS

Probe Bank	Probe Row	Gas Temp. (°F)	Deposit Layer	Thickness (Inches)	Physical State	Deposit Strength	Overall Deposit-To-Tube Bonding Strength
I	A	2160	Outer Inner Initial	1-2 1/8 1/16	Sintered Sintered Powder	Moderate Friable --	Low (<6.5)*
I	B	2160	Outer Initial	2-3 1/8	Sintered Powder	Friable/Moderate --	Low
II	C	1940	Outer Inner Initial	1/2-1 1/8 <1/16	Sintered Sintered Powder	Friable Friable --	Very Low (<5.0)*
	D	1940	Outer Initial	1-2 1/8	Sintered Powder	Very Friable --	Very Low
III	E	1700	Outer Inner Initial	<1/4" 1/16 <1/16	Sintered Sintered Powder	Very Friable Friable --	Very Low
	F	1700	Outer Initial	1/2-1" 1/8	Sintered Powder	Very Friable --	Very Low
IV	G	1510	Outer Initial	<1/8 1/16	Sintered Powder	Very Friable --	Very Low
	H	1510	Outer Initial	<1/4 1/8	Sintered Powder	Very Friable --	Very Low

*In situ bonding strength measurements with penetrometer probe.

TABLE XXII
PHYSICAL CHARACTERISTICS OF CONVECTION DEPOSITS
LOW FIRING RATE
EDS RESIDUE
FPTF RESULTS

Probe Bank	Probe Row	Gas Temp. (°F)	Deposit Layer	Thickness (Inches)	Physical State	Deposit Strength	Overall Deposit-To-Tube Bonding Strength
I	A	1810	Outer Initial	<1/4" 1/16	Sintered Powder	Very Friable --	Very Low
	B	1810	Outer Initial	1/4-1/2 1/8	Sintered Powder	Very Friable --	Very Low
II	C	1680	Outer Initial	<1/4 1/16	Sintered Powder	Very Friable --	Very Low
	D	1680	Outer Initial	<1/2 1/8	Sintered Powder	Very Friable --	Very Low
III	E	1550	Outer Initial	- <1/16	-- Powder	-- --	--
	F	1550	Outer Initial	<1/4 1/8	Sintered Powder	Friable --	Very Low
	G	1380	Outer Initial	- <1/16	-- Powder	-- --	--
	H	1380	Outer Initial	<1/4 1/8	Sintered Powder	Friable --	Very Low

sintered strength. At gas temperatures between 1900⁰ and 2100⁰F, outer deposits were slightly sintered and friable. Below 1900⁰F gas temperatures deposition was very light (less than an inch buildup in 8 hrs) and the deposits that did accumulate at these temperatures were very friable and very weakly bonded to probes.

The appearance of the outer deposits formed during the subject tests was typical of those formed by most coals. Deposits, light brown in color, had a typical crystalline/sintered type structure with the particle-to-particle bonding increasing in strength from the tube side to the gas-side of the deposit. However, even the outermost edge of deposits remained sintered (not molten) up to the highest gas temperatures studied (2190⁰F).

At the end of the intermediate firing rate, deposit samples from the front probes of banks I, II, and III were separated into three layers. (See Table XX.) The additional, "inner" deposit consisted of a slightly sintered layer between the outer and initial deposits. This inner layer was not distinctively different than the outer deposit, but varied somewhat in color and density. This layer was only approximately 1/16" to 1/8" thick. The inner layer was not separated from the outer deposits after the high and low firing rate runs.

The chemical composition of convection deposits collected from each run are contained in Tables XXIII through XXV. Overall, convection deposits analyses compared fairly closely to the as-fired residue ash. Convection probe deposit analyses do, however, reflect the variations in physical characteristics previously discussed. Analyses can therefore be more easily reviewed by comparison of deposit layers and probe location. In general, initial deposits had higher sodium and sulfur contents than outer deposits. Composition of both initial and outer deposits varied somewhat between the front and back probes of each bank.

TABLE XXIII
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
HIGH FIRING RATE: RUN 1

Sample Probe	Probe Bank I			Probe Bank I		
	A	A	A	B	B	B
	Outer	Initial	Back	Outer	Initial	Back
<u>Ash Fusibility</u>						
I.T. ^{OF}	I.S.	I.S.	2110	2000	I.S.	2040
S.T. ^{OF}	I.S.	I.S.	2220	2110	I.S.	2140
H.T. ^{OF}	I.S.	I.S.	2350	2310	I.S.	2300
F.T. ^{OF}	I.S.	I.S.	2440	2420	I.S.	2520
<u>Ash Composition</u>						
SiO ₂	43.7	35.3	47.6	48.0	I.S.	49.5
Al ₂ O ₃	16.5	11.8	16.0	15.1	I.S.	15.7
Fe ₂ O ₃	25.1	28.9	21.9	22.2	I.S.	20.7
CaO	6.2	10.0	3.0	3.1	I.S.	3.7
MgO	0.9	0.9	1.0	1.0	I.S.	0.9
Na ₂ O	1.5	1.2	1.8	1.8	I.S.	1.6
K ₂ O	1.7	1.4	2.1	2.1	I.S.	2.0
TiO ₂	1.3	1.0	1.2	1.3	I.S.	1.2
SO ₃	2.9	7.1	3.8	2.6	I.S.	3.0
Total	99.8	97.6	98.4	98.2	--	98.3

I.S. - Insufficient Sample for Analysis.

TABLE XXIII-A
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
HIGH FIRING RATE: RUN 1

SAMPLE PROBE	Probe Bank II			Probe Bank II		
	C	C	C	D	D	D
	Outer	Initial	Back	Outer	Initial	Back
<u>ASH FUSIBILITY</u>						
I.T. ^{°F}	2010	I.S.	2040	2030	I.S.	2020
S.T. ^{°F}	2130	I.S.	2200	2210	I.S.	2350
H.T. ^{°F}	2210	I.S.	2320	2330	I.S.	2380
F.T. ^{°F}	2380	I.S.	2490	2530	I.S.	2430
<u>ASH COMPOSITION</u>						
SiO ₂	48.5	33.3	48.5	49.5	46.7	49.7
Al ₂ O ₃	16.5	11.0	16.3	15.9	15.6	16.4
Fe ₂ O ₃	21.5	28.2	22.2	21.5	23.2	20.9
CaO	4.5	5.9	2.7	3.4	3.5	2.8
MgO	1.0	1.1	1.0	0.9	1.0	0.9
Na ₂ O	1.5	2.7	1.8	1.9	2.0	1.6
K ₂ O	1.8	2.9	2.1	2.0	2.2	1.8
TiO ₂	1.3	1.4	1.3	1.1	1.2	1.3
SO ₃	1.5	12.1	2.9	2.9	4.8	3.2
P ₂ O ₅						
Total	98.1	98.6	98.8	99.0	100.2	98.6

TABLE XXIII-B
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
HIGH FIRING RATE: RUN 1

SAMPLE Probe Deposit	PROBE BANK III			PROBE BANK III		
	E	E	E	F	F	F
	Outer	Initial	Back	Outer	Initial	Back
<u>ASH FUSIBILITY</u>						
I.T.(°F)	I.S.*	I.S.	2020	2060	I.S.	2050
S.T.(°F)	I.S.	I.S.	2330	2350	I.S.	2290
H.T.(°F)	I.S.	I.S.	2360	2390	I.S.	2370
F.T.(°F)	I.S.	I.S.	2400	2430	I.S.	2400
<u>ASH COMPOSITION</u>						
SiO ₂	35.7	35.9	48.5	49.3	47.5	51.3
Al ₂ O ₃	13.8	14.0	16.2	16.5	16.7	16.0
Fe ₂ O ₃	21.7	21.6	21.2	22.6	23.2	20.6
CaO	4.6	4.0	2.8	2.7	2.7	2.8
MgO	1.6	1.6	0.9	0.9	1.0	0.9
Na ₂ O	3.3	3.3	1.7	1.8	1.8	2.1
K ₂ O	3.3	3.1	2.0	1.9	2.0	1.8
TiO ₂	1.2	1.5	1.2	1.3	1.3	1.1
SO ₃	12.4	13.0	3.8	2.1	2.1	3.6
Total	97.6	98.0	98.3	99.1	98.3	100.2

* I.S. = Insufficient Sample

TABLE XXIII-C
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
HIGH FIRING RATE: RUN 1

SAMPLE PROBE DEPOSIT	Probe Bank IV		Probe Bank IV		As-Fired
	G Outer	G Back	H Outer	H Back	EDS Residue Ash
<u>ASH FUSIBILITY</u>					
I.T. ^{°F}	I.S.	2010	I.S.	2050	1980
S.T. ^{°F}	I.S.	2080	I.S.	2100	2010
H.T. ^{°F}	I.S.	2380	I.S.	2390	2120
F.T. ^{°F}	I.S.	2410	I.S.	2420	2500
<u>ASH COMPOSITION</u>					
SiO ₂	39.3	32.3	30.1	49.7	48.8
Al ₂ O ₃	15.8	19.7	21.2	17.4	15.5
Fe ₂ O ₃	24.8	29.2	33.0	21.2	19.4
CaO	3.3	4.6	4.4	3.2	5.3
MgO	1.4	1.3	1.4	1.0	1.0
Na ₂ O	3.0	2.7	2.9	2.2	1.8
K ₂ O	2.6	2.5	2.9	1.9	1.8
TiO ₂	1.4	0.9	0.7	1.0	1.0
SO ₃	7.5	3.9	2.9	3.1	4.5
Total	99.1	97.1	99.5	100.7	99.1

III

I.S. Insufficient Sample

TABLE XXIV
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
INTERMEDIATE FIRING RATE: RUN 2

SAMPLE					
Probe	A	A	A	B	B
Deposit	Outer	Inner	Initial	Outer	Initial
<u>ASH FUSIBILITY</u>					
I.T.(°F)	I.S.*	I.S.	I.S.	2110	2130
S.T.(°F)	I.S.	I.S.	I.S.	2290	2260
H.T.(°F)	I.S.	I.S.	I.S.	2420	2340
F.T.(°F)	I.S.	I.S.	I.S.	2480	2410
<u>ASH COMPOSITION</u>					
SiO ₂	49.0	47.5	45.5	48.1	49.1
Al ₂ O ₃	16.8	15.0	15.8	17.7	16.5
Fe ₂ O ₃	21.9	22.9	24.4	22.6	21.2
CaO	3.4	3.0	3.0	2.9	3.2
MgO	1.0	1.0	1.0	1.0	1.0
Na ₂ O	2.1	2.2	2.4	2.4	2.1
K ₂ O	2.1	2.1	2.3	2.0	1.9
TiO ₂	1.3	1.2	1.2	1.2	1.2
SO ₃	1.3	2.8	2.5	0.7	2.8
Total	98.9	97.7	98.2	98.6	99.0

*I.S. = Insufficient Sample

TABLE XXIV-A
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
INTERMEDIATE FIRING RATE: RUN 2

SAMPLE Probe Deposit	C		D		D
	Outer	Inner	Initial	Outer	Initial
<u>ASH FUSIBILITY</u>					
I.T. (°F)	2160	2190	2040	2180	I.S.*
S.T. (°F)	2240	2250	2270	2240	I.S.
H.T. (°F)	2350	2340	2310	2330	I.S.
F.T. (°F)	2380	2490	2380	2390	I.S.
<u>ASH COMPOSITION</u>					
SiO ₂	47.2	49.5	28.5	51.4	45.8
Al ₂ O ₃	17.5	17.0	12.7	16.0	15.6
Fe ₂ O ₃	23.2	22.0	26.9	20.3	22.6
CaO	3.0	2.6	8.1	3.1	3.3
MgO	1.1	1.0	1.4	0.9	1.0
Na ₂ O	2.2	2.2	3.2	2.0	4.6
K ₂ O	2.1	2.0	2.2	1.8	2.2
TiO ₂	1.3	1.2	1.1	1.1	1.1
SO ₃	1.4	2.7	14.6	3.0	3.4
Total	99.0	100.2	98.7	99.6	99.6

*I.S. = Insufficient Sample

TABLE XXIV-B
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
INTERMEDIATE FIRING RATE: RUN 2

SAMPLE PROBE DEPOSIT	PROBE BANK III			PROBE BANK III	
	E	E	E	F	F
	OUTER	INNER	INITIAL	OUTER	INITIAL
<u>ASH FUSIBILITY</u>					
I.T. °F	2040	I.S.	I.S.	2050	I.S.
S.T. °F	2230	I.S.	I.S.	2200	I.S.
H.T. °F	2320	I.S.	I.S.	2330	I.S.
F.T. °F	2400	I.S.	I.S.	2490	I.S.
<u>ASH COMPOSITION</u>					
SiO ₂	48.3	45.1	36.6	52.2	46.0
Al ₂ O ₃	16.1	15.8	14.2	15.4	15.1
Fe ₂ O ₃	22.1	22.4	22.5	20.3	24.7
CaO	2.9	3.0	3.5	3.2	3.3
MgO	1.0	1.0	1.3	0.9	1.2
Na ₂ O	2.2	2.2	3.2	2.0	2.6
K ₂ O	2.1	2.0	2.5	1.8	2.4
TiO ₂	1.1	1.2	1.2	1.1	1.4
SO ₃	2.8	5.8	14.4	2.8	1.7
Total	98.6	98.5	99.4	99.7	99.8

I.S. = Insufficient Sample for Analysis

TABLE XXIV-C
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
INTERMEDIATE FIRING RATE: RUN 2

SAMPLE PROBE DEPOSIT	PROBE BANK IV		PROBE BANK IV		AS-FIRED EDS RESIDUE ASH
	G	G	H	H	
	OUTER	INITIAL	OUTER	INITIAL	
<u>ASH FUSIBILITY</u>					
I.T. °F	2040	I.S.	2040	I.S.	1980
S.T. °F	2200	I.S.	2110	I.S.	2010
H.T. °F	2330	I.S.	2320	I.S.	2120
F.T. °F	2510	I.S.	2460	I.S.	2520
<u>ASH COMPOSITION</u>					
SiO ₂	49.0	I.S.	49.5	47.1	48.3
Al ₂ O ₃	14.9	I.S.	15.5	15.8	15.3
Fe ₂ O ₃	20.2	I.S.	20.6	22.7	19.0
CaO	2.9	I.S.	2.8	2.6	5.3
MgO	0.9	I.S.	0.9	1.0	0.9
Na ₂ O	2.1	I.S.	2.1	2.1	1.7
K ₂ O	1.9	I.S.	1.9	1.9	1.6
TiO ₂	0.9	I.S.	1.0	1.2	1.0
SO ₃	5.3	I.S.	4.2	4.1	4.6
Total	98.1		98.5	98.5	97.7

I.S. = Insufficient Sample for Analysis

TABLE XXV
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FFTF RESULTS
LOW FIRING RATE: RUN 1

SAMPLE PROBE DEPOSIT	Probe Bank I			Probe Bank I	
	A&B	A	A	B	B
	Outer	Initial	Back	Initial	Back
<u>ASH FUSIBILITY</u>					
I.T. ^{°F}	2070	I.S.	2060	I.S.	2080
S.T. ^{°F}	2250	I.S.	2240	I.S.	2220
H.T. ^{°F}	2330	I.S.	2340	I.S.	2350
F.T. ^{°F}	2450	I.S.	2460	I.S.	2420
<u>ASH COMPOSITION</u>					
SiO ₂	44.7	38.4	46.2	48.0	49.2
Al ₂ O ₃	15.1	14.8	16.8	16.3	16.1
Fe ₂ O ₃	23.2	27.1	22.3	21.7	21.2
CaO	3.0	4.4	2.8	3.1	2.9
MgO	1.0	1.1	1.0	1.0	1.0
Na ₂ O	1.0	2.0	1.9	1.8	1.7
K ₂ O	1.9	2.0	1.8	1.6	1.6
TiO ₂	1.3	1.4	1.3	1.2	1.1
SO ₃	5.4	6.4	5.0	3.4	4.1
Total	98.5	97.6	99.1	98.1	98.9

I.S. = Insufficient Sample

TABLE XXV-A
CONVECTION PROBE DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS
LOW FIRING RATE: RUN 3

SAMPLE PROBE DEPOSIT	Probe Bank II C&D	Probe Bank III E&F	As-Fired EDS Residue Ash
	Outer	Outer	
<u>ASH FUSIBILITY</u>			
I.T. °F	2070	2150	2130
S.T. °F	2250	2220	2170
H.T. °F	2370	2360	2310
F.T. °F	2470	2470	2390
<u>ASH COMPOSITION</u>			
SiO ₂	46.1	47.9	47.3
Al ₂ O ₃	17.1	17.5	17.7
Fe ₂ O ₃	21.0	20.9	19.5
CaO	3.1	2.8	4.8
MgO	0.9	0.9	0.9
Na ₂ O	1.6	1.5	1.4
K ₂ O	1.7	1.7	1.5
TiO ₂	1.3	1.3	1.3
SO ₃	5.3	3.3	4.4
Total	98.1	97.8	98.8

I.S. Insufficient Sample

Initial deposits on front probes generally contained more sulfur (SO_3 contents up to 7 times higher) than those on back probes within a particular bank. In general, sulfur contents increased in deposits formed at lower gas temperatures. Overall, the sodium content in initial deposits were roughly double that in the as-fired ash. However, sodium concentrations were still relatively low in these deposits due to the low sodium content in the residue ash. Initial deposits also showed slight enrichment of iron content and small reductions in silica and alumina contents compared to the as-fired ash.

Outer deposits generally contained slightly higher concentrations of iron and approximately the same concentration of sodium as the as-fired residue ash. Front probe outer deposits generally contained higher concentrations of calcium than back probes within the same bank. Fusibility temperatures of the outer deposits varied slightly from those of the as-fired ash. The initial deformation (I.T.) and, in particular, the softening temperatures (S.T.) of the deposits were somewhat higher than the as-fired ash. Fluid temperatures (F.T.) of the deposits were lower than the as-fired ash.

Fusibility temperatures of convection deposits should be kept in proper perspective; however, as the essential bonding for these deposits occurs at the interface between individual particles, and therefore the average melting characteristics may not be representative of bonding tendencies. Very few fusibility measurements were run on initial deposits due to the small quantity of samples. Samples were first used to determine composition, since fusibility temperatures of these powdery deposits have limited usefulness.

As discussed earlier, after the intermediate firing rate run front probe deposits were separated into three layers. The additional inner layer was the tube-side interface area between the outer and initial deposits. Generally, these inner deposits also had compositions somewhere in between those of the outer and initial deposits. Inner deposit samples

had slightly higher sodium and sulfur contents than outer deposits and the as-fired ash. In addition, samples of the deposit buildup on the back (or downstream) side of the probes were collected and analyzed (from the high firing rate run). This deposit consisted of light, uncompacted powder. The analysis of this material varied little from that of the as-fired ash. The maximum thickness of the buildup on the back of the probes reached was approximately 3/8". Its analysis was conducted primarily as a matter of interest and its presence should have little significance on convection section performance.

Although deposits varied somewhat between deposit layer, probe geometry, and gas temperature, overall convection deposits did not differ substantially in composition from each other nor from the as-fired residue ash. Lack of substantial enrichment of particular ash constituents in convection deposits is what would typically be expected from low fouling fuels such as the subject residue.

4.4.4 Radiant Section Deposition

Overall, test results indicate that the subject residue has a high slagging potential. Highly fused, molten ash deposits were generated on waterwall test surfaces at relatively low furnace loadings/temperatures. Although deposits were relatively thin, they resulted in a significant reduction in heat transfer. The physical nature of the waterwall deposits generated at the high and intermediate firing rate tests were such that removal was difficult. (The formation of these tenacious deposits should be minimized/controlled by the low thermal loadings in the hybrid boiler design.)

The physical characteristics of waterwall deposits are summarized in Table XXVI. Waterwall deposits formed in three distinct layers: a highly fused outer deposit comprising the bulk of the buildup; a sintered inner layer; and an initial layer of fine powder. Photographs taken of waterwall panel deposits at the end of testing at each firing rate are shown in Figure 40. The left column contains photographs of the deposits in situ after transitioning to gas firing at the end of the testing. Note

TABLE XXVI
WATERWALL DEPOSIT CHARACTERISTICS
EDS RESIDUE
FPTF RESULTS

RUN	FIRING RATE	HEAT INPUT (BTU/HR)	FLAME TEMP. (°F)	DEPOSIT LAYER	THICKNESS (INCHES)	COLOR (COLD)	PHYSICAL STATE	DEPOSIT STRENGTH	RELATIVE BONDING STRENGTH	PANEL COVERAGE
1	HIGH	3.67×10^6	2530	OUTER	3/8	BROWN/BLACK	MOLTEN	HIGH/FUSED	HIGH	80%
				INNER	1/8	RUST	SINTERED	MODERATE		100%
				INITIAL	1/16	GRAY	POWDER	---		100%
2	INTER.	2.95×10^5	2480	OUTER	1/4	BROWN/BLACK	MOLTEN	HIGH/FUSED	HIGH	60%
				INNER	1/8	RUST	SINTERED	MODERATE		90%
				INITIAL	1/16	GRAY	POWDER	---		100%
3	LOW	2.25×10^6	2200	OUTER	1/4	GRAY	HIGHLY SINTERED	MODERATE	MODERATE	20%
				INNER	3/8	RUST	SINTERED	FRIABLE		50%
				INITIAL	1/16	GRAY	POWDER	---		100%

WATERWALL PANEL DEPOSITS

EDS RESIDUE

PANEL DURING TEST

PANEL AFTER TEST

High Firing Rate

Intermediate Firing Rate

Low Firing Rate

FIGURE 40

the fluid, running slag present during the high and intermediate firing rates. The thickness of this molten slag (outer deposit) was between 1/8 and 1/2 inch. Molten outer deposits covered a greater percentage of the panel during the high firing rate (approximately 80% compared to 60% at the intermediate rate) and had a greater thickness during the high rate (typically 3/8" thick compared to approximately 1/4" thick at the intermediate rate). At the low firing rate, spotty outer deposit buildup accumulated covering only about 20% of the panel. The thickness of outer deposits during the low firing rate was approximately the same as the other two rates, however the sintered inner layer below the outer deposit was considerably thicker than that at the higher rates (3/8" for the low rate vs. 1/8" thick for high and intermediate rates).

The great thickness of the sintered layer present during the low firing rate is a typical effect of gas temperature. Generally, for a given coal, waterwall deposits become more fused as they grow out from the cooled metal and increase in temperature. As gas temperatures decrease, the thickness which deposits must obtain before reaching a limiting molten condition increases. In commercial practice waterwall deposits will generally vary in physical characteristics with elevation. Gas temperatures during the high firing rate at the same elevation (2530°F) better represent burner zone elevations, whereas the lower temperatures (2290°F) at the low firing rate are more representative of the upper portion of commercial furnaces.

Waterwall deposits during the high and intermediate firing rate runs were highly fused, very dense and tightly bonded to the panel. Waterwall deposits were removed on-line once during the high and intermediate runs to assess bonding strength/cleanability. In each case, deposits were difficult to remove through normal sootblowing procedures.

Although waterwall deposits were not removed during the low firing rate run, the bonding strength of deposits during this run could be classified as moderate based upon past experience with deposits of similar characteristics. Deposits during the low firing rate would tend to respond better to sootblowing due to the greater thickness of the friable inner deposit layer. This layer would act as a weak link facilitating removal.

The physical characteristics of the waterwall deposits generated by the subject residue were very similar to those produced when previously testing Old Ben Illinois #6 coal. Figure 41 shows photographs of outer waterwall deposits from these two tests. The left two photographs are deposits from the Illinois coal at the intermediate and high firing rates, and the right two photographs are those produced by the residue. The respective deposits from each fuel are essentially identical in physical appearance. The color, density, and structure of comparative deposits are very similar. Note the dripping/running appearance of the slag at the intermediate firing rates, and the more uniform thickness of molten slag at the high rates. Overall, the slagging characteristics of the subject residue are very similar to Old Ben Illinois #6 coal, and presumably similar to its parent coal.

Deposits forming in upper furnace sections upstream of convection passes (2400⁰ to 2200⁰F gas temperature zone) are likely to buildup rapidly and to substantial thickness. The relatively low melting temperatures of the residue yield thin, fluid deposits in high temperature zone, but as temperature decreases and the bulk of the ash goes through a phase change the potential for heavy deposition is high. This behavior was illustrated by the thicker waterwall deposits during the low firing rate and massive deposit buildup in FPTF furnace outlet ducting immediately upstream of the first convection bank. This type of deposition would primarily occur on radiant panel sections of a boiler. No radiant panels are present in the hybrid boiler design, and therefore the effects of this behavior will be minimized.

The effect of waterwall deposits on heat transfer is illustrated by the plots of heat flux through the waterwall panel versus time shown in Figures 42 through 44. Heat absorbed by the panel is accurately and continuously monitored. Changes in the heat absorbed by the panel reflect the combined effect of the quantity of ash deposit accumulated and the thermal properties of these deposits. The actual magnitude of the heat flux is dependent on many parameters. These parameters include the thermal properties of the deposit (conductivity, emissivity,

COMPARATIVE WATERWALL DEPOSITS

EDS RESIDUE
(FPTF RESULTS)

INTER. FIRING RATE
ILLINOIS #6 COAL

INTER. FIRING RATE
EDS RESIDUE

HIGH FIRING RATE
ILLINOIS #6 COAL

HIGH FIRING RATE
EDS RESIDUE

FIGURE 41

EDS RESIDUE
HIGH FIRING RATE: RUN 1
HEAT ABSORPTION RATE OF WATERWALL PANEL
HEAT FLUX vs TIME

Figure 42

EDS RESIDUE
INTERMEDIATE FIRING RATE: RUN 2
HEAT ABSORPTION RATE OF WATERWALL PANEL
HEAT FLUX vs TIME

Figure 43

EDS RESIDUE
LOW FIRING RATE: RUN 3
HEAT ABSORPTION RATE OF WATERWALL PANEL
HEAT FLUX vs TIME

Figure 44

absorptivity), the deposit thickness, and also operating parameters such as flame temperature, gas velocity and panel metal temperature. Operating parameters remained relatively constant during a particular firing rate. Therefore, the variations within a particular curve in these plots primarily represent changes in the quantity of ash deposits.

A summary of the waterwall deposit thermal properties derived from the heat flux plots is given below.

<u>HEAT INPUT</u> (Btu/Hr)	<u>AVG. HEAT FLUX</u> (Btu/ft ² Hr)	<u>FINAL AVG. HEAT FLUX/ CLEAN PANEL VALUE</u>	<u>MIN. HEAT FLUX</u> (Btu/ft ² - Hr)
3.67X10 ⁶	27,500	.17	10,200
2.95X10 ⁶	29,500	.41	24,000
2.25X10 ⁶	28,000	.44	21,500

Although heat transfer during the high firing rate was restricted substantially, on a comparative basis, values were only slightly below moderate. Figure 45 contains plots of the heat flux through the waterwall panel versus time for three previously tested coals. Figure 45A can be laid on top of Figure 45 to compare the relative heat absorption rate during the subject test (all of the curves were plotted from data acquired at the high firing rate, approximately 3.75×10^6 Btu/hr input.) Heat absorption rates when testing the residue were initially higher, but with time drop to moderately low levels. The average heat flux through the panel during the subject test was relatively high because of the relatively thin deposits (less than 1/2" thick). The dense, fused deposits present in this test also are not as effective insulators as dry, sintered deposits.

The initial heat flux obtained when the panel was relatively clean was somewhat higher than the comparative coals. Although the gas temperatures at the panel level were not particularly high, the high initial heat flux may be the result of the rapid, intense burning below the panel. As previously discussed, a very bright, intense flame was observed close to the burner. The panel may have received a greater quantity of radiation from this portion of the flame than was typically obtained from tests with coals.

FPTF RESULTS:
 RELATIVE SLAGGING TENDENCIES
 HEAT ABSORPTION RATE OF WATERWALL TEST PANEL

Figure 45

A very important characteristic reflected by the plots for the residue is that the heat flux continuously decreases with time when firing the residue. (The increase in heat flux at the end of the test was due to soot blowing.) The constant decrease in heat flux with time (other than minor fluctuations) shows that deposits did not slough off the panel with time and indicates that deposits were tightly bonded. This characteristic is indicative of high slagging coals. (Note the waterwall heat flux for Coals A and B which are high slagging coals based both upon FPTF test results and field experience.)

The minimum waterwall heat flux values obtained when firing the residue at high rate were between 10,000-15,000 Btu/hr. Although these values are not as low as those for coals A and B, they do represent a significant drop in transfer (more than 70%) as reflected by the ratio of initial-to-final heat flux. Minimum heat flux values can be considered a worse case or equilibrium condition occurring when deposits reach their limiting quantities.

Analytical data on waterwall deposits generated during runs with the subject residue at high, intermediate and low firing rates are contained in Table XXVII. In general, the composition of waterwall deposits closely resembled that of the as-fired residue ash. These samples all represent the bulk of the deposit, consisting of a composite of the outer and inner layers. The sulfur contents of the deposits were low (less than 9.5% SO_3). Comparing the composition of the deposit to the as-fired ash on a SO_3 -free basis, there is slight enrichment of iron in the deposits, particularly at the high load. Overall, however, ash constituents varied little from as-fired ash on an SO_3 -free basis.

Fusibility temperatures of waterwall deposits were also similar to those of the as-fired ash. In general, a slight increase in fusibility temperatures of the deposits was observed with the exception of fluid temperatures. The magnitudes of the fusibility temperatures for these waterwall deposit samples are somewhat higher than would be expected for deposits with similar physical characteristics. Typically coals with ash which is

TABLE XXVII
WATERWALL PANEL DEPOSIT ANALYSES
EDS RESIDUE
FPTF RESULTS

SAMPLE Run Firing Rate	1	2	3
	High	Inter	Low
<u>ASH FUSIBILITY</u>			
I.T.(°F)	2040	2030	2040
S.T.(°F)	2100	2080	2090
H.T.(°F)	2400	2240	2400
F.T.(°F)	2510	2410	2520
<u>ASH COMPOSITION</u>			
SiO ₂	53.1	50.2	50.0
Al ₂ O ₃	17.0	18.0	17.6
Fe ₂ O ₃	20.5	18.7	17.9
CaO	5.6	4.6	5.5
MgO	0.9	0.9	0.9
Na ₂ O	1.7	1.8	1.5
K ₂ O	1.5	1.6	1.7
TiO ₂	1.0	0.9	1.0
SO ₃	0.1	0.1	0.4
Total	101.4	96.9	98.5

comparative to the residue's have shown greater iron enrichment in water-wall deposits and greater reductions in fusibility temperatures. It must be noted that fusibility temperatures are determined on a cold, prepared (ground) samples of deposit, and the subsequent melting characteristics may not be representative of the in situ material. Deposit/ash particle reactions in the furnace are very complex and may differ in behavior at the higher temperatures, over the longer periods, and under different gas compositions.

4.4.5 Fly Ash

Fly ash generated during each of the three runs was collected and analyzed. Analytical results for samples obtained from a cyclone collected prior to stack are summarized in Table XXVIII. Fly ash composition and fusibility temperatures varied little from the as-fired ash. The SO_3 content of the fly ash ranged from 4.3 to 2.7%, decreasing as the firing rate decreased. Slight enrichment of calcium was observed compared to the as-fired ash. The percentage of unburned carbon remaining in the fly ash ranged from 1.8% to 2.6%. These values reflect good carbon burnout, particularly considering the periodic operational problems experienced due to burner coking.

The particle size distribution for fly ash collected isokinetically during the intermediate firing rate is shown in Figure 46. The sample was screened to minus 325 mesh (44 micron), then analyzed with Bahco classifier and a Coulter Counter analyzer. (The principle of separation for the Bahco analyzer is based on the terminal velocity of the particle. The instrument utilizes air as a transport medium. The Coulter Counter detects particle size by measuring a change in electrical resistance as a particle passes through a standard orifice. A strong electrolyte is used as a transport medium.) Although the two techniques are totally different, results from the Bahco and Coulter Counter showed very little variation. Data obtained from the Bahco and Coulter Counter were normalized to include the entire sample using the screen data. Results reflect a normal distribution, with typical fly ash particle fineness. The mean particle size was approximately 7.5 microns, and about 15% (by weight) of the sample was less than 2 microns.

TABLE XXVIII
FLY ASH ANALYSES
EDS RESIDUE
FPTF RESULTS

SAMPLE	1	2	3
Run			
Firing Rate	High	Inter	Low
<u>ASH FUSIBILITY</u>			
I.T. (°F)	1980	2010	2120
S.T. (°F)	2020	2030	2180
H.T. (°F)	2310	2310	2320
F.T. (°F)	2410	2450	2490
<u>ASH COMPOSITION</u>			
SiO ₂	47.4	48.6	48.5
Al ₂ O ₃	14.7	14.5	17.3
Fe ₂ O ₃	20.2	19.2	19.1
CaO	7.4	6.8	5.7
MgO	1.1	1.0	1.1
Na ₂ O	2.0	1.8	1.5
K ₂ O	1.4	1.2	1.3
TiO ₂	1.0	1.1	1.2
SO ₃	4.3	3.9	2.7
P ₂ O ₅			
Total	99.5	98.1	98.4
<u>CARBON CONTENT</u>			
Wt. %	1.9	1.8	2.6

FLY ASH PARTICLE SIZE DISTRIBUTION
EDS RESIDUE
FPTF TEST RESULTS

4.4.6 Nitrogen Oxide Emissions

The nitrogen oxide emission levels measured during combustion of the residue in the FPTF are summarized in Table XXIX. Nitrogen oxide emissions were obtained during the low and intermediate runs and measured with chemiluminescent analyzer. Reliable data was not obtained at the high heat input due to problems associated with the analyzer.

The NO_x levels generated in the FPTF with the residue were relatively high compared to those of previously tested coals. The average concentration of NO_x measured during the intermediate run was 920 ppm compared to concentrations ranging from approximately 400 to 700 ppm from previously tested coals. It must be noted that the FPTF is not normally used to assess NO_x potential, and correlation between FPTF results and field data has not been established. The NO_x levels measured in the FPTF have consistently been significantly higher than those measured in C-E tangentially fired boilers burning similar fuels. FPTF NO_x results can not be extrapolated to field performance, and due to the high sensitivity of NO_x emissions upon firing system, these results should not be used to rank the relative NO_x potential of fuels in tangentially-fired units.

The FPTF is fired by a single swirl-type burner which provides rapid mixing between fuel and combustion air. This generally results in rapid, intense single-stage combustion; conditions which tend to promote NO_x formation. Bench-scale and DTFS results indicate that a relatively high level of fuel nitrogen is released in the volatiles of the residue. This indicates the potential for high NO_x formation during single-stage combustion (as in FPTF). However, the high concentration of fuel nitrogen released in the volatiles also indicates that NO_x generation is more amenable to low NO_x control measures such as staged combustion.

Overall, the FPTF NO_x emission data obtained on the residue indicates the need for further evaluation of NO_x emissions. FPTF results indicate that

the low ash residue has a high potential for NO_x formation during single combustion. However, this data cannot be extrapolated to predict NO_x potential in tangentially-fired systems.

TABLE XXIX

EDS RESIDUE
 NITROGEN OXIDE EMISSIONS
 FPTF RESULTS
 (LOW ASH-ONCE THRU BOTTOMS)

<u>Heat Input</u>	<u>NO_x Measured</u> (ppm)	<u>O₂ in F.G.</u> (%)	<u>NO_x @ 3% O₂</u> (ppm)
$2.95 \times 10^6 \frac{\text{Btu}}{\text{Hr}}$	820	3.4	840
	850	3.8	890
	880	3.9	930
	835	4.6	920
	910	4.7	1000
	880	3.9	930
			Avg = 920 ppm (1.35 lb NO ₂ /10 ⁶ Btu)
$2.25 \times 10^6 \frac{\text{Btu}}{\text{Hr}}$	690	6.2	840
	650	6.7	820
	550	5.2	630
	600	7.0	770
	760	7.0	980
	675	6.5	840
	850	6.0	1020
			Avg = 840 ppm (1.18 lb NO ₂ /10 ⁶ Btu)

- NOTE: 1) Single Stage Combustion
 with highly turbulent flame
- 2) Previous FPTF NO_x Emissions
 at approximate 3×10^6 Btu/hr
 heat input ranged from 400 to
 700 ppm.

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APPENDIX A
BENCH-SCALE EQUIPMENT

BENCH-SCALE EQUIPMENT

In addition to the standard ASTM analytical procedures used to perform conventional coal and ash analyses, the following less common bench-scale equipment and procedures were used:

TGS-2 SYSTEM

The Perkin-Elmer Model TGS-2 is a complete, second-generation system for accurately recording the weight loss or weight gain or rate of weight change of a sample as it is subjected to a precisely controlled temperature environment. It is a completely modular system consisting of the following independently packaged units: the Thermobalance Analyzer, the Electronic Balance Control, the Temperature (program) Microprocessor Controller, the Heater Control Unit, the First Derivative Computer (FDC) and recorder (Figure A-1).

This apparatus uses a small solid sample to determine either its micro-proximate analysis using the general procedure established by the American Society for Testing Materials (ASTM) or its thermo-gravimetric reactivity under specific experimental conditions (heating rate, reaction medium, and reaction temperature).

The micro-proximate analysis is determined as follows: A sample (4-6 mg) is purged with nitrogen to remove oxygen traces. The moisture loss is obtained by heating it in an inert atmosphere (nitrogen) to 105°C and holding for three minutes. Subsequently, the sample is heated at 100°C/min to 950°C and held at this temperature for five minutes to obtain volatile matter. After this, the temperature is lowered to 750°C and a switching valve is used to introduce oxygen for the combustion of fixed carbon at this temperature. The residue represents the ash content.

The isothermal char reactivity test is determined as follows: A 4-6 mg sample (sized to 100% through 200 mesh) is purged in nitrogen to remove traces of oxygen. It is then heated in nitrogen at 20°C/min to 700°C.

FIGURE A-1
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After stabilization at this temperature, air is introduced to burn off the fixed carbon. Percent weight of the unburned char and rate of weight loss are recorded on a strip chart as a function of time. These results are subsequently used to determine the char's burn-off (combustion efficiency) history and reactivity parameter (which indicates the maximum rate of weight loss per unit weight of the original sample in the TGS-2 system).

QUANTASORB SURFACE AREA ANALYZER

The principle of operation of the Quantasorb Surface Area Analyzer (Figure A-2) involves passing a mixture (~ 20 cc/min) of helium (used as a carrier) and adsorbate (N_2 , CO_2 , etc.) through a U-shaped small cell containing the sample.* The amount of adsorbate physically adsorbed at various partial pressures on the sample (adsorbent) surface can then be used to calculate the sample's surface area and other pore structural parameters (average pore size, pore size distributions). A 0.5-1 g of adsorbent is used in these determinations.

Adsorption and desorption occur when the sample is immersed into and then withdrawn from the liquid controlling the adsorption temperature. Liquid nitrogen and room temperature water are used for nitrogen adsorption and desorption, respectively. Room temperature and hot ($60^\circ C$) water are used for carbon dioxide adsorption and desorption, respectively. Changes in the ratio of He to adsorbate in the flowing stream, due to adsorption and desorption, are sensed by a specially designed thermal conductivity detector. The signals delivered by the detector are nearly Gaussian in shape. The instantaneous signal height is proportional to the quantity of gas adsorbed. As such, the function of the Quantasorb Surface Analyzer is to measure the quantity of gas adsorbed at a given temperature and partial pressure.

*Ovendried at $105^\circ C$ overnight, then outgassed in the Quantasorb at $150^\circ C$ for two hours using nitrogen as the sweeping gas.

SURFACE AREA ANALYSIS EQUIPMENT

A BET (Brunauer, Emmett, Teller) single or multi-point method is used in conjunction with N_2 adsorption at $-196^{\circ}C$ ($-321^{\circ}F$) to determine the sample's N_2 specific surface area (generally known as the BET surface area). A Dubinin-Kaganer method is used in conjunction with CO_2 adsorption at $25^{\circ}C$ ($77^{\circ}F$) to determine the sample's CO_2 specific surface area.

FLAMMABILITY INDEX APPARATUS

The Flammability Apparatus (Figures A-3, A-4) is a device used to determine the ignition temperatures of pulverized solid fuels under specific conditions. Briefly, about 0.2 g of sample sized to 200 X 0 mesh is placed in the sample holder. The furnace is preheated to a desired level, then the solenoid-operated valve is released, allowing oxygen from the 2-liter storage reservoir to suspend and convey the sample through the furnace. If ignition does not occur, the procedure is repeated at higher temperatures, in $50^{\circ}F$ increments, until ignition occurs. If on the other hand ignition does occur in the first trial, then the procedure is repeated to determine the temperature below which ignition does not occur. In either case, fine tuning is necessary to further narrow the error margin. This ignition temperature is called Flammability Index. The value of the Flammability Index compared to other fuels indicates the ignition temperature/stability on a relative basis.

ACEDIC ACID LEACHING

While ash deposit formation is a complex phenomenon depending on many variables, it is recognized that alkali metals play important roles in ash deposition processes. Certainly for some coals, the alkali metals are the dominant reason for adverse fouling. The mechanism for alkali-induced deposition in boiler convection sections is believed to be the vaporization and subsequent condensation of the alkalies. Alkalies also act as strong fluxing agents, reducing the melting temperatures of most mixtures of ash constituents.

Figure A-3 SCHEMATIC OF FLAMMABILITY APPARATUS

FLAMMABILITY APPARATUS

Unfortunately, the total concentrations of the alkalies, which is what is measured by conventional ash analyses, are not always accurate indices of potential furnace fouling. In the combustion process, the fouling reactions may be influenced as much by the nature of the alkali as by the total amount of the alkali in the coal.

It is therefore desirable to separate the total alkalies into meaningful categories that may be related to fouling behavior. This concept is not new among coal investigators; it has generally been assumed that the total alkali may be separated into two general categories, as follows:

- 1) "Active alkalies," which are those alkalies that readily vaporize during combustion and are, therefore, available to react chemically and physically downstream in the boiler. These active alkalies have been found to be readily extracted from coal by leaching in a weak solution of acetic acid.
- 2) "Inactive alkalies" are more stable forms, contained in mineral impurities, which remain relatively inert during the combustion process and are less influential in ash deposition. The inactive alkalies are found not to be extracted from coal by leaching in a weak solution of acetic acid.

Out of all the active metals such as sodium, potassium, calcium, magnesium, etc., which are leachable by a weak acetic acid solution, the active sodium has been found by C-E to correlate well with the degree of fouling in utility boilers. Coals containing large amounts of active sodium, leachable by weak acetic acid solution, have been found, in general, to result in high degree of fouling problems in the convective surfaces of the boilers.

The procedure for measuring the active alkali metal contents of coal by acetic acid leaching involves the following. A 20 gram sample of normal boiler grind (70% through 200 mesh) is treated with about 100 ml of a weak acetic acid solution at a selected pH value. Normally two pH values - pH3 and pH5, have been used by C-E, although initial indications are that the

2. *Phragmites* (common)

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APPENDIX B

DROP TUBE FURNACE SYSTEM (DTFS)

DROP TUBE FURNACE SYSTEM (DTFS)

The Drop Tube Furnace System (Figures B-1 and B-2) is comprised of a 1-inch inner diameter horizontal tube gas preheater and a 2-inch inner diameter vertical tube test furnace for providing controlled temperature conditions. Both tubes are electrically heated and are rated at 2800°F. The DTFS was used to study devolatilization, combustion and NO_x formation characteristics of solid fuel.

The principle of operation of the DTFS is as follows: Pulverized fuel (.06-1.0 gm/min) is introduced with a small amount of carrier gas into the hot reaction zone of the test furnace through a water-cooled fuel injector. A preheated secondary gas stream is introduced around the primary stream. Injection of pulverized fuel particles into the hot gas stream results in a rapid heating of the particles to the prevailing gas temperature (at a rate commensurate with that in a utility boiler, on the order of 10⁴°C/sec). Following the rapid heating period, devolatilization and/or combustion of particles occur for a specific time. Then all reaction products are aspirated into a water-cooled sampling probe where all reactions are rapidly quenched. Solid products are separated from the gaseous products in a filter assembly. The gas sample is passed through two in-line filters before it is sent to the Gas Analysis System.

The solid products collected at various locations along the axis of the DTFS reaction zone can be analyzed to determine solid conversion and NO_x formation efficiencies. An ash tracer method, which is based on the assumption that ash remains inert during either pyrolysis or combustion, is used to calculate the fuel's pyrolysis or combustion efficiency as a function of operational parameters (temperature, residence time, particle size, and gaseous reaction medium). An aliquot of the effluent gas sample is analyzed on-line to determine NO_x, O₂, CO, and CO₂ concentrations as a function of the same operational parameters given above.

The DTFS experimental conditions are closely controlled and monitored. Secondary gas preheated and test furnace wall temperature are measured with bare thermocouples. Gas temperature profiles inside the test furnace are measured with suction pyrometer. A uniform fuel feed rate was achieved by use of a mechanical vibrator and by partial fluidization of the coal particles in the feeder. Volumetric flow rates of primary and secondary gas and reaction products streams are measured with appropriate rotameters.

FIGURE B-1 OVERALL VIEW OF THE DROP TUBE FURNACE SYSTEM

APPENDIX C

SUMMARY OF DTFS DATA

FIGURE B-2 SCHEMATIC OF THE COMBUSTION ENGINEERING DROP TUBE FURNACE SYSTEM.

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/12/81
 TEST NO.:EDSOHA-1-1
 FUEL :EDS OLD HIGH ASH
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .091
 GAS FEED RATE (L/MIN) = 11.9

EXCESS O2 = 1690.40

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1488.	.1	27.4	12.	20.250	.360	600.
2.0	1502.	0.0	27.8	20.	20.250	.420	430.
4.0	1557.	0.0	69.2	40.	19.500	.990	300.
8.0	1645.	.3	89.7	41.	20.000	.760	95.
12.0	1770.	.1	90.5	30.	20.000	.660	60.
16.0	1860.	.1	95.2	23.	20.000	.720	20.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1488.	.064	7.9	3.45	35.98	136.
2.0	1502.	.128	9.6	3.44	36.24	136.
4.0	1557.	.253	84.5	3.38	37.26	134.
8.0	1645.	.494	96.1	3.30	38.88	130.
12.0	1770.	.723	96.4	3.19	41.19	126.
16.0	1860.	.944	98.3	3.12	42.86	123.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1488.	.064	.00607	.20233	.00626	.030
2.0	1502.	.128	.00373	.20342	.00379	.018
4.0	1557.	.253	.02751	.20768	.03171	.122
8.0	1645.	.494	.01965	.21444	.02164	.092
12.0	1770.	.723	.01359	.22392	.01447	.061
16.0	1860.	.944	.01154	.23067	.01215	.050

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/13/81
TEST NO.:EDSOHA-I-2
FUEL :EDS OLD HIGH ASH
GAS :AIR

FUEL FEED RATE (GM/MIN)= .106
GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 = 1772.86

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1880.	.1	22.3	1.	20.250	.150	120.
2.0	1900.	.5	28.6	25.	19.750	.900	1200.
4.0	1900.	.3	79.3	33.	19.750	.900	180.
8.0	1955.	0.0	95.3	35.	19.750	.990	0.
12.0	2098.	.1	97.4	25.	19.900	.810	0.
16.0	2218.	0.0	94.7	35.	20.000	.660	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1880.	.046	0.0	3.10	52.67	149.
2.0	1900.	.091	11.3	3.09	53.12	148.
4.0	1900.	.181	90.8	3.09	53.12	148.
8.0	1955.	.358	98.2	3.05	54.36	147.
12.0	2098.	.526	99.1	2.95	57.57	142.
16.0	2218.	.687	98.0	2.87	60.27	138.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1880.	.046	0.00000	.23216	0.00000	0.000
2.0	1900.	.091	.00640	.23364	.00658	.027
4.0	1900.	.181	.04499	.23364	.05571	.193
8.0	1955.	.358	.03070	.23771	.03525	.129
12.0	2098.	.526	.02218	.24816	.02435	.089
16.0	2218.	.687	.01557	.25684	.01657	.061

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/14/81
 TEST NO.:EDSOHA-1-3
 FUEL :EOS OLD HIGH ASH
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .106
 GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 = 1772.86

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2065.	.1	22.8	100.	20.500	.420	100.
2.0	2147.	.3	71.4	70.	19.900	.960	400.
4.0	2222.	.1	86.1	50.	19.500	.900	300.
8.0	2335.	0.0	97.7	83.	19.500	1.020	20.
12.0	2402.	0.0	86.7	93.	19.500	1.080	0.
16.0	2437.	0.0	94.5	70.	19.750	.900	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2065.	.043	0.0	2.97	56.83	143.
2.0	2147.	.084	86.0	2.92	58.68	140.
4.0	2222.	.165	94.3	2.87	60.36	138.
8.0	2335.	.319	99.2	2.80	62.91	135.
12.0	2402.	.471	94.6	2.77	64.42	133.
16.0	2437.	.620	97.9	2.75	65.20	132.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2065.	.043	0.00000	.24579	0.00000	0.000
2.0	2147.	.084	.08393	.25175	.12591	.333
4.0	2222.	.165	.05627	.25713	.07204	.219
8.0	2335.	.319	.03760	.26525	.04381	.142
12.0	2402.	.471	.01988	.27000	.02147	.074
16.0	2437.	.620	.01741	.27244	.01859	.064

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/17/81
 TEST NO.:EDSLA-I-1A
 FUEL :EOS LOW ASH(RIGHT)
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .097
 GAS FEED RATE (L/MIN) = 14.5

EXCESS O2 = 1724.81

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1488.	.1	26.7	20.	20.000	.720	1680.
2.0	1502.	.4	45.3	55.	20.000	.750	530.
4.0	1557.	.2	79.0	50.	19.930	.760	150.
8.0	1645.	.1	80.7	54.	18.870	.870	100.
12.0	1770.	.2	85.6	53.	19.870	.870	60.
16.0	1860.	.3	85.6	44.	19.750	.810	50.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1488.	.053	53.1	4.09	43.85	166.
2.0	1502.	.106	79.5	4.08	44.16	165.
4.0	1557.	.208	95.5	4.01	45.40	163.
8.0	1645.	.407	95.9	3.91	47.38	159.
12.0	1770.	.595	97.2	3.78	50.19	153.
16.0	1860.	.776	97.2	3.70	52.22	150.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K	KDIFF (*GM./CM2.SEC.ATM.*)	KS	K/KDIFF
1.0	1488.	.053	.06737	.18573	.10572	.363
2.0	1502.	.106	.06215	.18673	.09315	.333
4.0	1557.	.208	.04962	.19064	.06708	.260
8.0	1645.	.407	.02737	.19685	.03179	.139
12.0	1770.	.595	.01882	.20555	.02072	.092
16.0	1860.	.776	.01452	.21174	.01559	.069

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/17/81
 TEST NO.:EDSLA-1-2A
 FUEL :EDS LOW ASH(RIGHT)
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .094
 GAS FEED RATE (L/MIN) = 13.6

EXCESS O2 = 1666.17

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1880.	.1	19.6	25.	20.300	.240	600.
2.0	1900.	.6	32.1	50.	19.600	.750	600.
4.0	1900.	.3	75.9	63.	19.250	.900	0.
8.0	1955.	.2	07.1	59.	19.500	.930	0.
12.0	2098.	.1	96.4	61.	19.750	.970	0.
16.0	2218.	.1	94.8	51.	20.000	.900	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY	REYNOLDS NUMBER
1.0	1880.	.048	30.0	3.68	49.40	140.
2.0	1900.	.096	64.2	3.66	49.82	139.
4.0	1900.	.191	94.6	3.66	49.82	139.
8.0	1955.	.377	97.9	3.61	50.98	137.
12.0	2098.	.553	99.4	3.50	53.99	133.
16.0	2218.	.723	99.1	3.41	56.53	130.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K	K/DIFF (*GM./CM2.SEC.ATM.*)	K3	K/KDIFF
1.0	1880.	.048	.03669	.21311	.04432	.172
2.0	1900.	.096	.04948	.21448	.06432	.231
4.0	1900.	.191	.05434	.21448	.07279	.253
8.0	1955.	.377	.03164	.21821	.03700	.145
12.0	2098.	.553	.02390	.22780	.02670	.105
16.0	2218.	.723	.01750	.23577	.01890	.074

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/16/81
 TEST NO.:EDSLA-1-3A
 FUEL :EDS LOE ASH(RIGHT)
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .084
 GAS FEED RATE (L/MIN) = 13.2

EXCESS O2 = 1818.30

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2065.	.3	24.3	40.	20.250	.480	500.
2.0	2147.	.5	81.9	50.	19.750	.940	60.
4.0	2222.	.1	93.7	65.	19.620	1.000	0.
8.0	2335.	.1	98.1	63.	19.870	.860	0.
12.0	2402.	0.0	99.4	68.	19.750	.840	0.
16.0	2437.	0.0	99.7	66.	19.810	.915	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2065.	.047	47.0	3.52	51.74	130.
2.0	2147.	.091	96.3	3.46	53.42	128.
4.0	2222.	.178	98.9	3.40	54.94	126.
8.0	2335.	.346	99.7	3.33	57.27	123.
12.0	2402.	.510	99.9	3.28	58.64	121.
16.0	2437.	.672	99.9	3.26	59.35	120.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	X/KDIFF
1.0	2065.	.047	.06437	.22563	.09006	.285
2.0	2147.	.091	.11831	.23110	.24240	.512
4.0	2222.	.178	.07087	.23604	.10127	.300
8.0	2335.	.346	.03971	.24349	.04745	.163
12.0	2402.	.510	.02855	.24786	.03226	.115
16.0	2437.	.672	.02210	.25009	.02424	.088

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/11/81
 TEST NO.:KHC-I-1
 FUEL :KENTUCKY HARLAN -70
 GAS :AIR

FUEL FEED RATE (GM/MIN) = .072
 GAS FEED RATE (L/MIN) = 13.8

EXCESS O2 = 2349.96

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1488.	.1	12.2	20.	20.400	.240	360.
2.0	1502.	.3	27.7	40.	19.900	.660	160.
4.0	1557.	.3	47.3	40.	19.900	.690	70.
8.0	1645.	.1	68.1	42.	19.900	.720	20.
12.0	1770.	.1	75.3	37.	19.900	.660	0.
16.0	1860.	.2	74.9	36.	19.900	.660	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1488.	.056	29.1	3.64	41.73	158.
2.0	1502.	.112	74.4	3.63	42.03	157.
4.0	1557.	.220	89.1	3.57	43.21	155.
8.0	1645.	.429	95.4	3.48	45.09	151.
12.0	1770.	.628	96.8	3.37	47.77	146.
16.0	1860.	.820	96.7	3.29	49.70	143.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1488.	.056	.02859	.19688	.03345	.145
2.0	1502.	.112	.04955	.19794	.06610	.250
4.0	1557.	.220	.03595	.20209	.04372	.178
8.0	1645.	.429	.02266	.20867	.02542	.109
12.0	1770.	.628	.01647	.21790	.01781	.076
16.0	1860.	.820	.01258	.22446	.01333	.056

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/06/81
 TEST NO.:KHC-1-2
 FUEL :KENTUCKY HARLAN -70
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .078
 GAS FEED RATE (L/MIN) = 12.5

EXCESS O2 = 1948.46

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1880.	1.0	13.8	37.	19.750	.780	460.
2.0	1900.	.5	41.8	50.	19.750	.720	120.
4.0	1900.	.3	62.4	40.	19.750	.660	50.
8.0	1955.	.1	81.4	50.	19.750	.780	0.
12.0	2098.	.1	91.2	43.	19.900	.720	0.
16.0	2218.	0.0	97.8	50.	19.750	.840	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1880.	.052	37.5	3.28	45.40	129.
2.0	1900.	.104	86.0	3.26	45.79	128.
4.0	1900.	.208	93.9	3.26	45.79	128.
8.0	1955.	.411	97.7	3.22	46.86	126.
12.0	2098.	.603	99.0	3.11	49.63	122.
16.0	2218.	.788	99.8	3.03	51.95	119.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K	KDIFF	KS	K/KDIFF
			(*GM./CM2.SEC.ATM.*)			
1.0	1880.	.052	.04227	.22591	.05200	.187
2.0	1900.	.104	.07056	.22735	.10231	.310
4.0	1900.	.208	.04468	.22735	.05561	.197
8.0	1955.	.411	.02663	.23132	.03010	.115
12.0	2098.	.603	.01979	.24148	.02156	.082
16.0	2218.	.788	.01684	.24993	.01806	.067

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :11/4/81
 TEST NO.:KHC-I-3
 FUEL :KENTUCKY HARLAN (70X0)
 GAS :AIR

FUEL FEED RATE (GM/MIN)= .077
 GAS FEED RATE (L/MIN) = 11.5

EXCESS O2 = 1809.06

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2065.	.9	14.9	80.	20.000	.840	1320.
2.0	2147.	.2	39.1	160.	20.000	1.630	280.
4.0	2222.	.1	79.0	170.	20.100	1.800	30.
8.0	2335.	0.0	98.1	170.	19.600	1.810	0.
12.0	2402.	.1	98.7	250.	20.000	2.290	0.
16.0	2437.	0.0	99.5	200.	20.000	1.800	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2065.	.054	43.6	3.14	45.07	113.
2.0	2147.	.105	84.5	3.08	46.54	111.
4.0	2222.	.205	97.4	3.03	47.87	109.
8.0	2335.	.397	99.8	2.96	49.89	107.
12.0	2402.	.585	99.9	2.92	51.09	105.
16.0	2437.	.771	99.9	2.90	51.71	105.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2065.	.054	.04887	.23917	.06142	.204
2.0	2147.	.105	.06665	.24498	.09156	.272
4.0	2222.	.205	.05154	.25021	.06491	.206
8.0	2335.	.397	.03398	.25811	.03913	.132
12.0	2402.	.585	.02305	.26274	.02527	.088
16.0	2437.	.771	.01802	.26511	.01934	.068

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/7/81
 TEST NO.:KHCC-II-3
 FUEL :200X400 KHC CHAR
 GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN)= .075
 GAS FEED RATE (L/MIN) = 10.2

EXCESS O2 = 135.18

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2372.	.2	13.0	0.	3.550	0.000	60.
2.0	2407.	.4	15.8	33.	3.000	.540	720.
4.0	2449.	.3	30.2	70.	2.470	1.200	320.
8.0	2502.	.3	52.7	85.	2.300	1.380	120.
12.0	2558.	.6	82.1	95.	2.200	1.510	100.
16.0	2585.	.2	80.8	95.	2.100	1.380	40.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2372.	.053	0.0	3.31	44.84	107.
2.0	2407.	.105	17.0	3.29	45.39	107.
4.0	2449.	.208	64.0	3.26	46.06	106.
8.0	2502.	.411	86.0	3.23	46.90	105.
12.0	2558.	.610	96.7	3.20	47.79	104.
16.0	2585.	.808	96.3	3.19	48.21	103.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (GM./CM2.SEC.ATM.)	KDIFF	KS	K/KDIFF
1.0	2372.	.053	0.00000	.23755	0.00000	0.000
2.0	2407.	.105	.05071	.23975	.06431	.212
4.0	2449.	.208	.14880	.24238	.38537	.614
8.0	2502.	.411	.13502	.24569	.29974	.550
12.0	2558.	.610	.13415	.24916	.29061	.538
16.0	2585.	.808	.10428	.25083	.17048	.416

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/17/81
TEST NO.:KHCC-II-2
FUEL : (200X400) KHC CHAR
GAS : 3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .072
GAS FEED RATE (L/MIN) = 14.8

EXCESS O2 = 252.77

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2111.	0.0	13.4	0.	3.500	0.000	100.
2.0	2136.	.1	14.0	2.	3.370	.060	260.
4.0	2162.	.3	17.3	15.	3.250	.300	280.
8.0	2222.	.3	21.9	27.	3.100	.480	260.
12.0	2271.	.2	35.0	38.	2.930	.600	260.
16.0	2268.	0.0	46.7	43.	2.900	.720	280.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2111.	.041	3.3	3.47	59.01	163.
2.0	2136.	.081	8.2	3.45	59.59	162.
4.0	2162.	.161	28.7	3.44	60.19	162.
8.0	2222.	.317	46.9	3.40	61.57	160.
12.0	2271.	.471	72.3	3.37	62.69	158.
16.0	2268.	.625	82.9	3.37	62.63	158.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K	KOIFF	KS	K/KOIFF
1.0	2111.	.041	.02075	.22090	.02290	.094
2.0	2136.	.081	.02729	.22251	.03111	.123
4.0	2162.	.161	.05411	.22418	.07133	.241
8.0	2222.	.317	.05110	.22805	.06599	.224
12.0	2271.	.471	.06683	.23114	.09402	.289
16.0	2268.	.625	.06509	.23098	.09062	.282

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/9/81
 TEST NO.:EDSLA-II-3
 FUEL : (200X400)EDS LOW ASH CHAR
 GAS : 3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .076
 GAS FEED RATE (L/MIN) = 12.1

EXCESS O2 = 203.83

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2372.	0.0	28.6	0.	3.400	.060	150.
2.0	2407.	.4	39.2	18.	2.920	.480	400.
4.0	2449.	.5	53.9	32.	2.620	.780	240.
8.0	2502.	.3	83.3	47.	2.420	1.030	100.
12.0	2558.	.2	80.0	48.	2.400	1.100	40.
16.0	2585.	.1	86.1	43.	2.500	1.020	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2372.	.045	31.7	2.94	53.19	127.
2.0	2407.	.090	57.8	2.93	53.85	126.
4.0	2449.	.178	76.8	2.91	54.64	126.
8.0	2502.	.352	94.6	2.88	55.63	124.
12.0	2558.	.523	93.2	2.85	56.69	123.
16.0	2585.	.692	95.6	2.84	57.19	123.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2372.	.045	.19312	.25181	.82858	.767
2.0	2407.	.090	.23756	.25414	3.64260	.935
4.0	2449.	.178	.20641	.25692	1.04982	.803
8.0	2502.	.352	.18261	.26043	.61110	.701
12.0	2558.	.523	.11805	.26411	.21347	.447
16.0	2585.	.692	.09355	.26588	.14434	.352

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/18/81
 TEST NO.:KHCC-11-1
 FUEL :KHC(200X400) CHAR
 GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN)= .072
 GAS FEED RATE (L/MIN) = 13.3

EXCESS O2 = 217.59

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1480.	.1	13.1	0.	3.350	0.000	0.
2.0	1530.	0.0	13.1	0.	3.400	0.000	0.
4.0	1653.	.4	15.6	1.	3.350	.090	320.
8.0	1804.	0.0	13.4	13.	3.150	.300	440.
12.0	1880.	.2	16.3	28.	2.830	.510	380.
16.0	1871.	.1	18.8	30.	2.830	.510	220.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1480.	.058	.8	3.99	40.04	169.
2.0	1530.	.114	.6	3.94	41.07	167.
4.0	1653.	.221	19.4	3.83	43.61	162.
8.0	1804.	.423	3.2	3.70	46.73	156.
12.0	1880.	.618	23.3	3.64	48.31	154.
16.0	1871.	.815	35.4	3.64	48.12	154.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KOIFF	KS	K/KOIFF
1.0	1480.	.058	.00349	.17884	.00356	.020
2.0	1530.	.114	.00148	.18228	.00149	.008
4.0	1653.	.221	.02474	.19067	.02843	.130
8.0	1804.	.423	.00215	.20081	.00218	.011
12.0	1880.	.618	.01280	.20587	.01365	.062
16.0	1871.	.815	.01558	.20528	.01686	.076

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/17/81
 TEST NO.:EDSLA-II-2
 FUEL :EDS LOW ASH CHAR(200X400)
 GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN)= .076
 GAS FEED RATE (L/MIN) = 14.9

EXCESS O2 = 281.69

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2111.	.3	26.4	1.	3.370	.060	300.
2.0	2136.	.4	27.0	2.	3.300	.090	340.
4.0	2162.	.2	35.0	16.	3.130	.480	460.
8.0	2222.	.3	45.5	20.	2.950	.600	230.
12.0	2271.	.3	53.3	23.	2.850	.550	150.
16.0	2268.	.1	62.9	28.	2.800	.600	100.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2111.	.041	15.1	3.09	59.33	164.
2.0	2136.	.081	17.8	3.07	59.71	163.
4.0	2162.	.161	43.4	3.06	60.51	163.
8.0	2222.	.318	63.6	3.03	61.91	161.
12.0	2271.	.471	73.4	3.00	63.03	159.
16.0	2268.	.625	82.0	3.00	62.97	159.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2111.	.041	.09618	.23416	.16321	.411
2.0	2136.	.081	.05884	.23586	.07839	.249
4.0	2162.	.161	.08559	.23763	.13378	.360
8.0	2222.	.318	.07625	.24174	.11139	.315
12.0	2271.	.471	.06636	.24501	.09100	.271
16.0	2268.	.625	.06216	.24484	.08391	.254

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/18/81
TEST NO.:EDSLA-11-1
FUEL :EDS LOW ASH(200X400)CHAR
GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN)= .078
GAS FEED RATE (L/MIN) = 13.0

EXCESS O2 = 217.66

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NUX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1480.	.7	25.6	0.	3.450	0.000	0.
2.0	1530.	0.0	23.8	0.	3.450	0.000	0.
4.0	1653.	.2	24.9	0.	3.450	0.000	0.
8.0	1804.	.1	26.1	3.	3.320	.090	380.
12.0	1880.	.4	30.7	10.	3.100	.300	460.
16.0	1871.	.2	41.1	20.	2.850	.540	160.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1480.	.060	20.0	3.55	39.14	165.
2.0	1530.	.118	11.7	3.51	40.15	163.
4.0	1653.	.228	17.0	3.41	42.63	158.
8.0	1804.	.436	22.0	3.29	45.68	153.
12.0	1880.	.637	38.1	3.24	47.22	150.
16.0	1871.	.839	60.6	3.24	47.04	151.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1480.	.060	.08742	.18957	.16224	.461
2.0	1530.	.118	.02496	.19322	.02866	.129
4.0	1653.	.228	.01916	.20211	.02116	.095
8.0	1804.	.436	.01374	.21785	.01469	.065
12.0	1880.	.637	.01870	.21823	.02045	.086
16.0	1871.	.839	.02791	.21760	.03201	.128

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/9/81
 TEST NO.:EDSHA-II-3
 FUEL :200X400 HIGH ASH CHAR
 GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN)= .086
 GAS FEED RATE (L/MIN) = 11.8

EXCESS O2 = 207.92

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2372.	.2	44.4	5.	3.350	.060	300.
2.0	2407.	.2	54.7	33.	2.930	.540	620.
4.0	2449.	.2	65.2	50.	2.550	.900	560.
8.0	2502.	.1	85.1	60.	2.450	1.080	180.
12.0	2550.	0.0	95.3	70.	2.260	1.260	40.
16.0	2585.	0.0	98.5	70.	2.250	1.320	0.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2372.	.046	37.1	3.18	51.87	124.
2.0	2407.	.092	58.5	3.16	52.52	123.
4.0	2449.	.182	73.3	3.14	53.28	122.
8.0	2502.	.359	91.2	3.11	54.26	121.
12.0	2558.	.533	97.5	3.08	55.28	120.
16.0	2585.	.706	99.2	3.07	55.78	120.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2372.	.046	.24037	.24212	33.31158	.993
2.0	2407.	.092	.24511	.24436	0.00000	1.003
4.0	2449.	.182	.19939	.24704	1.03376	.807
8.0	2502.	.359	.16430	.25041	.47776	.656
12.0	2558.	.533	.15283	.25395	.38380	.602
16.0	2585.	.706	.13144	.25565	.27052	.514

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/17/81
 TEST NO.:EDSHA-II-2
 FUEL :EDS HIGH ASH CHAR(200X400)
 GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN) = .093
 GAS FEED RATE (L/MIN) = 13.5

EXCESS O2 = 227.73

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	2111.	0.0	44.9	10.	2.950	0.000	0.
2.0	2136.	.1	50.7	18.	2.950	.420	540.
4.0	2162.	.1	57.2	25.	2.700	.480	480.
8.0	2222.	.1	67.4	35.	2.600	.660	260.
12.0	2271.	0.0	82.0	35.	2.650	.840	100.
16.0	2268.	0.0	87.1	33.	2.700	.780	70.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	2111.	.045	37.1	3.34	53.87	149.
2.0	2136.	.089	50.2	3.33	54.39	148.
4.0	2162.	.176	61.7	3.31	54.94	148.
8.0	2222.	.347	75.3	3.27	56.20	146.
12.0	2271.	.515	88.7	3.24	57.22	145.
16.0	2268.	.683	92.4	3.24	57.17	145.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	2111.	.045	.28263	.22515	0.00000	1.255
2.0	2136.	.089	.20642	.22679	2.29749	.910
4.0	2162.	.176	.15000	.22849	.43661	.656
8.0	2222.	.347	.10740	.23244	.19966	.462
12.0	2271.	.515	.09858	.23558	.16452	.410
16.0	2268.	.683	.08130	.23542	.12418	.345

DROP TUBE FURNACE SYSTEM DATA REDUCTION PROGRAM

DATE :12/18/81
 TEST NO.:EDSHA-II-1
 FUEL :EDS HIGH ASH CHAR(200X400)
 GAS :3 PCT O2/97 PCT N2

FUEL FEED RATE (GM/MIN)= .088

GAS FEED RATE (L/MIN) = 12.6

EXCESS O2 = 221.32

DISTANCE (INCHES)	TEMPERATURE (DEG F)	MOISTURE IN CHAR (PCT)	ASH IN CHAR (PCT)	NOX (PPM)	O2 (PCT)	CO2 (PCT)	CO (PPM)
1.0	1480.	0.0	35.8	0.	3.200	0.000	0.
2.0	1530.	0.0	36.1	0.	3.200	.030	0.
4.0	1653.	.1	35.4	2.	3.050	.030	280.
8.0	1804.	.2	44.8	9.	2.700	.360	700.
12.0	1880.	.3	47.5	13.	2.600	.480	780.
16.0	1871.	0.0	56.6	21.	2.500	.480	280.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	CONVERSION EFFICIENCY (BY ASH TRACER) (PCT)	PARTICLE (FREE-FALL) VELOCITY (CM./SEC.)	GAS VELOCITY (CM./SEC.)	REYNOLDS NUMBER
1.0	1480.	.061	9.7	3.84	37.93	160.
2.0	1530.	.120	10.8	3.79	38.91	158.
4.0	1653.	.233	8.2	3.68	41.32	153.
8.0	1804.	.446	38.2	3.56	44.27	148.
12.0	1880.	.652	44.6	3.50	45.77	146.
16.0	1871.	.859	61.4	3.51	45.59	146.

DISTANCE (INCHES)	TEMPERATURE (DEG F)	TIME (SEC.)	K (*GM./CM2.SEC.ATM.*)	KDIFF	KS	K/KDIFF
1.0	1480.	.061	.04446	.18228	.05880	.244
2.0	1530.	.120	.02531	.18579	.02931	.136
4.0	1653.	.233	.01029	.19434	.01087	.053
8.0	1804.	.446	.03198	.20467	.03791	.156
12.0	1880.	.652	.02744	.20983	.03157	.131
16.0	1871.	.859	.03291	.20923	.03905	.157

APPENDIX D
FIRESIDE PERFORMANCE TEST FACILITY

FIRESIDE PERFORMANCE TEST FACILITY

The Fireside Performance Test Facility (FPTF) is a pilot-scale combustion facility (Figure 1) used primarily to assess fuel properties which influence fire-side (ash deposition, external corrosion, etc) boiler performance. The facility is comprised of a complete coal handling and pulverization system, and air preheater, and a vertically-fired test furnace.

A schematic of the facility is shown in Figure 2. Crushed coal (1-1/2" top size) is fed from a 5-Ton capacity outside-storage hopper to a C-E Model 271 Bowl Mill where it is pulverized to the desired fineness. The small, deep bowl, single-journal (roller) mill is equipped with a direct gas-fired air heater to provide mill drying air. The pulverized coal is pneumatically transported to a cyclone collector where most of the coal is dropped into a 3-ton capacity storage hopper. Fines in the cyclone effluent are collected in a bag filter and returned to the storage hopper. Pulverized coal is fed by a belt type gravimetric feeder from the hopper into a rotary air lock, from which it is pneumatically transported into the furnace. Secondary air can be heated up to 800°F in an indirect gas-fired air preheater.

The test furnace basically consists of a refractory-lined 36 inch I.D. cylinder, 18 ft. in height (Figure 3). A six inch thick refractory lining minimizes the potentially high heat losses associated with the large surface-to-volume present with small scale units. Cooling air is drawn through the 1-1/2 inch annulus surrounding the refractory lining providing the necessary cooling for furnace structural shell, as well as control of the heat absorption by the lower furnace.

The furnace is fired from the bottom through a single, swirl-type burner (Figure 4). The burner has adjustable vanes allowing adjustment of the desired swirl to secondary air. The maximum capacity of the furnace is approximately 4.0×10^6 Btu/Hr which corresponds to roughly 350 lb/Hr of

FIGURE 1 THE FIRESIDE PERFORMANCE TEST FACILITY (FPTF)

FIRESIDE PERFORMANCE TEST FURNACE

Figure 2

FIRESIDE PERFORMANCE TEST FURNACE

Fuel Preparation and Feed System

Figure 3

FIGURE 4 THE VARIABLE SWIRL-TYPE BURNER

pulverized coal feed. Firing in the test furnace is designed to simulate commercial boiler time-temperature history. Firing rate can be varied to obtain a wide range of conditions (Flame temperatures from 1900 to 3000°F and residence times from 1 to 2 seconds).

Located in the radiant section of the furnace (approximately 3 ft. above the burner is a simulated waterwall test surface (Figure 5). This water-wall test panel is used for the study of lower furnace ash deposition and is capable of providing detailed data on the slagging characteristics of the test fuel. A water-cooled frame surrounds the panel to reduce interference from slag generated on hot refractory surfaces. The panel is relatively large (approximately 4.7 square feet surface area), and actually consists of three separate panels (Figure 6). Each panel section is cooled by fluid passing through serpentine tubing. The bottom panel is our primary tool. This test section is designed to simulate the conditions in the lower furnace of a commercial boiler. Metal temperature of the panel is typically controlled at 700°F. Therminol 66, a high boiling point organic liquid, is utilized as the coolant and flows in a closed cycle through panel. Gas/flame temperatures at the panel elevations typically range from 2400-2800°F (depending on firing rate). The heat absorption rate of the panel is continuously monitored by recording the coolant flow rate and temperature rise through the panel.

Flue gases leave the combustion zone at a right angle through a horizontal water cooled superheater duct (Figure 7). The cross-sectional area of this duct is one square foot (144 inches²). A water-cooled transition section surrounds the entrance of the superheater duct. The duct section of the furnace is designed to simulate the convection sections of a commercial boiler, and consists of five sections totaling 13 feet in length. Four banks of eight inches long, 2 inch diameter, air-cooled probes are used to simulate superheater tubes (Figure 8). Each bank contains two rows of probes. Probe metal temperature is typically controlled at 1100°F. The

FIGURE 5 LOWER FURNACE FEATURING WATERWALL TEST PANEL

FIGURE 6 WATERWALL TEST PANEL

FIGURE 7 UPPER FURNACE SECTION OF FPTF AND SUPERHEATER DUCT

FIGURE 8 AIR-COOLED SUPERHEATER PROBE BANKS

probe banks are inserted vertically into the duct and are located between 18 and 140 inches downstream from the furnace outlet (Figure 9). Typical gas temperatures and gas velocities at the probe banks range from 2200-1500⁰F and 60-40 ft/sec, respectively.

The facility is fully instrumented to accurately monitor and record all fuel and air inputs (Figure 10). Cooling flows and temperatures are measured to obtain mass and energy balances around the furnace. A gas analysis system allows continuous measurement of O₂, CO₂, CO, NO_x and SO₂ concentrations in the flue gas (Figure 11). Flame temperature is continuously measured with an automatic radiation pyrometer at the waterwall panel elevation, and local gas temperatures are periodically measured with high velocity suction pyrometers.

SUPERHEATER DUCTS SHOWING PROBE LOCATIONS

FIGURE 9

FIGURE 10 CONTROL CABINETS OF THE TEST FACILITIES

FIGURE 11 GAS ANALYSIS SYSTEM

APPENDIX E

FIRESIDE PERFORMANCE TEST FACILITY TESTING PROCEDURES

FPTF TEST PROGRAM PROCEDURES

Standardized FPTF tests have been developed to permit a comprehensive study of the influence of furnace operating parameters on ash deposition. The comparison of results from several coals tested under these standard conditions allows the evaluation of relative ash deposit characteristics as a function of fuel properties.

Each standardized ash deposit characterization test consists of a series of three individual trials conducted at firing rates of 2.25, 3.0, and 3.75 $\times 10^6$ Btu/hr, respectively. The test sequence which is carried out at each firing rate is shown in Figure E-1. The total time span for each test is sixty hours, including more than forty hours of consecutive coal firing.

A test sequence begins with a furnace warm-up period followed by a transition to coal. Once on coal, a three hour period is allowed for thermal stabilization at test conditions. All lower furnace and superheater probe deposits are removed at this time, and the first phase of the pressure drop tests (Pressure Drop Test I) is started.

During the pressure drop tests, the time required for deposits to build up to a standard resistance is recorded. Pressure Drop Test I is conducted with the first probe bank (Probe Bank I) removed. Upon completion of this 20 hour segment of the test, Probe Bank I is installed, on line, in the higher temperature gas stream preceding the other probe banks. A three hour interval is allowed for Probe Bank I to reach equilibrium, then all probe deposits are removed and the second phase of the pressure drop tests (Pressure Drop Test II) is conducted. The purpose of Pressure Drop Test II is to evaluate the effect of higher gas temperatures and probe location on ash deposition.

Following Pressure Drop Test II, the superheater probes are thoroughly cleaned, and the Deposit Buildup Test is begun. During this test, the mass of deposits accumulated on the probes during a standard time period is quantified. After the eight (8) hour buildup test, the furnace is shut down.

Lower furnace waterwall panel data is simultaneously collected during the entire test sequence. Waterwall panel coolant flow rate along with inlet and outlet temperatures are recorded continuously during the entire test

COAL ASH DEPOSIT CHARACTERIZATION FPTF

FIGURE E-1

sequence. Furnace operating data is logged hourly. Observations concerning deposit characteristics are carefully noted and superheater probe deposit growth is documented with photographs.

During the shutdown period (10 hours), deposit accumulation is collected and weighed. Samples of deposits are collected from each row of the superheater probes and from the waterwall panel. Samples are carefully separated into individual layers for later analysis. Analyses are also obtained on a composite sample of pulverized coal feed. Analytical data includes ash composition, fusibility temperatures, deposit density, and water and acid soluble alkalies.

Upper Furnace Deposit Characterization

The test facility has been designed and a standardized test procedure developed which allows separate characterization of coal ash deposits forming in the radiant (lower furnace) and convection (upper furnace) sections. For the upper furnace, superheater probe deposits are characterized as a function of firing rate, gas temperature and probe location. Deposits are evaluated in terms of buildup rate, bonding strength, physical properties (physical state, appearance, density, etc.) and chemical properties. Superheater deposition rate is studied by two methods:

1. Pressure drop tests
2. Deposit buildup tests

One method of quantifying deposit buildup is to establish the frequency of soot blowing in the FPTF. Soot blowing criterion is determined by the increase in pressure drop across the leading probe bank. Ash deposit growth is monitored both visually and measured by the pressure differential across the probe bank. When deposit buildup produces a specified resistance (standard ΔP), the deposits are removed with an air lance. The time required to reach the standard pressure drop indicates the frequency of soot blowing in the FPTF.

The pressure drop tests establish time required for superheater probe deposits to accumulate causing a given resistance to gas flow. The deposit buildup tests establish the mass of deposit accumulated during a given period. The final eight (8) hours of the test sequence is allotted for collection of superheater probe deposits. At the conclusion of this sequence, the ash deposits accumulated on each probe bank are collected and weighed. The weights of these deposits indicate the relative quantity of ash deposition from the test coal at the given conditions in the FPTF.

The tenacity of the bond between the deposit and the heat transfer surface is the primary factor in determining the cleanability (degree of difficulty in removing deposits by soot blowing) of the ash deposits. A technique was developed to obtain a quantitative measure of the relative bonding strength of superheater probe deposits. A surface penetrometer was adapted to measure the force required to push the deposit off the probe surface. Determination of the deposit cleanability is the most important factor influencing the overall assessment of fouling potential.

Bonding measurements are performed in situ at the end of each cycle during the pressure drop tests. Evaluations are made at a time when the quantity of deposits are similar. Measurements of bonding strength are made with the direction of the force applied perpendicular to the bond and tangent to the probe surface (See Figure E-2).

Lower Furnace Deposit Characterization

Lower furnace ash deposition is studied primarily with the aid of a heat transfer panel simulating a waterwall surface. Panel coolant flow rate and the coolant temperature increase through the panel are continuously recorded providing a history of the heat flux through the panel during the test period. The temperature differential is directly measured by detecting the voltage differential between two calibrated thermocouples to increase the precision.

SUPERHEATER DEPOSIT BONDING STRENGTH MEASUREMENT

The extent to which ash deposits impede heat transfer is reflected by the panel heat flux. Variations of heat flux are attributed to the combined effect of the quantity of deposits and the thermal properties of these deposits (thermal conductivity, absorptivity, emissivity). In order to help characterize waterwall deposition, three indices were derived based on the panel heat flux curves (heat flux vs. time).

The Average heat flux/Total heat input is an index which reflects the average effects of ash deposition on heat transfer. Dividing by the total furnace heat input helps to normalize the index for minor variations in firing rate (flame temperature).

The average cycle time is the period during which the deposits build up and slough off. This index is influenced by the rate of deposit buildup and the deposit bonding strength. Cycle time used in conjunction with average heat flux provides an indication of the range of deposit thermal resistance.

The ratio of the average heat flux over the final twelve hours of the test to the heat flux of the clean panel is an index developed to reflect long term nature of the deposit. Well bonded deposits of high thermal resistance would yield a low ratio. As the effect of ash deposition on heat transfer decrease, the ratio would approach unity.

GLOSSARY AND ABBREVIATIONS

ADP: Availability Data Program

Assembly: Coplanar tubes in the direction of the gas flow.

BET: Brummer, Emmet, Teller.

C-E: Combustion Engineering, Inc.

Circulation Ratio: The ratio of the mass flow rate of the water fed to the steam generating tubes to the steam flow rate generated.

Counter Flow: Flow type in which the hot end of the one fluid and the cold of the other are in the same cross section, and vice versa.

Devolatilization: Reaction the coal undergoes when it is heated.

where HC indicates hydrocarbons higher than CH_4 and ΔH the heat released (exothermic reaction)

DNB: Departure from nucleate boiling

DTFS: Drop Tube Furnace System

ECLP: EDS Coal Liquefaction Pilot Plant

Electrostatic Precipitator (ESP): Fly ash removal system. Suspended particles in the gas are electrically charged and then driven to collecting electrodes by an electrical field.

ER&E: Exxon Research and Engineering Company

ESP: electrostatic precipitator

Fireball Flame Scanner: Flame monitoring device, detecting the presence or absence of flame.

FD: forced draft

GLOSSARY AND ABBREVIATIONS (Cont'd)

Forced Draft Fan: Fan providing the required pressure to introduce the secondary air to the furnace.

FGD: Flue Gas Desulfurization System

Fouling: The adherence of ash on the convection surface.

FPTF: Fireside Performance Test Facility

FSSS: Furnace Safeguard Supervisory System

Furnace Height: From the centerline of the lower header to the furnace roof.

Fusion Welding: Molten metal deposited by welding arcs between the tubes.

Gas Recirculation (GR): Flue gas is taken from the main gas stream and reintroduced into the furnace. It is normally used for steam temperature control.

ID: induced draft.

IFM Ignitor: Ionic Flame Monitoring Ignitor

Induced Draft Fan: Fan providing the required static head to assure flow of the combustion products from the furnace to the stacks.

KDL: Kreisinger Development Laboratory

KHB: Kentucky high volatile bituminous (coal)

LNCFS: low NO_x concentric firing system

Longitudinal Spacing (S_L): The distance between the centerlines of two consecutive tubes in the direction of the gas flow.

MCR: Maximum Continuous Rating (Full Load)

MTBF: Mean Time Between Failures

MTTR: Mean Time to Repair

GLOSSARY AND ABBREVIATIONS (Cont'd)

Net Heat Input (NHI): Net heat released inside the furnace; include the following:

- i) Gross fuel heat input based on high heating value of the fuel.
- ii) Sensible heat; calculated above 80°F, contained in the fuel, preheated air and recirculated gas, and
- iii) Heat content of the fuel atomizing steam above 80°F (when such steam is used).

From the previous items, the latent heat of vaporization of liquid water in the fuel and water formed from the hydrogen, along with the combustible loss are subtracted:

NHI/PA: Net Heat Input Per Plan Area

OD: Outside Tube Diameter

Overfire Air: Air introduced at the top of the windbox

PA: primary air

Parallel Flow: Flow type in which the hot ends of both fluids are in the same cross section.

Pendant Superheater: Tube assemblies hanging vertically to the direction of the gas flow.

Plan Area (furnace): Cross section of the furnace vertically to the direction of the gas flow; (width) x (depth).

Platenized Pendant: Assemblies with small longitudinal spacing (clear space between tubes small).

PM: pollution minimum

Primary Air: Air needed to transport and drying of the coal.

GLOSSARY AND ABBREVIATIONS (Cont'd)

Primary Air Fan: Fan providing the required static head for the Primary Air System.

Recuperative Air Heater (tubular): It utilizes the heat contained in the products of combustion to preheat the combustion air. It is essentially a nest of straight tubes expanded into tube sheets and enclosed in a reinforced steel casing. Air or gas are running through the tubes.

Regenerative Air Heater: In a rotating plate-type air heater, heat-storage plate elements are heated progressively in a flowing gas stream, and then rotated by mechanical means into an air stream where the stored heat is released.

R_c : Convective Heat Transfer Rate, $\frac{\text{Btu}}{\text{hr-sq.ft.} \cdot \text{F}}$

R_n : Non-luminous Heat Transfer Rate

R_t : Total Heat Transfer Rate; $R_t = R_c + R_n$

Secondary Air: Air required for combustion of the fuel.

SGR: separating gas recirculation

SHO: superheater outlet

Slagging: Fused deposits or resolidified molten material that forms primarily on furnace walls.

SSC: Submerged Scraper Conveyor; Continuous Ash Removal System

Steam Quality: Ratio of steam leaving to water entering the heated circuit. Quality is the inverse of the circulation ratio.

TGA: Thermogravimetric Analysis

TGS-2: Perkin Elmer Model TGS-2 thermogravimetric analysis apparatus

Transverse Spacing (S_T): The distance between the centerlines of the