

# Influence of Coal Mineral Matter on Slagging of Utility Boilers

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Prepared by

BATTELLE, COLUMBUS LABORATORIES  
505 King Avenue  
Columbus, Ohio 43221

Principal Investigator  
H. R. Hazard

Prepared for

Electric Power Research Institute  
3412 Hillview Avenue  
Palo Alto, California 94304

EPRI Project Manager  
J. P. Dimmer

Fossil Plant Performance and Reliability Program  
Coal Combustion Systems Division

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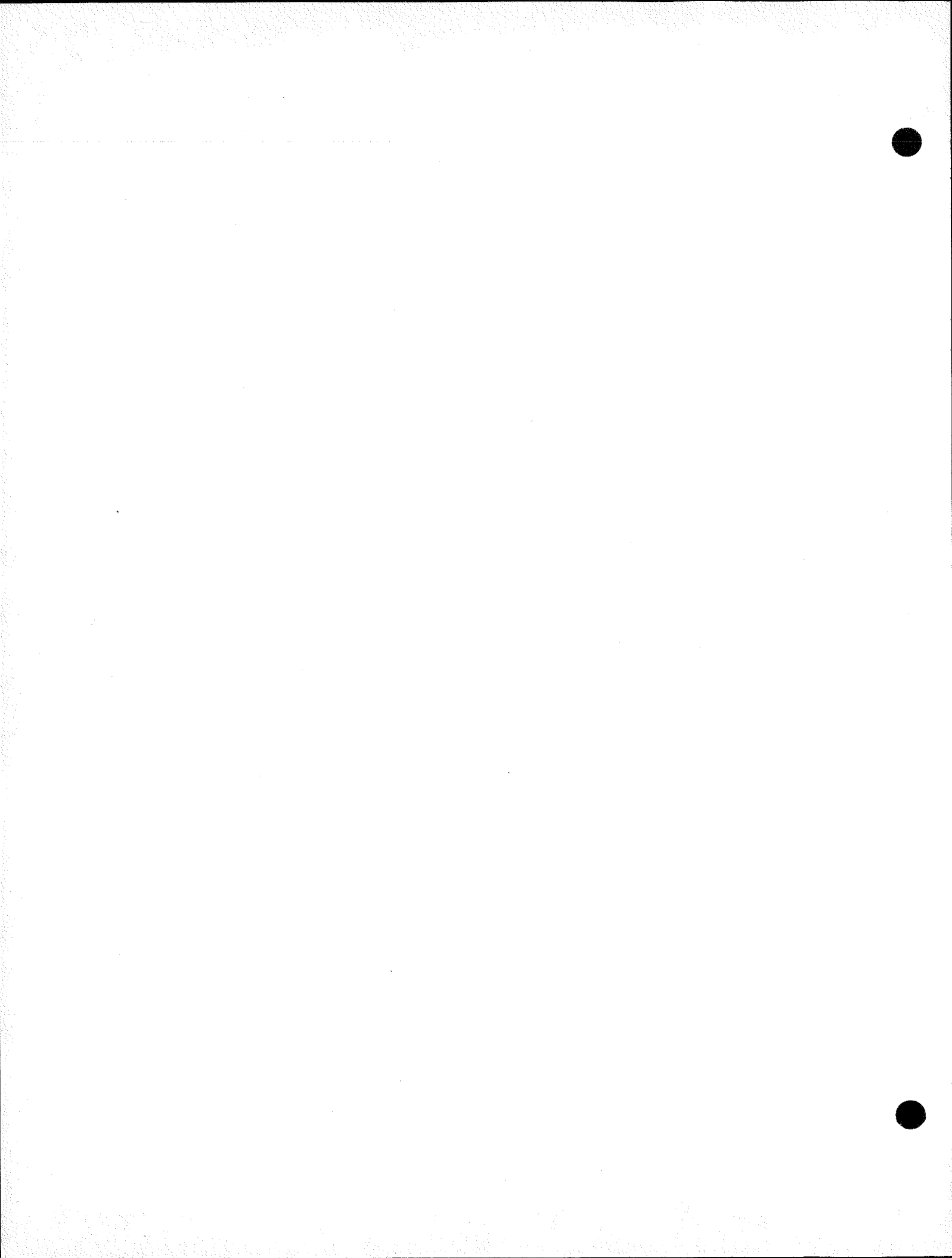
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Prepared by  
Battelle, Columbus Laboratories  
Columbus, Ohio

## ABSTRACT

In an experimental project to explore the role of coal minerals in boiler slagging and fouling, five tangentially fired boilers having different slagging experiences and fired with different coals were studied. Temperatures and compositions of furnace gas were measured, samples of pulverized coal, furnace ash, and fly ash were collected and analyzed, boiler ash deposits were observed, and operating data were recorded. Marked differences were found in compositions and fusion properties of ash from different coal density fractions. For two slagging coals, 35 and 50 percent respectively, of the total ash was found in the coal fractions heavier than 1.6 sp. gr, and the viscosity of ash in these fractions at 2300 F was extremely low. Ash in lighter coal fractions was of high viscosity and should not cause slagging problems. The dense fractions of three non-slagging coals had no comparable low-viscosity ash. In parallel studies of furnace deposit structure, it was found that glassy spherical particles forming much of the deposit were similar in composition to ash found in individual coal particles, so that they could be formed without interaction between particles.



## EPRI PERSPECTIVE

### PROJECT DESCRIPTION

Presented in this final report are the results of a 40-month exploratory study directed at gaining an improved understanding of the influence of coal minerals on the slagging characteristics of coals. The methodology used to realize this general objective consisted of: (1) making systematic observations of the operation of six similar boilers, burning different coals, and experiencing slagging problems ranging from severe to none; (2) obtaining data on the distribution of minerals in pulverized coals by bulk sample, particle size, and density fractions; and (3) performing laboratory analysis of coal, ash, and slag samples using a variety of modern microanalysis techniques.

### PROJECT OBJECTIVES

The objectives of the research were to:

1. Seek evidence that mineral types, quantities, and their distribution in coal influence slagging and fouling in ways not predictable from the American Society for Testing and Minerals ash fusion data
2. Explore the influence of furnace design, size, burner arrangements, and operation on slagging and fouling characteristics
3. Explore the possibility of developing improved techniques for relating slagging and fouling potential to coal mineral matter and boiler design.

### PROJECT RESULTS

Large numbers of coal and ash samples were analyzed in this effort, using a variety of sophisticated techniques. Only two techniques indicated promise for improving our understanding of the role mineral matter in coal plays in the slagging and fouling of utility boilers.

One promising technique was the elemental analysis of ash in coal density fractions. This technique detected a significant distinction between severely slagging and nonslagging coals. The slagging coals were found to contain a much higher percentage of calcium within the specific gravity range of 2.0 to 2.8 than the nonslagging coals. The calculated slag viscosity for this fraction was found to be low enough to become fluid in the flame and therefore could form wall deposits. The slagging coals were also found to contain much higher concentrations of iron in the 1.6 to 2.0 gravity fraction than the nonslagging coals, such that this ash fraction would also be fluid in the flame. For the two slagging coals, 35 and 50 percent of the total ash were calculated to be fluid in the flame in contrast to only 6, 8, and 4 percent of the total ash calculated for the three nonslagging coals, respectively.

It therefore appears, from this limited sampling of five coals, that the segregation of a large percentage of ash minerals into small, separable fractions of coal, in combinations that produce fluid ash in the flame, could result in more severe slagging characteristics than would be normally anticipated from the overall ash characteristics.

The other promising analytic technique was the microanalysis of furnace ash deposits using optical metallography, hot-stage microscopy, and energy-dispersive x-ray analysis. Many significant observations, based primarily on a detailed analysis of two samples from a severely slagging boiler, are presented in the text. It is clearly demonstrated that these analytic procedures can be successfully used to investigate and characterize the constituents of furnace deposits including material that bonds the particulate matter together. These microanalysis procedures are very complementary to coal analysis by density fractions, as they provide a means for verifying ash constituents that are calculated to have a liquid phase at furnace operating temperatures. They would also be very useful in identifying ash characteristics that could be modified by coal cleaning or chemical fuel-addition treatments.

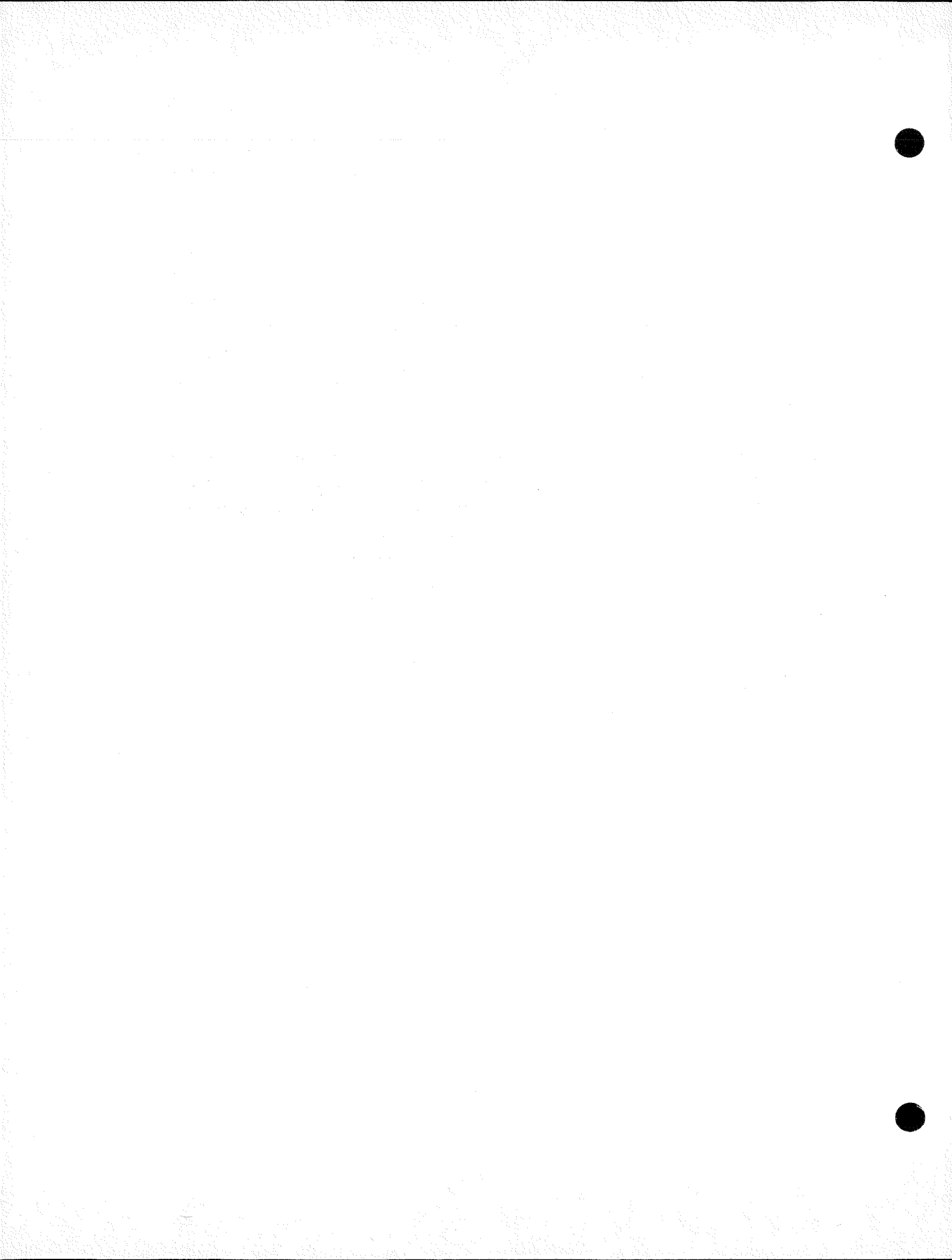
Study of operating and design characteristics of the slagging versus nonslagging boilers revealed that the slag-limited boilers were burning coal containing approximately 30 percent more ash than the design coal. It was concluded that if they had been burning design coal or coal with less ash content, rather than different ash composition, it is quite possible they would not be slag limited. It is suggested that both slagging boilers would be good candidates for using

washed coal. Coal washing would not only reduce the ash loading of the slagging boilers but more importantly would also reduce the slagging potential of the remaining ash.

Based on the successful results of this limited exploratory study it is recommended that further research employing these promising techniques be carried out on other coals used in slagging and nonslagging boilers to: (1) confirm the validity of the approach using ash analysis of coal density fractions as a measure of a coal's slagging potential and (2) further investigate the initial slag-bonding mechanism and/or properties by microanalysis of furnace slag and ash deposits.

Loss-of-boiler availability due to slag or slag-related problems is very costly to the Electric Utility Industry. It is apparent from this limited research effort that better predictive tools are required to assess the slagging potential of coal not only for consideration in initial boiler design, but to allow utilities to determine the possible detrimental effects of degraded or changed coal supplies.

J. P. Dimmer, Project Manager  
Fossil Plant Performance and Reliability Program  
Coal Combustion Systems Division



#### ACKNOWLEDGMENT

The research discussed in this report was conceived by the ASME Corrosion and Deposits Committee, who selected Battelle as the contractor. EPRI then incorporated the project into its program and provided both funding and guidance. Over the three years of the program, the EPRI Project Managers were Howard Swenson, Don Anson, and John Dimmer.

A number of Battelle staff members have made significant contributions to the research. Richard E. Barrett assisted with selection of the five units for field trials, which required review of 38 potential sites. David A. Trayser led the field team that included Paul Webb, Sue Jarrett, Harry Leonard, and Tom Lyons.

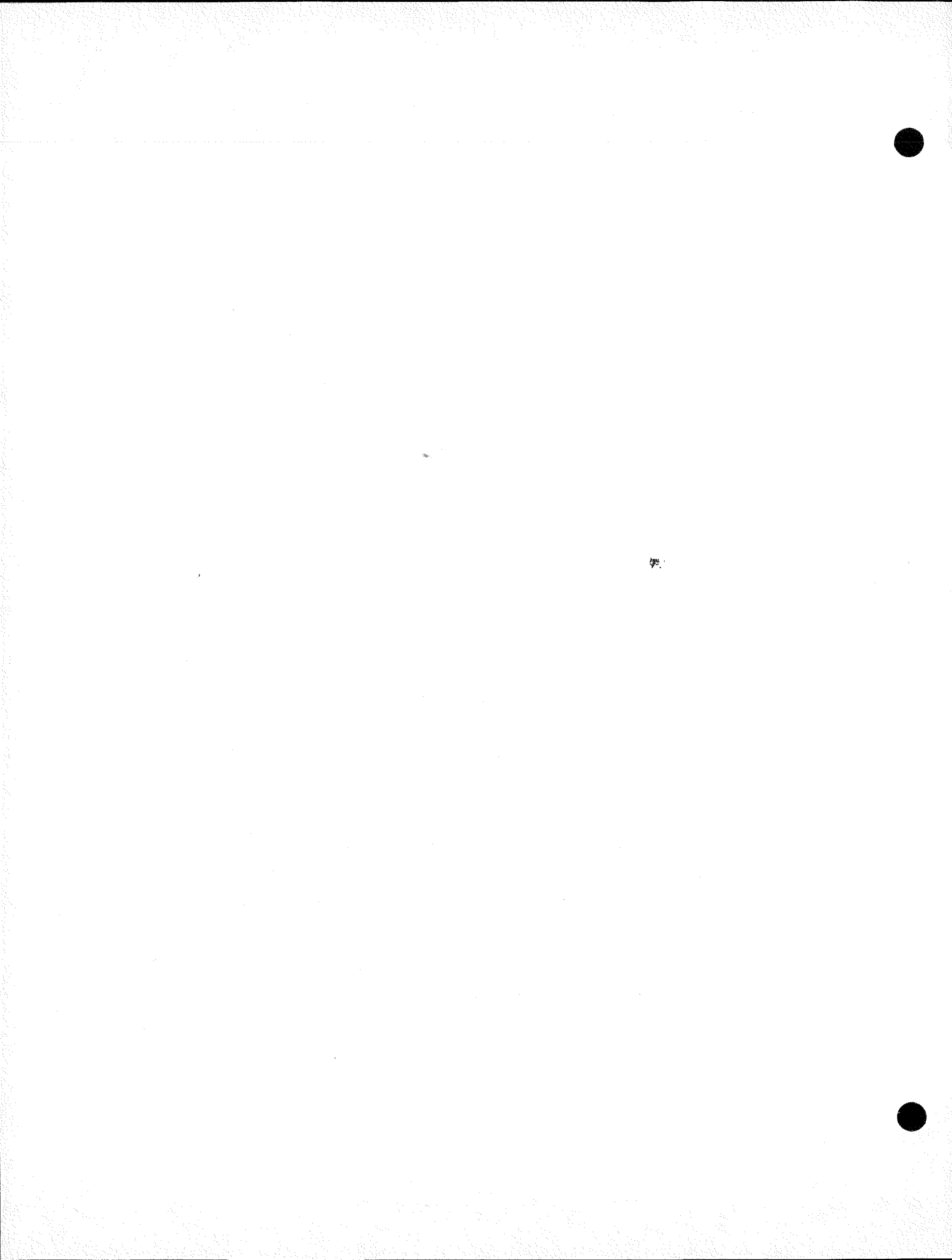
Studies of the melting behavior of low-temperature ash, and of ground furnace ash, were carried out by John Lennon using the hot-stage microscope. Scanning Electron Microscope studies of the structure of furnace ash deposits were carried out by R. R. Fessler and A. J. Skidmore.

The very comprehensive analyses of coal and ash samples were carried out by the Coal Research Laboratory of the Pennsylvania State University, under the direction of Dr. William Spackman.

William T. Reid, as a consultant to Battelle and EPRI, has carried out calculations of slag viscosities for selected ash samples and contributed much to the interpretation of data on ash characteristics.

The project would not have been possible without the cooperation of the utilities who provided sites for field trials, and the excellent cooperation by their generating-station personnel. The cooperating utilities were:

Labadie 1 and 4	Union Electric Company
Mill Creek 1	Louisville Gas and Electric Company
Cliffside 5	Duke Power Company
Morgantown 1	Potomac Electric Power Company
Montour 1	Pennsylvania Power and Light Company

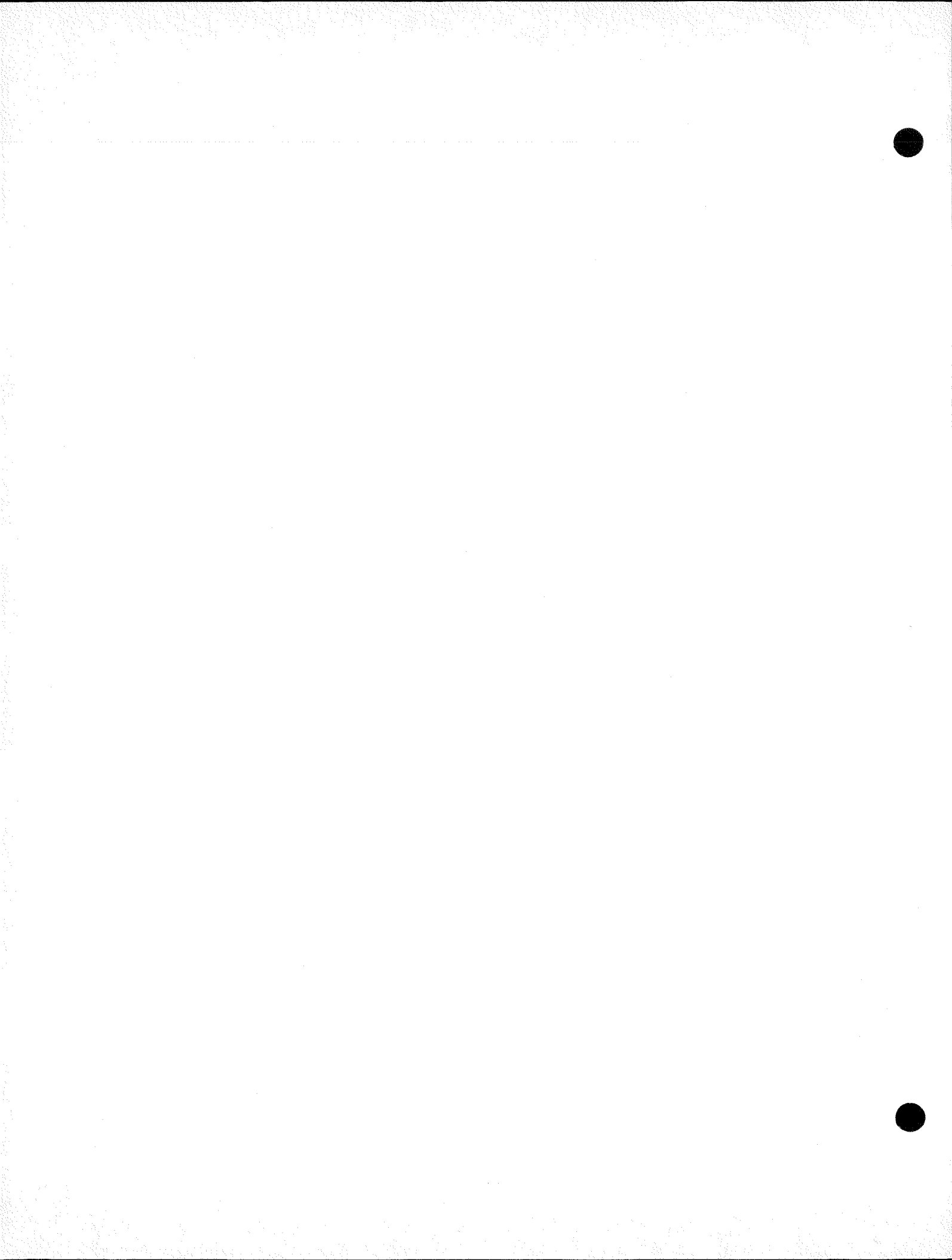


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## Section 1

### INTRODUCTION

Empirical correlations of slagging and fouling characteristics of coal with ash content, ash elemental analysis, and/or ash fusion temperatures have been used for boiler design with relatively good success. However, occasionally a boiler design based on such correlations will have unexpected slagging or fouling problems. It is suspected that specific slagging problems may be related to certain mineral constituents of the coal--their species, their form, and their distribution within the coal--but very little is known about the role of coal minerals in slagging and fouling. An understanding of these effects should result in better boiler design and better prediction of slagging and fouling potential for specific coals.

Throughout this report, slagging is defined as furnace deposits having a molten surface, and fouling is defined as hard deposits on superheater tubes. Slagging causes operating problems when it cannot be removed without dropping load; fouling causes problems when it cannot be removed using soot blowers. Although the research was aimed at study of both slagging and fouling, none of the five boilers tested had a superheater fouling problem. Thus, no information on fouling was developed, although observations of deposit structure may prove significant relative to sintering processes.

Current techniques for separation of minerals from coal, and for the non-destructive analysis of individual coal and ash particles, permit a more detailed examination of the effects of specific impurities than could have been made a decade or two ago. This is particularly important in relation to the build up of deposits--in which we are concerned with the elements and compounds which initiate the bonding processes. These processes are the precursors of slagging, which results as the thickness and surface temperature of a deposit rise. They include partial ash fusion and sintering, which are much less precisely definable than the behavior of the melted ash or slag, in which individual ash particles lose their identity and the melt approaches a homogenous state.

The research reported here is based on the knowledge that the ASTM ash fusion temperatures for a coal are not truly representative of the fusion temperatures of individual particles of coal minerals, only some of which are released from the coal during pulverization. Ash forming substances occur within the coal as a variety of mineral species, each with a different melting point. Very finely divided inherent ash will occur in even the smallest of coal particles, but larger bits of ash may be separated from the coal during pulverization, and may pass through the flame and melt without contact with carbon or other minerals. Any significant quantity of segregated low-melting-point minerals could influence slagging and fouling behavior. In addition, undesirable material that can be segregated may be removable by washing of the coal. In this research, coal mineral forms have been determined for each of five types of coal, and the compositions of ash in coal screen fractions and coal density fractions have been determined. In addition, the structure and analyses of furnace ash deposits have been studied by Scanning Electron Microscope techniques. These data are used as a basis for exploring the effects of coal mineral characteristics on furnace slagging.

#### RESEARCH OBJECTIVES

The objectives of the research were:

1. To seek evidence that mineral types, quantities, and distribution in coal influence slagging and fouling in ways not predictable from ASTM ash fusion data. The mixture of minerals in each coal particle will determine the fusion temperature of ash from that particle, and different particles may contain different mineral constituents.
2. To explore the influence of furnace design, size, arrangements, and operation on slagging and fouling with coals having slagging or fouling potential.
3. To explore the possibility of developing improved techniques for relating slagging and fouling potential with coal mineral matter and boiler design.

The project was carried out in four tasks, as follows:

1. Selection of field trial units, including consideration of coals used, slagging experience, and test conditions.
2. Field trials for collection of coal and ash samples, and of data on boiler operation.
3. Laboratory analyses of coal and ash samples.
4. Data summation, analysis, and correlation.

## Section 2

### SUMMARY

#### OBJECTIVE

The objective of this research project was to determine the influence of specific coal minerals on slagging of utility boilers, as a step toward improvement of boiler design and as an aid in coal selection. The research was based on the premise that bulk ash fusion temperature for coal is not truly representative of the fusion temperatures of discrete ash particles released by combustion of individual particles of coal. Any significant quantity of segregated minerals of low melting temperatures could adversely influence slagging and fouling behavior.

#### METHODOLOGY

The research was based on field trials of five test boilers selected on the basis of slagging experience, coal characteristics and boiler configuration. For similarity of design, five Combustion Engineering units with tangentially fired furnaces were selected, as follows:

<u>Unit</u>	<u>Slagging</u>	<u>Coal</u>	<u>MW</u>
Mill Creek 1	Severe	W. Kentucky	350
Labadie 1 and 4	Severe	S. Illinois	600
Montour 1	Moderate	E. Pennsylvania	750
Morgantown 1	Slight	E. Pennsylvania	625
Cliffside 5	None	E. Kentucky	600

The Mill Creek, Labadie, and Cliffside boilers had single furnaces, and the Morgantown and Montour boilers had divided furnaces.

Mill Creek had a severe slagging problem that limited continuous operation to 300 MW, or to 325 MW for 8 to 10 hours. A Western Kentucky coal of high slagging potential\* was fired. The Labadie boiler could carry 580 MW for about 12 hours before dropping load to deslag the furnace. Montour operated somewhat above design rating, but required 5.3 percent oxygen in the flue gas to avoid slagging. Both Morgantown and Cliffside boilers could be operated at rated load for extended periods without slagging problems.

\* Slagging potential refers to predictions based on the empirical relationship discussed in Section 10 of the report.

During field trials at each test site, furnace gas temperatures and furnace gas compositions were measured by traversing at two or more elevations, and samples were obtained of pulverized coal, furnace ash deposits, fly ash from economizer hoppers, and fly ash from electrostatic precipitators. Detailed visual observations of furnace ash deposits were also made during boiler operation. Coal and ash samples were analyzed subsequently to identify differences contributing to slagging behavior.

## EXPERIMENTAL RESULTS

### Furnace Gas Temperatures and Atmospheres

Furnace gas temperatures and atmospheres were measured by traversing through existing ports across the front of each furnace at the furnace outlet, and above the burners through ports located 3 to 4 feet from the furnace corners on all boilers. Additional measurements were made below the furnace nose and below the burners at Labadie, Mill Creek, and Cliffside. These measurements showed that average furnace exit temperatures ranged from 2248 F at Mill Creek to 2413 F at Montour. Furnace temperatures were nearly identical for the identical Labadie and Cliffside furnaces even though the coals fired and the degree of slagging problems were much different. In effect, both operated with similar effects of ash cover on heat transfer, but maintenance of this condition required constant wall blowing at Labadie and almost no wall blowing at Cliffside. Furnace gas temperatures were lower at Mill Creek than elsewhere, reflecting the lower design thermal loading and derating. Furnace temperatures were higher at Morgantown and Montour, both firing coals of low slagging potential. Gas temperatures varied from point to point at a given level, and with time at a single point as deposit coverage changed. It was usual to see two hot corners and two cold corners at the burner level in each furnace, as the result of burner arrangement, with differences of about 100 F between them. These factors, and the limited access for measurement, limited the extent of thermal analysis that was possible. Furnace gas atmospheres showed gradual consumption of oxygen between the burners and the furnace exit. Oxidizing atmospheres were found everywhere, with excess air of 50 to 80 percent just above the burners, and 13 to 35 percent at the furnace outlets. The rate of combustion with furnace height varied among furnaces.

### Results of Coal and Ash Analyses

A large number of coal and ash samples were analysed to determine the difference between the coals fired to the two slagging boilers and those fired to the three

non-slugging boilers. The most promising analytical technique identified was the analysis of ash from density fractions of pulverized coal samples. Segregation of minerals of low melting temperature was found in high-density fractions of two coals of high slugging potential but was found to a much lesser extent in three coals of low slugging potential.

Coal proximate analyses were run on daily samples from every pulverizer to check variation of ash content. The percentage variation was about the same for all coals and sites and did not appear to be a factor in furnace slugging.

Coal fineness varied considerably among boilers, and among pulverizers on the same boiler, but there was no identifiable relation between coal fineness and slugging behavior among the five test boilers. It appears that any effects of coal fineness were outweighed by ash characteristics for these units. Both ash content and ash analyses were determined for coal screen fractions. The variations in ash content, ash analysis, and calculated ash viscosities among screen fractions of coal for each boiler were minor and do not appear significant.

Coal mineral analyses showed considerable difference among the test coals, but the accuracy and sensitivity of the methods used for mineral analyses were such that major minerals were determined in 5-percent increments and minor minerals were not detected. It was concluded that ash elemental analysis was, in the circumstances, a more useful tool for study of differences in ash composition.

Mineral distribution in coal size fractions was also measured. The variations among size fractions were small and provided little insight into differences in slugging characteristics.

#### Ash Analysis of Coal Density Fractions

Analyses of coal density fractions showed marked differences between the slugging coals and the non-slugging coals that were not evident from analyses of the entire coal samples. As might be expected, the ash content increased with density of the coal fraction, as the density of most ash constituents is higher than the density of coal. The ash composition and the ash viscosity characteristics also showed wide differences among density fractions.

All the coals contained a small, dense fraction with a specific gravity above 2.8, which on combustion, produced ash with 72 to 88 percent iron oxide. The calculated

viscosity of this ash was only 3 poises at 2300 F, suggesting that all of it would occur as liquid particles in the flame. This fraction was 4.1 to 8.6 percent of the total ash for the three non-slugging boilers, 7.3 percent for the Labadie boilers, and 14.6 percent for the Mill Creek boiler. The values below 8.6 percent were not associated with slugging problems in the test boilers and, thus, do not appear to be a major factor in slugging. The 14.6 percent at Mill Creek may have contributed to severe slugging, but it was only part of the 50 percent of low viscosity ash in the Mill Creek coal.

For Labadie and Mill Creek coals the fractions having specific gravities below 1.6 formed markedly more viscous slags than did the heavier fractions. This difference resulted from concentration of calcium and iron in the dense fractions of both coals, in the specific gravity range between 2.0 and 2.8. This fluid, low-viscosity fraction of the ash was 18 percent of the total Labadie ash and 28 percent of the Mill Creek ash. It appears that this segregation of a large proportion of ash minerals into a very low viscosity ash fraction could result in more severe slugging difficulties than would be indicated from criteria based on over-all ash characteristics. There was no corresponding fraction of low viscosity ash in the three non-slugging coals.

The marked differences in the composition and viscosity characteristics of ash from density fractions of the test coals appears to be an important factor in furnace slugging performance. It is recommended that this type of analytical research be carried further, to study other types of coal.

Another aspect of the marked segregation of ash of low viscosity in the high-density coal fractions for Mill Creek and Labadie coals is the observation that coal cleaning would not only decrease the quantity of ash in the coal, but it should improve coal quality by reducing slugging potential of the remaining ash. Coal cleaning would have little effect on slugging characteristics of coals at Cliffside, Morgantown, and Montour.

#### Analyses of Furnace Ash and Fly Ash

Ash samples from four elevations in each furnace were analyzed, and the analyses compared with analyses of fly ash from economizer hoppers and from electrostatic precipitator hoppers. These analyses showed that composition of furnace ash, fly ash, and coal ash was similar for Labadie, Mill Creek, and Cliffside. However,

there was considerable enrichment of furnace ash with iron at both Montour and Morgantown, both firing coals of low slagging potential with minimum slagging problems. There was some iron enrichment of economizer hopper fly-ash samples for every boiler, as heavy particles would be selectively trapped there by a 90-degree bend. Iron enrichment of furnace ash deposits would lower the slag viscosity of these deposits, and is being studied by others<sup>(1)</sup> as a factor contributing to unexpected slagging difficulties.

#### Microanalysis of Furnace Ash Deposits and Coal Mineral Matter

An exploratory study of the structure and composition of furnace-ash deposits was carried out using optical metallography, electron microprobe analysis, scanning electron microscopy, and energy-dispersive X-ray analysis. The results of these analyses were supplemented by studies of particle melting temperatures using hot-stage microscopy, and energy-dispersive X-ray analyses was used to measure composition of melted particles. It was found that the general structure of the ash deposit was a matrix of glassy, spherical particles having a wide range of compositions in which unfused particles containing iron oxide and calcium oxide were also dispersed. At the imprint of the tube surface a considerable concentration of calcium, sulfur, and iron was found. Near the fused outer surface of the deposit, the glassy materials had melted into a porous, glassy slag containing spherical globules of iron oxide combined with other materials. There were no systematic compositional gradients from the tube surface to the fused outer layer except for the sulfur layer found only at the tube surface. However, there were significant differences in composition from particle to particle, and these differences were similar to those found in the coal mineral matter as isolated by low-temperature ashing. Single particles of low-temperature ash<sup>(2)</sup> were found having low fusion temperatures, in the range of fusion temperatures for particles in furnace ash. Thus, the glassy spheres found in furnace deposits could originate from single coal particles, without the need for interactions among coal particles or ash particles.

SEM analytical techniques, supported by hot-stage microscopy and low temperature ashing of pulverized coal, permit the isolation and identification of particles

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(1) Borio, R. W., and R. R. Narciso, Jr., "The Use of Gravity Fractionation Techniques for Assessing Slagging and Fouling Potential of Coal Ash", ASME Paper No. 78-WA/CD-3. Presented at ASME Winter Annual Meeting, December 10-15, 1978.

(2) Low-temperature ash is formed by ashing coal in a radio-frequency field to preserve original mineral forms.

having low melting temperatures and the measurement of particle melting temperatures. The analyses of ash in pulverized coal density fractions provide complementary information, showing that, for some coals, minerals forming ash particles of low melting temperature can be segregated in coal pulverization. The combination of these techniques shows promise of providing means of determining the probable roles of coal minerals in ash deposition and the development of slagging problems.

#### Furnace Slagging Correlations

The rate of ash deposition and the difficulty of wall cleaning are influenced by coal ash content and composition. Several indices of slagging characteristics of coals are based on ash composition, including Base Acid Ratio, Slagging Factor, and Silica Percentage. Ash fusion temperatures and calculated ash viscosity characteristics are also useful information.

A review of furnace Plan Area Heat Release in relation to these conventional slagging indices shows that the test furnaces were sized in the order suggested by the indices for their design coals. However, the achieved heat-release rates were lower than the design rates by 17 percent at Mill Creek and 7 percent at Labadie. These boilers were both fired with coals containing 33 percent more ash than the design coal, and this would increase significantly the severity of slagging. It is quite possible that both furnaces would operate satisfactorily with the "design" coal.

Present practice is to design furnaces with larger plan area and larger volumes than those of the 1960's because of the reliability problems that were encountered with minimum-sized furnaces when coal quality changed. It is probable that the larger furnaces offered today would operate satisfactorily with the Labadie coal.

However, slagging with the Mill Creek coal appears to be worse than anticipated by the furnace sizing method used, and the nature of compositional segregation of ash in coal density fractions may be a factor in this problem.

#### Improving Operation of Slagging Boilers

Slagging of both Mill Creek and Labadie furnaces resulted from loss of wall blower cleaning effectiveness because ash deposits grew excessively hard and strong between blowing cycles. R&D toward optimization of wall blowing cycles could

improve wall cleaning. For example, it appears possible to operate blowers more frequently, using higher rotational speeds and shorter blowing periods to remove deposits more frequently and, thus, avoid excessive deposit thickness and strength. This would require changes in wall-blower gearing and timing.

Coal washing would remove a high percentage of the ash from the Mill Creek and Labadie coals. However, a more important factor is that the ash remaining would have a lower slagging potential than the ash removed by washing, as shown by differences in analyses of ash in different coal density fractions. It appears probable that both boilers could fire washed coal without slagging problems.

During pulverization of coal fired at Labadie and Mill Creek, a large fraction of ash of low melting temperature was released and could be segregated in the heavier coal density fractions. No comparable segregation of low-melting-temperature ash was found in coal density fractions of the coals fired in the three boilers without slagging problems. It appears possible that ash analysis of coal density fractions is a new and useful way to identify coals likely to cause slagging problems in existing boilers and, thus, avoid them.

#### CONCLUSIONS

Two analytical techniques used in the present investigation show promise of improving the understanding of furnace slagging: analysis of ash in coal density fractions, and microanalysis of furnace ash deposits. The analysis of coal density fractions has shown distinct differences between two coals of high slagging potential and two coals of low slagging potential, which would not be apparent from conventional analysis. The microanalysis of furnace deposits is complementary to coal analysis by density fractions, as it provides a means for detailed study of the structure and formation of furnace deposits.

The analysis of ash in coal density fractions showed that each of the test coals contained a small fraction of coal of high iron content, with specific gravity above 2.8. The ash from this coal fraction would be fluid in the flame and would be likely to stick to the furnace wall on contact. It would also contribute iron as a flux to the wall deposit, lowering its potential viscosity if melted.

The severely slagging coals fired at Labadie and Mill Creek contained a fraction of high calcium content, with specific gravity in the 2.0 to 2.8 range. The

calculated slag viscosity for this fraction was very low, and it would also be fluid in the flame and contribute to wall deposits. This low-fusion, high-calcium ash fraction accounted for 18.0 percent of the coal ash at Labadie, and 27.7 percent of the coal ash at Mill Creek. The coals of low slagging potential fired at Cliffside, Morgantown, and Montour had no corresponding fraction.

Analyses of furnace ash deposits showed that iron enrichment of furnace ash had occurred at Morgantown and Montour, suggesting that the small fraction of high-iron coal contributed more to furnace deposits than did other fractions. However, there was no iron enrichment of furnace deposits at Labadie and Mill Creek, suggesting that much of the total ash would be fluid in the flame and stick to the walls on impact. In these tangentially-fired furnaces, the centrifugal force developed in the swirling flame results in considerable particulate impact on walls, but not all particles stick to the walls.

A comparison of the microanalyses of furnace deposits with those of particles of minerals separated from coal by low-temperature ashing led to the conclusion that the glassy spheres of melted ash making up the bulk of the furnace deposit could have originated from individual particles of pulverized coal without the need for interaction among particles in the flame. The compositions of particles of furnace ash deposits that melted at low temperature differed from the compositions of low-temperature ash particles that melted at low temperatures but were similar in composition to dense coal fractions.

The present sample of five different coals is too small to provide a basis for general conclusions. However, results are encouraging enough that it appears desirable to investigate more types of coal.

#### RECOMMENDATIONS FOR FUTURE RESEARCH

It appears desirable to extend this research to other coals and other slagging and non-slagging boilers, to explore the relation between furnace slagging behavior and the analysis of ash in coal density fractions. This additional research should be concerned with collection and analysis of coal and ash samples, observations of furnace ash deposits, and collection of panel-board and historical data on boiler operation and slagging experience. At this time the cost of furnace traversing to measure gas temperatures and compositions does not appear to be justified. Eventually, with more data, it may be possible to classify slagging characteristics of coals more effectively than at present. This would provide a better basis for selection of coals for existing boilers, and for design of

future boilers.

To confirm the validity of this approach, based on ash analysis of coal density fractions, it appears necessary to obtain data for a range of Eastern, Midwestern, and Western coals representative of those available for use in steam plants. The coals should cover a range of slagging characteristics, and should probably include both washed and unwashed coals.

### Section 3

#### SELECTION OF FIELD TRIAL UNITS

##### SELECTION CRITERIA

Five test boilers for field trials were selected on the basis of slagging experience, coal characteristics and boiler configuration. As a first requirement, each test boiler was to be fired with a consistent, identifiable coal throughout the test period. If this coal came from several mines, the differences among the coals were to be small. As a second requirement, the furnace designs of all units were to be similar, to the greatest extent possible. This requirement led to selection of five boilers made by one manufacturer. The third requirement was for specific types of furnace slagging behavior, ranging from severe slagging that limited plant output, to the opposite extreme of operating with little or no deslagging. None of the test units had superheater fouling problems. Of the five boilers selected, three were of single-furnace design and two were of divided-furnace design. All were tangentially fired. Because the number of units was small, only Eastern coals were included in the program to reduce the number of variables.

##### IDENTIFICATION OF SUITABLE FIELD-TRIAL UNITS

The four principal U.S. boiler manufacturers were contacted to explore their interest in participating in the project, and to obtain recommendations regarding suitable field trial units. The Babcock and Wilcox Co. and Combustion Engineering, Inc., each expressed interest in the project. Battelle and EPRI personnel met with representatives of each company separately to discuss program objectives and selection criteria. Babcock and Wilcox provided a list of 18 candidate units, and Combustion Engineering proposed a list of 8 units.

In the course of evaluating potential field-trial units, Battelle personnel visited and inspected those that appeared most promising. It was found that many had pressurized furnaces, and that these had very small view ports through which it would be difficult to obtain furnace ash samples. The field of view was also narrow, so that visibility of furnace deposits was limited. Accordingly, an effort was made to limit the field program to units with balanced-draft furnaces. With this restriction, the 26 units investigated did not include five suitable

units from either manufacturer.

The list of candidate boilers was then expanded by examination of power-plant surveys published in Power for the years 1965 through 1973, and 24 additional balanced-draft units were identified.

Table C-1, Appendix C, lists 38 candidate units that were identified, and summarizes their characteristics. From Table C-1, five Babcock and Wilcox units and five combustion Engineering units were selected for comparison. Of the Babcock and Wilcox units, three had pressurized furnaces. It was possible to select four Combustion Engineering units with balanced-draft furnaces, and this appeared preferable. Accordingly, five Combustion Engineering units were selected for field trials, as follows:

<u>Unit</u>	<u>Slagging</u>	<u>Coal</u>
Mill Creek 1	Severe	W. Kentucky
Labadie 1 or 4	Severe	S. Illinois
Montour 1	Moderate	E. Pennsylvania
Morgantown 1	Slight	E. Pennsylvania
Cliffside 5	None	E. Kentucky

#### CHARACTERISTICS OF TEST BOILERS

The five test boilers were selected on the basis of slagging experience, coal characteristics, and boiler configuration. Three of the boilers were of single-furnace design and two were of divided-furnace design. All except Montour 1 had balanced-draft furnaces.

Figure 3-1 shows furnace-outline drawings to the same scale for Labadie 1, a typical single-furnace unit, and Morgantown 1, a typical divided furnace unit. The divided furnace increases surface-to-volume ratio and reduces furnace height and volume significantly. Figure 3-1 also shows the locations of view ports and traversing locations used in measuring furnace gas temperatures and analyses.

Table 3-1 lists the dimensions and design characteristics of the five test units. The Boiler MW Rating listed is the boiler manufacturer's Maximum Continuous Output rating. This value is different from the generator nameplate rating in every case. In Table 3-1 the percentages of rating for test conditions are based on the boiler manufacturer's maximum continuous rating, rather than the generator rating.

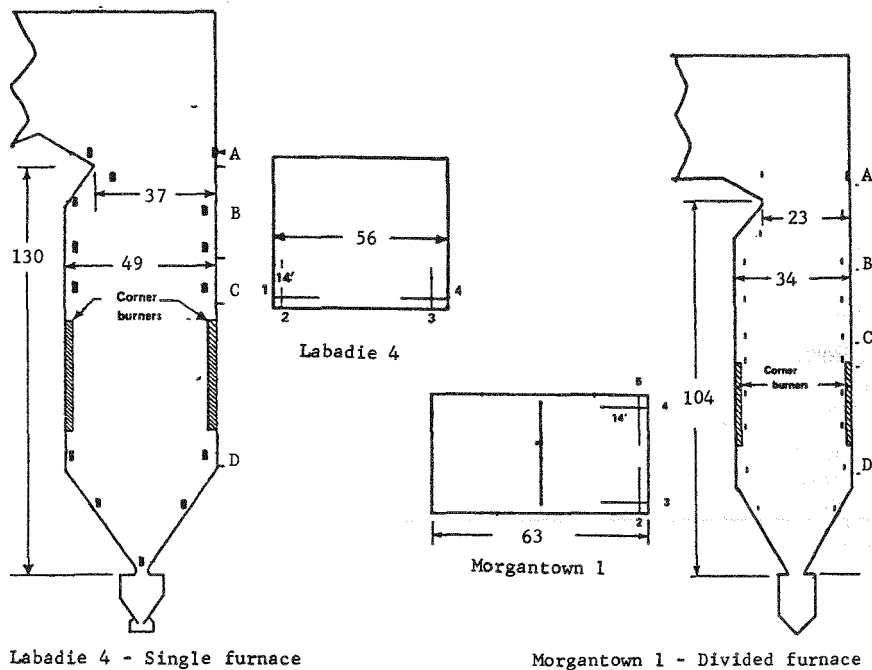


Figure 3-1. Comparison of Single-Furnace and Divided-Furnace Boiler

Table 3-2 summarizes coal characteristics and ash analyses for Test Composite pulverized-coal samples for each boiler. The main features of each boiler, and the reasons for its selection, are summarized below. Where coal slagging potential is mentioned, it is based on interpretation of the last four lines of Table 3-2.

#### Labadie Boiler 4

Labadie 4 was selected as a test site because of severe furnace slagging that limited operation to no more than 12 hours at 580 MW, after which it was necessary to drop load for furnace deslagging. The 580-MW load represents 97 percent of the boiler maximum continuous load rating of 600 MW. The boiler has a single tangentially-fired furnace with 86 wall blowers that are cycled continuously in pairs, using steam at 400 psi as blowing medium. A Southern Illinois coal of medium to high slagging potential is fired. When the boiler went into service in 1973 it was operated regularly at 600 MW. However, with changes in coal quality, the unit was officially derated to 580 MW in 1977. The generator nameplate rating is 571 MW, but Labadie personnel expect the boiler to operate at its design rating of 600 MW. The boiler was designed for coal of 8.9 percent ash, but was being fired with coal of 11.8 percent ash during the test period. The load

TABLE 3-1. BOILER CHARACTERISTICS

Boiler	Labadie	Mill Creek	Cliffside	Morgantown	Montour
<u>Design Conditions<sup>(1)</sup></u>					
Boiler rating, MW	600	350	600	625	750
Steam flow, 10 <sup>6</sup> lb/hr	4.08	2.32	4.08	4.25	5.70
Steam press, SH outlet, psi	2625	2600	2625	3810	3830
Steam temp SH outlet, F	1005	1005	1005	1005	1005
Steam press, RH outlet, psig	613	586	592	724	678
Steam temp, RH inlet, F	642	635	644	585	572
Steam temp, RH outlet, F	1005	1005	1005	1001	1005
Feedwater temp, F	488	485	488	509	554
<u>Furnace Dimensions, ft</u>					
Height, ashpit to nose	130	115	130	104	103
Width	56	45	56	63/2	84/2
Depth	49	38	49	34	41
Net heat input, 10 <sup>6</sup> Btu/hr <sup>(2)</sup>	5672	3242	5675	5596	7346
<u>Design heat release rates</u>					
10 <sup>6</sup> Btu/ft <sup>2</sup> plan area	2.06	1.90	2.06	2.57	2.15
10 <sup>3</sup> Btu/ft <sup>3</sup> furnace vol	12.35	14.10	12.35	18.00	14.70
10 <sup>3</sup> Btu/ft <sup>2</sup> wall area <sup>(3)</sup>	191.2	171.3	191.2	186.0	194.4
Coal ash content, percent	8.9	11.3	8.9	13.7	14.4
<u>Test Conditions</u>					
Generator output, MW	555	297	576	563	748
Steam flow, 10 <sup>6</sup> lb/hr	3.64	1.94	3.74	4.00	6.06
Percent of design MW	92.5	84.9	96.0	90.1	99.7
Percent of design steam flow	89.2	83.5	91.7	94.1	106
Net heat input, 10 <sup>6</sup> Btu/hr	5059	2707	5204	5266	7787
<u>Test heat-release rates</u>					
10 <sup>6</sup> Btu/ft <sup>2</sup> plan area	1.84	1.59	1.89	2.28	2.28
10 <sup>3</sup> Btu/ft <sup>3</sup> furnace vol	11.02	11.77	11.33	16.94	15.60
10 <sup>3</sup> Btu/ft <sup>2</sup> wall area	176.6	143.0	175.3	175.0	205.6
Coal ash content, percent	11.8	15.0	15.3	13.8	14.6
<u>Furnace gas temperatures, F</u>					
Above burners	2638	2569	2607	2738	2513
Above nose	2256	2211	2277	2299	2409
Flue-gas oxygen, percent	5.1	4.5	3.6	2.8	5.3
Furnace slugging impact	Severe	Severe	None	Slight	Moderate

(1) Maximum continuous boiler rating.

(2) Net heat input = coal low heat value + heat in preheated air - carbon loss.

(3) Area up to point of furnace nose, including upward projected area.

(4) Calculated from design value by ratio of steam flow rates.

TABLE 3-2. SUMMARY OF COAL AND ASH CHARACTERISTICS  
Dry basis

	Labadie 1	Labadie 4	Mill Creek	Cliffside	Morgantown	Montour
Carbon	67.57	68.82	67.46	71.97	72.78	74.01
Hydrogen	5.17	5.29	5.07	4.75	4.62	4.64
Oxygen	9.76	8.24	6.23	5.44	5.90	4.33
Nitrogen	1.28	1.36	1.33	1.33	1.42	1.34
Sulfur	3.28	3.62	4.23	1.24	1.40	1.06
Ash	12.63	11.78	14.96	15.26	13.84	14.62
Low temp. ash	15.5	14.7	18.7	18.9	16.8	16.7
Vol matter	38.68	39.83	38.94	30.28	25.01	25.33
Fixed Carbon	48.69	48.39	46.10	54.46	61.15	60.05
HHV, Btu/lb	12,468	12,468	12,289	12,808	12,993	13,231
<u>Ash Analyses</u>						
SiO <sub>2</sub>	53.5	51.8	45.5	55.0	50.9	54.3
Al <sub>2</sub> O <sub>3</sub>	19.7	19.2	18.5	26.5	27.3	27.8
Fe <sub>2</sub> O <sub>3</sub>	17.0	19.8	24.5	10.4	14.1	7.97
TiO <sub>2</sub>	1.01	1.00	0.93	1.25	1.42	1.36
MgO	1.07	1.04	0.99	1.39	1.09	1.12
CaO	4.70	4.08	6.25	1.16	1.63	4.10
Na <sub>2</sub> O	0.51	0.53	0.44	0.48	0.26	0.33
K <sub>2</sub> O	2.38	2.30	2.59	3.61	2.65	2.68
P <sub>2</sub> O <sub>5</sub>	0.16	0.12	0.19	0.16	0.47	0.31
<u>Coal minerals, percent of low-temp. ash</u>						
Quartz	25	20	20	20	15	15
Pyrite	20	20	30	7	10	5
Calcite	5	5	10	1-5	0	1-5
Gypsum	1-5	1-5	1-5	1-5	1-5	1-5
Kaolinite	20	20	20	20	30	35
Illite + MLC	25	25	20	40 *	30	35
FeSO <sub>4</sub>	1-5	1-5	1-5	5-10	0	0
<u>Ash fusion temperatures, F, Oxidizing atmosphere</u>						
ID	2220	2380	2280	2540	2570	2660
Softening	2400	2400	2360	2560	2680	2720
Hemisphere	2420	2440	2380	2620	2700	2740
Fluid	2480	2500	2420	2640	2720	2760
<u>Reducing atmosphere</u>						
Initial def.	2020	1980	1940	2320	2460	2460
Softening	2140	2060	2041	2560	2530	2530
Hemisphere	2220	2120	2140	2620	2560	2540
Fluid	2300	2260	2200	2680	2650	2660
Silica percentage	70	68	59	81	75	80
Base/acid ratio	.35	0.39	0.54	0.21	0.25	0.19
Slag visc/2600F	150	100	28	800	325	800
Slagging factor	1.13 Med.	1.39 Med.	2.26 High	0.25 Low	0.35 Low	0.21 Low

\* Illite + Montmorillite

during the test period was below the usual 580 MW because a feedwater heater was out of service.

#### Mill Creek Boiler 1

Mill Creek 1 was also selected because of severe furnace slagging that limited load. Although rated at 350 MW, the plant could be operated at only 325 MW for 8 to 10 hours, or at 300 MW for a 3- or 4-day period. A Western Kentucky coal of high slagging potential was fired. The single tangentially fired furnace has 62 wall blowers using 400 psi steam as a blowing medium, and these operate continuously in pairs.

#### Cliffside Boiler 5

The Cliffside 5 boiler is identical in design to the Labadie 4 boiler, but it has no slagging problems when operated at or below its maximum continuous rating of 600 MW. It is usually operated at the generator rating of 571 MW. In addition it is designed for firing Western Kentucky coal of high slagging potential, but is fired with Eastern Kentucky coal of low slagging potential. The boiler can be operated at 590 MW for extended periods without slagging problems, and operation at 610 to 620 MW is possible for periods up to 8 hours before it is necessary to drop load to shed slag. The furnace contains 76 wall blowers using 400 psi steam as blowing medium. However, at loads below 580 MW, wall blowers are not used except for occasional manual operation of selected blowers as needed to remove excessive local ash accumulations. The furnace is largely self-cleaning, as ash sheds spontaneously. The principal slagging problem, if any, is to assure sufficient slag cover to maintain superheat temperature.

#### Morgantown Boiler 1

The Morgantown 1 boiler is a 625 MW, divided-furnace unit serving a 575 MW generator. It is fired with Eastern Pennsylvania coals of low slagging potential. Continuous operation at 580 MW is possible for extended periods without slagging problems. It is usual to carry 580 MW from 7 am to 10 pm daily, and this is considered to be full load. Load is dropped to 200 MW at night and on Sunday as needed to meet demand. Wall blowers are not operated continuously, but are cycled manually once per shift for removal of local ash accumulations. Toward the end of a week of operation, ash deposits at the centers of boiler walls become difficult to remove, but these appear to cause no operating difficulties, and are shed during Sunday low-load operations.

### Montour Boiler 1

Montour Boiler 1 is a 750 MW unit with a pressurized, divided furnace. It is fired with eastern coals of low slagging potential. However, it is necessary to operate with 5.3 percent oxygen in the flue gas (33 percent excess air) to avoid furnace slagging at full load. At this condition, furnace ash deposits appear moderate and are readily removed by wall blowers. However, large ash deposits sometimes form beside burners or high in the furnace, in areas not reached by wall blowers. Another problem is that the bottom-ash removal system does not have sufficient capacity to handle all of the ash shed by a weekend load drop. Accordingly, present practice is to drop load two or three times per week to prevent large ash accumulations and to avoid overloading the bottom-ash system.

Section 4  
METHODOLOGY

TEST SCHEDULE AND DATA

Arrangements for each field trial were made well in advance of the test date. Preliminary arrangements included a visit to each plant to review sources of water for probes, layout of view ports, external obstructions that would limit furnace probing, and arrangements needed for sampling of coal, fly ash, and furnace ash deposits. General operating procedures and scheduling of plant operations were reviewed, and arrangements were made to fire preselected coals to the test boiler for about one week prior to the test period, and throughout the test period.

Every boiler tested was operated with a load drop to about half load over each weekend, so that the furnace was very clean on each Monday. By Tuesday morning, slag cover was at equilibrium on all units, although some of them gradually accumulated deposits through the week. Accordingly, work was scheduled for setup of equipment, connecting of water hoses and drains, and other test preparations, on Monday. Furnace probing was started Tuesday at noon, continuing through about eight hours, and resumed each day at noon until furnace probing was completed. By noon, furnace deposits were well developed following any load drop during the night. It would be normal to obtain both temperature data and gas composition data for one furnace level in one day of testing, except that two days were required for sampling at the nine ports at the boiler outlet. However, delays in testing were frequent at Labadie, because of boiler operating problems, and tests required four weeks.

At each field trial site, the following types of data were obtained:

- 1 Traverses of furnace-gas temperatures and analyses
- 2 Observations of furnace slagging and wall blower operation
- 3 Panel-board data on boiler operation
- 4 Coal samples, from each pulverizer for each day
- 5 Samples of furnace ash deposits at most sighting ports
- 6 Fly-ash samples from economizer hoppers and precipitator hoppers

Each of the test boilers was run throughout each test day at its practical maximum load. Three units dropped load at night, as this was normal operation, and two were operated through the night at full load. During test periods all boilers were operated at a constant, manually-set load.

## TEST PROCEDURE

### Furnace Measurements

During the test period furnace gas temperatures were measured by traversing with high-velocity thermocouples. Gas temperatures of greatest interest were those at the level just above the burners, and those at the furnace outlet. The arrangement of sighting ports on all boilers was such that a good traverse of furnace temperature could be obtained at Elevation A, Figure 3-1, above the furnace nose; however, at lower elevations it was only possible to measure gas temperatures along traverse lines parallel to walls, three to four feet from each corner except at Montour. Here it was possible to traverse on the furnace centerline through a port on the back wall above the burners.

Furnace gas was sampled during temperature traversing and analyzed in Orsat gas analyzers. Normally, only oxygen and carbon dioxide were measured, but CO was checked when the sum of oxygen and carbon dioxide was low.

Furnace slag was observed through all sighting ports, starting at the top of the furnace and going around the furnace at each level. Operation of wall blowers was also observed in detail. A water-cooled TV camera and video tape recorder were used to observe operation of wall blowers over many hours at a time, to gain insight into long-term effects.

### Coal and Ash Sampling

Coal samples were taken from the outlet of each coal pulverizer on each day of testing, using apparatus and methods recommended by the ASME Performance Test Code for Coal Pulverizers, PTC4.2. One set of samples was screened to check pulverizer performance, and proximate analyses were made for every sample. The samples were combined into Daily Composites, and a Test Composite of all samples, for various analyses.

Furnace ash samples of two kinds were taken. First, after cleaning all sighting ports at the beginning of the test day, samples were taken from the sills of the sighting ports. It was observed that pieces of ash blown from furnace walls

by nearby wall blowers deposited on these sills; although the exact source of each sample is not defined, most samples probably came from a point near the port. A second type of sample was removed from the wall tubes next to the sighting port by reaching into the furnace with an asbestos glove and quickly breaking off a sample. Later, special tongs were made for this purpose.

Every ESP hopper, and every economizer hopper, were sampled for fly ash at least once per test. All ESP hopper samples for one day were combined into one sample, and all economizer-hopper samples for one day were combined into one sample for analysis.

It should be noted that furnace ash samples and fly ash samples are representative of a single operating day, and that coal samples are composites for the entire test period of 2 to 4 days, so that ash content and composition may differ somewhat between coal samples and ash samples because of daily variations. Screen fractions and density fractions were taken from composite coal samples.

#### Coal and Ash Analyses

Composite coal samples were the subject of extensive analyses. In addition to the standard proximate and ultimate analyses, ash fusion temperatures, and heating value, the coal mineral matter was determined using a low-temperature ashing technique. Coal samples were divided into density fractions and screen fractions, and these fractions were analyzed to determine ash content, ash composition, and mineral content.

All coal and ash samples were analyzed by the Coal Research Laboratory of the Pennsylvania State University under the direction of Dr. William Spackman. The standard coal analyses were carried out by standard ASTM techniques, but the coal mineral analyses merit special mention. For mineral determination, coal samples were ashed at 199-163 C in a radio-frequency field. At this low temperature, mineral constituents were not decomposed or melted. The low-temperature ash was then analyzed by a combination of techniques, including determination of quartz, pyrite and calcite by X-ray diffraction, and determination of gypsum and kaolinite by infrared techniques. The presence of other clays and phases was determined by qualitative X-ray and infrared scans and the amounts of each were estimated on the basis of chemical data.

The structure of furnace ash deposits was studied in detail at Battelle using the Scanning Electronic Microscope (SEM). With this instrument, deposit structure can be seen at high magnification with great depth of field. In addition, it is possible to analyze for the principal elements in the ash at any point on any particle, permitting study of variations of composition from particle to particle, and within particles.

The melting characteristics of both low-temperature ash from the coal, and of ground furnace deposits, were studied with a hot-stage microscope. The ash materials are glassy in structure, with no fixed melting point; they just become softer as temperature rises. Melting temperatures for this study were defined as the temperature at which rounding of the corners of particles began. The analyses of the melted particles were then made by SEM and Electron Microprobe.

#### MEASUREMENT AND SAMPLING METHODS

##### Measurement of Furnace Gas Temperature

The measurement of true gas temperature in a boiler furnace is difficult because of high gas temperatures, high particulate loadings, and intense radiation from the sensing thermocouple to cold furnace walls. In principle, it is necessary to shield the thermocouple junction from radiation and heat it to gas temperature by enhanced convection to avoid radiation error, which may be several hundred degrees. The High Velocity Thermocouple (HVT) has been developed for use in coal-fired furnaces and provides a suitable compromise between accuracy and practicality for test purposes. At the temperatures of interest in these tests, 2200 to 2800 F, the measurement error is less than 100 F, and it is usually possible to measure temperatures at six or eight points before the probe plugs with ash.

Figure 4-1 shows the three types of HVT probes which have been developed. The single-shielded HVT, at the top, was used for these tests. The MHVT probe, at the bottom, is the standard of accuracy against which others are calibrated. However, because of its small flow passages it plugs immediately in coal-fired furnaces and, thus, is useful only in furnaces fired with gas or oil, and as a calibration tool.

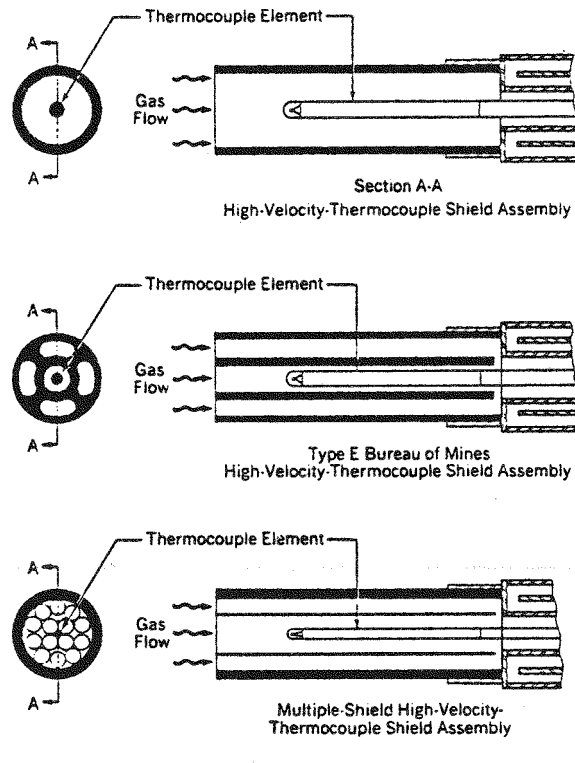


Figure 4-1. Construction of High Velocity Thermocouples

The radiation shield for the probes used is a ceramic tube of 3/4-in. OD and 9/16-in. ID, and the thermocouple protection tube is a ceramic tube of 7-mm OD and 5-mm ID with a closed end. Both the protection tube and the radiation shield must be discarded after each 7-point traverse, as the space between them becomes plugged with ash and molten slag, which cannot be removed.

In carrying out the HVT measurements, the thermocouple is positioned and the rate of aspirated gas flow is adjusted upward until further increase in gas flow causes no further increase in indicated temperature. This requires a mass flow rate of 15,000 lb/ft<sup>2</sup> hr over the thermocouple. It was found that the pressure drop for these conditions was 2-in. Hg, with flow rate of 2 scfm gas. Any significant increase in pressure drop indicated plugging of the probe tip, requiring cleaning or replacement of ceramic parts to avoid measurement error. Gas was aspirated through the probe using a Pemberthy No. 22A ejector, which could provide flow rates up to 8 cfm against 5 in. Hg negative pressure. Usual driving-air pressure was 50 psi, and maximum compressed-air demand was 24 scfm at 100 psi.

The thermocouples used in the HVT probes are Type S (platinum, platinum 10 percent rhodium). Temperatures were read using a direct-reading digital meter (Doric Model 400A). At the end of each day of testing the thermocouples were calibrated in a small electric furnace. Thermocouple calibration did not change; in any test period.

Probe-cooling water flow of 20 to 25 gpm was sufficient to limit water discharge temperature to 160 F with the probe fully inserted into the furnace. Two-inch fire hose was used for water supply and drain lines.

#### Measurement of Furnace Gas Composition

Gas from the furnace was analyzed using two Burrell portable, industrial-type Orsat analyzers. In these analyzers a 50-cc sample of gas is bubbled through successive solutions to absorb CO<sub>2</sub>, O<sub>2</sub>, and CO selectively, and the gas remaining after each absorption is measured. A complete analysis takes about ten minutes, but analyzing for CO<sub>2</sub> and O<sub>2</sub> requires only about five minutes. CO was not measured at most points because it was usually present in insignificant amounts. When the sum of CO<sub>2</sub> and O<sub>2</sub> was low, CO was measured to be sure that the analysis was correct. During each analysis the measured values were plotted on a triangular combustion chart (Figure 7.1) to confirm validity; if data did not plot close to the theoretical line the analysis was repeated.

#### Sampling of Furnace Particulates

For furnace particulate sampling, a separate probe was used. This probe was a water-cooled HVT probe with the thermocouple removed and a 3/8-in. diameter stainless steel tube inserted through the probe as a sample line. This sample line was isolated from the cooling water surfaces by an air gap to minimize condensation and thus loss of particulate material within the probe.

#### Sampling of Pulverized Coal

Pulverized coal was sampled from the outlet of each coal pulverizer using apparatus and techniques recommended in the ASME Performance Test Code for Coal Pulverizers, PTC 4.2.

In the sampling operation the coal duct was traversed on two diameters, 90 degrees apart. During each traverse the probe was moved into the duct and back out at a constant rate, to obtain about one pint of coal on each diameter.

Coal was separated from the air stream by a high-efficiency cyclone backed up by a bag filter. The rate of coal flow into the sampler was determined by the pressure in the coal pipe and the flow resistance of the sampling system. It has been shown that the departure from isokinetic sampling resulting from such a procedure does not influence the composition of the sample significantly.

In the first three boiler tests the small amount of coal lost from the sampling cyclone exhaust was collected in a bag filter for analysis. The quantity proved to be less than two percent of the coal collected, and the fineness proved very similar to that of the coal collected. Thus, the bag filter appeared unnecessary and was not used in the last two tests.

#### Video Camera and Tape Recording System

The basic video taping system consists of a Diamond ST-11 TV camera with associated mounting brackets and cables, a special 24-in. lens tube with a 60-degree viewing angle (another set of lenses is available for a 90-degree viewing angle), a Model 8020 Panasonic reel-to-reel tape recorder, and a 9-in. screen TV monitor. For short term use, less than 15 minutes, an air-cooled lens tube was used. For extended use a water-cooled lens tube was used. The TV camera is air-cooled, using a high-temperature housing in conjunction with a Demon Vortex cooler.

#### Sampling of Fly Ash

No special apparatus or procedure was used to collect ash samples from the economizer and ESP hoppers. Each plant tested had slightly different problems and requirements. Long-handled scoops were used in most of the plants to reach through access pipes to the bottom areas of the hoppers. In some cases, internal pressure due to the weight of the ash buildup forced ash out of the access pipes, requiring the use of a pail to collect the ash. At one plant, economizer ash was collected using a cyclone collector and sampling system installed in the economizer duct by plant personnel and used routinely.

Every reasonable effort was made to obtain representative ash samples from the economizer and ESP hopper systems. In most cases, samples were obtained from every hopper, although some hoppers contained no ash.

## Section 5

### FIELD TRIALS

#### LABADIE FIELD TRIAL

##### Description of Labadie Boiler

The Labadie Generating Station of Union Electric Company has four similar 600 MWe units. Boilers are rated at 4.08 million lb steam/hr at 2625 psi, 1005/1005 F. This station was selected as a test site because of slagging problems that have required derating of each unit to 580 MW, and because the source of coal to one boiler could be controlled. The Illinois coal fired was also of interest because of its high slagging potential\*.

Table 3-2 summarizes furnace dimensions and heat release rates. The boiler furnace is 56 ft wide, 49.2 deep, and 182.8 ft high, with 57,400 sq ft of heating surface. Superheater surface includes seven radiant platens at the top of the furnace, and convection banks, with total surface of 144,100 sq ft. Reheater surface of 56,500 sq ft includes radiant platens and convection surface.

Figure 5-1 is a boiler drawing showing furnace dimensions and location of temperature traverses. Each boiler has 86 wall blowers for control of furnace ash deposits and 18 long-lance retractable blowers for control of tube-bank deposits. These blowers operate continuously in pairs, controlled by an automatic cycling system. During the 7.9-hr cycle the corner wall blowers are blown twice and others are blown five times. Air at 300 psi is the blowing medium for Boilers 1 and 2, and steam at 400 psi is used in Boilers 3 and 4.

Six Combustion Engineering Raymond bowl mills fire each boiler. Each pulverizer supplies coal to four burners, one in each corner of the furnace at the same level. These burners fire tangentially and can be tilted for control of flame position.

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\* The term "slagging potential", as used throughout this report, is a non-specific term indicating the relative potential for slagging based on ash properties such as silica percentage, base-acid ratio, and slagging factor. These numerical indicators are listed at the bottom of Table 3-2 and are discussed in Section 10.

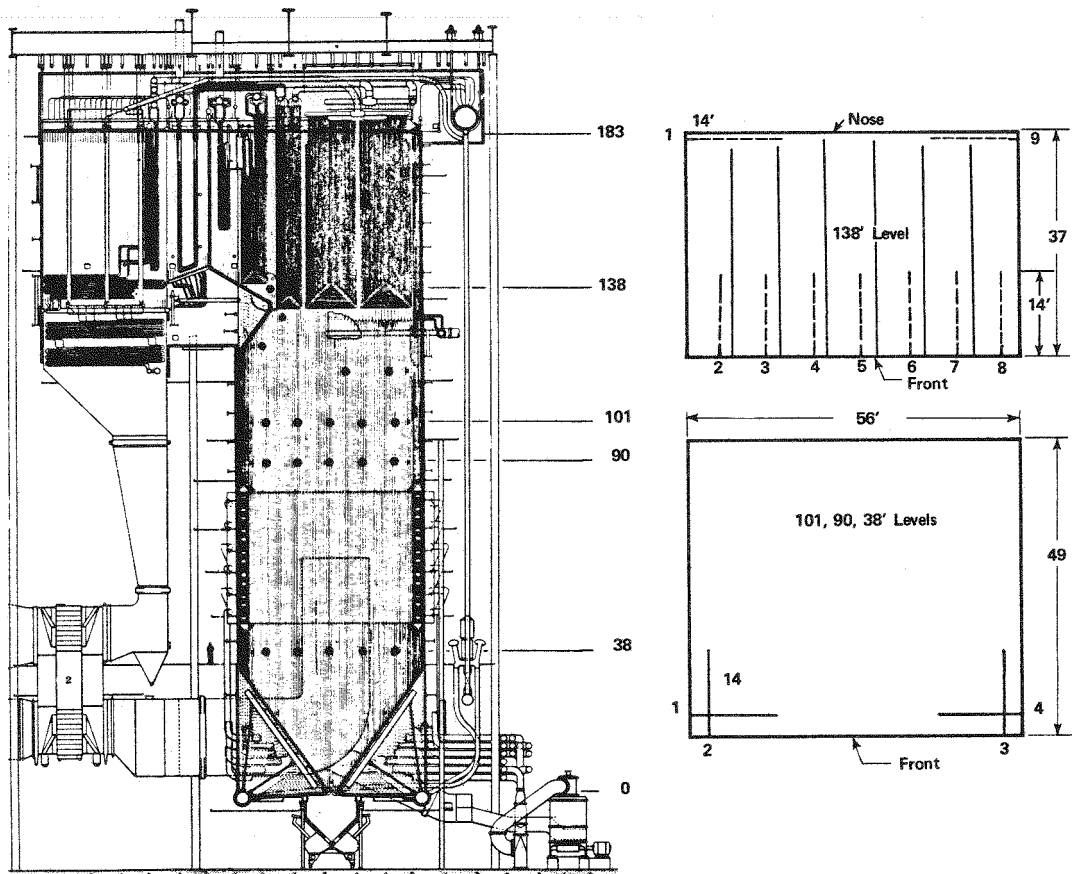


Figure 5-1. Labadie Boilers 1 and 4, Showing Traversing Lines

The usual boiler load profile is continuous operation through each day at 580 MW, with a load drop at night to about 300 MW for furnace deslagging. During the day furnace ash deposits become progressively heavier, reducing furnace heat absorption and increasing furnace exit gas temperature. The desuperheater water flow is increased to maintain design steam temperatures.

Maximum desuperheater water flow is reached after about 12 hours of operation at 580 MW and load is then dropped for furnace deslagging. During the test of Boiler 4, load was only 555 MW because a feedwater heater was out of service.

Coal Sources

Coal burned during the test period came from four mines in Southern Illinois. These mines are close together and coal characteristics are similar. Most of the coal fired came from the Leahy and Burning Star No. 4 mines, with small amounts

from the Captain and Burning Star No. 5 mines. These coals contained approximately 12 percent ash and 40 percent volatile matter on a dry basis. Moisture content of raw coal is about 13 percent, and coal leaving the pulverizer contains 4 percent moisture.

#### Description of Tests

Tests of Boiler 1 were begun in August, 1977, but boiler operating problems limited full-load testing to only three days of a 10-day period. During this time a 49-point traverse of furnace gas temperature and composition was completed at the 138-ft level (furnace outlet). Because of continuing problems with Boiler 1, a new test of Boiler 4 was begun in September. This test was completed in four test days without problems but at reduced load (555 MW) because a feedwater heater was out of service. The following types of data were obtained:

1. Traverses of furnace-gas temperatures and analyses
2. Observations of furnace slagging and wall blower operation
3. Panel-board data on boiler operation
4. Coal samples, from each pulverizer for each day
5. Slag samples from furnace walls at most sighting ports
6. Fly ash samples from economizer and precipitator hoppers.

During each day of test the boiler load was brought up to 580 MW (Boiler 1) or 555 MW (Boiler 4) at 7 a.m. and held at that level until 8 p.m. The collection of test data was started at about noon, after operation and wall deposits were stabilized.

Furnace gas temperatures were measured using aspirating, single-shielded high velocity thermocouples, as described in Section 4. Most measurements were made using a 15-ft water-cooled probe extending 14 feet into the furnace.

Traverses were run at the nine sighting ports at the 138-ft level, and through four corner ports at the 101, 90, and 38-ft levels, as shown in Figure 5-2.

Furnace gas was sampled during temperature traversing and analyzed in Orsat gas analyzers. Normally, only oxygen and carbon dioxide were measured, but CO was checked when the sum of oxygen and carbon dioxide was low.

Furnace slag was observed through all sighting ports, starting at the top of the furnace and going around the furnace at each level. Operation of wall blowers was also observed in detail. A water-cooled TV camera and video tape recorder were used to observe operation of two blowers over many hours at a time, to gain insight into long-term effects.

Coal samples were taken from the outlet of each of the six coal pulverizers on each day of testing, using apparatus and methods described in Section 4. One set of samples was screened to check pulverizer performance, and proximate analyses were made for every sample. The samples were combined into Daily Composites, and a Test Composite of all samples, for various analyses.

Furnace ash samples of two kinds were taken. First, after cleaning all sighting ports at the beginning of the test day, samples were taken from the sills of the sighting ports. It was observed that pieces of ash blown from furnace walls by nearby wall blowers deposited on these sills; although the exact source of each sample is not defined, most samples probably came from a point near the port. A second type of sample was removed from the wall tubes next to the sighting port by reaching into the furnace with an asbestos glove and quickly breaking off a sample. Later, special tongs were made for this purpose.

Fly ash samples were taken from economizer hoppers, and from electrostatic precipitator hoppers. Each day economizer-hopper samples were combined for analysis, and samples from the 16 hoppers on each side of the electrostatic precipitator were combined for analysis, using equal quantities of ash from all hoppers.

In following sections discussing test results, data on coal and ash analyses for both Boiler 1 and Boiler 4 are presented. Data for the complete traverse of gas temperature and composition at the furnace outlet of Boiler 1 are compared with data for the partial traverse at the furnace outlet of Boiler 4, and data for traverses at other elevations in Boiler 4 are presented.

### Furnace Ash Deposits

The Labadie plant was selected as an experimental unit because of furnace-wall ash deposition problems that required derating of the unit from 600 to 580 MWe. These problems appeared to result from the combination of a high rate of ash deposition on the walls, high furnace temperatures that caused the ash deposit to sinter hard or melt if left on the walls for too long, and a wall blowing system which was not fully effective in removing the deposit on each blowing cycle.

During normal plant operation, the unit was deslagged during the night and brought up to 580 MW at 7 a.m. This load was held for 12 to 13 hours to meet system demands, after which load was dropped to deslag the furnace. During the low-load period the wall-blowing cycle was continued. Deslagging was very gradual, some areas shedding slag as long as eight hours after the load drop.

The Labadie soot-blowing system includes 86 wall blowers for cleaning tube banks. These are programmed in a 7.9-hour cycle during which most wall blowers operate five times, with an average interval of 96 minutes per wall blower. During this 96-minute period ash accumulated to a depth of about 2 inches.

Action of two wall blowers was observed by videotaping, using a Diamond air-cooled TV camera with a water-cooled lens that extended into the furnace. A 9:1 time compression was used to permit taping for 9 hours, then reviewing the tape in 1 hour. The tapes showed that, for one blower next to the corner, early in the day the blower cleaned only half of the circle swept by its steam jet (the half toward the corner) and had no effect on the other half. Later in the day it had no effect on any part of the area covered. Another blower was observed to have no effect in eight operating cycles, but the deposit was removed completely in the ninth cycle, after load had been dropped.

At Labadie, the ash deposit removed by wall blowers generally came off in large sheets rather than in small pieces. It appeared that large areas of deposit, having a hard crust, were broken into a few large pieces instead of into many small pieces.

Figure 5-2 is a drawing summarizing the wall conditions observed for the front and sidewalls in the early afternoon, after ash deposits had hardened to the extent that many wall blowers were not effective in hot areas. These conditions were observed by looking into each sighting port and extend over about two blowing cycles. Thus, in areas being effectively cleaned, the thickness observed has a random relation with the blowing cycle. The conditions shown are assumed to be representative in terms of establishing a fouling factor on which to base heat-transfer calculations.

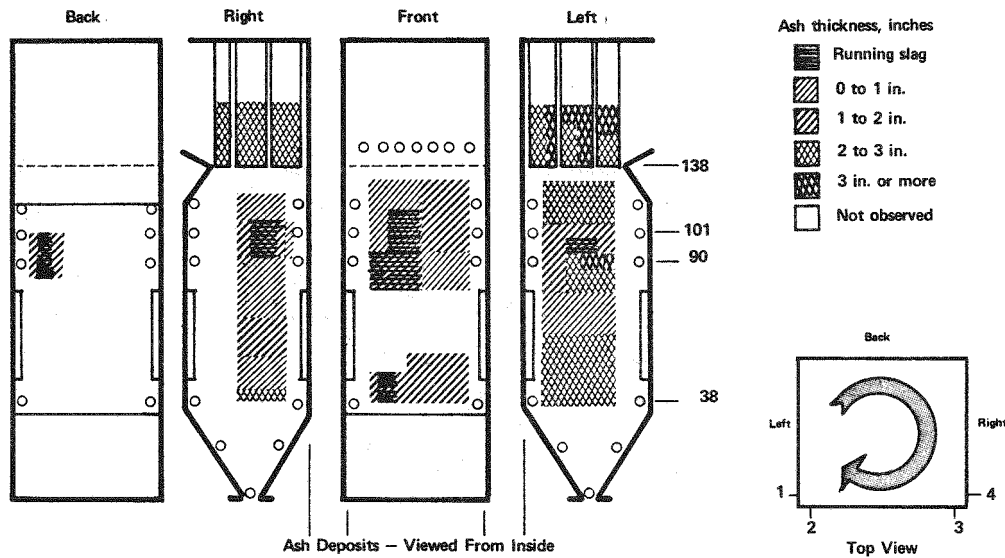


Figure 5-2. Thickness of Ash Deposits Observed in Furnace, Labadie Boiler 4  
(As viewed from inside of furnace)

Summary of Labadie Test Results

Test results are discussed in detail in following sections of this report.

The most significant results were as follows:

1. Furnace gas temperatures were the same as those at Cliffside, for an identical boiler fired with a non-slugging coal. Wall blowers were used infrequently at Cliffside, where the problem was to maintain sufficient ash cover to reach full superheat temperature
2. Furnace gas compositions were similar to those for Cliffside
3. Distribution of iron in furnace ash deposits, fly ash, and coal was fairly uniform, showing little segregation.

4. Ash analyses of coal density fractions showed that 28 percent of the total coal ash was found in the coal fraction heavier than 1.6 specific gravity, and the viscosity of this ash at 2300 F was extremely low. Ash in lighter coal fractions was of high viscosity and should not cause slagging problems. It appears probable that washing the Labadie coal to eliminate the fraction denser than 1.6 specific gravity would eliminate the most troublesome part of the ash and reduce or eliminate slagging problems.

#### MILL CREEK FIELD TRIAL

The Mill Creek Generating Station of the Louisville Gas and Electric Company consists of two identical 360 MW units. Each unit includes a single boiler, a single turbine with one stage of reheat, and auxiliary equipment. The nominal steam conditions at the turbine inlet are 2400 psi/1000 F/1000 F.

The Mill Creek Station was selected as a test site because of slagging problems that have required derating of each unit to 325 MW, and because the quality of coal to the test boiler could be controlled.

#### Boiler Description

The Mill Creek boilers were constructed by Combustion Engineering, Inc. Each has a single, tangentially-fired, balanced-draft furnace. Four tilting burners are placed at each corner of the furnace, with each of four pulverizers firing four burners, one in each corner. Boiler 1, selected for the tests, was placed in service in 1970. Each boiler is rated at 2.326 million lb steam per hour with superheat and reheat temperatures of 1005 F. Figure 5-3 is an outline drawing showing Boiler 1.

The boiler furnace is 45 ft wide, 38 ft deep and 150 ft high with 23,190 sq ft of heating surface. Economizer heating surface is 111,348 sq ft. Other design data are summarized in Table 3-2.

The boiler is equipped with 62 wall blowers and a number of long retractable soot blowers in the superheater and reheater sections. Steam at 400 psi is the blowing medium. The blowers are cycled in pairs by an automatic sequencer that operates continuously.

The boiler is generally operated at high load throughout the day, from about 9 a.m. to 10 p.m., and at reduced load (100 to 125 MW) at night and on Sunday. To avoid excessive slagging, operation is limited to 300 MW for a 3 or 4 day period or 325 MW for 8 to 10 hours. The boiler load was 297 MW during the test period.

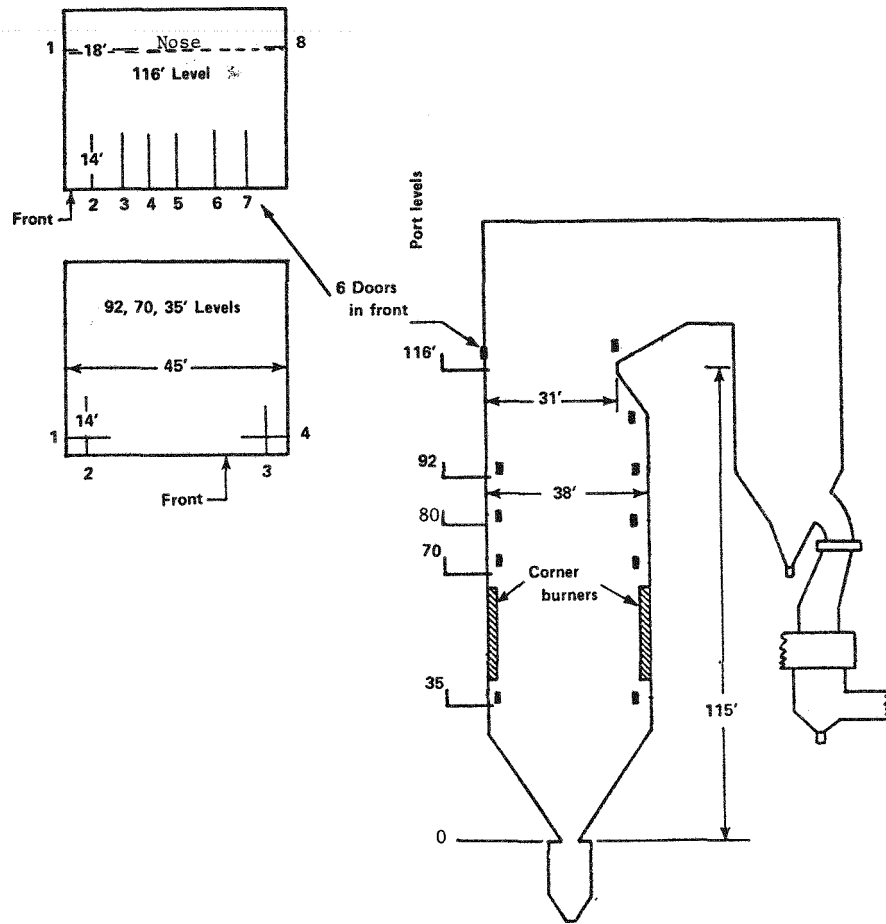


Figure 5-3. Mill Creek Boiler 1, Showing Access Ports and Traversing Lines

Lines show coverage of 15-ft and 20-ft probes

The heaviest slag deposits occur at the 70 ft and 80 ft levels just above the top burners. Slag buildup starts immediately above and below the burners. As load remains high, slagging moves up the furnace walls to the outlet. Running slag is observed about 4 to 6 hours after the start of high load operation. Troublesome slag accumulations often occur in the hot corners at the B and C wall blower levels, with the blowers becoming ineffective. The ultimate limitation on high-load operation is lack of sufficient superheater spray water to control the steam outlet temperature. During periods of high-load operation, burner tilt angles ranged from zero to minus ten degrees.

### Coal Sources

It is estimated that 75 to 80 percent of the coal burned during the test period came from Peabody Coal Company's Starr Mine. Most of the remainder came from the River Queen Mine, with a small fraction from the River View Mine.

### Description of Tests

Boiler tests were carried out during a five-day period starting Tuesday, October 11, 1977. The following types of data were obtained:

1. Traverses of furnace-gas temperatures and analyses
2. Observations of furnace slagging and wall blower operation
3. Panel-board data on boiler operation
4. Coal samples, from each pulverizer for each day
5. Slag samples from furnace walls from most sighting ports
6. Fly-ash samples from economizer and ESP hoppers.

Figure 5-3 is an outline drawing showing the locations of traversing lines. Traverses were run at the eight ports at the 116-ft level, and through the four corner ports at the front of the boiler on the 92-ft, 70-ft, and 35-ft levels. All traverses were run using a probe that extended 14 ft into the furnace, with measurements at 2-ft spacings, except that a 20-ft probe was used in the side ports at the 116-ft level. The 20 ft probe could not be used in other locations because of external obstructions.

Coal and ash sampling followed procedures described in Section 4. Coal was sampled daily from the outlet of each of the four pulverizers, and ash samples were taken from the four economizer hoppers, four ash hoppers below the air heaters, and 16 ESP hoppers.

### Observations of Furnace Ash Deposits

Figure 5-4 is a graphic representation of the distribution of ash and slag on the furnace walls. The ash thickness, and areas of running slag, are indicated by the pattern of shading. Figure 5-4 shows that ash thickness exceeded 2 inches over large areas, and that considerable running slag occurred on all walls for about 20 ft above the burners. The viewing sequence took about 4 hours, during which all wall blowers operated at least once.

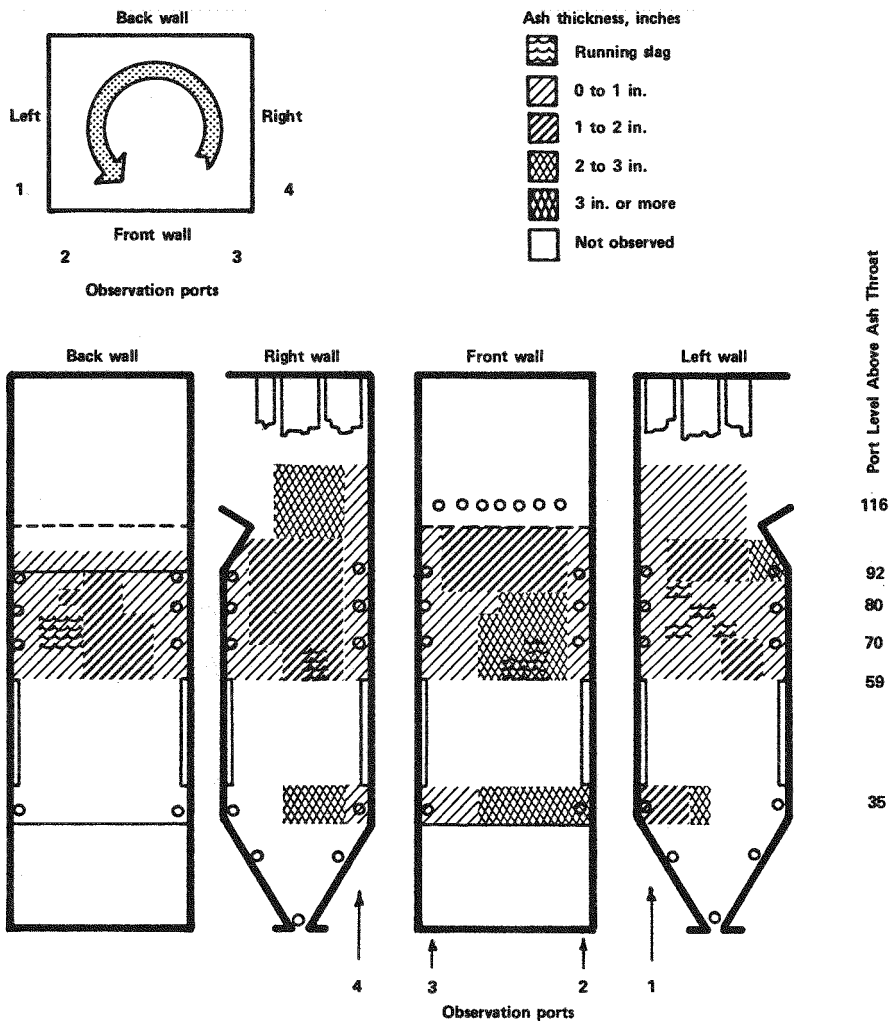


Figure 5-4 . Furnace Ash Deposits, Mill Creek Boiler 1  
(As viewed from inside of furnace)

Thus, the wall conditions were changing constantly and the condition shown in Figure 5-4 was not a continuous, stable condition.

The effectiveness of wall blowers varied with time and position, but no clearly defined pattern was observed. In the corners, where deposits were far from the flame, blowers were nearly always effective in removing deposits. Near the center of the wall, where the flame radiation was higher, it was not unusual to observe blower cycles that had no visible effect on the deposit. This was particularly true just above, and just below, the burners. From samples taken off the walls next to observation ports, and from observations,

it appeared that light, sintered ash deposited to a thickness of about two inches. If not removed, a very hard sintered crust would develop and, later, this crust might fuse. After the ash surface became hard and strong, blowing over the surface with a wall blower did not remove it. However, if the deposit had covered the blower, when the blower extended into the furnace it might push off a large piece of ash and weaken the bond of adjacent ash sufficiently for partial cleaning of the wall. Otherwise, it appeared that the deposit remained on the wall until load was dropped during the night, after which it was shed by the combination of differential thermal contraction on cooling, and action of the wall blower.

#### Summary of Mill Creek Test Results

Mill Creek test results are discussed in detail in following sections of this report. The most significant results were as follows:

1. Furnace gas temperatures were the lowest of the five boilers tested, reflecting the low thermal loading of the Mill Creek furnace.
2. Excess air below the burners was considerably higher than in the other boilers tested. (Discussed on Page 7-6)
3. The distribution of iron in coal, furnace deposits, and fly ash was very uniform, indicating that slagging was not the result of segregation of pyrites from the coal
4. Ash analyses of coal density fractions showed that 42 percent of the total coal ash was found in the coal fraction heavier than 1.6 specific gravity, and the viscosity of this ash at 2300 F was extremely low. Ash in the lighter coal fractions was of high viscosity and should not cause slagging problems. It appears probable that coal washing to eliminate the fraction denser than 1.6 specific gravity would eliminate the most troublesome part of the ash and eliminate slagging problems.

#### CLIFFSIDE FIELD TRIAL

##### Boiler Description

The Cliffside Generating Station of the Duke Power Company consists of one 571 MW unit in one building and four smaller units in another building. The 571 MW unit, Boiler 5, is an exact duplicate of the Labadie units. The boiler maximum continuous rating is 600 MW and the boiler is specified for a Western Kentucky coal of high slagging potential. However, the unit is normally operated at 571 MW, and burns Eastern Kentucky coal of low slagging potential. Accordingly, furnace slagging is not a problem. The boiler dimensions and operating conditions are listed in Table 1.

Boiler 5 is operated as a load-scheduled unit and follows load demand because it has cooling towers and is more expensive to operate than some base-loaded plants in the system. The boiler can operate at 590 MW for extended periods without slagging problems. Operation at 610 and 620 MW is feasible for periods up to 8 hours, after which load must be dropped to shed slag. At normal full load of 590 MW, occasional wall blowing is sufficient to control furnace ash deposits. The operators manually actuate single blowers once per shift as needed to remove excessive accumulations of ash in isolated locations. At loads below 580 MW the wall blowers are seldom used. The angles of burner tilt observed ranged from + 20 degrees to -5 degrees. Angles near zero degrees were used for full-load operation.

#### Coal Sources

Nearly all of the coal burned at Cliffside comes from the Clinchfield Coal Company, and originates from five mines in Eastern Kentucky. Coal from these mines is quite similar. Coal is received at the plant only 5 days per week, and is burned from the storage pile on other days.

#### Description of Tests

The tests run at Cliffside were similar to those run at Labadie and Mill Creek, and included measurement of furnace gas temperatures and compositions, observations of furnace ash deposits, and sampling of coal and ash.

Figure 5-5 is an outline drawing showing locations of access ports and traversing planes for measurement of furnace gas temperature and composition.

#### Furnace Traverses

Furnace gas temperatures were measured by traversing at four elevations. The furnace outlet level, at 138 ft, was traversed at 9 ports, and each of the four ports at the front corners of the boiler were traversed at the 115-ft, 90-ft, and 38-ft. levels.

The average furnace outlet temperature, based on traverses of ports 2 through 8, was 2356 F. The gas temperatures at other levels were 2561 F at 115-ft, 2607 F at 90-ft and 2218 F at 38-ft. The "hot corner" effect observed at Labadie and Mill Creek was not evident above the burners at Cliffside, although some effect could be seen at the 38-ft level, below the burners. (This effect is discussed on page 6-3)

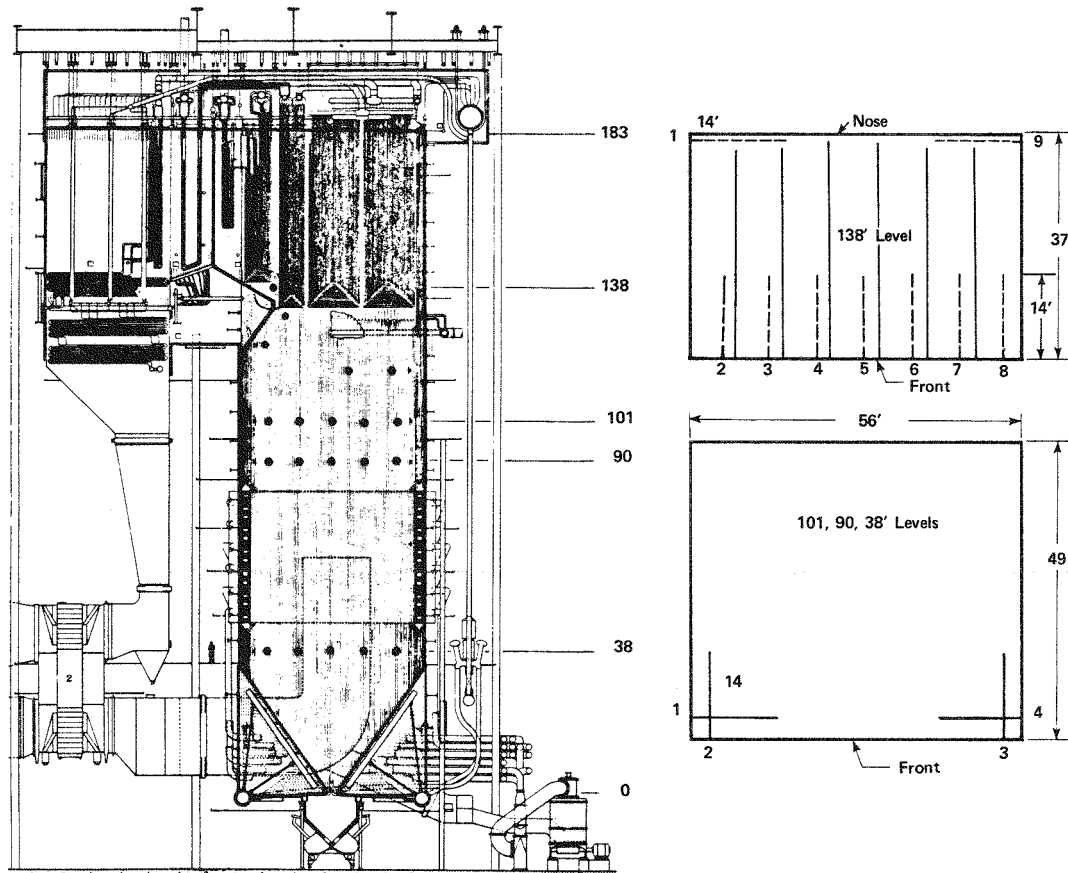


Figure 5-5. Cliffside Boiler 5, Showing Access Ports and Traversing Lines  
Lines show coverage of 15-ft and 20-ft probes

A daily temperature traverse was run at Port 1 at 138 ft to observe day-to-day variations in furnace-outlet temperature. The daily average temperatures for these traverses were 1918 F, 1896 F, 1953 F, and 1946 F, for days when furnace traverses were run at elevations of 38-ft, 90-ft, and 115-ft, respectively.

Orsat gas analyses were obtained concurrently with temperature traverses at the same four elevations. The excess air at the boiler outlet was considerably lower than for the other boilers tested.

Excess air, or oxygen level, at the other furnace levels was higher than for the boiler outlet, but much lower than for the other boilers tested. Ability to operate at these low values of excess air reflects freedom from slagging problems because of the generous furnace volume for the coal fired. Low excess air would reduce ash fusion temperatures and increase the tendency toward slagging, but the

furnace size provided sufficient margin that slagging was not a problem with this coal.

#### Observations of Furnace Ash Deposits

Figure 5-6 shows the distribution of ash deposits on furnace walls. The thickness of ash, and areas of running slag, are indicated by the shading pattern. It is evident from Figure 5-6 that ash thickness varied considerable over the walls, and that some running slag was present.

Unlike previous test units, the Cliffside No. 5 boiler was not load-limited by slagging problems. The furnace was generously sized for the coal fired, and it was necessary to retain a substantial ash deposit in the furnace to reach the nominal superheat temperature of 1005 F. Thus, there was no need to drop load for deslagging and wall blowers were not operated on an automatic cycle. Instead, the furnace was inspected once per shift and blowers were operated manually where a heavy local deposit was observed. However, small areas of plastic slag were observed to shed spontaneously of their own weight, so that thickness and appearance of the deposits changed with time. Although slag did not limit load, and was removed easily by wall blowers, there was considerable liquid slag on the walls. Thin, fluid slag, of about 1/8-in. thickness, was observed flowing in rivulets over otherwise bare tubes, and considerable wet slag was seen in the areas just above and below the burners.

In one observation at the port just above the burners, observing the front wall, a section of viscous, plastic deposit about one foot wide by three feet high was observed to fall off the wall. A piece of slag about the size of a baseball struck the slag cover and stuck. The weight of this piece caused the slag cover to gradually bend outward into the furnace, until a 180-degree bend had formed, and the slag layer gradually peeled back until it broke, at a length of about three feet. The thickness of this slag was about two inches, and the consistency appeared to be that of solid granules joined with a viscous fluid, like soft popcorn balls. After the slag peeled off the tubes looked clean. However, the wall was 50 percent covered with slag particles in the 1/8 to 1/2-inch size range within one minute, and in two minutes the tubes were no longer visible. A continuous rain of these fairly large particles impinged on the wall. It appeared that they were particles falling from higher elevations, centrifuged outward by the swirling flame.

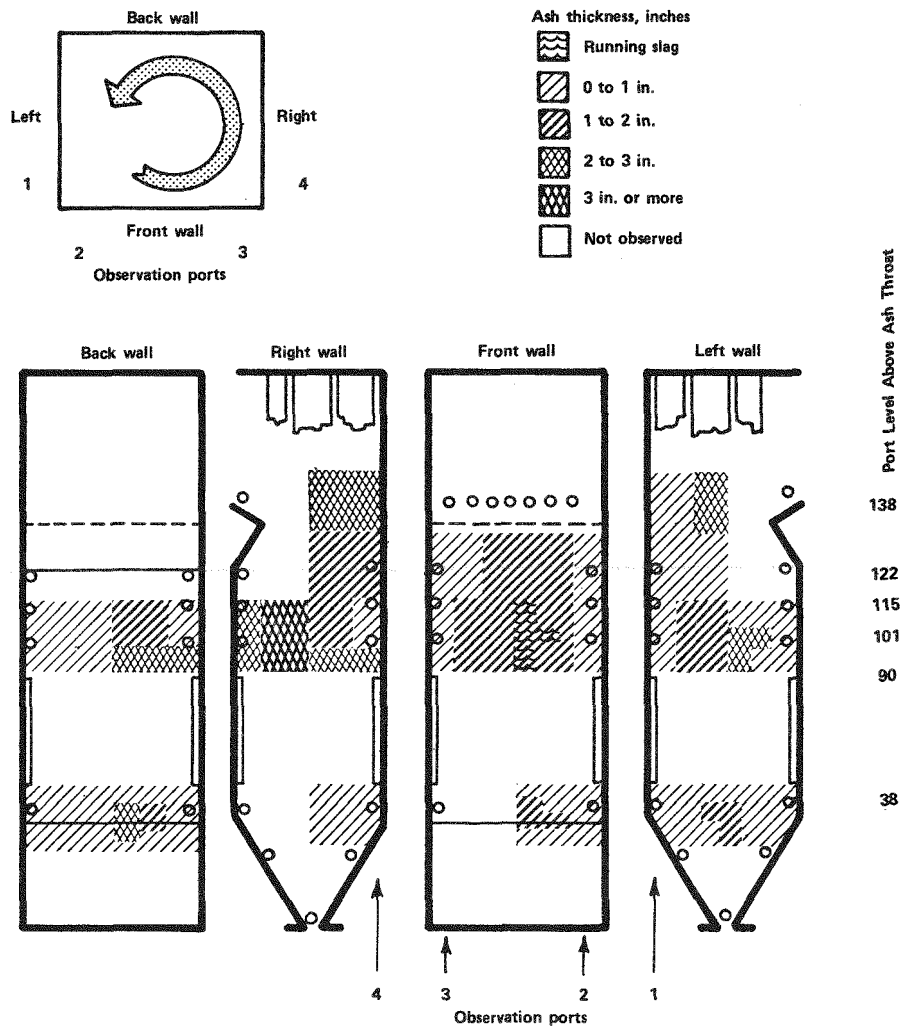


Figure 5-6. Furnace Ash Deposits, Cliffside Boiler 5  
(As viewed from inside of furnace)

Summary of Cliffside Test Results

Cliffside test results are discussed in detail in the following sections of this report. The most significant results were as follows:

1. Furnace gas temperatures were nearly identical to those at Labadie, an identical boiler fired with a different coal, even though continuous wall blowing was required at Labadie for control of ash deposits. Labadie wall-blower operation compensates for the more severe slagging characteristic of the Labadie coal.
2. The distribution of iron in the coal, furnace deposits, and fly ash was extremely uniform, showing that there was little segregation of ash constituents during pulverization and burning.

- 3 The distribution of elements in the coal ash of coal densits fractions was quite uniform, and the ash viscosity at 2600 F was high for every fraction except the 2.8 specific gravity sink fraction. This fraction contained 5.2 percent of the coal ash, and was of extremely low viscosity, at 3 poise at 2300 F. It appears that the quantity of low-viscosity ash was too low to cause slagging difficulties. A similar dense high-iron fraction was found in the other non-slagging coals, as well as in the slagging coals.

#### MORGANTOWN FIELD TRIAL

The Morgantown Generating Station of Potomac Electric Power Company has two identical 575-MW units. These operate at supercritical steam pressure of 3675 psi and 1000 F at the turbine inlet, with reheat to 1000 F.

#### Boiler Description

The Morgantown boilers are balanced-draft supercritical reheat (3500 psi 1000 F/1000 F) units with a tangentially fired divided furnaces as shown in Figure 5-7. Each furnace is divided into two parallel sections by a division wall, and each section is tangentially fired. There are, therefore, 8 burners at each level, and there are five firing levels. Each of the five coal pulverizers supplies coal to the eight burners at one level. The divided-furnace arrangement requires less furnace volume than a single-furnace unit for the same total wall surface, as shown in Figure 1-1. Boiler 1, the test unit, was placed in service in 1970.

Both boilers are normally operated at full load, 580 MW, from 7 a.m. to 10 p.m. for six days per week. Load is dropped to about 200 MW at night and on Sundays in response to system demand, but continuous operation at full load is possible for extended periods without serious slagging problems. Wall blowers are operated only as needed, and it is not necessary to cycle them regularly.

Coals burned at Morgantown came from a number of mines in Eastern Pennsylvania, including the Cooney, Shawville, and Patton mines.

#### Furnace Traverses

Figure 5-7 shows the locations of view ports and traversing lines for the Morgantown boiler. All traversing was carried out in the south furnace section, using Ports 1-6 at the 121-ft level, and ports 2-5 at the 83-ft level. External obstructions prevented traverses at the 68-ft or 72-ft levels, which would have been

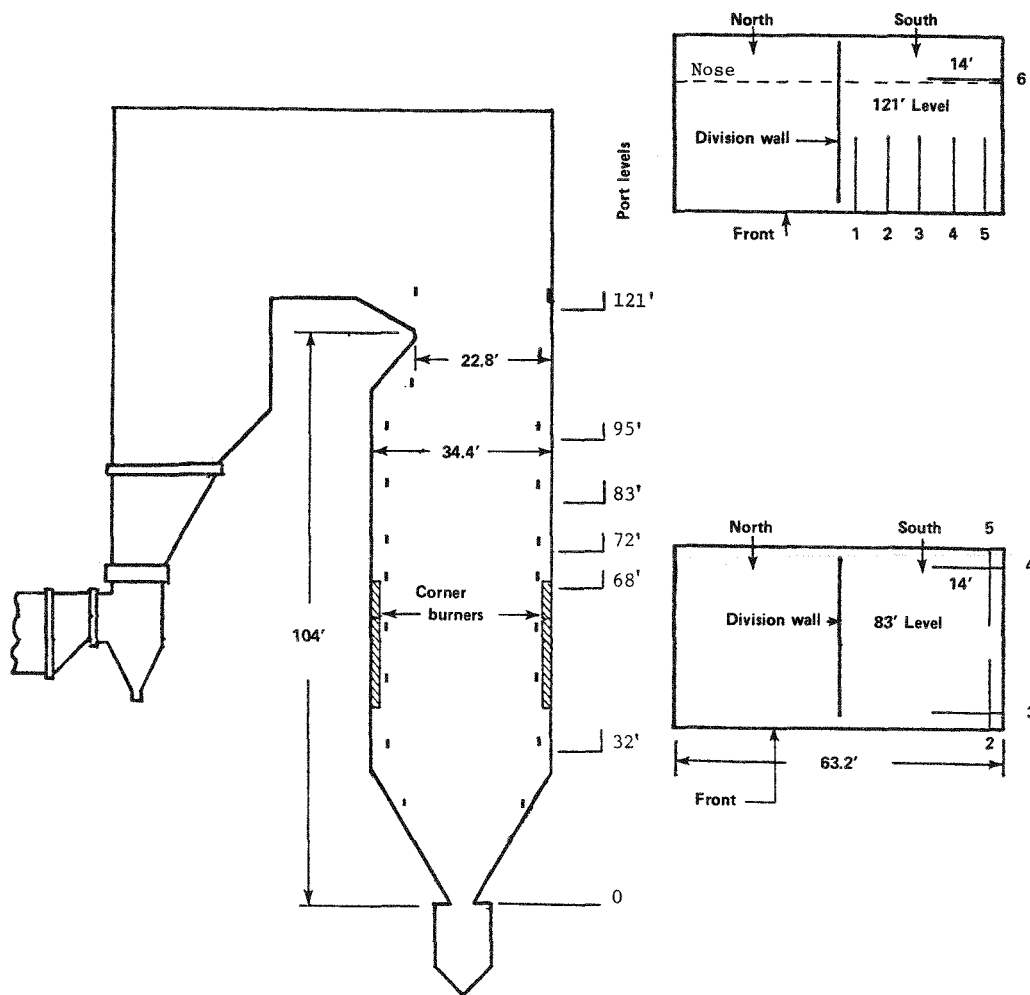


Figure 5-7. Morgantown Boiler 1, Showing Access Ports and Traversing Lines  
Lines show coverage of 15-ft probe

preferable. Only two temperatures were measured at each port at the 83-ft level because the high-velocity thermocouple plugged with molten slag and had to be replaced after only two readings, despite the fact that the coal ash fusion temperatures was above 2700 F.

The furnace exit temperature was 2299 F, and the gas temperature at 83 ft was 2738 F, which is appropriate for the high ash fusion temperatures of the coal fired.

Furnace gas compositions at the 121-ft and 83-ft levels were measured concurrently with gas temperatures. As with previous boilers, the oxygen concentration at the 83-ft level was considerably higher than at the 121-ft level.

### Ash Sampling

ESP ash samples were obtained for only 13 of 32 ESP hoppers, because 8 hoppers had no sampling ports, access pipes on 4 hoppers were smaller than the sampling scoop, two hopper ports were inaccessible because of external obstructions, and no ash had collected in five hoppers.

Economizer hopper ash accumulation was insufficient for normal sampling. Approximately one cup of sample was collected from two hoppers by leaving a sample can under each port overnight with the valve open. No samples were deposited at the other four hoppers.

### Observations of Furnace Ash Deposits

Figure 5-8 shows the distribution of ash and slag on walls of the south furnace section. The ash thickness, and areas of running slag, are indicated by the pattern of shading. The heaviest deposits occurred near the top of the burners, with running slag on the back wall. Some running slag was also observed at the middle of the front wall just under the furnace nose. The thickness of deposits appeared to reach an equilibrium such that little wall blower operation was needed for reheat control.

On this supercritical boiler, superheat temperature is controlled by firing rate and desuperheater water flow, and reheat temperature is controlled by burner tilt. When burners are tilted fully downward, additional reheat control is obtained by use of attemperater water. The furnace deposit equilibrium occurs with burners tilted fully downward and some reheat water flow. During the 2-day test period steam flow was nearly constant, fluctuating between 3.8 and 4.2 million lb/hr. For these conditions, the angle of burner tilt ranged from -20 degrees to -15 degrees most of the time, with occasional short excursions toward -10 degrees.

### Summary of Morgantown Test Results

Morgantown test results are discussed in detail in following sections of this report. The most significant results were as follows:

1. Furnace gas temperatures were the highest measured among the five test boilers, reflecting the high thermal loading of the furnace designed for a coal of low slagging potential.
2. Excess air, at 22 percent, was the second lowest measured.

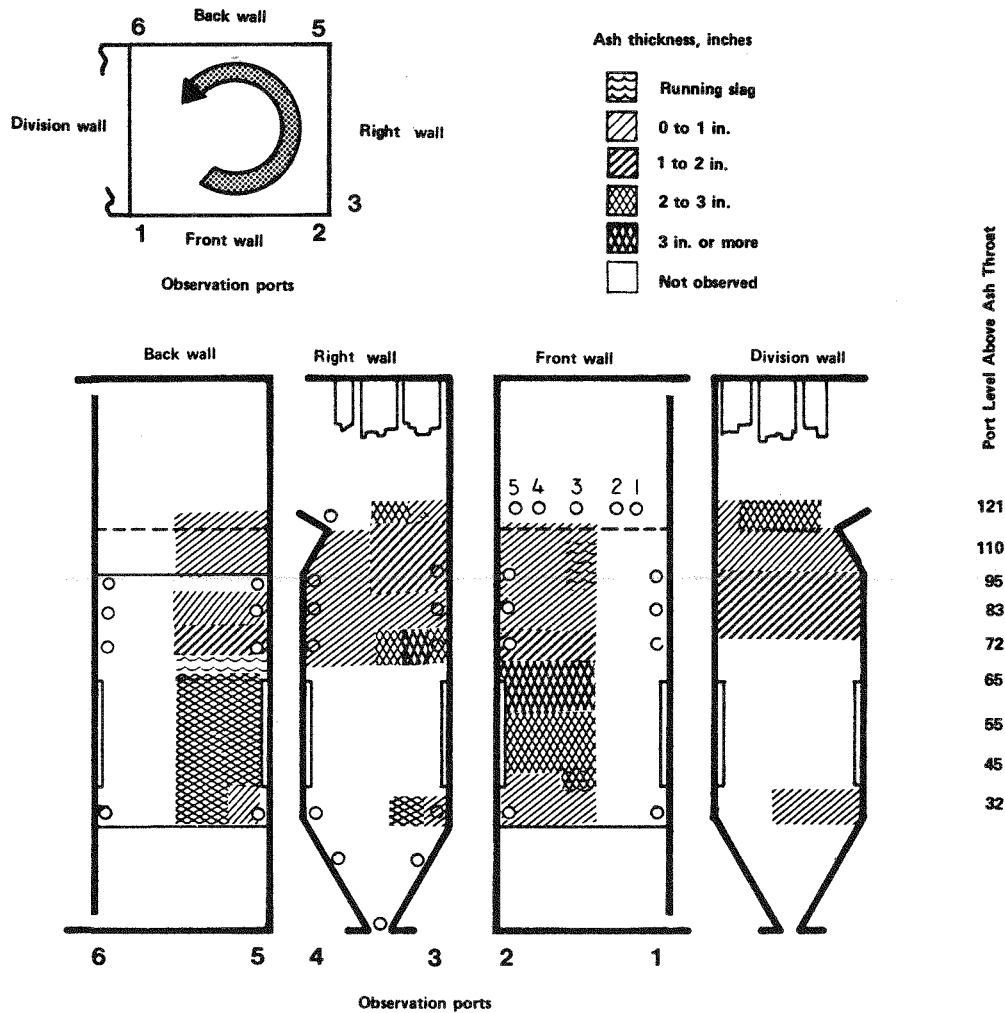


Figure 5-8. Furnace Ash Deposits, Morgantown Boiler 1  
(As viewed from inside of furnace)

3. The analysis of coal ash, furnace ash deposits, and fly ash showed that furnace ash deposits were enriched in iron by about 50 percent above coal ash and fly ash. Furnace deposits contained 16.8 to 25.7 percent  $\text{Fe}_2\text{O}_3$ , compared with 14.0 percent for the coal and 13.9 percent for the fly ash. There was definite segregation of iron in this unit, and ash fusion temperatures for furnace deposits would be lower than for the coal. However, ash fusion temperature for this furnace deposit was high enough to avoid slagging difficulties. This is indicated by the high ash viscosity at 2600 F for the furnace ash.
4. Analyses of ash in coal density fractions showed that ash viscosity would be high for all fractions lighter than 2.8 specific gravity. The fraction denser than 2.8 contained 7.2 percent of the coal ash.

Iron content of this fraction was 86.1 percent, and calculated ash viscosity at 2300 F was only 3 poise. This fraction of the ash would be extremely fluid at furnace temperatures, but the quantity was too small to cause slagging problems. However, it probably accounted for the iron enrichment of furnace ash deposits.

## MONTOUR FIELD TRIAL

### Boiler Description

The Montour Generating Station of the Pennsylvania Power and Light Company has two identical 750-MW units. These operate with turbine-inlet steam conditions of 3500 psi, 1000 F, with reheat to 1000 F. Boilers are not enclosed in a building, but turbines and auxiliaries are enclosed.

Figure 5-9 shows the arrangement of Montour Boiler 1, including the locations of view ports and traversing lines. The divided, pressurized furnaces are tangentially fired by tilting burners arranged in columns at the four corners of each furnace. Coal is supplied from six pulverizers, each of which supplies eight burners, one in each of the eight furnace corners. Boiler 1 was placed in service in 1970. Table 3-2 summarizes dimensions and operating data for this boiler.

It is interesting that the Montour furnaces are of virtually the same height as the Morgantown furnaces, with an extra level of burners and larger plan area. One would expect higher gas temperatures and radiation levels in the upper furnace than for Morgantown.

Both boilers are normally operated at full load through each week, with a 50-percent load drop twice each week to deslag the furnace. Although wall blowers are effective in controlling furnace deposits, large deposits can build up high in the furnace, and in the burner zone, where there are no blowers. Periodic deslagging avoids massive ash accumulations. In addition, the capacity of the bottom-ash removal system is not great enough to accommodate the amount of ash that is discharged with a weekly deslagging, and more frequent deslagging avoids backing of ash into the furnace hopper. The utility expected to operate these boilers at 800 MW, based on experience with their other boilers, but find it necessary to operate with rather high excess air in order to carry 750 MW, the manufacturer's maximum continuous boiler rating. Burner tilt is the primary control for reheat temperature. Burner tilt range is blocked to limit tilt to angles between +15 degrees and 0 degrees, and is under automatic control.

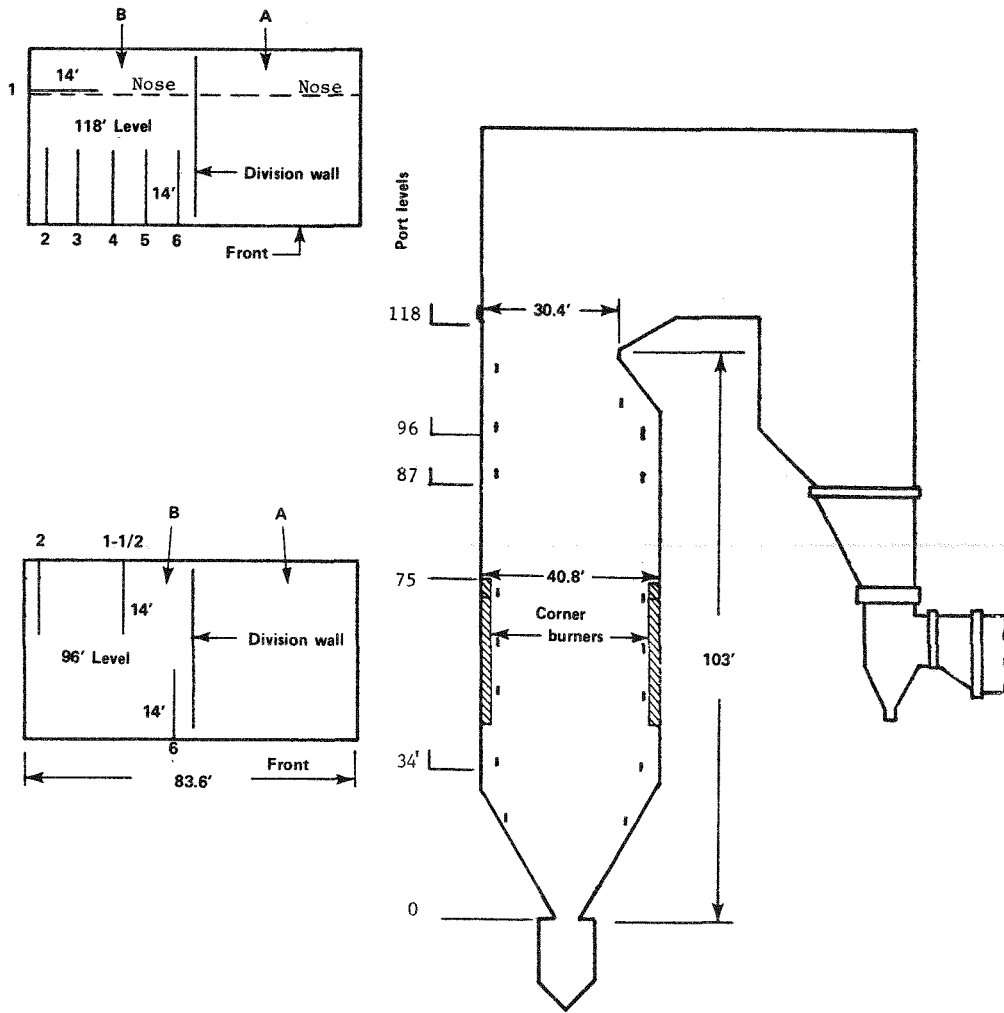


Figure 5-9. Montour Boiler 1, Showing Access Ports and Traversing Lines

Lines show coverage of 15-ft and 20-ft probes

### Coal Sources

Table 5-1 lists coal sources and analyses for the coals fired at Montour, and for the design coal. Most of the coal comes from the utility-owned Greenwich mine. All coals have similar characteristics. The characteristics of the coal fired during the field trial are summarized in Table 3-2.

### Furnace Gas Temperatures

Furnace gas temperatures were measured by HVT traverses at the furnace outlet and at the 96-ft level, on the traverse lines shown in Figure 5-9. The five

TABLE 5-1. ANALYSES OF TYPICAL COALS BURNED AT MONTOUR

Vendor	Btu/lb (a.r.) <sup>(1)</sup>	Moist, % (a.r.)	Ash, % (d.b.) <sup>(2)</sup>	S, % (d.b.)	(ST)		% of Burn
					Ash Softening, Ave	Temp, Range	
Greenwich	12100	8.0	14.0	1.2	2450	2350-2550	72
Bonder	12200	6.0	14.4	1.8	2700	2400-2800	15
Coal Util	12800	5.0	11.5	2.0	2400	2100-2600	4
Pel Bro	13000	4.0	11.4	3.1	2250	2100-2500	3
Poles	12800	6.5	9.1	2.0	2500	2100-2700	3
Wesott	12600	7.0	10.2	1.7	2400	2200-2700	2
Composite Ave	12200	7.5	14.0	1.4	2600		100
Design coal <sup>(3)</sup>	12261	6.0	14.4 <sup>(1)</sup>	--	2394 <sup>(4)</sup>	--	--

(1) As received basis.

(2) Dry basis.

(3) Volatile matter 22.0 percent, fixed carbon 57.6 percent.

(4) Ash fusion temperature.

ports across the front of B furnace were traversed at the 118-ft level, and Ports 2, 1-1/2, and 6 were traversed at the 96-ft level. Traverses at the 87-ft level, just above the burners, had been planned, but could not be carried out because of external obstructions.

The temperatures measured at Port 1-1/2, at the 96-ft level are particularly significant because it is the only port on any of the five boilers tested which was located to permit traversing into the center of the flame near the burners. All other ports permitted traversing along the furnace walls only, where gas temperatures are lower than in the flame. The average temperature measured at Port 1-1/2 was 2650 F. This compares with temperatures of 2453 F and 2434 F for Ports 2 and 6 at the same level, for a temperature difference of 206 F. It is quite probable that mid wall flame temperatures in the other four boilers tested were also about 200 F above the traverse values near the corners.

It is also of interest that the average temperature of 2444 F measured through Ports 2 and 6 was only slightly higher than the furnace outlet temperature of 2409 F. In this furnace, burning low-volatile coal, the intensity of combustion in the burner zone was less than in furnaces burning high-volatile coal, with more uniform heat release over the furnace height.

### Furnace Gas Compositions

Furnace gas compositions were measured at the 118-ft and 96-ft levels. As with other boilers, the oxygen level, or excess air, along the furnace walls is much higher than at the furnace outlet. The data obtained at Port 1-1/2 is of particular interest because it shows that oxygen concentration within the flame is nearly the same as that along the walls. Thus, the high oxygen concentrations measured along the walls in all furnaces probably occur because of incompleteness of combustion rather than stratification of air and coal from the burners.

### Observations of Furnace Ash Deposits

Figure 5-10 shows the distribution of ash and slag on walls of B furnace of Boiler 1 during the test period. The ash thickness is indicated by the pattern of shading. In general, the ash covering is comparatively light over most of the furnace, accumulating to more than 3 inches thick at only two places, both below the burners. However, station operators said that greater ash thickness was more usual. No areas of running slag were observed. The unshaded areas in Figure 5-10 could not be observed as the viewing angle through view ports was small.

Wall blowers were effective in removing deposits, so that deposition was not a problem in areas covered by wall blowers. However, some heavy ash deposits were observed at the leeward edge of the burners at one corner. Video taping over an extended period showed spontaneous shedding of ash at times.

The fireball in the Montour furnace was off center, so that fire passed close to the burners on one side of the furnace, and was far from the burners on the other side. On the hot side of the furnace, ignition occurred at the burner and flame was deflected to one side by the flow of furnace gas.

On the cold side, the jets of coal from the burner traveled about 5 feet and passed out of the viewing area without ignition. Modifications of coal piping to center the flame in the furnace are under consideration by the utility.

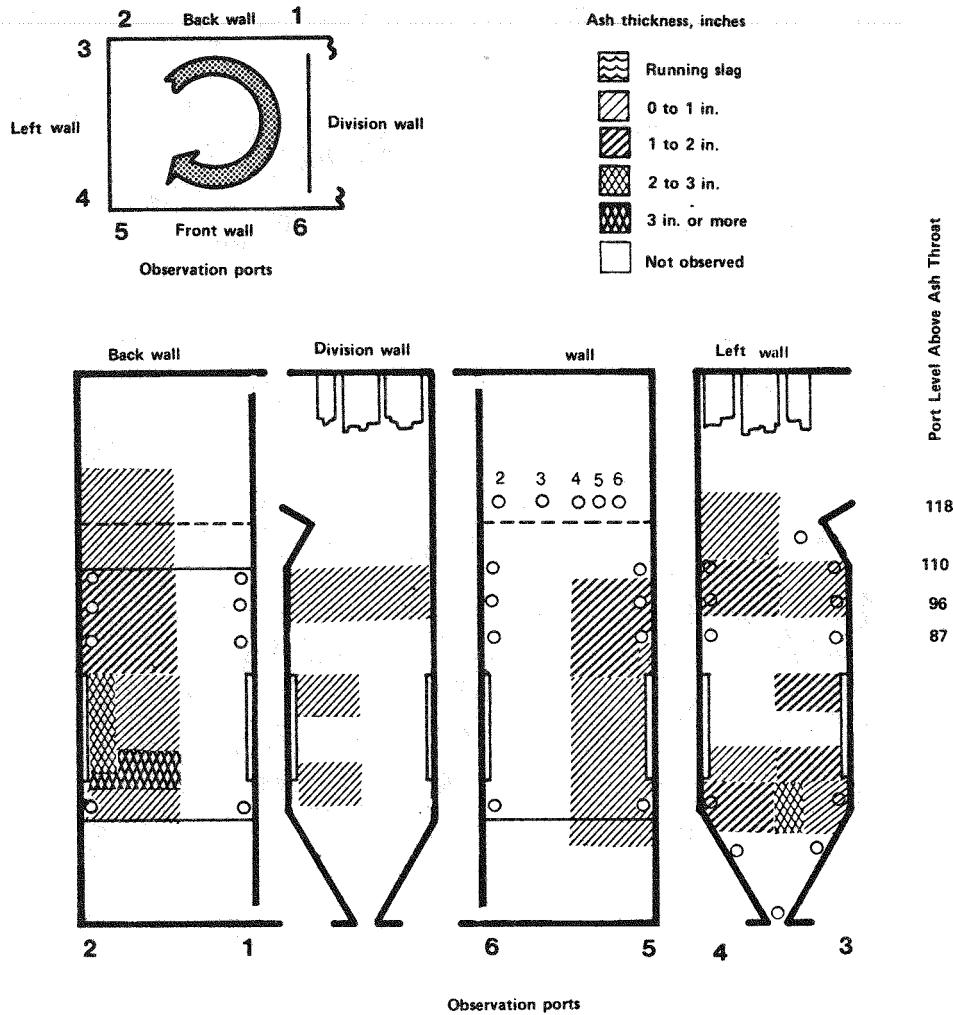


Figure 5-10. Furnace Ash Deposits, Montour Boiler 1  
(As viewed from inside of furnace)

Summary of Montour Test Results

Montour test results are discussed in detail in following section of this report. The most significant results were as follows:

1. Montour thermal loadings per unit of wall area were the highest of the five test boilers, but furnace temperatures were moderate. Furnace exit temperature, at 2413 F, was the highest value measured among the test boilers.
2. Excess air, at 35 percent, was the highest value measured among the test boilers. Mill Creek operated at the same level.

3. The coal ash characteristics were excellent. Ash analyses of coal density fractions showed that ash in coal less dense than 2.8 specific gravity was of high viscosity at 2600 F. A small fraction of the coal of greater density contained 3.5 percent of the total coal ash. This dense fraction contained 75 percent iron and had viscosity of 3 poise at 2300 F, which is extremely fluid. The quantity appears too small to cause slagging problems, but it could account for iron enrichment of furnace ash.
4. Analysis of furnace ash, fly ash, and coal ash showed that iron content of furnace ash deposits was variable and higher than for the coal. This resulted in considerable variation in calculated ash viscosity at 2600 F, although all values were high enough to avoid slagging problems.

## Section 6

### FURNACE GAS TEMPERATURES

The behavior of ash deposits on furnace walls will vary with heat flux, which affects deposit temperature, and with furnace gas composition, which affects the state of oxidation of iron in the ash and, thus, the ash fusion temperatures. Accordingly, as part of this study, measurements of furnace gas temperatures and compositions were made by traversing at various levels within the furnace.

Furnace gas temperatures are influenced by several factors:

1. The excess air for combustion.
2. The intensity of mixing of fuel and air, which affects local rates of heat release and, thus, local temperatures.
3. The thermal loading of the furnace, in terms of heat release per unit volume and per unit of furnace surface.
4. Gas flow patterns that result in flame asymmetry.
5. Heat transfer from the flame by radiation, which depends upon flame emissivity, wall emissivity, and the emissivity, thickness, and distribution of ash deposits on the walls.

Furnace gas temperatures were measured by HVT (High Velocity Thermocouple) traverses at four different levels in three units, and at two levels in two units. Detailed, point-by-point data for each traverse are listed in Tables A-1 through A-8 of Appendix A. The temperatures of greatest interest are those just above the burners, where gas temperatures are highest, and those at the boiler outlet, measured at a plane just above the furnace nose, between pendent superheaters. Furnace sections showing the traversing locations for each boiler are included in Section 5.

Figure 6-1 shows the outline of the furnace outlet, at the 116-ft elevation, for Mill Creek, showing gas temperatures at their measured locations. The temperatures measured through Ports 2 through 7 provide a good average of the temperature of gas flowing at the front half of the furnace outlet. The temperatures at Ports 1 and 8, which are just above the furnace nose, represent only that of gas flowing close to the water wall at this location and do not represent average gas temperature for the rear half of the furnace. Accordingly, in averaging data to an average furnace outlet temperature, only the data for Ports 2 through 7 have been used.

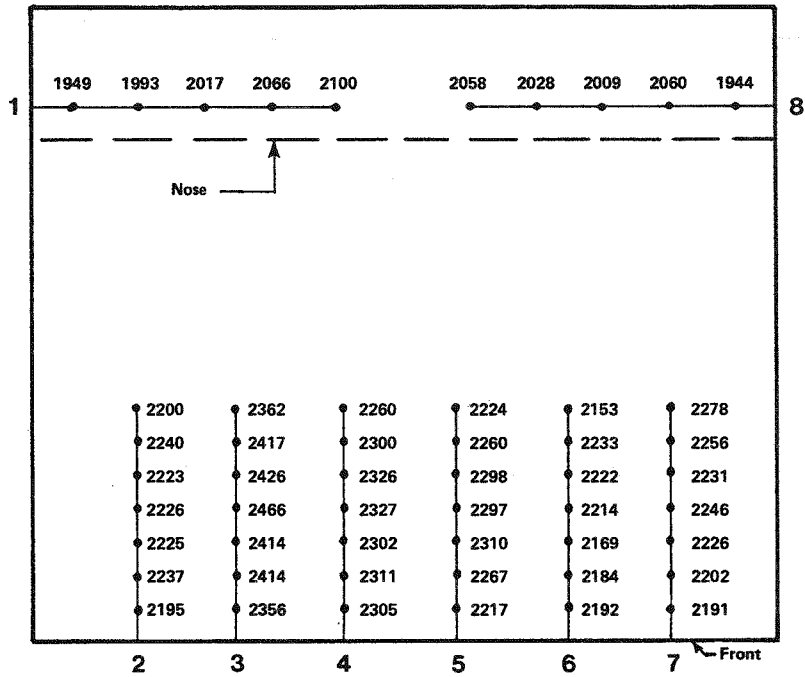


Figure 6-1. Map of Furnace Gas Temperatures at 116-ft Elevation (Furnace Outlet) Mill Creek Boiler 1

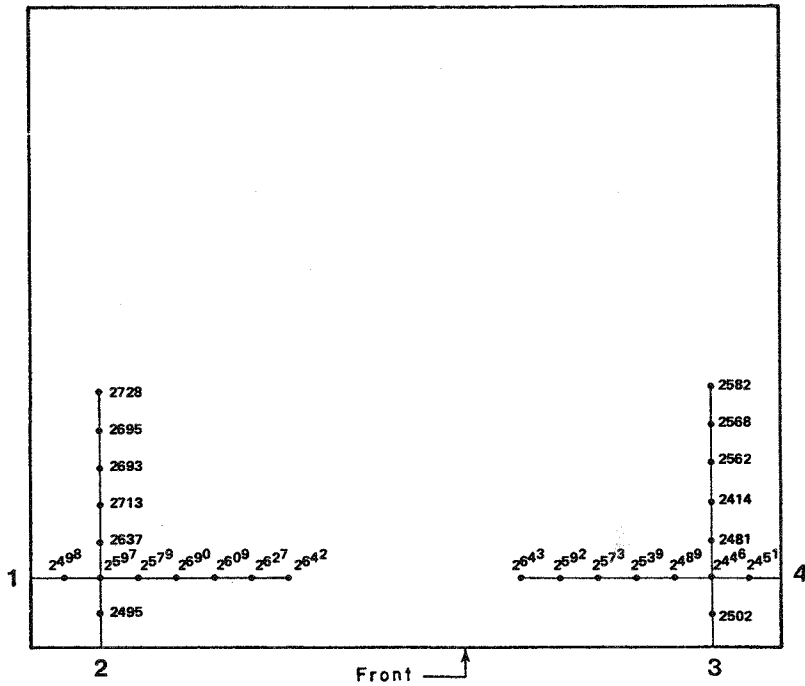


Figure 6-2. Map of Furnace Gas Temperatures at 70-Foot Elevation, Mill Creek Boiler 1

Figure 6-2 is a map of the Mill Creek furnace showing gas temperatures measured at the 70-ft elevation, which is eight ft above the burners. This is the hottest part of the furnace in which measurements were made. The temperatures shown in Figure 6-2 were used to calculate the reported average measured temperature at the 70-ft level. These temperatures were all measured near the walls however, and are almost certainly below the temperatures within the cylindrical flame, which does not reach the walls. In all boilers except Montour, the only view ports available for furnace traversing below the outlet were near the furnace corners, placed like those in Figure 6-2.

Figure 6-3 is a map of the Montour furnace showing gas temperatures at the 96-ft elevation, which is 21-ft above the burners. This was the only furnace of those tested having a viewport that permitted traversing into the flame. The temperatures measured through Port 1-1/2 averaged 206 F higher than the temperatures measured through Ports 2 and 6. These are the only data obtained to indicate the difference between temperatures as measured near walls, and flame temperature, but they are probably typical of all cases.

Figure 6-4 shows the variation of furnace gas temperature with height for Labadie Boiler 4. Each data point represents the average of temperatures measured at the view port identified by number. The four points at the 38-ft level show the difference between a "hot corner" (Ports 1 and 2), and a "cold corner" (Ports 3 and 4) caused by burner arrangements, and this pattern persists at the 90-ft level. The temperature difference between the two corners is nearly 100 F. Higher in the furnace this difference becomes less distinct with mixing in the swirling flow. The temperatures observed at the 138-ft level appeared to vary with time as well as position and this fact makes it impractical to attempt a detailed spatial analysis. The temperature spread was 200 F among the eight ports of Boiler 1, and 180 F for the three Boiler 4 ports. The furnace gas temperature patterns for the other boilers were generally similar to those for Labadie.

The principal design variable that influences gas temperature at the burner level is furnace plan area. The height of the furnace, with its resulting temperature gradient, influences furnace exit temperature. These temperatures also depend upon heat transfer to the furnace walls, which varies considerable with differences in ash coverage and thickness. It is evident that wall deposits will change through each 90-minute wall-blower cycle as the local wall sections are cleaned, then accumulate heavy ash deposits, and this will affect local gas

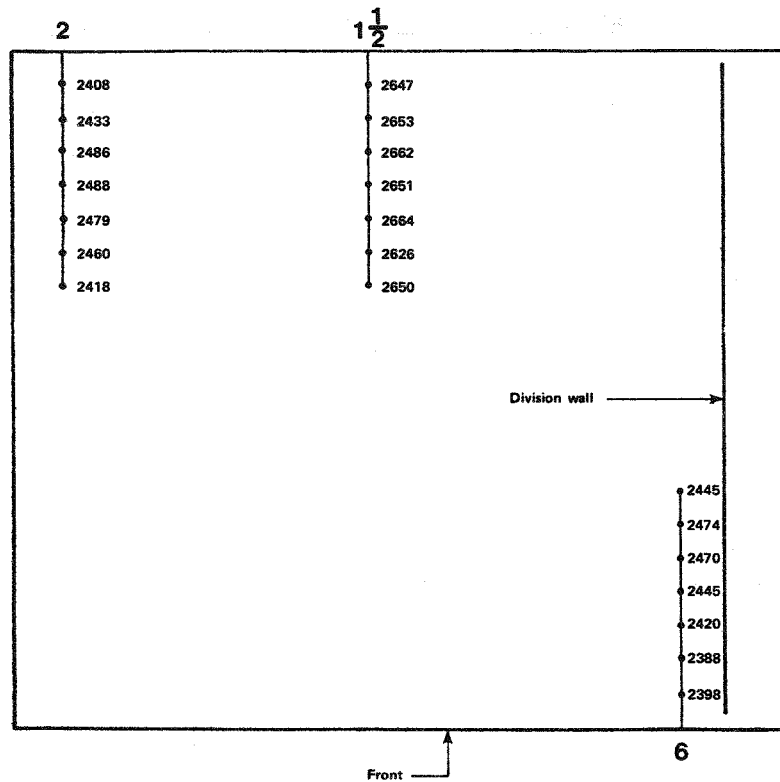


Figure 6-3. Map of Furnace Gas Temperatures at 96-Foot Elevation, Montour Boiler 1

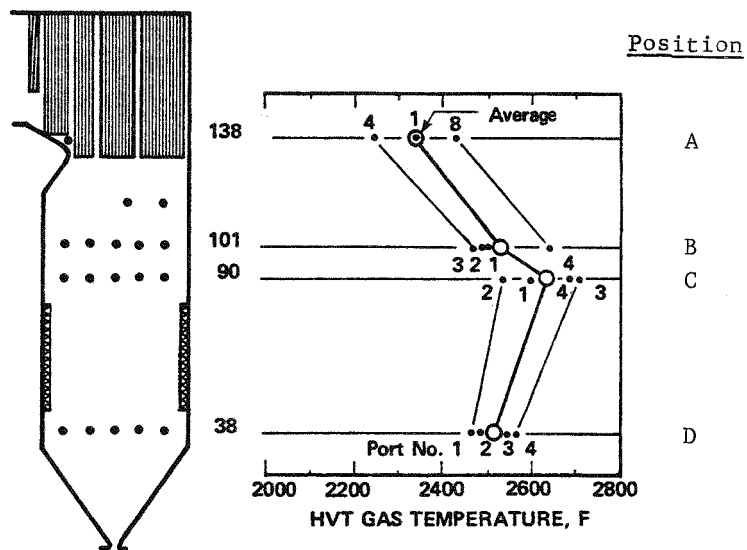


Figure 6-4. Variation of Furnace Gas Temperature With Height, Labadie Boiler 4

temperatures. To this is added a daily temperature cycle, with a gradual increase in temperature through the day, followed by deslagging at night, and a weekly cycle, with temperatures gradually increasing until a thorough weekend deslagging is carried out. These periodic temperature cycles, plus the spatial variations resulting from burner flow and mixing patterns, result in a variation of gas temperature with time and position at each elevation.

Table 6-1 summarizes furnace probing elevations, the distance of these probing elevations above the tops of the burners, and the average furnace gas temperature measured at each elevation. These data are plotted in Figure 6-5.

Figure 6-5 shows the relation of furnace gas temperature to height above the tops of burners for the five test boilers. In all cases the highest temperature is measured just above the burners, and temperature declines as the gas passes upward through the furnace. The point for the highest elevation on each curve represents the furnace outlet.

In Figure 6-5 the gas temperature curves for Labadie and Cliffside are nearly identical. The two furnaces are identical in design, although Labadie is fired with a severely slagging coal and Cliffside has no slagging problems. At Labadie, continuous wall blowing is needed to maintain the furnace exit temperature required for superheat control; at Cliffside, the problem is to maintain sufficient ash on the walls to have a sufficiently high furnace exit temperature for superheat control. It appears that the net result is that both furnaces achieve approximately the same wall radiation characteristics, although the somewhat higher temperature for Labadie at the 8-ft height suggests that slag may be heavier there.

The temperature curve for Mill Creek falls well below those for Labadie and Cliffside. The Mill Creek coal is a more severely slagging coal than that for Labadie, and the furnace size was made more generous to accommodate it. In addition, the furnace thermal loading for the test was considerably lower than the design loading, and it represents the maximum practical operating condition. The low thermal loadings result in lower gas temperatures throughout the furnace.

The Morgantown furnace was of divided-furnace design, with two parallel furnaces each of small cross-section. This design provides a high surface-to-volume ratio along with high volumetric heat-release rates when compared with a single-furnace design. In addition, the Morgantown coal had very high ash fusion temperatures, and the ash deposits on the walls were easily removed with wall blowers. The very high gas temperature near the burner reflects the high volumetric heat-

TABLE 6-1. SUMMARY OF GAS TEMPERATURE DATA

Unit	Position	Elevation, ft		Avg. gas temp, F
		above ash throat	above burners	
Labadie 1	A	138	56	2232
Labadie 4	A	138	56	2345
	B	120	38	2537
	C	90	8	2638
	D	38	--	2517
Mill Creek	A	116	54	2248
	B	92	30	2469
	C	70	8	2572
	D	35	--	1943
Cliffside	A	138	56	2356
	B	113	31	2561
	C	90	8	2607
	D	38	--	2218
Morgantown	A	121	57	2299
	B	83	31	2738
Montour	A	118	43	2413
	B	96	21	2444

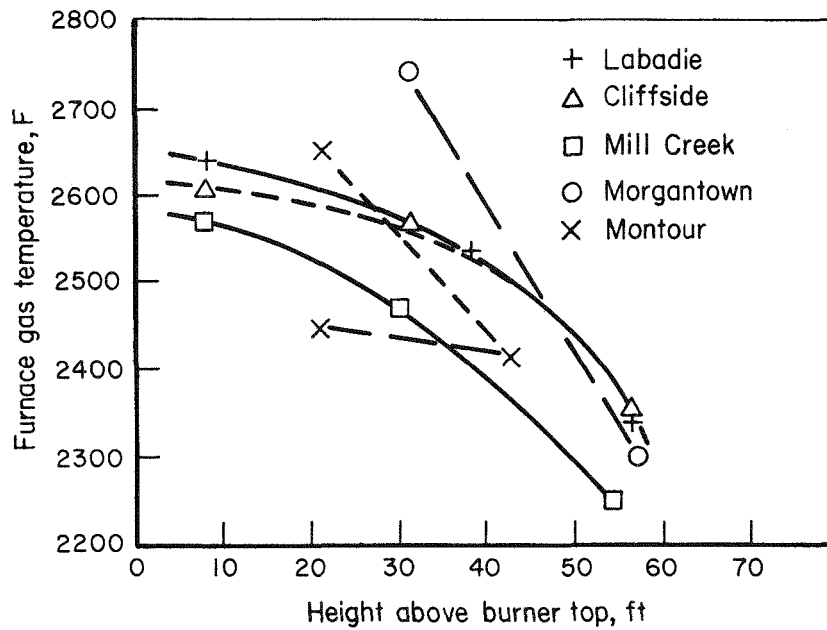


Figure 6-5. Relation of HVT Furnace Gas Temperature to Height Above Top of Burners

release rate, and low excess air and the very steep gas cooling curve reflects the high surface-to-volume ratio of this design as well as the relatively clean walls. The Montour gas temperature curve is nearly flat for reasons that are not obvious. The high furnace exit temperature, at the right end of the curve, is appropriate for the non-slagging coal fired. However, the temperature near the burners seems strangely low and may be the result of the traversing locations. As shown in Figure 6-3, traverses at Ports 2 and 6 are mirror-images in relation to the furnace temperature pattern, and both may be "cold corners". Only these two traverses are included in the average of 2444 F, to be compared with more complete data for other furnaces. The average temperature for Port 1-1/2, however, was 2650 F. This temperature, if plotted in Figure 6-5 appears much more reasonable when compared with temperatures for Morgantown, a boiler of similar design fired with a similar coal. Factors that would contribute to a low furnace temperature at Montour include rather high oxygen levels, an off-center fireball, and a coal of very low volatility that may burn more gradually than coals fired to other test boilers.

In summary, furnace gas temperatures, as shown in Figure 6-5, proved consistent with thermal loadings of furnaces and slagging potential of the coals fired. The characteristics of the divided-furnace boilers were somewhat different than those of the single-furnace boilers.

## Section 7

### FURNACE GAS COMPOSITION

Furnace gas composition is important because it influences the ash fusion temperatures of ash particles containing iron and may influence chemical reactions taking place within ash deposits. It is also an indicator of the state of combustion within the furnace. Local gas composition will be influenced by the following factors:

1. The excess air for combustion.
2. The intensity of mixing of fuel and air, and the resulting flame size and shape.
3. The overall furnace gas circulation patterns, including secondary flows of combustion products along walls and in corners of the furnace.
4. Leakage of air into the furnace.

Gas analysis data are of value to define the nature of the atmosphere to which coal and ash particles are exposed during their trajectory through the flame to the walls. To the extent that the data obtained in traverses near the furnace walls are also representative of conditions within the flame, gas analyses can also be used to trace the progress of combustion from burners to furnace outlet.

Furnace gas compositions were measured by Orsat gas analyses concurrently with measurement of furnace gas temperatures on the same traverse lines. At the furnace outlet it was possible to traverse the front of each boiler through ports between pendant superheaters. At lower levels in the furnace it was only possible to traverse on lines parallel to the walls, at 3 to 4 ft from each corner.

In the Montour furnace, a view port on the furnace centerline permitted traversing into the flame. The average concentrations of  $\text{CO}_2$  and  $\text{O}_2$  measured by traversing the centerline proved to be similar to the concentrations measured in traverses near the walls at the same elevation, although the gas temperatures were 206 F higher. Centerline traversing locations were not available at the other four boilers tested and there is no assurance that data taken in traverses along the

walls represent conditions within the flame. However, based on the evidence from the Montour test, the progress of combustion at each sampling plane was calculated, based on data from traverses along the walls.

In carrying out Orsat analyses, each analysis was plotted on a triangular chart like that of Figure 7-1, and analyses that did not plot within 0.5 percent of the theoretical line were rejected. All of the analyses for which both  $\text{CO}_2$  and  $\text{O}_2$  were reported meet this test; analyses for  $\text{CO}_2$  only cannot be checked except by their relation to other values measured nearby.

Figure 7-2 is a map of the Mill Creek furnace outlet showing  $\text{CO}_2$  and  $\text{O}_2$  values plotted in the positions at which they were measured. The values measured through Ports 2 through 7 were averaged as representative of the analysis for the front half of the boiler outlet, and this value was assumed to be representative of the entire outlet. The values measured at Ports 1 and 8 were not used in averages.

Figure 7-3 is a similar map showing measurements at the 90-ft elevation, made through view ports near the walls. The excess air at the left side of the plot is lower than at the right side, as shown by lower oxygen values and higher  $\text{CO}_2$  values. In previous Figure 6-2 it was seen that gas temperatures were much higher in the left corner, as would be expected with lower excess air.

Figure 7-4 is a map showing data from the 96-ft level of Montour Boiler 1, which includes a traverse into the flame on the furnace centerline. The average of  $\text{CO}_2$  values measured at Ports 2 and 6 was 8.9 percent, equivalent to 210 percent of theoretical air for combustion. The average of  $\text{CO}_2$  values measured on the centerline through Port 1-1/2, within the flame was 9.2 percent, equivalent to 195 percent theoretical air. This represents a variation of only 15 percent theoretical air, out of 210 percent, which is less than might be expected in this area of intense combustion.

Tables A-9 through A-16, in Appendix A, summarize Orsat traverse data for the five test units, and the following discussion is based on data from these tables.

Maps like those of Figures 7-2, 3, and 4 appear in site reports for each boiler.

Table 7-1 shows the variation of  $\text{CO}_2$  with furnace height, and calculated percentages of theoretical air (percentage of stoichiometric air) at the measuring plane. If it is assumed that combustion is complete at the furnace outlet, the percentage of fuel burned at every other plane can be calculated by ratio, and this is also

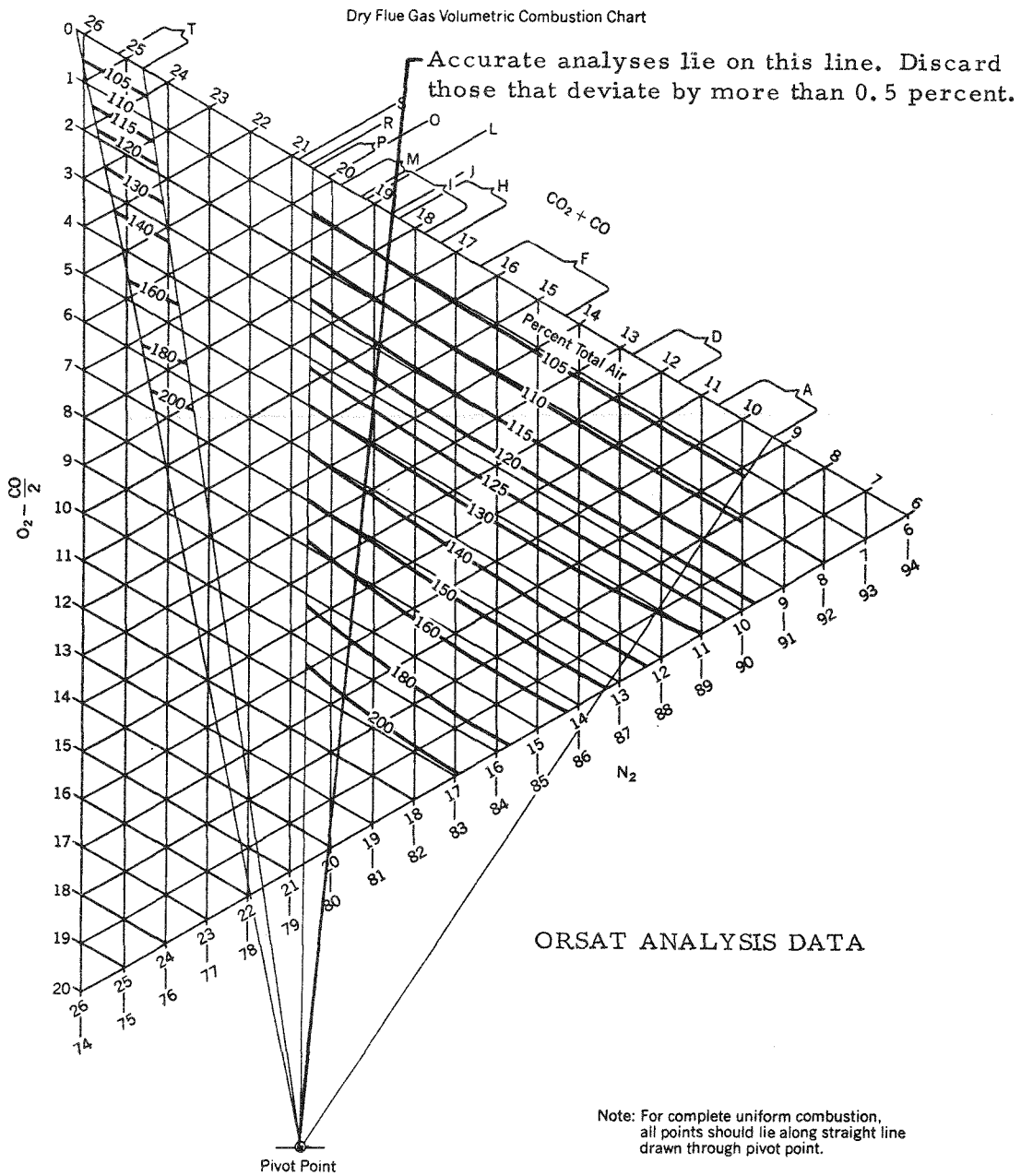


Figure 7-1. Validation Chart for Orsat Gas Analyses  
 Source: Steam, p 6-21

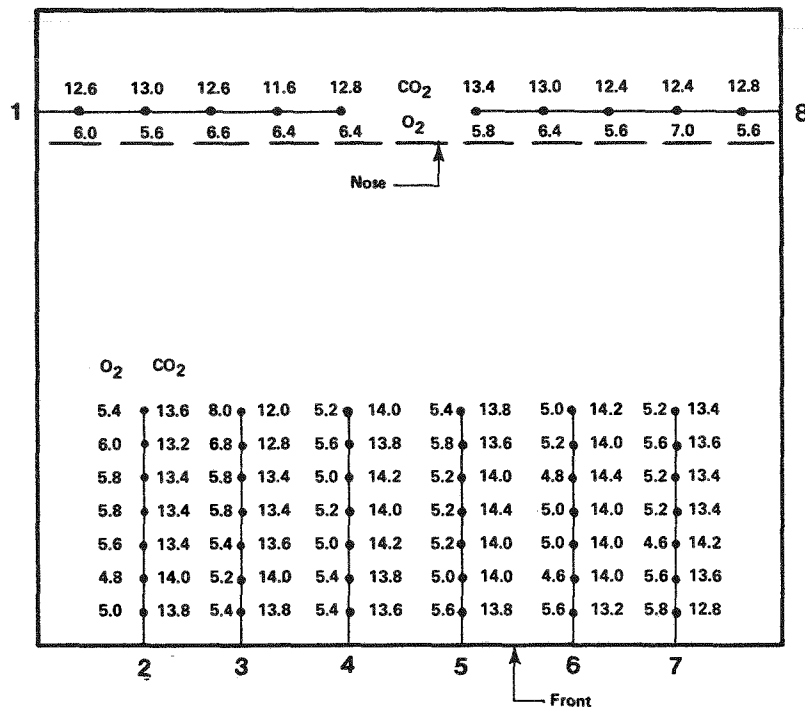


Figure 7-2 Gas Composition at Furnace Outlet, Mill Creek

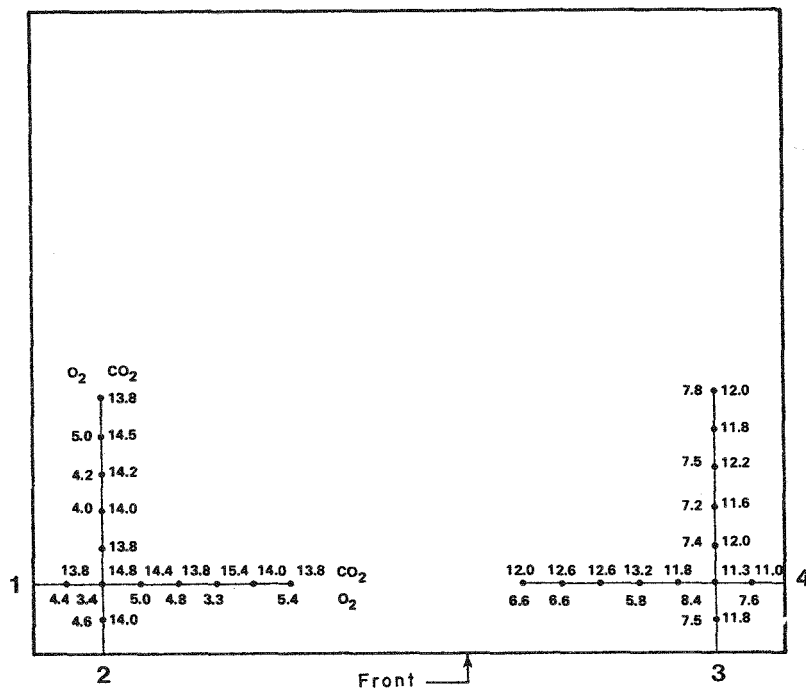


Figure 7-3. Gas Composition at 90-ft Level, Mill Creek

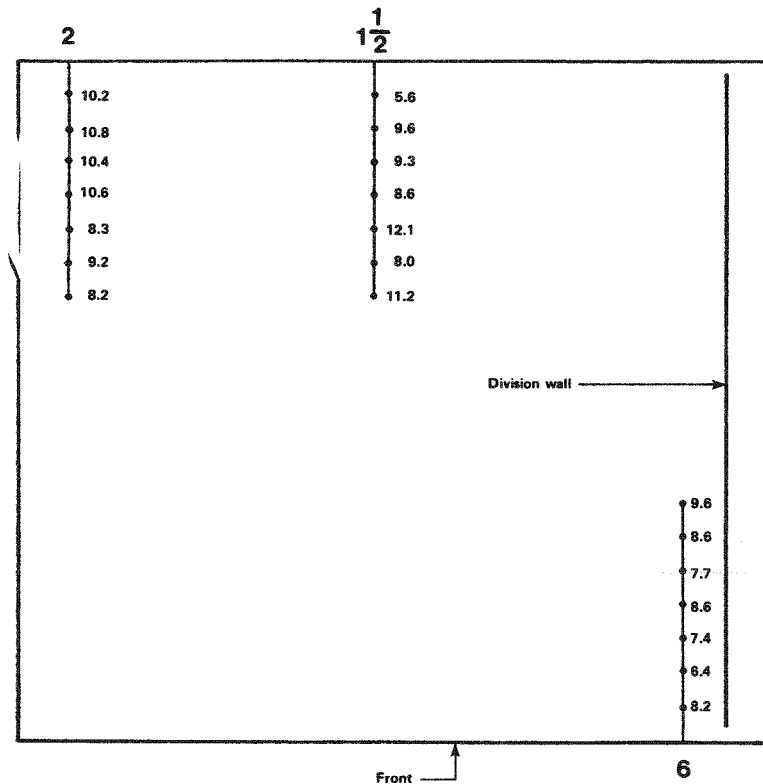


Figure 7-4. CO<sub>2</sub> Values at 96-Ft Level, Montour 1 listed in Table 7-1.

Figure 7-5 shows the percentage of fuel burned plotted against furnace height. On this plot the progress of combustion in the upper part of each furnace is indicated by the slope of the curve. The slopes of curves for Labadie, Cliffside, and Morgantown are parallel, indicating that the rate of carbon burnout is about the same for all three. The Labadie and Cliffside furnace are identical, although the coals burned are quite different. The rate of combustion with height in the Mill Creek furnace is considerably higher (because of relatively large furnace volume, there is more time per unit height), as is the rate of combustion in the Montour furnace. The rate of combustion with height is influenced by coal volatility, excess air, turbulence, gas temperature, and upward gas velocity.

The data of Figure 7-5 contribute some understanding to the gas temperature characteristics shown in Figure 6-5, which shows steep cooling curves for the Morgantown furnace to complete cooling within a small height. The parallel curves for Labadie, Cliffside, and Morgantown may be related to the fact that all

TABLE 7-1. VARIATION OF CO<sub>2</sub>, THEORETICAL AIR, AND COAL BURNED WITH ELEVATION IN FURNACE

Unit	Elevation, ft	CO <sub>2</sub> percent	Percent of theoretical air	Percent of coal burned
Labadie	138	14.6	128	100
	101	12.3	150	85
	90	11.2	163	79
	38	11.8	155	83
Mill Creek	116	13.7	135	100
	92	13.1	138	98
	70	9.8	180	75
	35	4.0	440	31
Cliffside	138	16.3	113	100
	115	13.9	132	86
	90	12.5	140	81
	38	13.5	135	83
Morgantown	121	15.2	122	100
	83	12.7	139	88
Montour	118	13.3	135	100
	96a	9.2	195	69
	96b	8.9	210	64

a Centerline port

b Side ports

three are operating at identical values of 175,000 Btu/ft<sup>2</sup> wall area/hr, while the value for Mill Creek is much lower, at 143,000 Btu/ft<sup>2</sup> hr, and the value for Montour is higher, at 205,500 Btu/ft<sup>2</sup> hr.

It is not evident why the calculated completeness of combustion is so low for Mill Creek below the burners; this value actually reflects very high excess air, and may be because of burner air circulating below the flame to a greater extent than for other units. The secondary flows in the boiler corners are sensitive to minor differences in aerodynamics, such as burner tilt, diameter of the circle at which burners are fired (rate of swirl), and differences that cause the flame to be off center. In most respects, Mill Creek appeared to have the most nearly symmetric furnace gas compositions and temperatures.

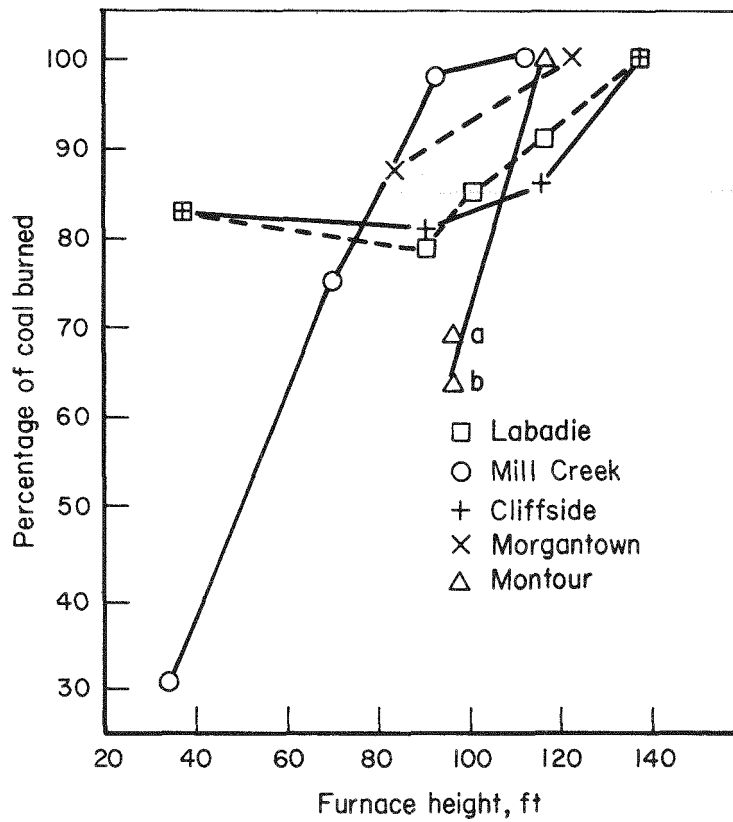


Figure 7-5. Percentage of Coal Burned at Furnace Height, Calculated From Furnace Gas Analyses

## Section 8

### COAL AND ASH ANALYSES

Table 8-1 summarizes the analyses carried out on coal and ash samples obtained during the field trials. All coal and ash analyses discussed in this report were carried out by the Coal Research Laboratory of the Pennsylvania State University, under the direction of Dr. William E. Spackman, unless otherwise noted. (Other analyses were run by Exxon, as discussed below, but Exxon results were not used except to compare with Penn State results.)

Pulverized coal samples were taken from each pulverizer for each day of testing. A proximate analysis was run on each daily mill sample to explore the variation in ash content from sample to sample, and screen analyses were made to evaluate performance of each pulverizer. Daily Composite samples were prepared for each day of test, and Test Composite samples were prepared for the entire test period. As shown in Table 8-1, most analyses were limited to Test Composite samples.

Samples of raw coal were taken from the pulverizer feeder, and two 55 gallon drums of coal for each test unit were sent to Mr. Edgar C. Winegartner, at the Exxon Research and Engineering Company, Synthetic Fuels Research Laboratory, P.O. Box 4225, Baytown, Texas 77520. Exxon carried out extensive coal analyses, which are summarized in Table 8-3. Samples of the Exxon coals are available to other researchers on request.

The temperature of critical viscosity, and slag viscosities at two temperatures were calculated from ash analyses for ash samples, coal samples, and coal density and size fractions, by William T. Reid. Mr. Winegartner also reported viscosity data for Test Composite coal samples. The various slagging factors customarily used were also calculated from ash analyses, and are listed in Tables 8-1 and 8-2.

In addition to these conventional types of analyses, an exploratory task of microanalysis of furnace ash samples, and of low-temperature ash was carried out using scanning-electron-microscope techniques. This task is reported in Section 9 of this report.

TABLE 8-1. SUMMARY OF COAL AND ASH ANALYSES

Type of Analysis	Coal			Ash			Table in Appendix
	Daily mill samples	Daily composites	Test composites	Daily composites	Test composites	Individual samples	
Coal proximate analyses	x	x	x				1
Coal Ultimate Analyses		x					2
Coal Screen Analyses	x						3
Ash fusion Temperatures		x	x				4
Analyses of ash in coal composite samples		x	x				5
Fly ash analyses				x			6
Ash content of coal screen fractions			x				7
Ash analyses of coal screen fractions			x				8
Mineral distribution in coal screen fractions			x				9
Ash content of coal density fractions			x				10
Ash analyses of coal density fractions			x				11
Summary: Analyses of ash in coal, furnace slag, and fly ash		x		x	x		12

All analyses listed in Table 8-1 are identified by a table number in the last column. Appendix B contains Tables B-1 through B-12, each table including data for the five test boilers. Characteristics of the test coals, as shown by these analyses, are discussed below.

COMPARISON OF PENN STATE AND EXXON ANALYTICAL RESULTS

Table 8-2 (identical to Table 3-2) summarizes results of analyses of Test Composite pulverized coal samples by the Penn State Coal Research Laboratory, and Table 8-3 summarizes results of analyses of raw coal samples by the Exxon Coal Research Laboratory.

TABLE 8-2. SUMMARY OF COAL AND ASH CHARACTERISTICS  
Dry basis

(Penn State Analyses)						
	Labadie 1	Labadie 4	Mill Creek	Cliffside	Morgantown	Montour
Carbon	67.57	68.82	67.46	71.97	72.78	74.01
Hydrogen	5.17	5.29	5.07	4.75	4.62	4.64
Oxygen	9.76	8.24	6.23	5.44	5.90	4.33
Nitrogen	1.28	1.36	1.33	1.33	1.42	1.34
Sulfur	3.28	3.62	4.23	1.24	1.40	1.06
Ash	12.63	11.78	14.96	15.26	13.84	14.62
Low temp. ash	15.5	14.7	18.7	18.9	16.8	16.7
Vol matter	38.68	39.83	38.94	30.28	25.01	25.33
Fixed Carbon	48.69	48.39	46.10	54.46	61.15	60.05
HHV, Btu/lb	12,468	12,468	12,289	12,808	12,993	13,231
<u>Ash Analyses</u>						
SiO <sub>2</sub>	53.5	51.8	45.5	55.0	50.9	54.3
Al <sub>2</sub> O <sub>3</sub>	19.7	19.2	18.5	26.5	27.3	27.8
Fe <sub>2</sub> O <sub>3</sub>	17.0	19.8	24.5	10.4	14.1	7.97
TiO <sub>2</sub>	1.01	1.00	0.93	1.25	1.42	1.36
MgO	1.07	1.04	0.99	1.39	1.09	1.12
CaO	4.70	4.08	6.25	1.16	1.63	4.10
Na <sub>2</sub> O	0.51	0.53	0.44	0.48	0.26	0.33
K <sub>2</sub> O	2.38	2.30	2.59	3.61	2.65	2.68
P <sub>2</sub> O <sub>5</sub>	0.16	0.12	0.19	0.16	0.47	0.31
<u>Coal minerals, percent of low-temp. ash</u>						
Quartz	25	20	20	20	15	15
Pyrite	20	20	30	7	10	5
Calcite	5	5	10	1-5	0	1-5
Gypsum	1-5	1-5	1-5	1-5	1-5	1-5
Kaolinite	20	20	20	20	30	35
Illite + MLC	25	25	20	40	30	35
FeSO <sub>4</sub>	1-5	1-5	1-5	5-10	0	0
<u>Ash fusion temperatures, F, Oxidizing atmosphere</u>						
ID	2220	2380	2280	2540	2570	2660
Softening	2400	2400	2360	2560	2680	2720
Hemisphere	2420	2440	2380	2620	2700	2740
Fluid	2480	2500	2420	2640	2720	2760
<u>Reducing atmosphere</u>						
Initial def.	2020	1980	1940	2320	2460	2460
Softening	2140	2060	2041	2560	2530	2530
Hemisphere	2220	2120	2140	2620	2560	2540
Fluid	2300	2260	2200	2680	2650	2660
Silica percentage	70	68	59	81	75	80
Base/acid ratio	.35	0.39	0.54	0.21	0.25	0.19
Slag visc/2600F	150	100	28	800	325	800
Slagging factor	1.13	1.39	2.26	0.25	0.35	0.21

TABLE 8-3. EXXON ANALYSES OF COAL COMPOSITE SAMPLES

COAL (STATION)	LABADIE		MILL CREEK		CLIFFSIDE		MORGANTOWN		MONTOUR	
% Ash Total	11.80		19.88		20.69		14.93		15.08	
SO <sub>3</sub> Free	11.30		18.70		20.50		14.67		14.59	
Calc. Minerals	16.40		26.06		24.24		18.03		17.45	
Volatiles	36.46		34.27		26.03		24.09		23.68	
Fixed Carbon	51.74		45.85		53.28		60.98		61.24	
BTU/lb	12,030		11,095		11,777		12,235		13,129	
C	67.77		61.97		66.96		71.42		74.18	
H	4.69		4.31		4.24		4.04		4.38	
N	1.15		1.14		1.09		1.02		1.14	
O <sub>2</sub>	11.33		8.50		6.02		7.38		4.05	
Cl	0.04		0.02		0.09		0.13		0.18	
S (Total)	3.25		4.19		1.00		1.21		1.16	
Pyritic	0.88		2.13		0.27		0.66		0.95	
Sulfate	0.60		0.72		0.20		0.22		0.06	
Organic	1.77		1.34		0.53		0.33		0.15	
CO <sub>2</sub>	0.38		0.68		0.54		0.47		0.69	
H <sub>2</sub> O Soluble Na <sub>2</sub> O	0.04		.04		.01		0.01		0.03	
K <sub>2</sub> O	0.06		.08		.14		0.11		0.01	
CaO	0.28		.50		.04		0.09		0.04	
HCl Soluble Na <sub>2</sub> O	0.04		.04		.03		0.03		0.03	
K <sub>2</sub> O	0.19		.37		.41		0.20		0.21	
CaO	0.01X		.01X		.01X		0.01X		0.07	
Ash Elements	Total	ex SO <sub>3</sub>	Total	SO <sub>3</sub> Free	Total	SO <sub>3</sub> Free	Total	SO <sub>3</sub> Free	Total	SO <sub>3</sub> Free
P <sub>2</sub> O <sub>5</sub>	0.14	0.15	.26	.27	.18	.18	.54	.54	0.34	0.35
SiO <sub>2</sub>	49.52	51.43	44.08	46.39	55.93	56.89	50.76	51.15	51.40	53.25
Fe <sub>2</sub> O <sub>3</sub>	20.89	21.69	23.91	25.16	10.24	10.42	13.90	14.01	11.90	12.32
Al <sub>2</sub> O <sub>3</sub>	18.76	19.48	18.18	19.13	24.74	25.17	28.28	28.50	25.30	26.20
TiO <sub>2</sub>	0.93	0.97	0.91	0.96	1.10	1.12	1.45	1.45	1.21	1.25
CaO	3.25	3.38	4.54	4.78	0.83	0.84	1.50	1.51	3.67	3.80
MgO	0.86	0.89	0.87	0.92	1.47	1.50	.89	.90	0.82	0.85
SO <sub>3</sub>	4.29	--	5.92	--	0.92	--	1.71	--	3.22	--
K <sub>2</sub> O	1.49	1.55	1.89	1.99	3.43	3.49	1.72	1.73	1.69	1.75
Na <sub>2</sub> O	0.45	0.47	0.39	0.41	0.39	0.40	.20	.20	0.24	0.25
Ash Fusion Temps	Reducing	Oxidizing	Reducing	Oxidizing	Reducing	Oxidizing	Reducing	Oxidizing	Reducing	Oxidizing
ID	1970	2330	1990	2290	2160	2320	2470	2650	2220	2500
H-W	2010	2380	2040	2340	2340	2580	2520	2700+	2460	2560
H-W/2	2030	2410	2050	2370	2390	2610	2560	2700+	2480	2600
Fluid	2320	2440	2280	2420	2450	2670	2630	2700+	2550	2700+
Total Alkalies as Na <sub>2</sub> O	0.17		0.32		.55		.20		0.20	
Grindability-HGI	48.1		56.1		58.0		91.3		84.5	

The pulverized coal samples were usually taken in the morning and the raw coal samples were usually taken in the afternoon, so that differences in coal composition were possible. A point-by-point comparison of these tables shows a number of differences, some of which appear random and some of which appear systematic. For example, ash content determined by Exxon was higher than that determined by Penn State for four of five samples, and volatile matter measured by Exxon was lower in four of five samples. Calorific values measured by Exxon were all lower than those measured by Penn State. These differences point out that the differences in coal characteristics from sample to sample, and the differences in analytical results from laboratory to laboratory, do not justify basing conclusions on small differences in coal or ash analyses.

#### COAL PROXIMATE ANALYSES

Table B-1 summarizes proximate analyses for each daily pulverizer sample, daily composite sample, and test composite sample of pulverized coal for the five test boilers. The constituent of greatest interest is the ash content of the coal and its variation from sample to sample.

Table 8-4 shows the range of variation in ash content for each test boiler. The ash content is quite variable, with the variation, from maximum to minimum, ranging from 15 percent for Labadie 1 to 26 percent for Montour. One of the unexplained features of the analyses in table B-1 is the fact that the ash content shown in the Daily Composite is often higher than the highest ash content of any sample included in the composite. Such variations could result from difficulties in taking representative analytical fractions from the samples, or from inaccuracies in analysis. Table B-1 shows that the coals fired in all test boilers are quite variable in ash content. It also reveals the problems of obtaining representative composite samples, in that the ash contents of many of the daily composite samples differ from the average analysis of the four to six samples from which they were prepared.

Table B-1 serves as an index of test dates and sample numbers for subsequent tables, B-2 through B-12.

#### COAL ULTIMATE ANALYSES

Table B-2, Appendix B, summarizes ultimate analyses of coal Daily Composite samples. Analyses were not run for the Test Composite samples. These analyses show day-to-day variations in coal constituents. The ash contents measured in these analyses were slightly different from the ash contents measured for proxi-

TABLE 8- 4. VARIATION OF ASH CONTENT FOR TEST UNITS

Station	Ash content			Percent variation
	Maximum	Minimum	Composite	
Labadie 1	13.9	12.0	12.6	15.1
Labadie 4	13.0	10.5	11.8	22.5
Mill Creek	16.9	13.2	15.0	24.6
Cliffside	17.4	13.6	15.3	24.8
Morgantown	15.6	12.4	13.8	23.2
Montour	16.8	13.0	14.6	26.0

mate analyses of the same samples as shown in Table B-1, providing a basis for assessing absolute accuracy of measurement of ash content.

#### COAL FINENESS

The fineness of pulverized coal from a pulverizer varies with coal moisture content, coal grindability, firing rate, pulverizer condition and adjustment, and classifier adjustment. In all of the test boilers there was considerable variation in coal fineness from pulverizer to pulverizer, and some variation from day to day. It would be expected that, at a constant firing rate, coal fineness would be consistent for each pulverizer except for variations caused by variations in coal ash content, grindability, and moisture content.

It is generally accepted that coarse coal particles, as indicated by the fraction larger than 50 mesh, contribute to increased ash deposition on furnace walls. Thus, the percentage of coarse coal fired to each boiler is one factor in furnace slagging. Carbon loss, or burnout of carbon in the furnace, is influenced by coal fineness also, and the percentage of coal passing through a 200-mesh screen is an indicator of coal quality affecting carbon burnout. None of the boilers tested had a carbon burnout problem.

The required fineness of coal pulverization varies with the coal type. In general, high-volatile coals, which are often low-grindability coals, do not have to be pulverized as fine as low-volatile coals, which are usually of high grindability

Table 8-5 summarizes values of coal fineness averaged for all pulverizers on each of the six test boilers, and also lists Hardgrove Grindability Index (HGI) for each coal. The low-volatile, high-grindability coals fired at Montour and Morgantown were the finest among the test boilers, with 1.5 and 3.9 percent coarser than 100 mesh. They were followed, in order of decreasing fineness, by Mill Creek, Labadie 1 and 4, and Cliffside. Labadie and Mill Creek, with the most severe furnace slagging, operated with finer coal than Cliffside, which had minimum slagging problems.

Table 8-6 summarizes data on the variations in coal fineness among pulverizers for the test boilers. Complete screen analyses for each pulverizer appear in Table B-3. The following variations are shown:

Labadie 1. Coal fineness for Labadie 1 was quite variable, with three pulverizers producing very fine coal and three producing coarser coal, having 13 to 16 percent of plus-100 mesh material. The coarsest was 57 percent through 200 mesh.

Labadie 4. Labadie 4 pulverizers produced consistently coarser coal than those for Boiler 1, with the plus-100-mesh fraction ranging from 8 to 23 percent. The coarsest coal had a minus-200-mesh fraction of 47 percent.

Mill Creek 1. Mill Creek coal was consistently finer than that from Labadie and Cliffside, partially because pulverizers were operated below rated capacity. The plus-100-mesh fraction ranged from 3.9 to 14 percent, and the minus-200 mesh fraction ranged from 60.9 to 78.2 percent.

Cliffside 5. The variation of fineness among pulverizers at Cliffside was small except for one pulverizer, which produced somewhat finer coal. The average of the plus-100-mesh fractions was 13.5 percent, with variation from 7.5 to 15.7 percent. The minus-200-mesh fraction averaged 65 percent, with variation from 60 to 75 percent.

Morgantown 1. The variation of coal fineness among the five Morgantown pulverizers was moderate, with all pulverizers producing much finer coal than that at Labadie, Mill Creek, and Cliffside. The plus-50-mesh fraction ranged from 0 to 2.2 percent; the plus-100-mesh fraction varied from 7.4 to 0.7 percent, averaging 3.6 percent; and the minus-200-mesh fraction ranged from 76 to 92 percent,

TABLE 8-5. COMPARISON OF AVERAGE COAL SCREEN ANALYSES  
CUMULATIVE PERCENTAGES

Station	U. S. Standard screen size						HGI*
	+50	+100	+200	+325	-200	-325	
Labadie 1	-	10.0	31.1	42.0	68.3	58.0	48
Labadie 4	-	12.3	35.7	58.0	64.3	42.0	48
Mill Creek	-	9.9	34.9	56.6	65.1	43.4	56
Cliffside	-	13.5	34.7	57.0	65.3	43.0	58
Morgantown	0.8	3.6	14.5	41.1	85.5	58.9	91
Montour	0.2	3.2	16.1	41.8	83.9	58.2	85

\* HGI = Hardgrove Grindability Index

TABLE 8-6. VARIATIONS IN COAL SCREEN ANALYSES FOR SIX TEST UNITS

	+ 50 mesh			+ 100 mesh			-200 mesh		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
Labadie 1	-	-	-	15.9	3.3	9.7	80	57	68
Labadie 4	-	-	-	22.6	7.8	12.3	68	47	64
Mill Creek	-	-	-	14.0	3.9	8.3	78	61	70
Cliffside	-	-	-	17.4	7.5	13.6	75	60	65
Morgantown	2.2	0	0.8	7.4	0.7	3.6	92	76	86
Montour	1.0	0	0.2	7.1	0	3.2	99	73	84

Complete screen analyses appear in Tables B-3

Montour 1. Pulverization at Montour was comparable to that at Morgantown, and much finer than that at Labadie, Mill Creek, and Cliffside. The percentage of coal on 50 mesh ranged from 0 to 1.0 percent, and that on 100 mesh ranged from 0 to 7.1 percent, averaging 3.2 percent. The percentage of coal through 200 mesh varied from 73.0 to 98.8 percent, averaging 83.9 percent. Although the variation in fineness of coal from the six pulverizers was quite large, the average fineness, and the fineness of coal from each pulverizer, is adequate.

There is no distinct correlation of coal fineness with slagging problems for the six boilers tested. The coarsest coal was fired at Cliffside and the finest coal was fired at Morgantown and Montour, with no serious slagging problems. The coals fired at Labadie and Mill Creek, with serious slagging problems were of intermediate fineness. It is generally assumed that coarser coal, especially that coarser than 50-mesh, contributes to furnace deposition and slagging. For the six test units, however, the ash composition and fusion characteristics proved much more important than coal particle size.

#### ASH FUSION TEMPERATURES

Ash fusion temperatures were determined for Daily Composite and Test Composite coal samples. They were measured as cone fusion temperatures in both reducing and oxidizing atmospheres. Table B-4, Appendix B, summarizes all ash fusion temperatures. The last column in each table is for the Test Composite sample, which was a composite of the other samples listed in the table. Ash fusion temperatures for Test Composite samples are listed in Table 8-5, along with other coal and ash characteristics.

Table 8-2 (same as Table 3-2) summarizes characteristics of coal and ash samples analyzed by the Penn State Coal Laboratory. Table 8-3 summarizes similar analyses carried out by the Exxon coal research laboratory. The Penn State analyses were carried out with pulverized coal samples taken early in each day; the Exxon analyses were carried out with raw coal samples taken late in each day. Thus, the differences in values found by the two laboratories reflect variations in coal, variations in sampling and compositing, and variations in analytical accuracy.

The ash fusion temperatures for Labadie and Mill Creek coals were generally low, with some variation from day to day, and those for Cliffside, Morgantown, and Montour were generally higher. Anomalous data were reported in the analyses for samples 771, 772, and 774, from Cliffside, in that seven temperatures measured under reducing conditions were higher than those measured for oxidizing conditions. It is assumed that these values indicate error in analysis. Comparison of data for Sample 774 and the corresponding Exxon data of Table 8-3 suggests that the temperatures measured for those samples under reducing conditions at Penn State were too high.

#### ASH ELEMENTAL ANALYSES FOR COAL COMPOSITE SAMPLES

Table B-5 presents ash elemental analyses for coal composite samples, including the percentage of ash in each sample. These data show the day-to-day variation in ash analysis. The final column in each table is the analysis for the Test Composite sample, which was used for analysis of coal screen fractions and coal density fractions, and which appears in Table 8-2.

#### FLY ASH ANALYSES

Table B-6 in Appendix B presents ash elemental analyses for fly ash samples from economizer hoppers and ESP (electrostatic precipitator) hoppers for each boiler. This table shows that the iron content of ash from the economizer hoppers was higher than that in the coal and that from the ESP hoppers at Labadie 4 and at Mill Creek, but that iron was evenly distributed in ash from Cliffside. The analyses from Table B-6 were averaged, and the average values used in Table B-12. Samples were obtained for only one day at Morgantown and Montour, and analyses for these samples appear in Table B-12.

#### ASH CONTENT OF COAL SCREEN FRACTIONS

Table B-7 summarizes data on ash content of coal screen fractions and coal weight percent in each screen fraction for the six test boilers. For all samples except the Montour sample, the lowest ash content was found in the intermediate size fraction, between 100 and 325 mesh. The highest ash content was found in the finest fraction, below 325 mesh, for samples from Labadie, Mill Creek, and Cliffside, with intermediate values for the coarse, +100-mesh fraction. For the Montour sample the ash content of the coarsest fraction was the highest, and that of the finest fraction was the lowest. In the Morgantown sample the coarsest fraction also had the highest ash content, but the ash content of the finest fraction was slightly higher than for the intermediate fraction. In both

the Morgantown and Montour samples, the ash content of the coarse +50-mesh and +100-mesh fractions was higher than the average for the coal; for the other samples, the ash content of the coarse fraction was below the average for the coal.

These variations, and the variations in slagging characteristics of the test furnaces, do not suggest a correlation between ash distribution in coal size fractions and furnace slagging.

#### ASH ANALYSES OF COAL SCREEN FRACTIONS

Table B-8, in Appendix B, summarizes ash analyses of coal screen fractions for five test units. In addition to ash analyses, Table B-8 also contains calculated temperatures of critical viscosity ( $T_{cv}$ ) and calculated slag viscosity at two temperatures, 2300 F and 2600 F. These calculated ash fusion characteristics provide a basis for evaluating changes in ash composition among coal fractions.

The most striking result of the analyses of Table B-8 is that the variation in ash analysis, and in calculated ash viscosities, is very small among coal screen fractions. The slag viscosity at 2600 F is low for every screen fraction of coal from Labadie and Mill Creek, and high for every screen fraction of coal from Cliffside, Morgantown, and Montour. It appears that variations of ash analysis among coal size fractions were not a significant factor in furnace slagging for the test boilers.

#### COAL MINERAL CONTENT

Table 8-2 summarizes coal mineral content, as percentage of low-temperature ash, for the six test boilers. In comparing analyses for the six boilers, the coals for Labadie 4, Mill Creek, and Cliffside contained 20 percent quartz, while coals from Morgantown and Montour contained 15 percent. Pyrite varied in approximate proportion with coal sulfur content, and was highest in the Mill Creek coal and lower in the other coals. Calcite varied from 0 to 5 percent in all coals except Mill Creek, with 10 percent, and gypsum was reported as 0-5 percent for all coals.

Morgantown and Montour coals, of low slagging potential, were low in pyrite, quartz, and sulfate and high in illite and kaolinite. Cliffside coal, also of low slagging potential, was also low in pyrite and sulfate, and high in illite, at 40 percent. Illite and montmorillite were identified in the two finest fractions.

The accuracy and sensitivity of the methods used for mineral determination are such that minor minerals cannot be detected, and the percentages of major minerals are reported in 5-percent increments. Small differences in ash composition, and the presence of minor constituents, appear to be described better by elemental analyses, which can be carried out with better precision.

#### MINERAL DISTRIBUTION IN COAL SCREEN FRACTIONS

Table B-9 summarizes analyses for mineral matter in coal screen fractions for Labadie, Mill Creek, and Cliffside coals. These analyses were not run for screen fractions of Morgantown and Montour coals. The values of mineral matter are expressed as percentage of low-temperature ash (LTA). The percentage of LTA in the coal is also listed in Table B-9.

The variations in mineral matter differed among the three boilers, as follows:

Labadie 4: The -325-mesh fraction contained 5 percent more quartz, 10 percent less pyrite, and 5 percent more gypsum than other fractions

Mill Creek: The pyrite content was 40 percent in the coarse fraction and 30 percent in the finest fraction, with intermediate values in other fractions.

Cliffside: The variation among fractions was small and random. The pyrite content of the mid-sized fraction was higher than for the coarse and fine fractions.

From these analyses it appears that the variation of mineral content among coal screen fractions reveals little about coal slagging characteristics. This is not surprising, in that variations in ash elemental analysis among coal screen fractions were small.

Table 8-7 lists the published melting temperatures of minerals listed in Tables B-9 and 8-2. All of these minerals except pyrite have melting temperatures above the Initial Deformation temperatures of coal ash from the test boilers. Low-melting-temperature materials identified in both low-temperature ash and furnace deposits by microanalysis techniques, as discussed in Section 9, were glasses containing aluminum, silicon, and a fluxing material in the form of sodium, potassium, calcium, or iron. It is probable that minerals in a single coal particle will melt during combustion of the particle and combine, to form a glass not present in the original coal minerals.

TABLE 8-7. MELTING TEMPERATURES OF  
COAL MINERALS

Quartz	1610C	2930 F
Calcite	1339	2442
Pyrite	1171	2140
Illite	1400	2550
Gypsum	1450	2642
Clay minerals to mullite	1920	3488

Handbook of Chemistry and Physics,  
52nd Edition, Chem Rubber Pub Co.

It had been hoped that study of coal mineral forms would contribute to the understanding of furnace slagging. However, the sensitivity of the analytical techniques used in this study for mineral identification in bulk samples was not high enough to identify minor minerals, and the accuracy was such that major minerals were reported in increments of five percent. Standard chemical analyses provide a more sensitive and accurate way of identifying minor ash elements.

#### ASH CONTENT OF COAL DENSITY FRACTIONS

Table B-10 summarizes coal weight percent and ash content of coal density fractions. Each Test Composite pulverized coal sample was divided into several density fractions by successive float-and-sink separations, following which the percentage of coal in each density fraction was determined, and each fraction was analyzed to determine ash content and ash composition. Samples from Labadie 4, Mill Creek and Cliffside were analyzed twice, first over the range of specific gravities from 1.3 to 1.6, and later over the range from 1.6 to 2.8. The higher-density fractions had been analyzed for Morgantown and Montour coals, and it had been found that the 2.8 sp gr sink fractions contained 86.1 and 75.1 percent of  $Fe_2O_3$  in the ash, indicating segregation of pyrities in this density fraction. The second set of analyses for the other coals was run to explore this aspect further.

The significance of analyses of coal density fractions is that they reveal differences in ash content and ash composition among individual coal particles, that can be separated by density. Coal particles from each density fraction should produce ash particles having fusion characteristics related to ash composition of that density fraction, and these may be quite different from fusion

characteristics of ash of the average composition for the entire coal sample.

As would be expected, all samples showed increasing ash content with increasing density of the coal fraction. The lightest fraction, lighter than 1.3 sp gr, contained only 1.9 to 6.0 percent ash in the five coals analyzed. The densest fraction, denser than 2.8 sp gr, contained 60 to 69 percent ash in the five coals. The fraction of coal lighter than 1.6 sp gr contained 5.8 to 8.3 percent ash, and accounted for 86.3 to 90.4 percent of the total coal for the five samples.

#### ASH ANALYSES OF COAL DENSITY FRACTIONS

Table B-11 summarizes ash analyses of coal density fractions for five test coals. These analyses show some variation in the compositions of ash found in different coal density fractions for every coal. One way of evaluating the overall effect of these variations in composition is by comparing the calculated temperature of critical viscosity ( $T_{cv}$ ), and ash viscosities at representative temperatures. Values for  $T_{cv}$ , and viscosities calculated for temperatures of 2600 F and 2300 F, are included at the bottom of each table as a means of comparing properties of the ash in each fraction.

The viscosities of fused slag at 2300 F and 2600 F, and the  $T_{cv}$  (temperature of critical viscosity), were calculated for the ash composition of each density fraction of each test coal, using methods summarized on pages 63-66 of Reid's book<sup>(1)</sup>, and presented in Appendix D.  $T_{cv}$  was calculated using the equation of Hoy, Roberts, and Wilkins. Viscosity at 2600 F was calculated using the Reid equation, and viscosity at 2300 F was calculated using the Watt and Fereday equation. These three equations are well accepted.

Viscosity of fused slag is the best available indicator of ash behavior in a boiler furnace. Since viscosity varies with temperature, 2600 F is usually taken as the reference point because most silicate melts contain no solid phase at this temperature and, hence, behave as a true Newtonian liquid. When a solid phase separates on cooling, the slag acts as a plastic solid (Bingham plastic) and flow ceases under gravitational forces. The temperature of critical viscosity is the temperature at which this transition occurs. This transition is important because it strongly influences the thickness of slag on a heat-receiving surface. The concept has not been widely used by utility operators but it provides a useful tool for evaluating slag behavior in a boiler furnace.

(1) External Corrosion and Deposits, by William T. Reid. American Elsevier Publishing Company, 52 Vanderbilt Ave, New York, NY, 1971 pp 63-66/

The calculated viscosity at 2300 F shows the rapid increase in viscosity as the slag cools. It is meaningless if  $T_{cv}$  is higher than 2300 F. Slag viscosity at 2300 F is roughly 10 times the viscosity at 2600 F. It is expected that any ash of low viscosity at 2300 F will result in running slag in a boiler furnace.

Table B-11 shows that the ash composition varies among density fractions of every coal. It is difficult to assess the importance of such variation except by comparison of  $T_{cv}$  and slag viscosities for different fractions, and these values are shown at the bottom of each table. In general, it is assumed that a slag viscosity lower than 250 poises leads to slagging problems in a dry-ash furnace.

The Labadie 4 data show compositional variations that result in values of  $T_{cv}$  and slag viscosities that are suitable for dry ash removal for those coal fractions of 2.0 and lower sp gr. However, the 2.0 x 2.8 sp gr fraction, which contains 18 percent of the total ash, contains 15.8 percent CaO, which is a good flux for Al-Si slags. The calculated slag viscosities for this composition are extremely low, but the  $T_{cv}$  is very high, at 3200 F. It appears probable that this rather large fraction of the coal ash will be a sticky fluid containing precipitated solids, tenacious enough to stick to the walls, but not fluid enough to flow. The heaviest fraction, denser than 2.8 sp gr, accounts for 7.3 percent of the coal. It contains 87.2 percent iron oxide, and also has extremely low viscosity of one poise at 2600 F and 3 poises at 2300 F. The  $T_{cv}$  of 2600 F indicates that this slag will be extremely fluid at 2600 F, and may be a sticky fluid containing solid precipitates at 2300 F. This fraction also appears to be a contributor to the slagging problem. Thus, the two densest coal fractions contain 25.3 percent of the coal ash, and this part of the coal ash appears potentially troublesome in forming sticky deposits. If the coal were to be washed to remove a large part of the densest fraction, the ash content would be reduced significantly and the ash fusion characteristics of the remaining ash would be greatly improved.

The Mill Creek coal density fractions also showed a marked change in ash fusion characteristics at coal sp gr of 2.0. The ash viscosity at 2600 F is well above 250 poises for fractions less dense than 1.6 sp gr, but falls to 97 poises for the 1.6 x 2.0 fraction; the viscosity at 2300 F is above 250 poises for all fractions less dense than 2.0 sp gr. However, like the Labadie coal, the calcium content of the 2.0 x 2.8 sp gr fraction is extremely high, at 17.7 percent,

leading to low slag viscosity. The  $\text{Fe}_2\text{O}_3$  content of the 2.8-sink fraction is high, at 88.3 percent, leading to low slag viscosity for this fraction. These two coal fractions account for 42.3 percent of the total coal ash, and appear to be the source of slagging problems. It is probable that coal washing to remove much of the ash found in the 1.6 sp gr sink fraction would greatly reduce slagging problems.

The ash analyses of Cliffside coal showed a considerably different pattern than that for Labadie and Mill Creek coals. The iron content was nearly constant for every density fraction, and the slag viscosities were high for every fraction except the lightest and the heaviest. The lightest fraction contained somewhat more iron, calcium, and titanium, and less silicon than other fractions, and slag viscosity at 2600 F was 200 poises. This is a high value, although lower than for other fractions. Only the 2.80 sp gr sink fraction, containing 5.6 percent of the coal ash, had low viscosity. This fraction contained 72.2 percent  $\text{Fe}_2\text{O}_3$  and the slag viscosity of one and three poises at 2600 F and 2300 F is extremely low. However, the quantity of ash in this fraction is too low to influence slagging greatly, although running slag was visible on the furnace walls.

The Morgantown coal, of low slagging potential, contained ash of high viscosity in all density fractions except the most dense, which contained 86.1 percent  $\text{Fe}_2\text{O}_3$ . This fraction, which contained 8.1 percent of the coal ash, was extremely fluid, but the quantity was too low to cause slagging problems.

The Montour coal ash for fractions less dense than 2.8 sp gr was also of very high viscosity. The fraction denser than 2.8 sp gr contained 75.1 percent  $\text{Fe}_2\text{O}_3$ , with viscosity of one and three poises at temperatures of 2600 and 2300 F. This very fluid fraction contained only 4.1 percent of the total ash.

Analysis of the ash in coal density fractions provides considerable insight into coal behavior in furnaces. The two coals of high slagging potential had large proportions of the total coal ash in a heavy fraction of low slag viscosity,

while the coals of low slagging potential contained very little ash of low slag viscosity. Both the Labadie and the Mill Creek Coals would be improved greatly by washing to remove the dense, high-ash fraction. Washing would have little or no effect on ash fusion characteristics of coals fired at Cliffside, Morgantown, and Montour. (Montour coal from the Greenwich mine, which provided most of the coal, was washed)

#### ANALYSES OF ASH IN COAL, FURNACE SLAG, AND FLY ASH

Table B-12, in Appendix B, summarizes analyses of ash in coal, in furnace slag, and in fly ash for five test boilers. The values for coal are those for the Test Composite samples. Values for furnace deposits are analyses of single ash samples taken from four elevations in each furnace. The analyses for fly ash are averages of all samples taken at each site. In addition to the ash elemental analyses, calculated values of  $T_{cv}$  and ash viscosities at 2600 F and 2300 F are included as a means of evaluating differences in ash composition.

Labadie data show that the ash analyses vary little for the various locations. Iron content, which is indicative of slagging characteristics because of its fluxing effect, is nearly uniform except for small increases at the 138-ft level and the economizer hoppers, where it is increased slightly. For these locations the calculated slag viscosity is lower than for other locations, as might be expected. There is no evidence of segregation of iron in furnace deposits, which has been found in some furnaces.

The Mill Creek data of Table B-12 also show great uniformity of composition. The samples from the economizer hopper were enriched with iron, reducing slag viscosity somewhat, but all other samples were similar in analysis and in slag viscosity.

The Cliffside ash analyses were also rather uniform, although iron content of the furnace ash deposits was slightly higher than the average for the coal. The variations in slag viscosity were relatively small and insignificant.

The Morgantown ash analyses show a large variation in iron content with sample location, and corresponding variations in slag viscosity. The furnace ash deposits contained 16.8 to 25.7 percent  $Fe_2O_3$ , compared with 14.0 percent for the coal and 13.9 percent for the fly ash. Economizer fly ash was also higher in iron than the coal. It appears that there was definite segregation of iron in this unit, and that the ash fusion temperatures for furnace deposits were lower than for the coal, and for fly ash. However, the slag viscosities were all high enough that slagging was not a problem in this furnace.

Montour ash analyses also showed a large variation of iron content with sampling location. The iron content of furnace ash deposits, and of economizer hopper ash, was considerably higher than the iron content of the coal ash and of the ash from the electrostatic precipitators. The effects of this iron segregation are shown by the wide variation in slag viscosity calculated for the various ash compositions. Viscosity at 2600 F was high for the coal ash, and for the fly ash, which accounts for about 80 percent of the coal ash. However, viscosity was lower, and variable, for the furnace ash deposits and the economizer ash.

It appears important that the coals of high slagging potential had rather uniform ash analyses throughout the boiler, while the coals of low slagging potential fired at Morgantown and Montour resulted in rather non-uniform analyses throughout the boiler, with considerable iron enrichment in the furnaces. The Cliffside coal, of low slagging potential, produced uniform iron distribution throughout the boiler. These characteristics suggest that iron segregation is not the most important factor in furnace slagging, although it may result in iron enrichment of furnace ash deposits. It may be more important that iron is present throughout the ash of the coals of high slagging potential, to act as a flux in formation of glasses of low melting temperature. Isolated particles of iron oxide derived from particles of pyrite would not be effective in fluxing aluminum silicates, but might simply accumulate in the furnace ash matrix without making slagging worse by its presence until the entire matrix is fused.

## Section 9

### MICRO ANALYSIS OF FURNACE DEPOSITS AND COAL MINERALS

This section reports a study of the microstructure of furnace ash deposits and of coal minerals from low-temperature ash. The objectives of the study were to identify compounds of low melting temperature found in coal minerals and in furnace ash deposits, and to determine the general nature of furnace ash deposits including their structure and the distribution of constituents within them. The furnace ash deposits were studied using optical metallography, electron microprobe analysis, scanning electron microscopy, and energy-dispersive X-ray analysis. A hot-stage optical microscope was used to identify compounds of low melting temperature found in ground furnace deposits, and in the original coal minerals, which were then analyzed by energy-dispersive X-ray techniques.

#### DESCRIPTIONS OF SAMPLES OF FURNACE ASH DEPOSITS

Six samples of furnace deposits from five boilers were used for this study. As is indicated in Table 9-1, two of those boilers had experienced severe slagging problems, whereas the other three had lesser or negligible problems from slagging. One sample, Number 273 from Labadie Boiler 1 provided an excellent opportunity to study the nature of the constituents of the deposit. As is shown in Figure 9-1, that sample contained the imprint of the furnace tube, and, much of the deposit consisted of sintered, identifiable particles. Thus, it was possible to correlate the nature of the furnace deposit with distance from the tube. Also, because particles were essentially unchanged after deposition, it was possible to correlate the constituents of the deposit with the mineral matter that was contained in the coal. Most of the other samples represented portions of the deposit farther from the furnace tube surface or from hotter furnace areas. They had largely fused into glassy slags and relatively little information on original ash structure could be obtained from them. The range of compositions of the ash in the coals and the mineral content of low-temperature ash samples from the coals are summarized in Table 9-2.

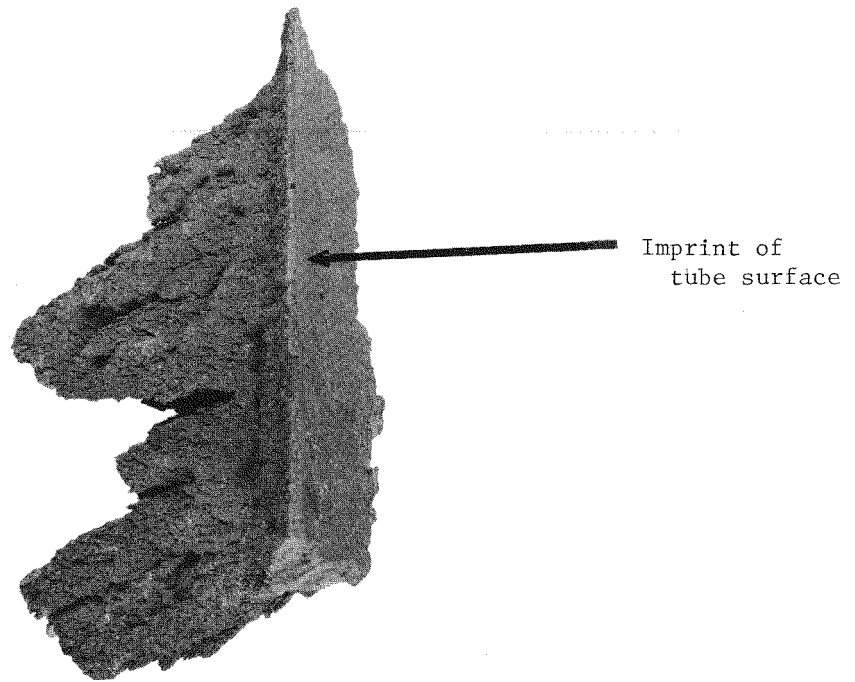
#### ANALYTICAL TECHNIQUES

The analytical techniques used in this study were relatively standard and straightforward. Optical metallography provided a convenient way for studying

Table 9-1

## DESCRIPTION OF SAMPLES OF FURNACE DEPOSITS

Sample Number	Furnace	Elevation in Furnace, ft	Slagging Characteristic of Furnace	Physical Description of Sample	Significance of Sample
273	Labadie 1	101	Severe	Sintered collection of particles containing imprint of furnace tube surface	Represents severe slagging problem
305	Labadie 4	117	Severe	More glassy than 273	Probably existed farther from furnace-wall tube than did 273
512	Mill Creek 1	35	Severe	More glassy than 273	Similar situation to that of 273
763	Cliffside 5	38	None	Glassy sintered deposit	Represents lower iron content
953	Morgantown	32	Slight	Glassy slag	Limited
1066	Montour	87	Moderate	Glassy slag	Limited



Actual Size

Figure 9-1. Photograph of the Sample From the Labadie Boiler Showing the Imprint of the Furnace-Tube Surface

Sample 273.

Table 9-2

## COMPOSITION RANGES FOR ASH AND LOW-TEMPERATURE ASH SAMPLES

Compounds in Ash		Minerals in Low-Temperature Ash	
Compound	Content, percent	Mineral	Content, percent
SiO <sub>2</sub>	45-55	Quartz (SiO <sub>2</sub> )	15-25
Al <sub>2</sub> O <sub>3</sub>	18-28	Pyrite (FeS <sub>2</sub> )	5-30
Fe <sub>2</sub> O <sub>3</sub>	8-25	Calcite (CaCO <sub>3</sub> )	0-10
TiO <sub>2</sub>	0.9-1.4	Gypsum (CaSO <sub>4</sub> ·2H <sub>2</sub> O)	1-5
MgO	1.0-1.4	Kaolinite (Al <sub>2</sub> O <sub>3</sub> ·2SiO <sub>2</sub> ·2H <sub>2</sub> O)	20-35
CaO	1.2-6.2	Illite + MLC (K <sub>2</sub> O·3Al <sub>2</sub> O <sub>3</sub> ·6SiO <sub>2</sub> ·2H <sub>2</sub> O)	20-40
Na <sub>2</sub> O	0.3-0.5	FeSO <sub>4</sub>	0-5
K <sub>2</sub> O	2.3-3.6		
P <sub>2</sub> O <sub>5</sub>	0.1-0.5		

the physical characteristics of the deposits and also provided suitable samples for study in the electron microprobe analyzer and scanning electron microscope. Samples prepared for chemical analysis by those techniques were ground only with diamond grinding material in order to avoid contamination by alumina or silicon carbide that could come from other types of grinding materials. The electron microprobe analyzer can be used to obtain quantitative analyses of spots or general areas within the sample. However, to do so requires comparatively long times, and that technique was soon abandoned because it was found that there were great variations in composition from particle to particle and the exact composition of any individual particle did not appear to be significant. Qualitative analysis by EDS (energy dispersive X-ray system) associated with the scanning electron microscope was found to be much more useful and more convenient. Although it did not provide exact analyses of individual particles, it provided information on the relative amounts of various elements at various locations so much more quickly that it was used as the primary analytical tool in this study.

The relationship between the EDS data and the chemical composition of the samples is summarized in Table 9-3. EDS analyses were conducted for several samples for which the composition was well known, and the amounts of the various compounds in the samples were compared with the percentage of the EDS counts attributable to the metallic element from each compound. In most cases, the ratio of the percentage of the sample represented by a certain oxide to the percent of the EDS counts associated with the metal from that oxide was between 1/2 and 2. Thus, as a first approximation, the percentage of EDS counts associated with a certain metal such as silicon, for example, can be taken to be comparable to the percentage of the oxide in the sample,  $\text{SiO}_2$  in this case. It should be recalled however that that rule of thumb is only good within about a factor of 2 because, for an EDS analysis, the relationship depends on the nature and quantities of other materials in the sample. Most of the information from the EDS comes from an area probably no more than 2 microns in diameter surrounding the aim point of the beam, or an area 2 mm in diameter at 1000X.

## NATURE OF THE FURNACE DEPOSITS

### Deposit in Contact With the Furnace Tube

For the sample shown in Figure 9-1, the surface of the deposit that had been in direct contact with the furnace tube was studied in the scanning electron microscope. A view of a portion of that surface is shown in Figure 9-2, where it can be seen that the deposit consisted of small spherical particles embedded in a

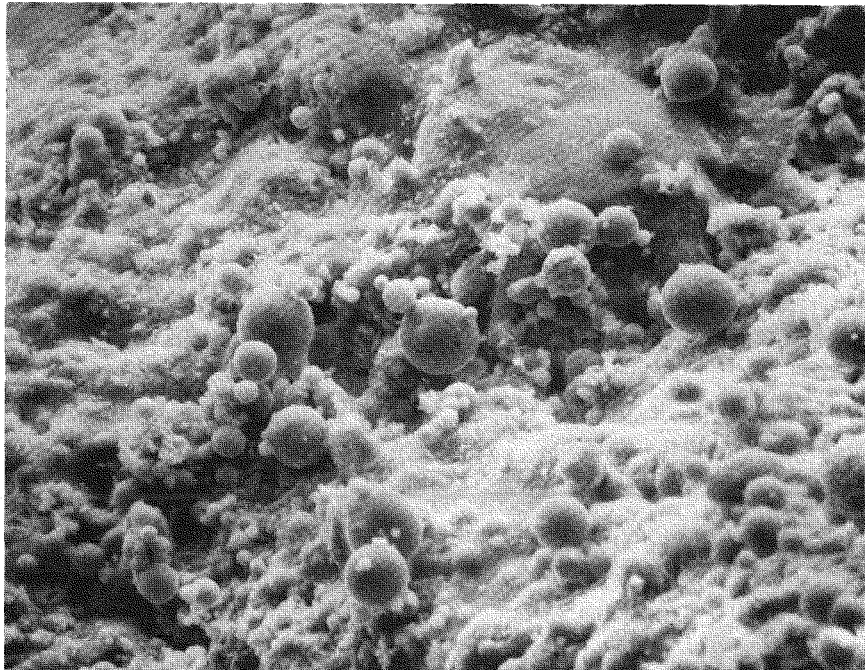
Table 9-3

RELATIONSHIP BETWEEN COMPOSITION OF A  
FURNACE-DEPOSIT OR ASH SAMPLE AND THE  
DATA OBTAINED BY ENERGY DISPERSIVE  
X-RAY ANALYSIS<sup>a</sup>

<u>Compound/Element</u>	<u>Range of Ratio of % Compound to % EDS Counts</u>
SiO <sub>2</sub> /Si	0.8 - 1.4
Al <sub>2</sub> O <sub>3</sub> /Al	0.7 - 1.8
Fe <sub>2</sub> O <sub>3</sub> /Fe	0.6 - 2.0
S	0 - 1.0
CaO/Ca	0.6 - 0.8
K <sub>2</sub> O/K	1.0 - 1.3
TiO <sub>2</sub> /Ti	0.9 - 1.0
P <sub>2</sub> O <sub>5</sub> /P	0 - 0.5
MgO/Mg	ND <sup>(b)</sup>
Na <sub>2</sub> O/Na	ND

<sup>a</sup>Based upon data obtained from two standard mixtures prepared at Battelle, an illite standard, and the furnace deposit from the Labadie boiler.

<sup>b</sup>ND = Not detected by EDS.



500X

Figure 9-2. Scanning-Electron Micrograph of the Part of Sample 273 From the Labadie Boiler That Showed the Imprint of the Furnace Tube

Table 9-4

RANGE OF COMPOSITIONS OBSERVED ON THE  
 IMPRINT OF THE FURNACE TUBE ON SAMPLE 273  
 FROM THE LABADIE BOILER<sup>a</sup>

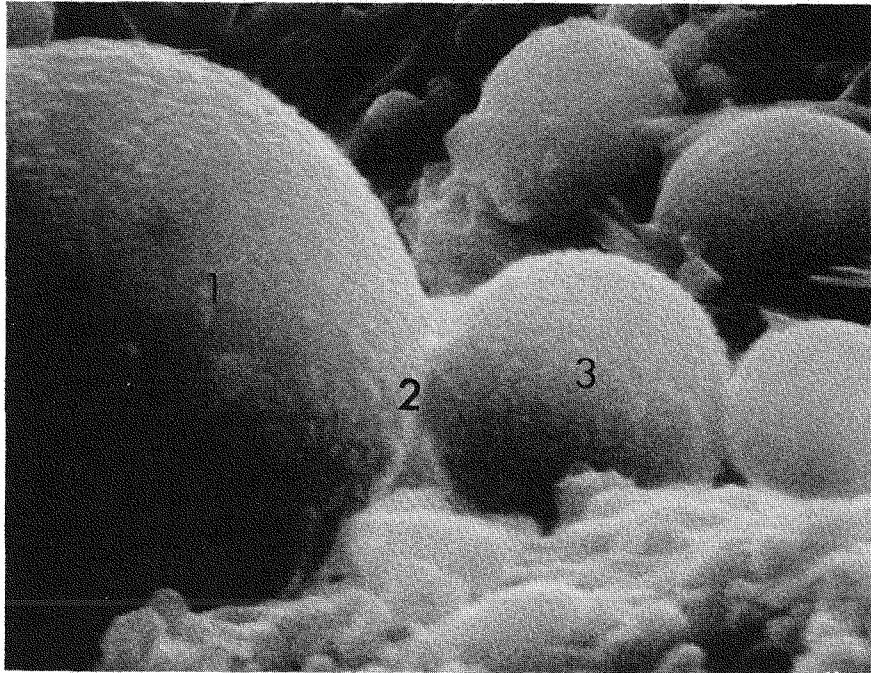
EDS Analyses, percent of total counts						
Si	Al	Fe	S	Ca	K	Ti
22-34	8-19	22-32	16-28	4-6	3-5	0.5-1.0

<sup>a</sup>Analyses were obtained for 5.2 square millimeter areas.

somewhat featureless matrix. The overall composition of the deposit at the furnace tube surface is indicated in Table 9-4. It agrees quite well with the overall composition of the deposit except that the sulfur content was much higher than that found in the bulk of the material. A higher magnification view of a portion of the deposit in contact with the furnace tube is shown in Figure 9-3. Using the EDS analysis, compositional variations from spot to spot at several such locations were studied, and the nature of those variations is summarized in Table 9-5. It can be seen that the spherical particles consisted primarily of silica and alumina, with small amounts of the oxides of the other elements in the deposit. At the point where two spherical particles were joined together, there was a somewhat higher concentration of iron, sulfur, and calcium. In addition, the matrix material contained much higher quantities of iron and sulfur than did the spherical particles.

#### Deposit Near the Furnace Tube

A section perpendicular to the furnace tube through the deposit shown in Figure 9-1 was prepared for an examination to detect any variations with distance from the tube wall. As is shown in Figure 9-4, the bulk composition of the deposit showed virtually no significant variations from the tube surface to a position 48 millimeters from the tube except for the high sulfur content immediately adjacent to the tube. However, as is shown in Figure 9-5, when the composition was measured on smaller areas, some significant variations in composition did occur from area to area but, again, there was no consistent trend from the tube surface to positions far away from it. Several interesting observations can be made from Figure 9-5. It is clear that there was a correlation among the silicon, aluminum, and potassium contents. This correlation probably was related to the fact that illite, which contains oxides of those three metals, was one of the main constituents of the furnace ash. It also is apparent from Figure 9-5 that there was a negative correlation between the iron content and the silicon content, but, in general, the iron content was not related to the sulfur content. The relationships suggest that the particles of pyrite, which also were major constituents of the original material, probably became oxidized to particles of iron oxide and those particles retained their identity. Furthermore, it is clear that there was a correlation between the calcium and sulfur contents, but those elements did not correlate with either the iron or the silicon. Apparently, much of the sulfur became associated with the calcium in the form of calcium sulfide or calcium sulfate, some of which probably existed in the original coal in the form of gypsum.



7500X

Figure 9-3. Scanning-Electron Micrograph Showing Spherical Particles in an Area in Contact With the Furnace Tube

Sample 273 from the Labadie boiler.

Table 9-5

COMPOSITIONS OF PARTICLES AND BONDING MATERIAL AT THE FURNACE TUBE

<u>Particle or Area</u>	<u>EDS Analysis, percentage of total counts</u>							
	<u>Si</u>	<u>Al</u>	<u>Fe</u>	<u>S</u>	<u>Ca</u>	<u>K</u>	<u>Ti</u>	<u>Mg</u>
Particle 1 <sup>a</sup>	68	18	7	1	2	3	0.5	0
Particle 3 <sup>a</sup>	51	28	6	3	1	5	3	3
Interface 1/3 <sup>a</sup>	46	16	11	16	5	4	2	0
Particle 5 <sup>b</sup>	58	26	5	3	2	5	1	0
Particle 6 <sup>b</sup>	77	15	2	0.5	0.5	4	0.5	0
Interface 5/6 <sup>b</sup>	48	19	15	5	5	5	2	0
Matrix material <sup>a</sup>	16	5	46	20	3	8	0.5	0

<sup>a</sup>Shown in Figure 9-3.

<sup>b</sup>Particles not shown in Figure 9-3.

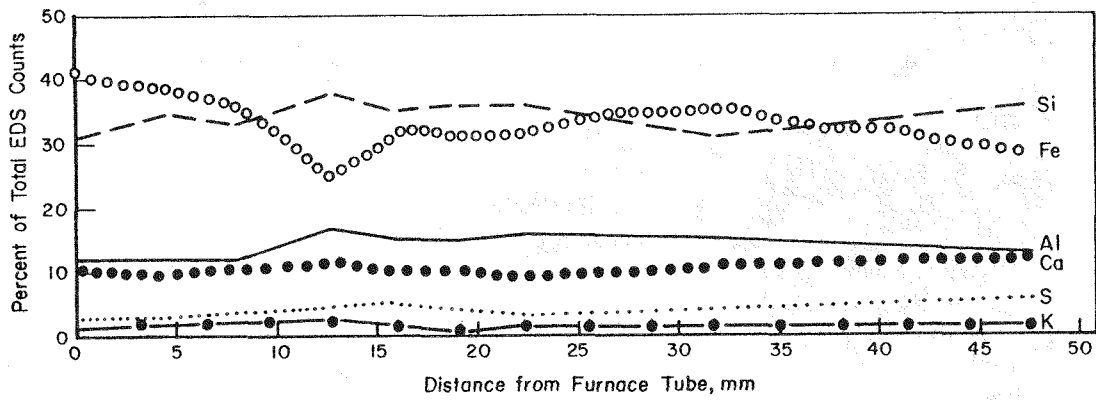


Figure 9-4. Variation in composition of furnace deposit in Labadie boiler as measured on 5.2 square mm areas

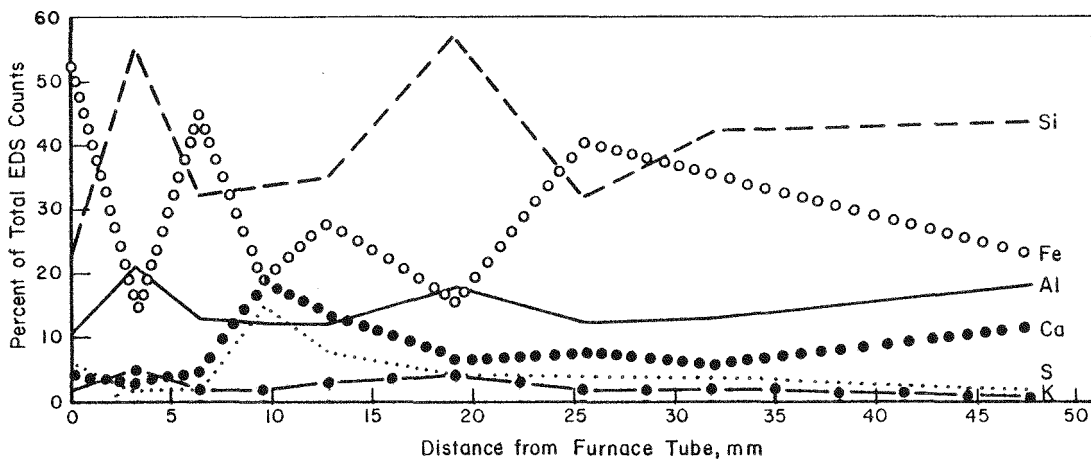


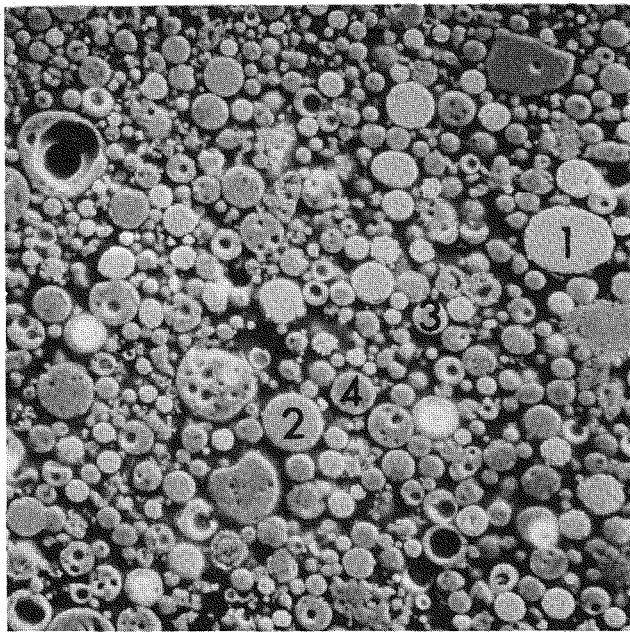
Figure 9-5. Variation in composition of furnace deposit in Labadie boiler as measured on 0.21 square mm areas

A typical example of one of the areas that was relatively high in silicon is shown in Figure 9-6, and the compositions of several representative particles are indicated in Table 9-6. It can be seen that many of the particles were hollow, but some appear to be solid. The optical photomicrograph shows that there was a considerable difference in reflectivity among the particles. Comparing the reflectivity with the data in Table 9-6 shows that the particles with higher reflectivity contained higher amounts of iron. Thus, it can be seen that most of the spherical particles near the furnace tube were rich in silica and alumina, but a few of the particles were relatively high in iron. The matrix in which the particles were embedded is rather high in iron and sulfur. The relatively high calcium content of the entire area compared with the individual particles suggests that there must have been many particles that were not analyzed individually that consisted of calcium sulphate or calcium oxide.

Two typical regions that contained relatively high amounts of iron and calcium are shown in Figure 9-7. Those regions contained numerous small spheres that presumably were primarily silica and alumina, together with large spheres and irregularly shaped particles. The overall composition of the area as shown in Table 9-7 suggested that the large particles probably consisted primarily of iron oxide and calcium oxide. That suggestion was verified for the areas shown in Figure 9-8 and the analyses given in Table 9-8. The area on the right side of Figure 9-8 is a high-magnification view of a small portion of the area shown in the upper left corner of the left portion of Figure 9-8. It can be seen that the small spheres consisted primarily of silica and alumina, whereas the large light colored areas were primarily iron oxide, and the large, dark areas contained large amounts of calcium oxide. It is interesting to note that the boundary between the iron oxide and calcium oxide particles (Particles 10 and 12, respectively) indicated by Points 11 and 13 contained a relatively large amount of sulfur, which was not found in either of the two particles.

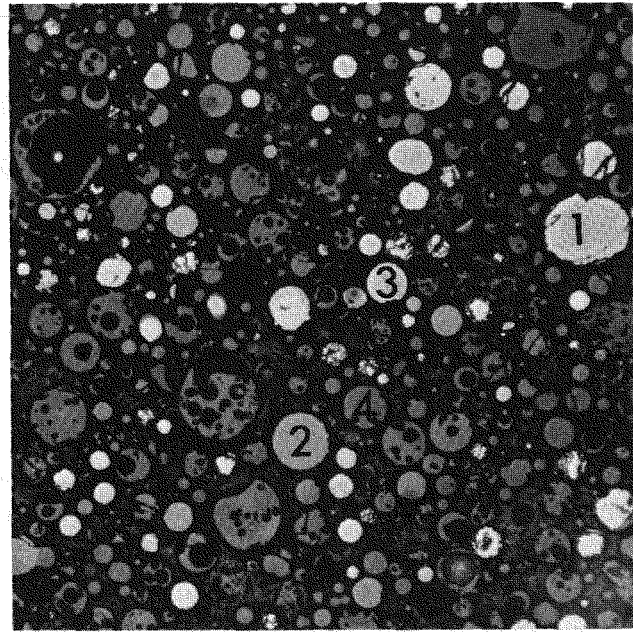
No measurable composition gradients were detected within any of the individual particles. Figure 9-9 and the data in Table 9-9 illustrate that observation. Note that the composition at all four spots within the spherical particles was virtually constant.

At many interfaces between two bound particles, no unusually high concentrations of any element were detected. An example of this is illustrated in Figure 9-10 and Table 9-10, where Particle 1, which contained a relatively large amount of iron, is bonded to Particle 3, which consisted primarily of silica and alumina. Note that the composition at the interface (Spot 2) was very close to that of



250X

a. Scanning Electron Micrograph



250X

b. Optical Micrograph of Same Area

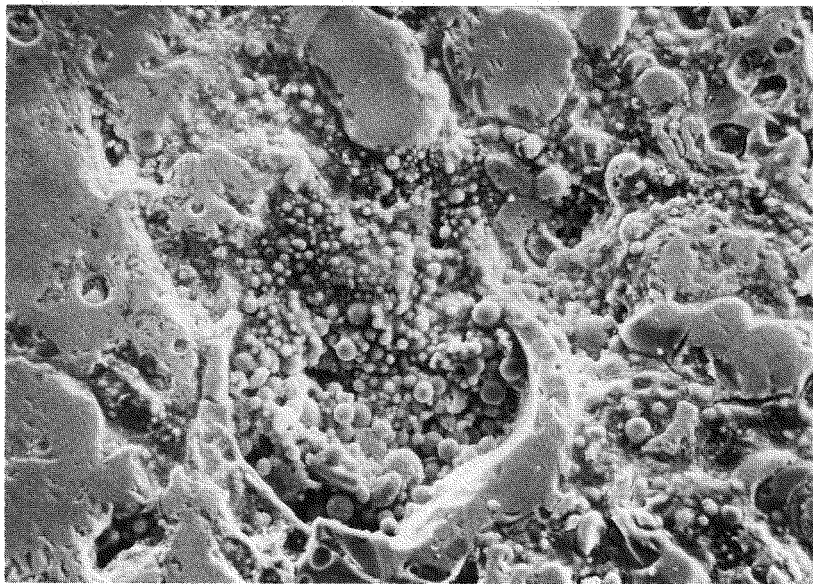
Figure 9-6. Section Through Furnace Deposit From the Labadie Boiler 19 millimeters From the Furnace Tube, Showing A Typical Area of Relatively High Silicon Content

Table 9-6

COMPOSITIONS OF SMALL SPHERICAL PARTICLES IN THE  
FURNACE DEPOSIT NEAR THE FURNACE TUBE

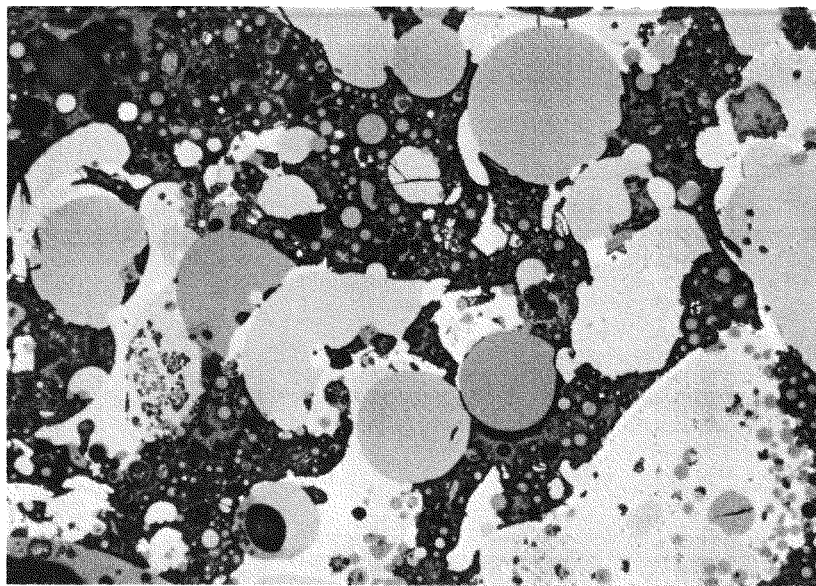
Particle <sup>a</sup>	EDS Analysis, percent of total counts						
	Si	Al	Fe	S	Ca	K	Ti
1	10	3	87	0	0	0	0
2	42	19	33	0	1	3	2
3	14	9	75	0	1	0	0.5
4	56	32	4	0	1	4	3
5 (not shown)	99	0	0.5	0	0	0	0
6 (not shown)	0.5	1	98	0	0	0	0
Matrix	23	10	40	13	2	2	6
Entire Area	36	15	32	4	10	1	1

<sup>a</sup>Numbers refer to particles shown in Figure 9-6.



250X

a. Scanning Electron Micrograph



250X

b. Optical Micrograph of Comparable Area

Figure 9-7. Section Through Furnace Deposit From the Labadie Boiler Less Than 1 millimeter From the Furnace Tube Showing a Typical Area of Relatively High Iron Content

Table 9-7

OVERALL COMPOSITION OF THE AREA SHOWN  
IN FIGURE 9-7a

EDS Analysis, percent of total counts						
<u>Si</u>	<u>Al</u>	<u>Fe</u>	<u>S</u>	<u>Ca</u>	<u>K</u>	<u>Ti</u>
31	12	41	3	11	2	0.5

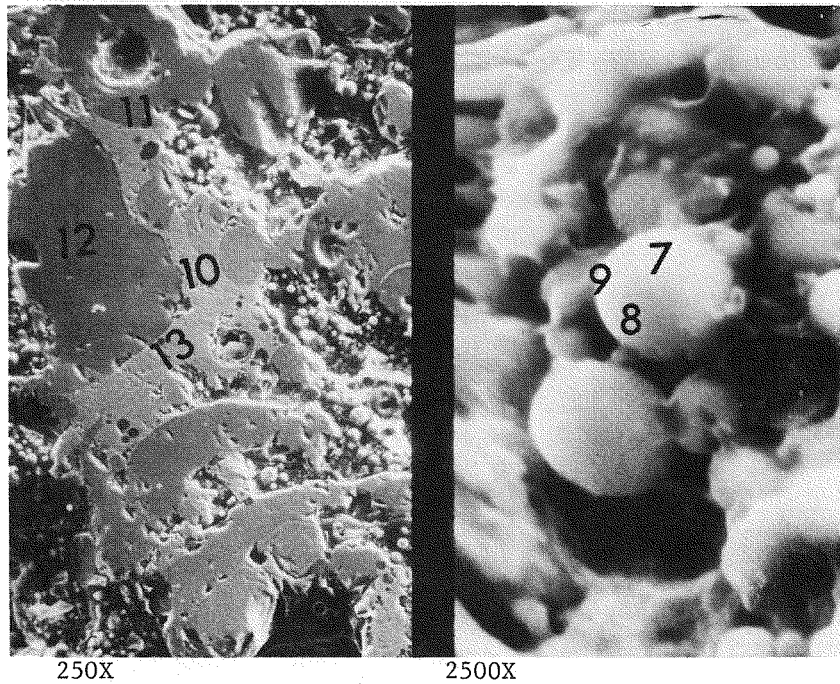


Figure 9-8. Scanning Electron Micrograph of a Section Through the Furnace Deposit From the Labadie Boiler 3 millimeters From the Furnace Tube

Table 9-8

COMPOSITION OF VARIOUS CONSTITUENTS IN THE PORTION OF THE FURNACE DEPOSIT SHOWN IN FIGURE 9-8

<u>Particle or Area</u>	<u>EDS Analysis, percent of total counts</u>							
	<u>Si</u>	<u>Al</u>	<u>Fe</u>	<u>S</u>	<u>Ca</u>	<u>K</u>	<u>Ti</u>	<u>Mg</u>
7	47	41	7	0	10	5	0	0
8	58	29	8	0	0	3	2	0
9	49	27	7	0	2	5	3	7
10	2	0	96	0	2	0	0	0
11 (boundary)	5	2	63	6	25	0	0	0
12	15	5	17	0	60	0	0	3
13 (boundary)	7	2	47	8	37	0	0	0

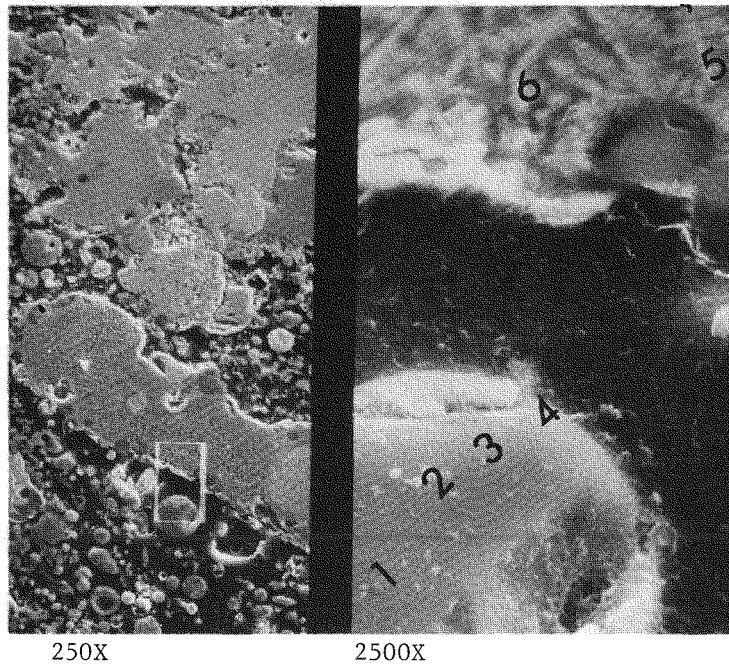


Figure 9-9. Scanning Electron Micrograph of a Section Through the Furnace Deposit From the Labadie Boiler 32 millimeters From the Furnace Tube

Table 9-9

COMPOSITION OF VARIOUS AREAS IN THE PORTION OF THE FURNACE DEPOSIT SHOWN IN FIGURE 9-9

Spot	EDS Analysis, percent of total counts							
	Si	Al	Fe	S	Ca	K	Ti	Mg
1	65	23	0	0	0	12	0	0
2	69	20	0	0	0	11	0	0
3	68	20	0	0	0	12	0	0
4	67	21	2	0	0	9	0	0
5	22	18	56	2	0	0	0	2
6	27	14	54	2	2	2	0	0

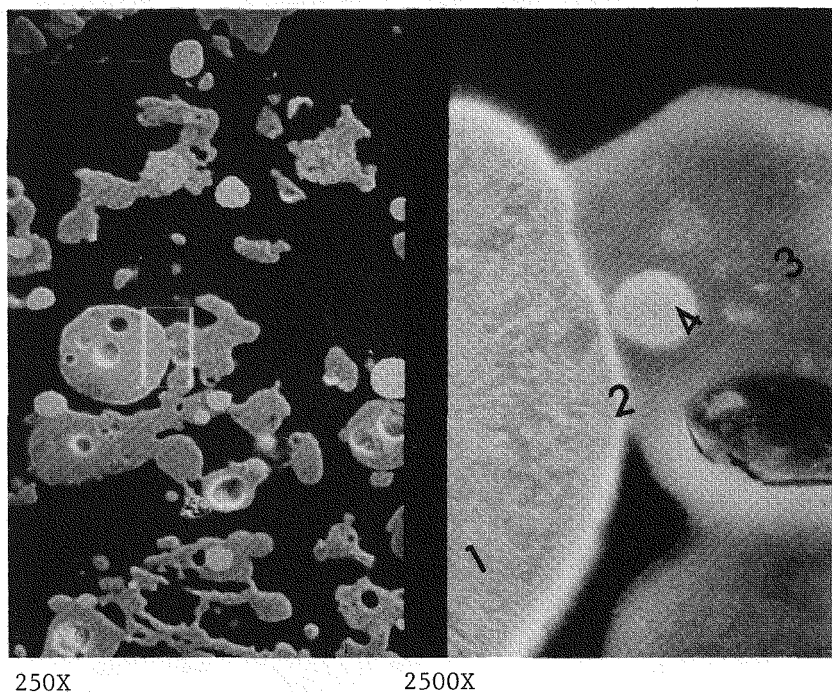


Figure 9-10. Scanning Electron Micrograph of a Section Through Several Particles From Sample 512 From the Mill Creek Boiler

The dark grey background is mounting material used to hold the particles.

Table 9-10

COMPOSITION OF TWO BONDED PARTICLES AND THE INTERFACE BETWEEN THEM, AS SHOWN IN FIGURE 9-10

Spot	EDS Analysis, percent of total counts							
	Si	Al	Fe	S	Ca	K	Ti	Mg
1	33	15	43	0	1	7	1	0
2	34	16	43	0	1	5	1	0
3	61	21	3	0	4	8	3	0
4	9	7	84	0	0	0	0	0

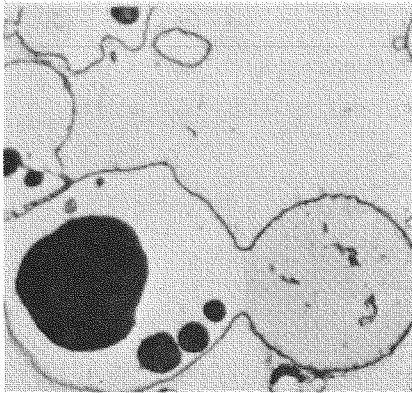
Particle 1. Figure 9-11 shows another way to illustrate the distribution of elements within the particles. Figure 9-11a shows an optical micrograph of two particles that are bound together; the lighter of the two contained several holes. The particles were embedded in a mounting material that was not part of the furnace deposit. The X-ray maps for the various elements show that the composition within each particle was relatively uniform and that there was relatively little diffusion of material from one particle to another across the interface. Also no unusually high concentration of any of the components was present at the interface. The X-ray maps shown in Figure 9-11 were made with an electron microprobe analyzer. Virtually identical maps could have been produced in the scanning electron microscope with the energy dispersive system.

#### Deposits Farther From the Furnace Wall-Tube Surface

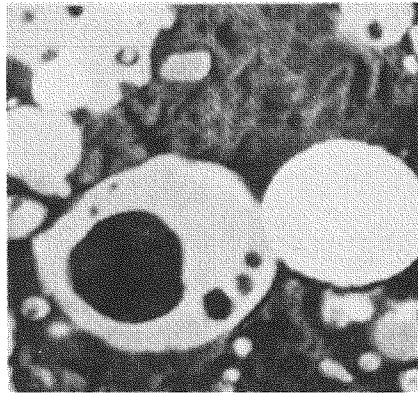
The temperature of the furnace deposit can be expected to increase significantly with increasing distance from the wall tube surface. The present study has shown that, because of those temperature differences, the physical nature of the furnace deposits changes while the average chemical composition is relatively unaffected. An example of a furnace deposit from a relatively long distance from the tube surface is shown in Figure 9-12. As is indicated by the data in Table 9-11, the deposit consists of roughly spherical regions that contained relatively large amounts of iron embedded in a glassy matrix that consisted primarily of silica and contained many holes. Apparently, because of the higher temperatures, the material that consisted of spherical particles of silica very near the furnace tubes had fused to form the glassy matrix, and the irregularly shaped particles containing iron had become spherical and possibly molten within the silica matrix. Several other representative sections through glassy slags are shown in Figure 9-13, and the average analyses are indicated in Table 9-12. Clearly, there is no direct relationship between the structures shown and the original particles that joined to form the furnace deposit. As a result, almost no significant information on the original structure of the ash deposit could be obtained from a study of those glassy samples.

#### CHARACTERIZATION OF THE LOW-MELTING POINT CONSTITUENTS IN THE GROUND FURNACE DEPOSITS AND THE LOW-TEMPERATURE ASH SAMPLES

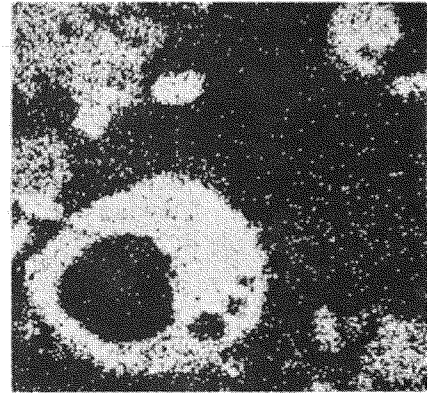
As an alternate approach to identifying the low-melting-point constituents of the ashes, ground samples of the furnace deposits and samples of corresponding low-temperature ash were heated in a hot-stage microscope, and the first particles to melt were then analyzed by EDS in the scanning electron microscope.



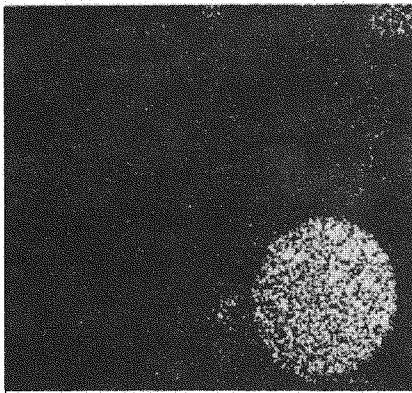
a. Optical Micrograph



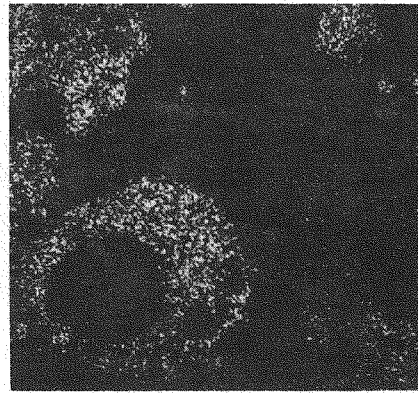
b. Back-Scatter-Electron Image



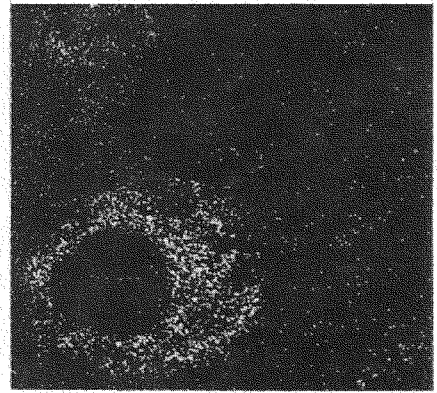
c. X-Ray Map for Silicon



d. X-Ray Map for Iron



e. X-Ray Map for Aluminum



f. X-Ray Map for Calcium



g. X-Ray Map for Potassium

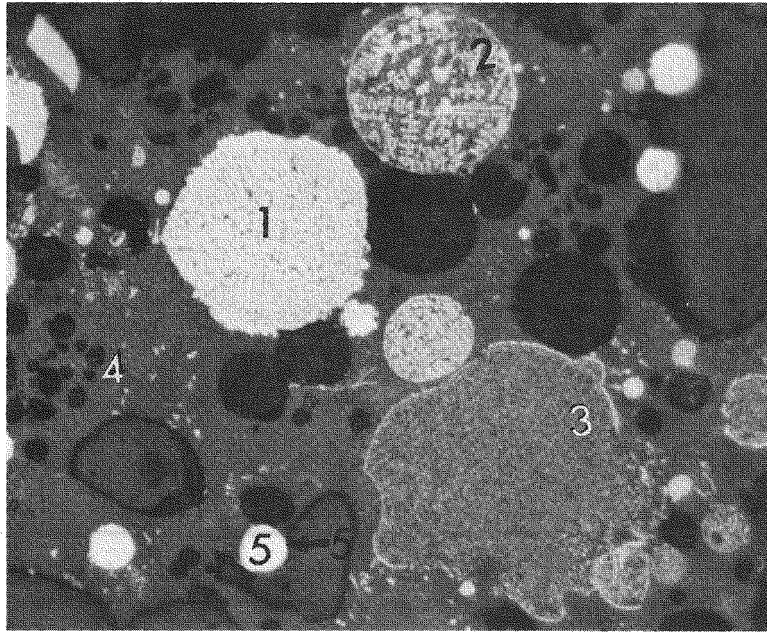


h. X-Ray Map for Titanium



i. X-Ray Map for Sulfur

Figure 9-11. Elemental Distribution in Two Bonded Particles From the Labadie Boiler as Revealed on X-Ray Maps Produced With the Electron-Microprobe Analyzer



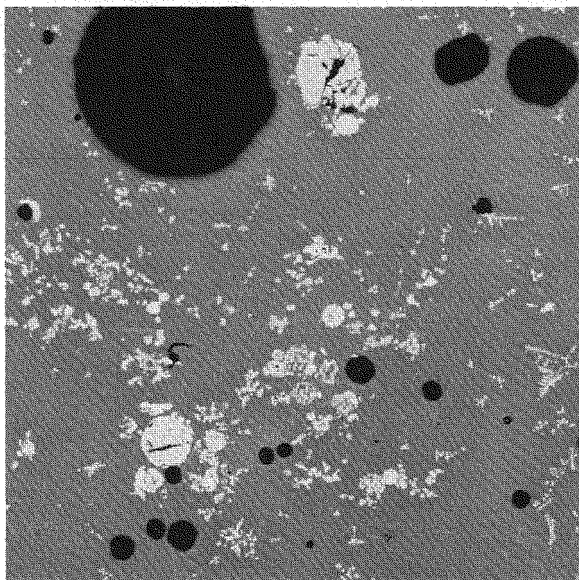
500X

Figure 9-12. Optical Micrograph of a Section Through a Portion of the Furnace Deposit From the Labadie Boiler at a Relatively Long Distance From the Furnace Wall

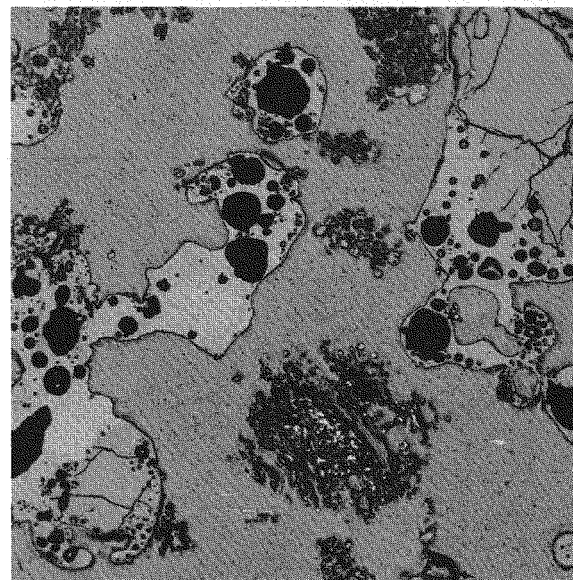
Table 9-11

COMPOSITION OF VARIOUS CONSTITUENTS OF THE FURNACE DEPOSIT FROM THE LABADIE BOILER AS SHOWN IN FIGURE 9-12

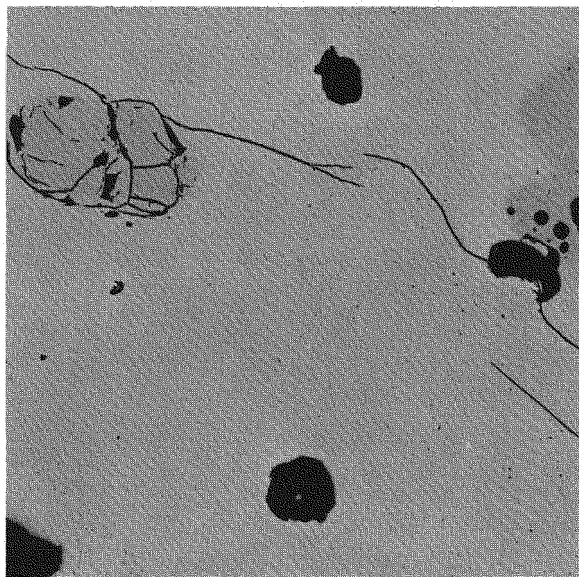
Spot	EDS Analysis, percent of total counts							
	Si	Al	Fe	S	Ca	K	Ti	Mg
1	12	5	82	0	0.7	0	0.3	0
2	41	14	38	0	3	3	1	0
3	51	23	18	0	1	3	0.7	2
4	95	0	2.3	0	2	0.7	0	0
5	10	4	84	0	2	0	0	0



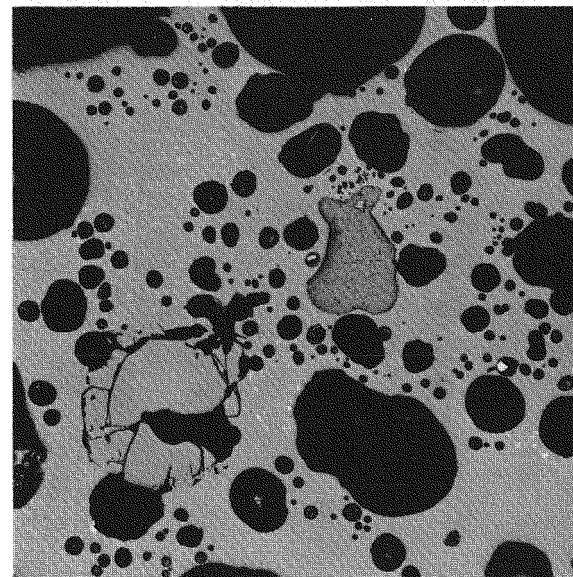
100X a. Sample 305



100X b. Sample 763



100X c. Sample 953



100X d. Sample 1066

Figure 9-13. Optical Micrographs of Sections Through Samples of Glassy Slags Obtained From Four Boilers

See Table 1 for identification of the boilers.

Table 9-12

AVERAGE COMPOSITIONS FOR THE AREAS SHOWN IN FIGURE 9-13

<u>Sample</u>	<u>EDS Analysis, percent of total counts</u>						
	<u>Si</u>	<u>Al</u>	<u>Fe</u>	<u>S</u>	<u>Ca</u>	<u>K</u>	<u>Ti</u>
305	51	22	17	0	4	4	1
763	57	24	8	0	2	6	2
953	51	28	15	0	1	3	1
1066	54	26	8	0	5	4	1

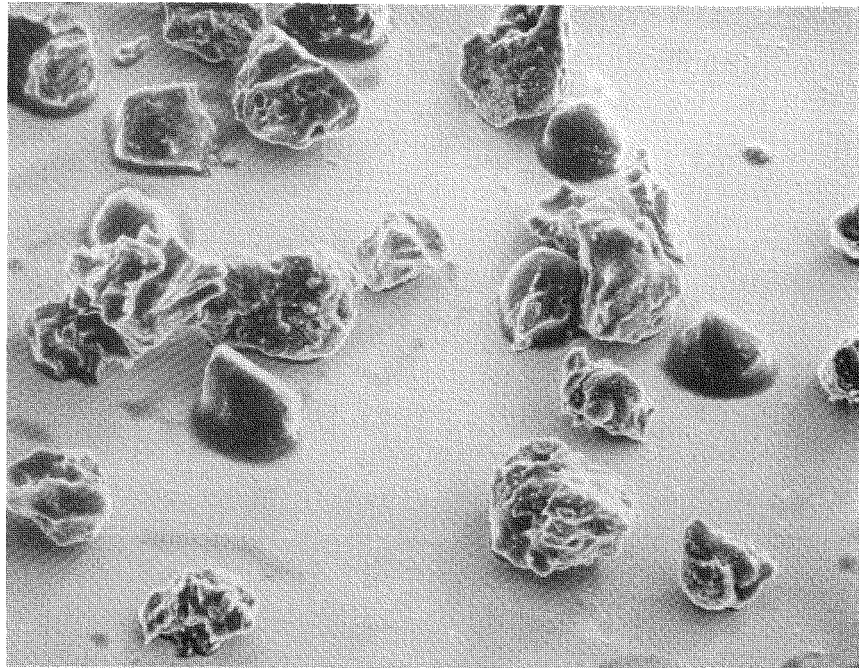
The LTA (Low Temperature Ash) samples were prepared from pulverized coal and contained a large proportion of powder too fine for observation in the hot-stage microscope at 160X magnification. Accordingly, the LTA was screened and those particles collected between a 270-mesh screen and a 325-mesh screen, with nominal dimensions of 44 to 53 micrometers, were used for hot-stage microscope observations. This selection eliminated all of the minerals contained within coal particles, leaving only those discrete mineral particles about as large as coal particles. These particles, thus, were not representative of the average coal ash. Particles of ground furnace ash deposits were also screened to obtain 44 to 53 micrometer particles.

Prior to melting, the ground furnace deposits were examined with a polarized-light microscope with transmitted light. The shapes of the particles ranged from angular to spherical, the color from clear to brown, and the transmittance from transparent to opaque. Many of the particles contained more than one phase. Thus, EDS analyses might represent either a single phase or a mixture of phases.

In the hot-stage microscopy study, particles of LTA or ground furnace ash were distributed over the surface of a platinum strip, and the strip was heated by resistance heating in a nitrogen atmosphere. Strip temperature was measured by an attached thermocouple while particles were observed at 160X magnification. The strip was heated rapidly to 800 C (1472 F), then heated in 25 C steps at intervals of one to two minutes. Heating was stopped when the first particles were observed to change shape, and the temperature was recorded. Following this heating, the platinum strip, with its samples, was cooled for later analysis by EDS in the scanning electron microscope. Figure 9-14 shows a sample of particles of ground furnace ash, some of which were starting to melt.

Table 9-13 summarized EDS analyses of particles of melted and unmelted LTA, and melted ground furnace ash particles. Table 9-14 shows averages of EDS analyses, which show trends common to all five coals.

The data of Tables 9-13 and 9-14 show that particles of LTA and of furnace ash with very low melting temperatures were found for every coal. These temperatures, which ranged from 1571 to 2012 F, were all well below the initial deformation temperatures of the ash from coals represented. (Ash fusion temperatures are summarized in Table B-4) In general, the compositions of LTA samples were



200X

Figure 9-14. Scanning Electron Micrograph of  
Particles From Furnace Deposit 512

Table 9-13

## COMPOSITIONS AND FUSION TEMPERATURES OF PARTICLES OBSERVED IN THE HOT-STAGE MICROSCOPE

Boiler	Sample Number	Condition	EDS Analysis, percent of total counts										Fusion Temp.	
			Si	Al	Fe	S	Ca	K	Ti	Mg	P	Si/Al	C	F
<u>Low-Temperature-Ash Particles</u>														
Labadie	364	Melted	68.6	9.2	7.1	--	4.6	8.7	1.8	--	--	7.5	1008	1845
	364	Melted	35.0	25.1	12.1	--	10.0	14.1	3.7	--	--	1.39	1008	1845
Mill Creek	534	Melted	23.1	12.0	25.6	--	13.3	17.3	2.9	--	5.8	1.92	1008	1845
	534	Melted	48.8	27.4	3.2	--	1.7	9.3	0.6	--	9.0	1.78	1008	1845
	534	Unmelted	50.0	32.1	4.9	--	--	4.4	--	--	8.1	1.56	--	--
Cliffside	774	Melted	51.4	32.4	2.2	--	2.7	--	1.1	--	10.2	1.59	1070	1958
	774	Melted	59.0	26.3	3.1	--	1.4	--	1.1	--	9.1	2.24	1070	1958
	774	Unmelted	86.4	8.9	1.6	--	--	--	1.7	--	1.4	9.7	--	--
Morgantown	982	Melted	40.3	32.8	17.0	--	1.4	2.8	1.5	--	4.2	1.23	869	1596
	982	Melted	51.0	29.2	8.2	--	1.7	3.5	1.3	--	5.1	1.75	869	1596
	982	Unmelted	82.7	6.2	0.6	--	--	1.2	--	--	9.3	13.3	--	--
Montour	1083	Melted	42.7	22.9	11.6	--	2.8	4.4	1.0	--	14.6	1.86	993	1819
	1083	Melted	43.4	45.8	0.8	--	0.8	4.8	--	--	4.4	0.95	993	1819
	1083	Unmelted	43.8	34.4	5.3	--	6.8	4.0	2.7	--	3.0	1.27	--	--
<u>Ground-Furnace-Deposit Particles</u>														
Labadie	273	Melted	24.5	12.2	48.0	--	10.2	5.1	--	--	--	2.0	855	1571
Labadie	305	Melted	46.4	13.7	25.2	--	7.4	6.0	1.3	--	--	3.4	1034	1893
	305	Melted	29.4	8.9	39.3	--	10.6	8.7	3.1	--	--	3.3	1034	1893
	305	Melted	59.3	20.2	11.7	--	4.1	3.6	1.1	--	--	2.9	1034	1893
Mill Creek	512	Melted	60.2	16.0	5.5	--	9.4	7.4	1.5	--	--	3.8	1022	1872
	512	Melted	38.2	10.2	23.8	--	18.1	7.9	1.8	--	--	3.8	1022	1872
Cliffside	763	Melted	50.4	29.6	13.5	--	1.6	4.3	0.6	--	--	1.7	1100	2012
	763	Melted	7.9	5.0	74.0	--	5.0	5.0	3.1	--	--	1.6	1100	2012
	763	Melted	58.2	15.8	17.1	--	1.7	6.6	0.6	--	--	3.7	1100	2012
Morgantown	953	Melted	45.1	19.0	26.0	--	2.1	5.9	1.9	--	--	2.37	922	1692
	953	Melted	37.2	14.9	39.3	--	2.1	3.8	2.7	--	--	2.50	922	1692
Montour	1066	Melted	60.5	17.4	4.5	--	8.6	7.5	1.5	--	--	3.48	1024	1875
	1066	Melted	47.3	28.7	5.3	--	3.5	8.4	4.3	2.5	--	1.65	1024	1875

Table 9-14

## AVERAGES OF THE EDS ANALYSES OF THE PARTICLES STUDIED IN THE HOT-STAGE MICROSCOPE

	EDS Analyses, percent of total counts									
	Si	Al	Fe	S	Ca	K	Ti	Mg	P	Si/Al
Melted LTA <sup>a</sup> particles	46.4	26.4	9.2	--	8.0	6.5	1.2	--	6.2	1.76
Unmelted LTA particles	65.7	20.4	3.1	--	1.7	2.4	1.1	--	5.5	3.22
Melted furnace-deposit particles	43.4	16.3	25.6	--	6.5	6.2	1.8	0.2	--	2.66

<sup>a</sup>Low-temperature ash.

different from the average ash compositions of the coals represented, but the compositions of the furnace ash deposit samples were similar to the compositions of the ash found in the dense, high-ash fractions of the coals represented, with specific gravity above 2.0. It appears that low-fusion ash particles from this dense fraction retain their identity in the wall deposits.

An examination of differences in composition shows that all LTA samples contained phosphorus, but no furnace ash samples contained phosphorus. It appears that phosphorus is lost from the ash during combustion.

The Si/Al ratios found in the different samples indicate that most of the LTA samples were different from the average coal ash. Eleven samples had Si/Al ratios below 2.2, and three had ratios above 7.5, for an average Si/Al ratio of 1.76. Si/Al ratios for coal density fractions ranged from 2.0 to 3.4 for the various coals. The Si/Al ratios for the melted furnace ash deposit particles ranged from 1.6 to 3.8, averaging 2.66, which were close to coal-ash compositions.

The iron contents of LTA samples that melted were higher than those of LTA samples that did not melt, but were lower than those of furnace ash samples. Iron is a flux, lowering the melting temperature of the Al-Si glasses. Variations in Ca, K, and Ti, which are also fluxes, were relatively small.

It appears that particles of coal minerals having low melting temperatures occur in every coal, and that these produce ash particles of low fusion temperature without the need for interaction with other particles during combustion. It also appears probable that ash particles formed from the dense, high-ash coal fractions retain their identity in wall deposits and could be isolated and identified by the techniques used.

#### FORMATION OF LOW-MELTING-TEMPERATURE MATERIALS IN THE FURNACE

The bonding of ash particles to furnace wall tubes and to existing ash deposits would be aided by the presence of ash constituents having a liquid phase at deposition temperature. A study of the various relevant phase diagrams for mixtures of the various components of the furnace ash shows that mixing the various constituents can cause significant decreases in melting temperature. For example, the phase diagram in Figure 9-15 shows that a proper mixture of FeO and SiO<sub>2</sub> can produce Fayalite, which has a melting point almost 200 C below that of

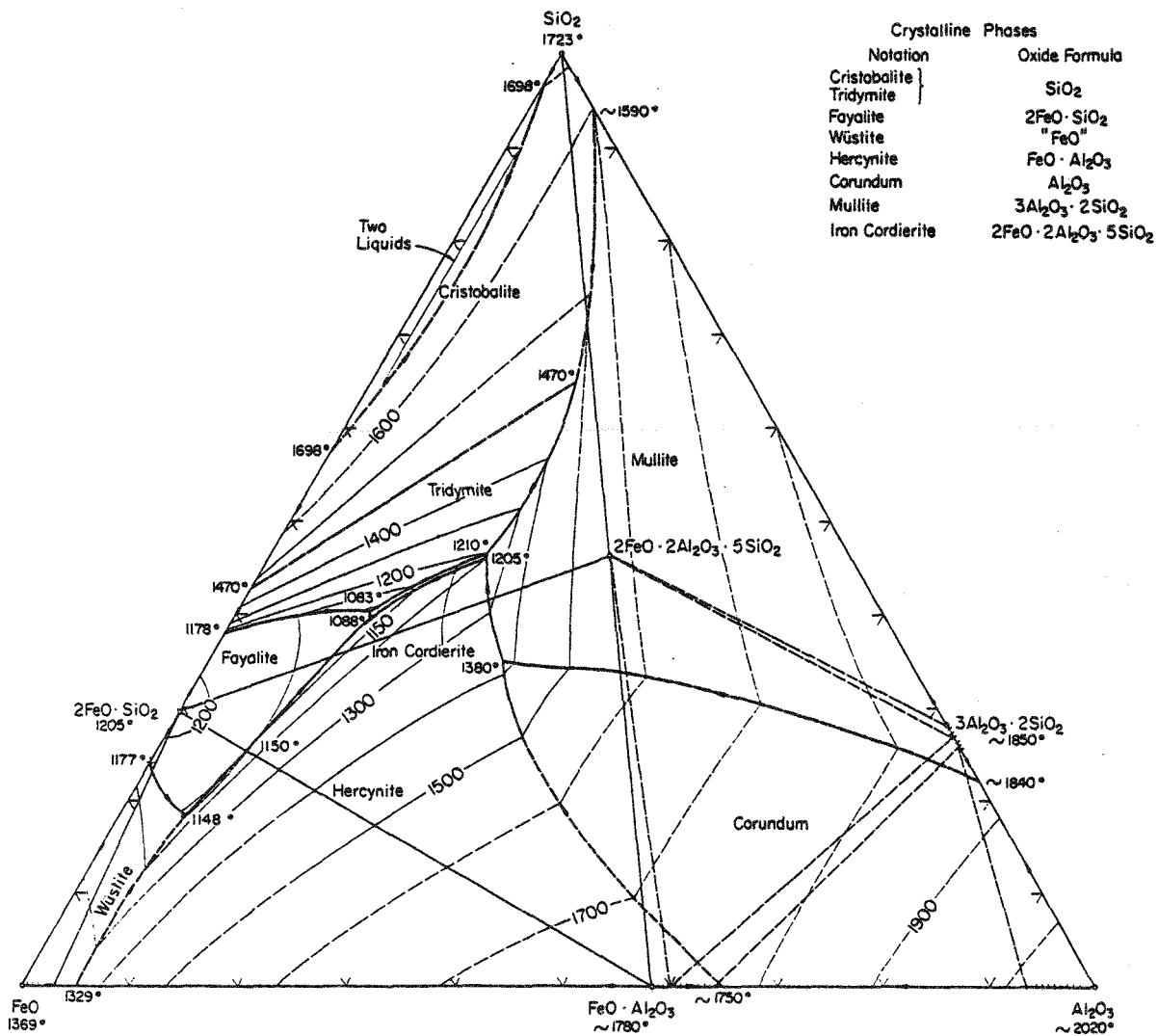


Figure 9-15. Phase Diagram for the FeO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> System (2) Showing Melting Temperatures as a Function of Composition

Temperatures are given in degrees C.

(2) Levin, E. M., Robbins, C. R., and McMurdie, H. F., Phase Diagrams for Ceramists, The American Ceramic Society (1964)

the iron oxide and 500 C below that of  $\text{SiO}_2$ . Adding an appropriate amount of  $\text{Al}_2\text{O}_3$  can depress the melting point further by almost 100 C. From the phase diagram shown in Figure 9-16, one could conclude that the addition of an appropriate amount of iron oxide would further lower the melting point by about 160C. Other materials, such as calcium oxide, potassium oxide, and sodium oxide are known to be good fluxes; that is, they also tend to lower the melting point of these oxide mixes. However, a fluxing material will not be effective unless it can react with or dissolve in other constituents.

Particles having low melting temperatures will be fused in the flame, where temperatures above 2500 F occur, and will approach the wall as molten spheres. As they approach the wall they radiate heat to the cold wall tubes, and may freeze before impact. However, if they are still molten on impact, they may bond mechanically or electrostatically to the tube surface. The tube surface is oxidized and quite rough; so that mechanical bonding may be sufficient for initial sticking of the particle to the wall. As the ash layer becomes thicker, the temperature gradient through the ash, which is a good insulator, will result in progressively higher surface temperatures, making bonding easier. At some thickness the ash surface will be molten, and will capture unmelted particles impinging on it. If the temperature is high enough, these may dissolve in the molten slag.

There appears to be some possibility that reactions may take place between molten particles and the iron oxide of the tube surface, or between particles of unlike composition. The reaction zone, if it exists, must be very thin, as diffusion of constituents from one particle to another appeared small or non-existent in scanning electron microscope and electron microprobe studies. For example, a clay particle containing silica and alumina might react with iron oxide to form a thin film of low-melting-temperature material that would bond them together.

A different explanation appears necessary for the concentration of calcium and sulfur near the tube surface. Here there appears to be a possibility that sulfur compounds diffuse into the ash deposit because of the temperature gradient, and concentrate near the tube surface where the temperature is low. They may not have been there when deposition first occurred.

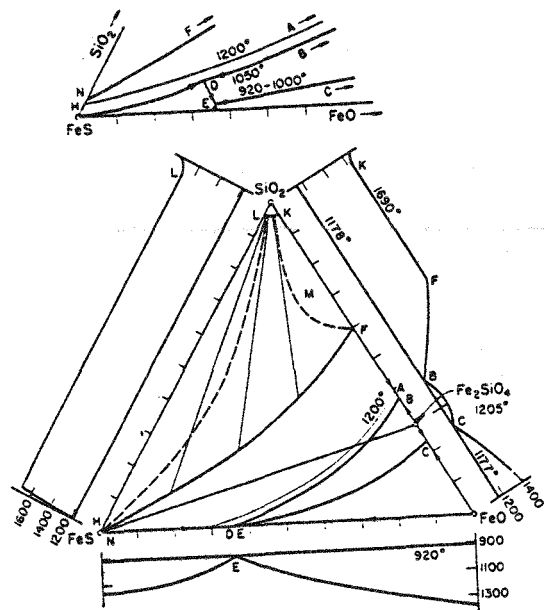


Figure 9-16. Phase Diagram for the FeS-FeO-SiO<sub>2</sub> System (2) Showing Melting Points as a Function of Composition

Temperatures are given in degrees C.

(2) Levin, E. M., Robbins, C. R., and McMurdie, H. F., Phase Diagrams for Ceramists, The American Chemical Society, (1964)

## OBSERVATIONS

It has been demonstrated that a number of analytical procedures can provide useful information for characterizing the constituents and structure of furnace deposits. These analytical procedures include scanning electron microscopy, energy dispersive X-ray analysis, electron microprobe analysis, hot-state microscopy, optical metallography, and polarized light microscopy.

The following significant features were observed in one Labadie sample that was particularly suitable for detailed study of ash deposit structure:

1. Ash deposits contained a high concentration of glassy spheres, varying widely in composition and size. Interspersed among these spheres were unmelted particles of iron oxide, calcia, and silica.
2. No measurable gradients in composition were detected within individual particles.
3. A unique bonding material cementing particles together was not found. There was no measured diffusion of constituents across boundaries between particles, and any reaction products joining particles were too thin to be observed or measured by the techniques used.
4. Particles of low-temperature ash having very low melting temperatures were found in each of the five coals. The melting temperatures of these particles were below the Initial Deformation temperatures of the ash from the coals they represented. The compositions of these particles were different from the average compositions of coal ash or furnace ash.
5. Particles of furnace ash, obtained by grinding furnace ash deposits, were found having very low melting temperatures. The compositions of these particles were similar to the compositions of the ash from dense, high-iron coal fractions. It appears probable that coal particles containing high-iron ash formed high iron ash particles, which deposited on the walls and could be isolated by the techniques used.
6. A high concentration of sulfur was found at the tube surface in a matrix material containing high amounts of iron, some silicon and aluminum, and minor amounts of calcium and potassium.
7. There were no gross compositional gradients within the deposit except for the sulfur concentration at the tube surface, but localized gradients were found. Certain areas were rich in silica, alumina, and potassium, found together. Iron-rich particles contained little silica. Sulfur was found in regions of high calcium content.

## Section 10

### DATA INTERPRETATION AND CORRELATION

#### RELATION OF BOILER DESIGN TO COAL VARIABLES

##### Overall Considerations

The art of furnace design is concerned with the selection of a furnace of optimum size and cost that can be operated without slagging problems, with complete combustion, and with close control of steam superheat and reheat temperatures. During boiler operation, furnace heat absorption varies with the amount of ash on the walls. Excessive ash deposits will reduce heat absorption, increasing furnace exit gas temperature and steam temperatures. Insufficient ash deposits will increase furnace heat absorption, decreasing furnace exit gas temperature and steam temperatures. The boiler operator controls furnace ash deposits by use of wall blowers (short retractable soot blowers) that clean a large circular area when actuated. So long as the wall blowers are effective in removing ash deposits, boilers can be operated continuously. However, if the boiler furnace is too small for the coal fired, ash in the most critical, highest-temperature zones may fuse so hard between blowing cycles that it isn't removed by the blower, and this uncleanable area of hard, fused deposit will grow larger with time. As the uncleanable area grows, furnace heat absorption decreases, furnace exit gas temperature increases, and flow of water to the steam desuperheater must be increased to hold steam temperature. When the limit of desuperheater water flow is reached it is necessary to drop load for furnace deslagging. (At Labadie and Mill Creek, load was dropped by about 50 percent each night for 8 hours or more for furnace deslagging.)

The optimum furnace size will depend upon fusion characteristics of the coal ash. An ash of high fusion temperature and low slagging potential will permit use of a relatively small furnace operating at high gas temperatures, but an ash of low fusion temperature and high slagging potential will require a larger furnace for satisfactory operation. Thus, furnace sizes are selected on the basis of coal ash characteristics.

The "cleanability" of ash deposits by wall blowers depends upon deposit strength and tenacity at the moment of blowing. Over a period of time the ash deposit will grow in thickness and strength. The temperature gradient through the deposit will result in an increase in surface temperature with thickness and, at some temperature, the surface will sinter to high strength. The appearance of flowing slag on the surface of a deposit is an indication that the deposit surface has formed a strong bond and that it will be difficult to remove with wall blowers.

The factors that control cleanability of wall deposits include the following:

1. The rate of ash deposition, which is influenced by furnace aerodynamics, and which is a strong function of coal ash content.
2. The frequency with which wall blowers are used, which determines the period within which the deposit thickness can grow.
3. The furnace size, in terms of plan area heat-release rate, which determines the flame temperature and the heat flux through the ash deposit. An increase in furnace size per unit heat input reduces local heat flux.
4. The characteristics of the ash deposit, including thermal conductance, sintering temperature and sintering strength for the exposure period, and the strength of bonding to the furnace wall.
5. The energy available for wall blowing, based on jet size and steam or air pressure.

It is usual to evaluate the slagging characteristics of a candidate coal by some sort of slagging index based on ash analysis, fusion temperatures, or slag viscosity. Three indices of this type are the Silica Percentage, the Base/Acid ratio, and the Slagging Factor.

#### Furnace Heat Release Rate as a Factor in Furnace Slagging

Publications by the principal boiler manufacturers (1,2,3,4,5,6) show that, during the 1960's reliability of large boilers became an issue, and considerable effort was devoted to improving reliability. One obvious result of this effort was a move toward larger furnaces. Many of the existing furnaces proved to be of marginal size for the design coal, leaving no margin for changes in coal quality. Degradation of coal quality became common with changes in mining regulations and with changes in coal sources, and lead to slagging problems. The present practice of all boiler manufacturers is to provide furnaces larger than those common in the 1960's, to handle coals of higher ash content now being burned. These furnaces should be large enough to provide greater flexibility in handling a range of coals,

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References 1 through 6 are listed on page 10-4.

and should, thus, experience fewer slagging problems.

Table 10-1 lists published design values of plan area heat release rates for three boiler manufacturers, and includes both design and actual maximum continuous ratings for the five boilers tested during this project. The listed references report a reduction in heat-release rates in the early 1970's, corresponding to an increase in furnace plan area and volume for each class of coal. The actual achieved heat-release rates for all test boilers except Mill Creek fit the published present design ranges. Mill Creek, however, requires a larger furnace than the ranges indicated for two manufacturers, at about  $1.5$  to  $1.6 \times 10^6$  Btu/ft<sup>2</sup> hr of plan area. It would be expected that the allowable heat release for specific coals would be adjusted for coal slagging characteristic and ash content, driving Mill Creek to the low end of the range for Midwest coals.

### Slagging Index Correlations

Several slagging indices are discussed in the literature on furnace slagging, each intended to assist in the selection of furnace size to match a specific coal ash of known analysis. The following are representative:

1. The Silica Percentage, calculated as:

$$100 (\text{SiO}_2) / (\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO})$$

2. The Base-Acid Ratio, calculated as:

$$(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}) / (\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2)$$

3. The slagging Factor, calculated as:

$$(\text{Base-Acid Ratio}) \times (\text{percent sulfur})$$

One comparison method for evaluating the effects of ash characteristics is to plot furnace heat release rates against ash slagging indices. Table 10-1 includes both design values and achieved values of furnace plan area heat input rates for the five test boilers, and Table 10-2 lists slagging indices for these boilers.

In Figures 10-1, Slagging Factor is plotted against furnace plan area heat release rate for the five test boilers. Two sets of data are plotted: one curve shows the actual maximum continuous operating points, and the other shows the design continuous operating points. The actual continuous operating data plot on a nearly straight line for Mill Creek, Labadie, Morgantown, and Montour, and this line represents a realistic design basis for the coals fired. Furnaces should be operated at values represented by the area below or to the left of this curve. The point from Cliffside is far from this curve because this boiler is fired with

TABLE 10-1. DESIGN VALUES OF PLAN AREA HEAT RELEASE RATES

Boiler Manufacturer	References	Period	Fuel Type	10 <sup>6</sup> Btu/ft <sup>2</sup> Hr Plan Area
Combustion Engineering	Lyons <sup>(1)</sup>	1977	Eastern bituminous	2.07
			Midwest bituminous	1.79
			Texas lignite	1.65
			North plains lignite	1.47
CE	Harris <sup>(2)</sup>	1972	Eastern bituminous	1.8 - 2.5
			Midwest bituminous	1.7 - 2.0
			Subbituminous	1.7 - 2.0
			Oil	2.3 - 2.7
CE	Tuppeny <sup>(6)</sup>		All - 60's vs 70's	
Babcock & Wilcox	Gray <sup>(3)</sup> or	1970's	All coals	1.45 - 1.90
	Heil <sup>(4)</sup>	1960's	All coals	1.90 - 2.15
Foster Wheeler	Frederick <sup>(5)</sup>	1970's	All coals	1.70 - 2.00

Plan Area Heat Release Rates for Test Boilers

		Design	Actual
Labadie	Midwest bituminous	2.06	1.84
Mill Creek	Midwest bituminous	1.90	1.59
Cliffside	Eastern bituminous	2.06	1.89*
Morgantown	Eastern bituminous	2.57	2.28*
Montour	Eastern bituminous	2.15	2.28

\* Not slagging-limited.

References:

1. Lyons, D. E. and Blackburn, S. S., "Design for availability - An Update", Proc. American Power Conf., Vol. 39, 1977, pp 349-368.
2. Harris, D. A., "Effect of Various Fuels on Furnace Design", presented at REA Generating Conference, Owensboro, Kentucky, June, 1972.
3. Gray, R. J., Brauer, W. C., and Leland, S. C., "Design and Initial Operation of the Wyokak Plant", Proc. 1979 American Power Conference.
4. Heil, T. C., Durrant, O. W., "Designing Boilers for Western Coal", presented at Joint Power Generation Conference, Dallas Texas, Sept. 1978.
5. Fredrick, J. L and Pai, R. H., "A Primer of Design Considerations for Western Coal", Heat Engineering, Sept. 1977, Foster Wheeler Energy Corp.
6. Tuppeny, W. H., Jr. "Effects of Changing Coal Supply on Steam Generator Design", Proc American Power Conference, Vol 40, 1978, pp 367-380

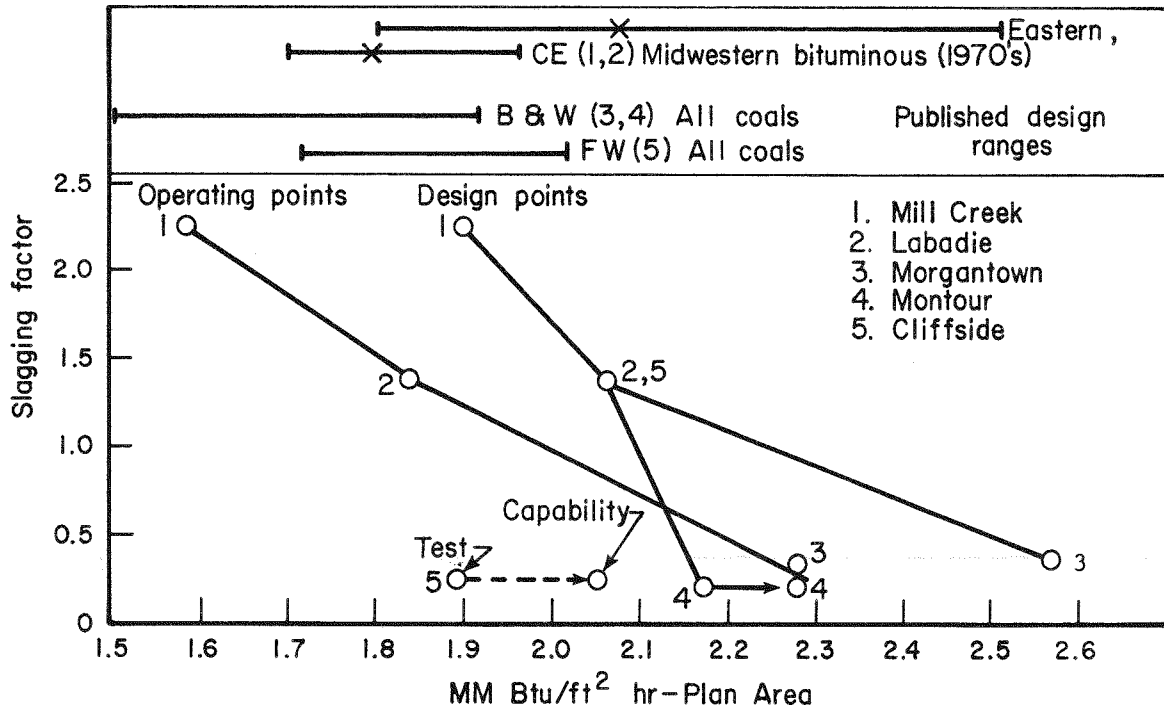


Figure 10-1. Relation of Slagging Factor to Plan Area Heat Release Rate

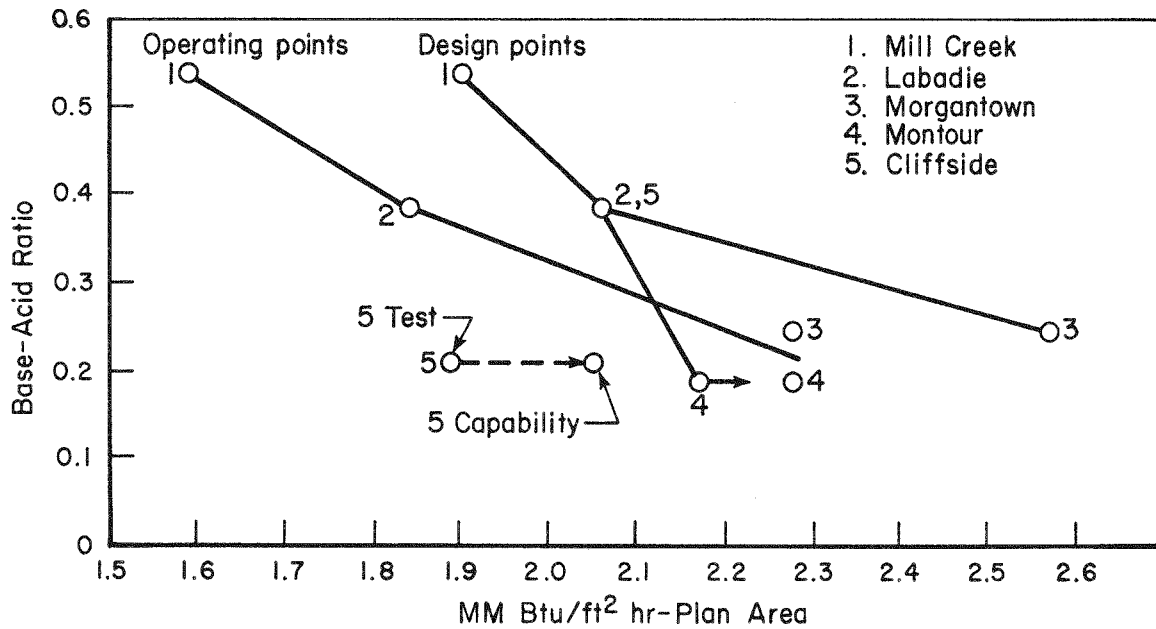


Figure 10-2. Relation of Base-Acid Ratio to Plan Area Heat Release Rate

a coal of low Slagging Factor and sized for a coal of high Slagging Factor (the design is identical to that of Labadie, but the Slagging Factor for the coal is much lower). The points for the design continuous operating point do not fall on a single curve. Points for Mill Creek and Labadie are to the right of the actual operating points, as these units are derated; points for Morgantown and Montour diverge widely for similar Slagging Factors but different design heat-release rates. The Montour boiler was operated slightly above its design point, and the Morgantown boiler was operated considerably below its design point although it was not slagging limited.

Published design ranges for plan area heat-release rates for three manufacturers, from Table 10-1, are plotted at the top of Figure 10-1 for comparison with operating points of the test boilers.

TABLE 10-2 VALUES OF CORRELATION PARAMETERS FOR RATING SLAGGING CHARACTERISTICS OF TEST COALS

	Coal Ash Content, percent	Coal HHV Btu/lb	Lb Ash per MM Btu	Base-Acid Ratio	Slagging Factor	Silica Percentage	Ash Softening Temp., F*
Labadie 4	11.8	12468	9.5	0.39	1.39	68	2060
Mill Creek	15.0	12289	12.2	0.54	2.26	59	2041
Cliffside	15.3	12808	12.0	0.21	0.25	81	2560
Morgantown	13.8	12993	10.6	0.25	0.35	75	2530
Montour	14.6	13231	11.0	0.19	0.21	80	2530

\* Reducing Atmosphere

Comparison of the operating point curve with the design point curve of Figure 10-1 shows the greatest divergence, 17 percent, for Mill Creek, less divergence, 7 percent, for Labadie, and divergence of 11 percent for Morgantown. Montour operated at 5 percent above the design rating. In reviewing coal characteristics, the most obvious difference between the design coals and the test coals was in ash content. Both the Mill Creek and Labadie coals had 33 percent more ash than the design coal, a significant difference. The ash contents of the Morgantown and Montour test coals were nearly identical to those of the design coals, and the ash content of the Cliffside test coal, at 15.3 percent, was 72 percent higher than the ash content of the design coal, at 8.9 percent. The difficulty of wall cleaning increases with increasing ash content, so that the increases in ash content could account for the derating shown for Labadie and Mill Creek.

In Figure 10-2 Base-Acid Ratio is plotted against plan area heat release rate. This plot is very similar to Figure 10-1, except that the differences in Base-Acid Ratio among the boilers is less than the difference in Slagging Factor, which is Base-Acid Ratio x sulfur content. The two highly slagging coals for Labadie and Mill Creek are both high-sulfur coals and the other three coals are low-sulfur coals, so that the differences between them are emphasized by use of the Slagging Factor. However, comparisons based on either Slagging Factor or Base-Acid ratio appear similar and would lead to the same conclusions. A comparison based on Silica Percentage would also be similar.

All the customary slagging indices predict that the Mill Creek coal has high slagging potential, the Labadie coal has moderate slagging potential, and the coals fired at Cliffside, Morgantown and Montour have low slagging potential. All are based on overall ash characteristics, but none includes a term for coal ash content, which effects wall cleanability and, thus, furnace slagging.

Effect of Furnace Ash Content on Furnace Cleaning

The furnace slagging observed at Labadie and Mill Creek resulted from the inability of wall blowers to clean ash deposits from the furnace walls on each operating cycle. Thus, wall cleanability is the key to minimizing slagging problems in these boilers.

Figure 10-3 is a nomograph developed by Hensel and Halfinger, of Combustion Engineering, to relate cleanability of furnace walls to coal ash properties and ash quantity. (6) They find it useful for predicting differences in cleanability for different coals in the same furnace, but have less confidence in its use for comparing cleanability of different boilers. It appears useful for evaluating the effects of ash content of Labadie and Mill Creek test coals, each of which contained 33 percent more ash than the design coal.

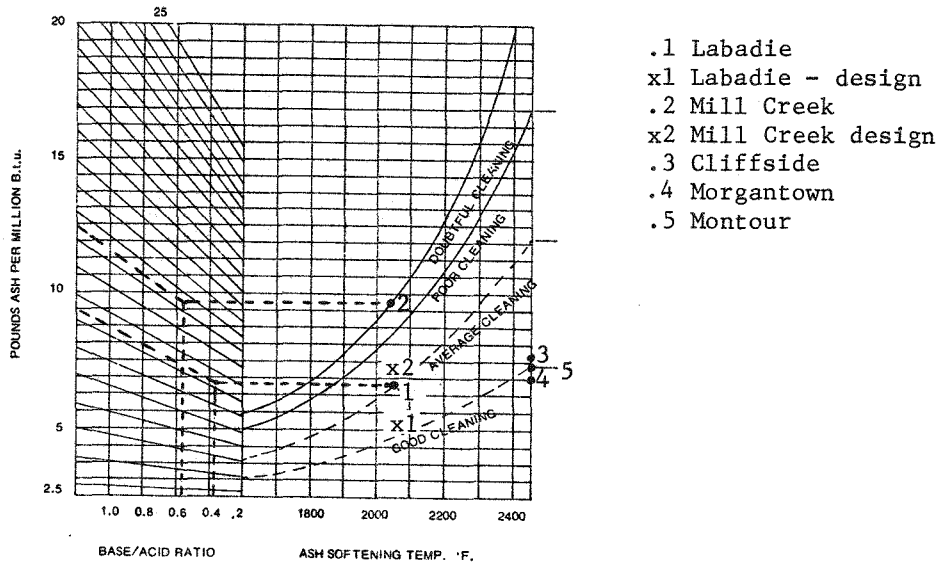


Figure 10-3. Nomograph relating Base-Acid Ratio, ash content, and ash softening temperature to furnace cleanability.

Date for test coals for the five test boilers are listed in Table 10-2 and plotted in Figure 10-4. Data for the design coals for Labadie and Mill Creek are also plotted to show the predicted effects of ash content. It was assumed that ash properties of the design coals were the same as those for the test coals, and that the ash contents were those specified for boiler design. The

plotted points representing coals fired at Cliffside, Morgantown, and Montour fall close to the upper limit of the "good cleaning" range. Operating experience confirms these predictions. Plotted points for the Labadie design coal and test coal both fall within the "average cleaning" range, but the low-ash design coal falls near the "good cleaning" range and the test coal falls at the boundary with "poor cleaning". The difference in ash content between the design coal and the test coal is predicted to increase the difficulty of wall cleaning. Early operating experience at Labadie with a coal having ash content close to that of the design coal was satisfactory, but experience with the test coal indicates that cleanability was unsatisfactory. The high ash content of the test coal could be the reason for current slagging problems. The ash content of the Mill Creek coal is high, and the point representing the design coal falls at the bottom of the "poor cleaning" range. However, the point representing the test coal falls at the top of the "doubtful cleaning" range. The large difference in ash content between the design coal and the test coal is predicted to result in cleaning difficulties, and this is confirmed by operating experience. We have no information on effects of firing a low-ash coal in this boiler.

From the data plotted in Figure 10-3 it is evident that the high ash contents of the Labadie and Mill Creek coals would be expected to make wall cleaning more difficult than for the design coals, and this effect was both predicted, and found to be greater at Mill Creek than at Labadie.

#### INSIGHTS FROM COAL AND ASH ANALYSES

##### Ash Analyses of Coal Density Fractions

Comparison of ash content and ash composition of coal density fractions showed marked differences among fractions of the same coal, and differences between slagging coals and non-slagging coals. The ash content of denser coal fractions was high, as the specific gravity of coal minerals is higher than that of coal. However, the ash composition and the calculated ash viscosity characteristics also showed wide differences among coal density fractions. The principal difference among the test coals was in the quantity of ash falling into the dense, severely slagging fractions. This quantity was high for slagging coals and low for non-slagging coals.

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6. Hensel, R.P., and Halfinger, G. G., "The Interpretation of Coal and Ash Analysis to Predict Unit Performance", presented at Industrial Coal Conference, University of Kentucky, April 13-14, 1966.

Table 10-3 summarizes ash content,  $T_{CV}^*$ , and slag viscosities at 2300 F and 2600 F for the highest-density fractions of the five test coals. The calculated slag viscosities are accurate for values above the  $T_{CV}$ ; slag viscosities for temperatures below the  $T_{CV}$  will be higher than the calculated values because solids precipitate as temperatures fall below  $T_{CV}$ , leading to a change in the slope of the viscosity curve not accommodated in the viscosity calculations. The data in Table 10-3 come from Table B-11, Appendix B. Total ash content for each coal was calculated by summation of ash in specific gravity fractions, and differs slightly from that determined for the total coal as listed in Table B-11.

TABLE 10-3. ASH CONTENT,  $T_{CV}$ , AND SLAG VISCOSITIES FOR HIGH DENSITY FRACTIONS OF FIVE TEST COALS

	Ash (1) Content	Sp gr of coal fraction	Percent of ash (2)	$T_{CV}$	Viscosity, poises	
					2600 F	2300 F
Labadie	11.45	1.6 x 2.0	9.5	2500 F	160	1600
		2.0 x 2.8	18.0	3200	15	70
		2.8 +	7.3	3600	1	3
		Total	34.8			
Mill Creek	14.15	1.6 x 2.0	8.0	2260	97	800
		2.0 x 2.8	27.7	2650	40	240
		2.8 +	14.6	2530	1	3
		Total	50.3			
Cliffside	14.31	2.0 x 2.8	41.0	2800	3200	26,300
		2.8 +	5.6	2280	1	3
Morgantown	12.42	2.0 x 2.8	35.0	2600	3700	23,000
		2.8 +	8.1	3100	1	3
Montour	12.77	2.0 x 2.8	46.9	2610	1600	11,000
		2.8 +	4.1	2360	1	3

1 Summation of ash in specific gravity fractions

2 Percentage of total coal ash in this fraction

All of the coals contained a small fraction of specific gravity above 2.8. The iron oxide content of this fraction ranged from 72 to 88 percent among the five coals, and the calculated slag viscosities were only 3 poises at 2300 F and 1 poise at 2600 F for the five coals. This would indicate that the ash in this coal fraction was present as fluid particles in the flame, and would be sticky on cooling to 2300 F. However,  $T_{CV}$  was above 2500 F for Labadie, Mill Creek, and Morgantown coals, indicating that this sticky deposit would contain precipitates and would not necessarily flow readily. The  $T_{CV}$  values for Cliffside and Montour coals were near 2300 F, indicating that, in these boilers, this small fraction of the coal would remain fluid at 2300 F. The quantity of the total coal ash falling in this plus-2.8 sp gr fraction ranged from 5.6 percent at Cliffside to 14.6 percent at Mill Creek.

\* Temperature of critical viscosity

A severely slagging fraction of coal in the 2.0-2.8 sp gr range was found at Labadie and Mill Creek. In this fraction, the Labadie coal contained 15.8 percent calcium oxide, and the Mill Creek coal contained 17.7 calcium oxide. The high calcium content resulted in very low calculated slag viscosities, although the  $T_{CV}$  was relatively high, at 3200 F for the Labadie fraction and 2650 F for the Mill Creek fraction. The ash from this fraction would be sticky, but slag viscosity would be well above the value calculated for 2300 F because of solids precipitation. The percentage of the total coal ash found in this fraction was 18 percent for the Labadie coal and 27.7 percent for the Mill Creek coal.

The 1.6 x 2.0 sp gr fraction of coals fired at Labadie and Mill Creek was enriched somewhat with iron, with the result that this fraction would be fluid in the flame at 2600 F. At 2300 F, however, ash from this fraction would be solid. Ash from coal in this density range fired at Cliffside, Morgantown, and Montour would be solid at 2600 F.

Table 10-4 shows the quantities of low-viscosity ash as percentages of the coal and as percentages of the ash for the five test boilers, and lists the viscosity of this ash at 2600 F. As shown in Table 10-3, ash from three coal density fractions of Mill Creek and Labadie coals would be fluid at 2600 F, and coal from only one density fraction of coals from Cliffside, Morgantown, and Montour would be fluid at 2600 F. Thus, 35 percent of the ash for Labadie coal, and 50 percent of the ash from Mill Creek coal, are concentrated in a small fraction of each coal of composition such as to produce fluid ash particles in the flame. In contrast, only 5.6, 8.1 and 4.1 percent of the ash from the three non-slagging coals is separable in a coal fraction producing fluid ash in the flame. It appears that this segregation of a large percentage of ash minerals into a small, separable fraction of the coal, in combinations that produce fluid ash in the flame, could result in more severe slagging characteristics than would be anticipated from the overall ash characteristics.

TABLE 10-4. PERCENT OF ASH THAT IS FLUID AT 2600 F IN COAL DENSITY FRACTIONS

Boiler	Sp. Gr of(1) coal fraction	Ash percent in coal		Fluid ash as percent of total ash	Viscosity of fluid ash, poises
		Total ash(2)	Fluid ash		
Labadie 4	1.6+	11.45	3.98	35	28
Mill Creek	1.6+	14.15	7.11	50	8
Cliffside	2.8+	14.31	0.80	5.6	1
Morgantown	2.8+	12.42	1.01	8.1	1
Montour	2.8+	12.77	0.52	4.1	1

- (1) Sp. Gr. above which ash in fraction has viscosity below 250 poises at 2600 F.  
(2) Summation of ash in specific gravity fractions.

Table 10-5 shows  $T_{cv}$  and slag viscosities at 2600 F and 2300 F for coal Test Composite samples. From these values it would appear that all of the ash from coals fired at Labadie and Mill Creek would be fluid in the flame at 2600 F, and none of it would be fluid at 2300 F. The more detailed information of Table 10-4 shows that a large percentage of the ash from separable density fractions of coal fired at Labadie and Mill Creek would have much lower viscosity than predicted by the composition of the Test Composite sample, and that some low-viscosity fluid ash particles are formed in burning the other coals.

TABLE 10-5. TEMPERATURE OF CRITICAL VISCOSITY, AND VISCOSITIES CALCULATED FOR ASH ANALYSES OF COAL COMPOSITE SAMPLES

	$T_{cv}$ , F	Slag viscosity, poises	
		2300 F	2600 F
Labadie 4	2500	1000	130
Mill Creek	2240	330	32
Cliffside	2400	6100	920
Morgantown	2600	(high)	550
Montour	2400	2250	860

It appears that the large percentage of low-viscosity ash was the source of the bulk of the furnace ash deposits at Labadie and Mill Creek. Microanalysis of the Labadie wall ash deposit, as discussed in Section 9, showed that much of the deposit was composed of fused, glassy spheres. These could have originated from the dense coal fraction described above, which would form the types of particles found in the wall deposit. The bulk of this material was so great that deposition of iron from the +2.8 specific gravity fraction in the wall deposits did not result in iron enrichment of furnace deposits.

#### Iron Enrichment of Furnace Ash Deposits

Iron enrichment of furnace ash deposits relative to iron content of the coal has been found in some furnaces, and can lead to slagging more severe than would be expected from the overall coal analysis. Such enrichment is attributed to segregation of pyrites in the pulverized coal, followed by selective deposition of the iron oxide on the furnace wall. This aspect of the furnace ash deposits for the five test boilers was also investigated.

Table 10-6 summarizes iron content, as  $Fe_2O_3$ , in coal, furnace deposits, and fly ash for the five test boilers. The furnace elevations listed are shown in Figure 3-1, with elevation A above the furnace nose, B below the furnace nose, C just above the burners, and D just below the burners. The iron in the coal is based on the Test Composite sample covering several days of testing, and the other analyses are based on a daily sample, so that the values of iron in coal samples may not correspond exactly to values for ash samples.

No iron enrichment of furnace ash is shown in Table 10-5 for Labadie or Mill Creek, the two boilers with the most severe slagging problems. Iron distribution was almost perfectly uniform at Cliffside. However, furnace deposits at Morgantown and Montour contained about 50 percent more iron than the coal. This high

TABLE 10-6. IRON CONTENT OF ASH IN COAL, FURNACE DEPOSITS, AND FLY ASH

	Coal	Furnace Deposits(elevation) <sup>(1)</sup>				Fly Ash	
		D	C	B	A	Economizer	ESP
Labadie 4	19.9	19.2	19.0	19.4	22.1	20.7	17.4
Mill Creek	24.5	19.5	19.2	19.8	19.4	27.4	21.1
Cliffside 5	10.4	11.9	12.1	11.2	11.3	10.2	10.3
Morgantown	14.0	21.5	19.2	16.8	25.7	17.5	13.9
Montour	8.0	16.8	10.2	9.2	69.9	13.7	9.3

(1) Elevations for each boiler are listed in Table 6-1 and shown in Figure 3-1 iron content lowered the slag viscosity, as shown in Table B-12, Appendix B, but slag viscosity was still high enough that slagging was not severe.

It is probable that the source of iron enrichment of furnace ash deposits at Montour and Morgantown was the coal density fraction with specific gravity above 2.8, as shown in Table 10-3. The ash of this dense coal fraction was high in iron and its viscosity was only 1 poise at 2600 F. This ash would be fluid in the flame and would stick to the furnace walls on impact. Much of the ash from the lighter coal fractions, representing most of the coal, was of such high viscosity at flame temperature that it would be less likely to stick to the walls. Thus, the fluid ash particles would be selectively caught on the furnace walls, and the densest coal fraction would be over-represented in the wall samples.

The coals fired at Labadie and Mill-Creek contained as much or more segregated, high-iron coal as the coals fired at Morgantown and Montour, but showed no iron enrichment of furnace wall deposits. However, 35 and 50 percent of the total ash, found in the coal fraction denser than 1.6 specific gravity, was of low viscosity and would be fluid in the flame. This ash would probably stick to the furnace walls on impact in such large quantities that the contribution of the densest, high-iron coal fraction would not be out of proportion with its percentage in the coal.

The relation of furnace ash characteristics to iron and calcium segregation in coal density fractions appears to be a fruitful subject for research. The amount of segregation can be measured readily by analysis of ash in coal density fractions.

The effects of this segregation on the composition of furnace deposits for the five test boilers appear explainable, but more data is needed before predictions could be based on coal analyses.

## Section 11

### PUBLICATIONS

Ten publications have resulted from the project to date, and one more is planned. Each of these had a different objective. They include a report on Phase 1, five site reports, the final report, and three technical papers. One more technical paper appears appropriate. The titles and objectives of these publications were as follows:

1. Interim Report on Influence of Mineral Matter of Coal on Fireside Slagging and Fouling of Utility Boilers, by R. E. Barrett and H. R. Hazard, July 8, 1977.

This report describes the selection and screening of candidate test boilers, and presents the proposed experimental program, including detailed summaries of test methods and data to be obtained.

2. Plant Test Report on Labadie Boilers 1 and 4, Union Electric Co.
3. Plant Test Report on Mill Creek Boiler No. 1, Louisville Gas and Electric Co.
4. Plant Test Report on Cliffside Boiler No. 5, Duke Power Company.
5. Plant Test Report on Morgantown Boiler No. 1, Potomac Electric Power Company.
6. Plant Test Report on Montour Boiler No. 1, Pennsylvania Power and Light Company.

The five plant test reports were written by David A. Trayser, Paul R. Webb, and Herbert R. Hazard.

Each plant test report summarizes all of the data obtained during the field trial at that plant, including listings of coal and ash samples, tabulations of coal and ash analyses, mapping of furnace temperatures and gas compositions, curves of load, attemperator water flow, and burner tilt angle throughout the test period, and information on the sources and analyses of coals fired. Much of this information is not included in the final report. The plant test reports serve as a repository of information available for future purposes.

7. Influence of Coal Mineral Matter on Slagging of Utility Boilers, by H. R. Hazard, John P. Dimmer, EPRI Project Manager. June 30, 1979.

This report summarizes all work done on the project. It includes the most important results and data from the six preceding reports and includes data analyses and correlations, and recommendations.

8. "Field Studies of Slagging in Tangentially Fired Boiler Furnaces - Part 1, Labadie Field Trial", by H. R. Hazard, R. E. Barrett, D. A. Trayser, P. R. Webb, and J. P. Dimmer. ASME Paper No. 78-WA/Fu-10. Presented at ASME Winter Annual Meeting, December 1978.

This paper summarized the Labadie field trial and included data on furnace temperatures, gas compositions, coal analyses, and ash analyses.

9. "Coal Mineral Matter and Furnace Slagging", by Herbert R. Hazard, Richard E. Barrett, and John P. Dimmer. Presented at the American Power Conference, April 25, 1979, at Chicago.

This paper describes the five field studies and presents data on coal analyses, ash analyses, and boiler characteristics. One feature of ash analyses was discussed: the distribution of iron in coal size fractions, coal density fractions, furnace ash, and fly ash.

10. "Composition and Microstructure of a Furnace Ash Deposit From a Coal-Fired Utility Boiler", by R. R. Fessler, A. J. Skidmore, H. R. Hazard, and John P. Dimmer. Submitted for presentation at the 1979 ASME Winter Annual Meeting, December 2-7, 1979.

This paper describes the structure and composition of samples of wall deposit from Labadie Boiler 4, as determined by SEM techniques.

APPENDIX A

Tables of Measured Furnace Gas Temperatures

Tables of Measured Furnace Gas Compositions

TABLE A-1. FURNACE GAS TEMPERATURES AT OUTLET, LABADIE BOILER 1

Traverse Distance(1)	Temperature, F						
	2(2)	3	4	5	6	7	8
2	2239	2249	2313	2225	2130	2170	2165
4	2263	2296	2290	2165	2090	2080	2200
6	2290	2315	2305	2165	2115	2080	2260
8	2340	2340	2310	2155	2100	2100	2260
10	2366	2379	2330	2165	2130	2145	2220
12	2384	2374	2318	2240	2100	2155	2255
14	2377	2375	2300	2230	2060	2180	2290
Average	2323	2333	2309	2192	2104	2130	2236
Overall avg.	2232						

(1) Distance in feet from boiler inside wall.

(2) Port number (typical).

TABLE A-2. FURNACE GAS TEMPERATURES, LABADIE BOILER 4

Traverse Distance(1)	Temperature, F															
	138-Foot Level				101-Foot Level				90-Foot Level				38-Foot Level			
	1(2)	4	8	9	1	2	3	4	1	2	3	4	1	2	3	4
2	2350	2240	2430	1850	2390	2470	2460	2570	2485	2485	2670	2690	2425	--	--	--
4	2385	2230	2405	1900	2380	2488	2470	2630	2535	2570	2710	2720	2460	2280	2505	2495
6	2410	2270	2410	1970	2445	2500	2490	2650	2540	2580	2680	2765	2475	2435	2480	2505
8	2380	2290	2425	2150	2520	2540	2510	2690	2635	2570	2700	2717	2490	2485	2550	2530
10	2340	2220	2455	1990	2565	2535	2515	2715	2650	2570	2725	2700	2520	2530	2607	2535
12	2275	2250	2465	1930	2580	2550	2446	2670	2600	2540	2750	2665	2530	2535	2625	2570
14	2250	2255	2475	2170	2620	2545	2390	2675	2720	2505	2770	2630	2490	2550	2670	2600
Average	2341	2251	2438	1994	2508	2511	2480	2648	2597	2543	2716	2697	2471	2484	2572	2540
Avg. front ports	2345				2537				2638				2517			
Overall avg.	2131				2537				2638				2517			

(1) Distance in feet from boiler inside wall.

(2) Port number (typical)

TABLE A-3. FURNACE GAS TEMPERATURES AT OUTLET, MILL CREEK BOILER 1

Traverse Distance <sup>(1)</sup>	Temperature, F							
	1 <sup>(2,3)</sup>	2	3	4	5	6	7	8 <sup>(3)</sup>
2	1949	2195	2356	2305	2217	2192	2191	1944
4	--	2237	2414	2311	2267	2184	2202	--
6	1993	2225	2414	2302	2310	2169	2226	2060
8	--	2226	2466	2327	2297	2214	2246	--
10	2017	2223	2426	2326	2298	2222	2231	2009
12	--	2240	2417	2300	2260	2233	2256	--
14	2066	2200	2362	2260	2224	2153	2278	2028
16	--	--	--	--	--	--	--	--
18	2100	--	--	--	--	--	--	2058
Average	2025	2221	2265	2304	2268	2195	2233	2020
Avg. front ports	2248							
Overall avg.	2191							

- (1) Distance in feet from boiler inside wall.
- (2) Port number (typical).
- (3) 20-foot probe (all others by 15-foot probe).

TABLE A-4. FURNACE GAS TEMPERATURES AT LOWER LEVELS, MILL CREEK BOILER 1

Traverse Distance <sup>(1)</sup>	Temperature, F											
	92-Foot Level				70-Foot Level				35-Foot Level			
	1 <sup>(2)</sup>	2	3	4	1	2	3	4	1	2	3	4
2	2514	2559	2348	2330	2498	2495	2502	2451	1530	1655	1743	1874
4	2596	2512	2395	2295	2610	2584	2482	2410	1775	1866	1931	1976
6	2619	2517	2396	2370	2579	2637	2481	2489	1862	2104	1961	1918
8	2532	2490	2453	2442	2630	2713	2414	2539	2025	2088	2018	1987
10	2521	2505	2456	2425	2609	2693	2562	2573	1895	2022	2071	2097
12	2516	2503	2472	2412	2627	2695	2568	2592	--	2155	2068	2127
14	2524	2564	2435	2431	2642	2728	2582	2643	--	1896	2090	2030
Average	2546	2521	2422	2386	2599	2649	2513	2528	1817	1969	1483	2001
Overall avg.	2469				2572				2943			

- (1) Distance in feet from boiler inside wall.
- (2) Port number (typical).

TABLE A-5. FURNACE GAS TEMPERATURES AT OUTLET, CLIFFSIDE BOILER 5

Traverse Distance <sup>(1)</sup>	Temperature, F						
	1(2,3)	2	4	5	7	8	9 <sup>(3)</sup>
2	--	2298	2398	2495	2355	2195	--
4	1908	2301	2415	2445	2355	2191	2235
6	--	2280	2372	2428	2350	2315	--
8	1935	2262	2378	2440	2339	2312	2314
10	--	2264	2383	2430	2347	2305	--
12	2010	2260	2378	2409	2350	2321	2312
14	--	2239	2335	2388	2330	2320	--
16	2150	--	--	--	--	--	2160
18	--	--	--	--	--	--	--
20	1746	--	--	--	--	--	2100
Average	1950	2272	2380	2434	2347	2347	2224
Avg. front ports	2356						
Overall avg.	2279						

- (1) Distance in feet from boiler inside wall.  
 (2) Port number (typical).  
 (3) 20-foot probe (all others by 15-foot probe).

TABLE A-6. FURNACE GAS TEMPERATURES AT LOWER LEVELS, CLIFFSIDE BOILER 5

Traverse Distance <sup>(1)</sup>	Temperature, F											
	115-Foot Level				90-Foot Level				38-Foot Level			
	1(2)	2	3	4	1	2	3	4	1	2	3	4
2	2575	2575	2475	2439	2511	2577	2365	2424	2192	2183	1982	1979
4	2522	2595	2500	2451	2634	2553	2520	2435	2286	2238	2054	2058
6	2538	2605	2545	2479	2700	2570	2580	2501	2351	2296	2090	2081
8	2573	2635	2584	2578	2720	2589	2662	2604	2351	2347	2125	2108
10	2556	2615	2621	2611	2671	2629	2679	2652	2344	2431	2136	2100
12	2530	2585	2624	2615	2625	2660	2665	2735	2314	2441	2122	2251
14	2534	2520	2616	2620	2575	2700	2703	2751	2304	2455	2122	2352
Average	2547	2590	2566	2542	2634	2611	2596	2586	2306	2342	2090	2133
Overall avg.	2561				2607				2218			

- (1) Distance in feet from boiler inside wall.  
 (2) Port number (typical).

TABLE A-7. FURNACE GAS TEMPERATURES, MORGANTOWN BOILER 1

Traverse Distance <sup>(1)</sup>	Temperature, F								
	121-Foot Level						83-Foot Level		
	1 <sup>(2)</sup>	2	3	4	5	6	2	3	4
2	2422	2135	2022	2327	2203	2225	2745	2595	2725
4	2407	2153	2082	2415	2294	2236	--	--	--
6	2414	2175	2120	2452	2320	2350	--	--	--
8	2434	2198	2145	2441	2374	2352	--	--	--
10	2434	2205	2158	2450	2387	2371	--	--	--
12	2413	2213	2178	2410	2365	2347	--	--	--
14	2327	2215	2220	2466	2380	2337	2698	2856	2806
Average	2407	2185	2132	2423	2332	2317	2722	2726	2766
Overall avg.	2299						2738		

- (1) Distance in feet from boiler inside wall.  
 (2) Port number (typical).

TABLE A-8. FURNACE GAS TEMPERATURES, MONTOUR BOILER 1

Traverse Distance <sup>(1)</sup>	Temperature, F								
	118-Foot Level						96-Foot Level		
	1	2	3	4	5	6	1-1/2	2	6
2	2298	2250	2444	2387	2405	2390	2647	2408	2398
4	2304	2330	2457	2435	2427	2420	2653	2433	2388
6	2348	2332	2447	2447	2436	2442	2662	2486	2420
8	2402	2356	2434	2450	2465	2451	2651	2488	2445
10	2433	2348	2426	2413	2460	2469	2664	2479	2470
12	2455	2339	2416	2407	2453	2436	2626	2460	2474
14	2447	2356	2417	2405	2457	2464	2650	2418	2445
Average	2384	2330	2434	2421	2443	2439	2650	2453	2434
Overall avg.	2409						2512		
	2444								

- (1) Distance in feet from boiler inside wall.  
 (2) Port number (typical).

TABLE A-9. FURNACE GAS COMPOSITION AT OUTLET, LABADIE BOILER 1

Traverse Distance (1)	138-Foot Level						
	2(2)	3	4	5	6	7	8
	<u>CO<sub>2</sub>, percent</u>						
2	14.8	12.8	15.0	15.0	15.0	14.8	11.4
4	--	--	--	--	14.0	14.4	11.2
6	--	--	--	12.8	15.3	14.8	12.8
8	--	--	--	--	13.4	14.0	12.0
10	--	11.5	14.5	--	14.6	14.8	13.8
12	--	--	--	10.6	13.5	14.2	12.2
14	--	10.5	11.8	15.0	12.6	15.0	13.8
	<u>O<sub>2</sub>, percent</u>						
2	3.7	7.4	8.7	3.2	--	3.4	7.4
14	--	9.5	4.0	3.0	5.1	3.7	5.2

(1) Distance in feet from boiler inside wall.

(2) Port number (typical).

TABLE A-10. FURNACE GAS COMPOSITION, LABADIE BOILER 4

Traverse Distance (1)	138-Foot Level				101-Foot Level				90-Foot Level				38-Foot Level			
	1(2)	4	8	9	1	2	3	4	1	2	3	4	1	2	3	4
	<u>CO<sub>2</sub>, percent</u>															
2	9.4	12.4	12.4	13.2	4.0	8.8	9.0	9.6	8.4	7.8	11.2	12.0	10.2	-	-	-
4	14.0	13.8	13.2	13.8	10.8	10.6	8.8	11.2	11.0	11.4	12.4	12.0	13.8	7.4	11.8	10.0
6	13.0	13.8	15.6	-	12.0	12.6	6.0	11.8	11.2	12.0	12.2	12.0	8.2	10.2	12.4	13.4
8	13.8	12.0	14.2	14.2	12.8	12.6	2.0	12.6	12.4	-	12.8	10.0	13.8	12.4	-	12.5
10	10.8	14.0	13.6	14.2	10.4	12.6	2.5	12.0	10.0	11.6	13.2	8.2	11.2	-	12.2	13.8
12	13.0	12.8	14.2	-	12.2	12.6	1.0	12.0	12.0	8.6	12.8	9.6	13.0	14.0	13.6	12.6
14	13.8	14.0	14.2	14.2	14.0	12.2	1.6	9.6	13.6	10.0	11.6	9.4	3.6	13.3	11.8	12.8
	<u>O<sub>2</sub>, percent</u>															
2	4.0	5.6	5.8	4.8	9.0	10.2	11.4	9.6	9.6	11.0	5.8	7.0	6.4	-	7.2	9.0
14	5.2	4.8	4.8	5.0	6.0	7.0	19.2	10.2	6.0	9.4	7.2	10.8	16.8	-	4.4	5.6

(1) Distance in feet from boiler inside wall.

(2) Port number (typical).

TABLE A-11. GAS COMPOSITION AT FURNACE OUTLET, MILL CREEK BOILER 1

Traverse Distance(1)	1(2;3) 2 3 4 5 6 7 8(3)							
	<u>CO<sub>2</sub>, percent</u>							
2	12.6	13.8	13.8	13.6	13.8	13.2	12.8	12.8
4	--	14.0	14.0	13.8	14.0	14.0	13.6	--
6	13.0	13.4	13.6	14.2	14.0	14.0	14.2	12.4
8	--	13.4	13.4	14.0	14.4	14.0	13.4	--
10	12.6	13.4	13.4	14.2	14.0	14.4	13.4	12.4
12	--	13.2	12.8	13.8	13.6	14.0	13.6	--
14	11.6	13.6	11.8	14.0	13.8	14.2	13.4	13.0
16	--	--	--	--	--	--	--	--
18	12.8	--	--	--	--	--	--	13.4
	<u>O<sub>2</sub>, percent</u>							
2	6.0	5.0	5.4	5.4	5.6	5.6	5.8	5.6
4	--	4.8	5.2	5.4	5.0	4.6	5.6	--
6	5.6	5.6	5.4	5.0	5.2	5.0	4.6	7.0
8	--	5.8	5.8	5.2	5.2	5.0	5.2	--
10	6.6	5.8	5.8	5.0	5.2	4.8	5.2	5.6
12	--	6.0	6.8	5.6	5.8	5.2	5.6	--
14	6.4	5.4	8.0	5.2	5.4	5.0	5.2	6.4
16	--	--	--	--	--	--	--	--
18	6.4	--	--	--	--	--	--	5.8

- (1) Distance in feet from boiler inside wall.
- (2) Port number (typical).
- (3) 20-foot probe (all others by 15-foot probe).

TABLE A-12. GAS COMPOSITION AT LOWER LEVELS, MILL CREEK BOILER 1

Traverse Distance(1)	92-Foot Level				70-Foot Level				35-Foot Level			
	1(2)	2	3	4	1	2	3	4	1	2	3	4
	<u>CO<sub>2</sub>, percent</u>											
2	13.8	14.0	11.8	11.0	9.0	9.6	10.4	8.0	2.2	4.0	4.8	6.8
4	14.0	15.6	11.2	11.4	11.0	10.4	10.4	8.2	2.8	6.0	4.0	6.0
6	14.4	13.8	12.0	11.8	10.2	11.0	9.6	8.8	2.2	5.8	3.8	6.8
8	13.8	14.0	11.6	13.2	11.0	12.0	9.6	8.0	1.0	6.4	3.0	6.0
10	15.4	14.2	12.2	12.6	9.8	-	11.0	7.8	-	4.4	2.6	5.6
12	14.0	14.5	11.8	12.6	9.6	10.0	10.4	8.0	-	2.0	2.8	7.0
14	13.8	13.8	12.0	12.0	9.0	11.4	10.5	8.8	-	3.2	1.6	5.6
	<u>O<sub>2</sub>, percent</u>											
2	4.4	4.6	7.5	7.6	9.6	10.0	8.2	11.4	21.1	16.2	15.6	12.8
4	-	3.4	-	8.4	5.9	-	-	11.5	-	-	-	14.0
6	5.0	-	7.4	-	-	8.6	9.6	-	-	-	-	-
8	4.8	4.0	7.2	5.8	9.0	8.2	9.6	11.8	19.2	13.9	17.8	14.2
10	3.3	4.2	7.5	-	-	-	7.8	-	-	-	17.0	-
12	-	5.0	-	6.6	10.2	-	-	11.3	-	19.2	-	-
14	5.4	-	7.8	6.6	10.4	8.0	8.9	10.4	-	17.4	19.2	14.8

- (1) Distance in feet from boiler inside wall.
- (2) Port number (typical).

TABLE A-13. FURNACE GAS COMPOSITION AT OUTLET, CLIFFSIDE BOILER 5

Traverse Distance (1)	Furnace Gas Composition							
	1 (2,3)	2	4	5	7	8	9	
<u>CO<sub>2</sub>, percent</u>								
2	--	14.0	17.0	15.4	15.8	16.4	--	
4	16.4	15.8	16.8	16.0	17.0	16.4	17.4	
6	--	15.0	16.4	16.0	16.6	16.6	--	
8	16.0	15.4	16.4	16.2	16.6	17.2	17.8	
10	--	16.4	16.4	16.4	16.4	17.0	--	
12	16.2	16.6	16.0	16.4	16.6	17.2	17.4	
14	--	16.6	15.8	16.6	16.4	17.4	--	
16	16.8	--	--	--	--	--	15.0	
18	--	--	--	--	--	--	--	
20	17.0	--	--	--	--	--	16.0	
<u>O<sub>2</sub>, percent</u>								
2	--	5.0	2.0	3.4	3.0	2.8	--	
4	2.6	3.0	2.2	3.0	2.0	3.0	1.4	
6	--	4.0	2.6	3.0	2.2	2.4	--	
8	3.2	3.6	2.8	3.0	2.0	2.0	1.4	
10	--	2.8	2.6	2.6	2.6	2.2	--	
12	3.0	2.8	3.0	2.4	2.2	1.8	1.6	
14	--	2.8	3.2	2.6	2.6	1.6	--	
16	2.2	--	--	--	--	--	4.0	
18	--	--	--	--	--	--	--	
20	2.0	--	--	--	--	--	3.0	

- (1) Distance in feet from boiler inside wall.
- (2) Port number (typical).
- (3) 20-foot probe (all others by 15-foot probe).

TABLE A-14. FURNACE GAS COMPOSITION AT LOWER LEVELS, CLIFFSIDE BOILER 5

Traverse Distance (1)	115-Foot Level				90-Foot Level				38-Foot Level			
	1 (2)	2	3	4	1	2	3	4	1	2	3	4
<u>CO<sub>2</sub>, percent</u>												
2	12.2	12.7	13.6	14.0	12.7	13.8	6.2	10.0	13.0	8.0	-	11.4
4	13.2	13.8	14.0	15.4	10.8	14.4	11.8	8.0	15.7	13.0	12.2	11.4
6	13.4	11.0	14.0	13.0	14.2	13.4	13.0	12.0	16.0	10.2	12.4	12.6
8	13.2	14.0	13.8	15.2	13.0	15.4	14.4	10.0	17.3	8.0	12.5	12.4
10	14.8	14.4	14.2	12.4	14.6	12.8	8.0	13.4	16.6	18.1	12.2	11.4
12	16.0	14.2	14.0	14.6	13.2	13.5	14.6	14.4	17.0	18.0	13.0	12.4
14	15.0	13.9	15.2	13.8	12.6	13.8	11.2	14.0	16.2	17.5	12.2	14.0
<u>O<sub>2</sub>, percent</u>												
2	7.0	4.5	5.8	4.8	6.5	5.0	9.6	9.0	6.2	12.6	-	6.0
4	7.0	5.6	5.6	4.6	6.0	5.8	7.8	9.2	3.6	6.6	8.0	8.8
6	6.0	8.8	5.4	5.2	4.7	6.6	6.3	7.2	3.0	10.1	7.4	7.4
8	6.8	5.2	4.6	3.8	6.0	4.3	4.8	7.3	1.5	11.8	6.8	6.6
10	4.2	4.8	5.0	5.6	4.0	6.2	5.2	5.2	2.0	0.4	5.6	7.6
12	3.2	5.2	4.4	4.0	5.2	5.6	5.0	3.2	1.6	1.2	6.6	7.2
14	4.2	5.7	4.0	5.2	6.6	6.0	4.4	5.0	2.2	0.5	4.6	5.6

- (1) Distance in feet from boiler inside wall.
- (2) Port number (typical).

TABLE A-15. FURNACE GAS COMPOSITION, MORGANTOWN BOILER 1

Traverse Distance(1)	121-Foot Level						83-Foot Level			
	1(2)	2	3	4	5	6	2	3	4	5
	<u>CO<sub>2</sub>, percent</u>									
2	14.6	16.2	16.0	13.6	14.6	11.0	12.6	13.2	11.3	11.8
4	16.7	14.4	16.8	13.9	14.3	11.8	-	-	-	-
6	16.3	13.9	15.6	15.2	14.7	16.2	10.2	16.4	12.3	13.6
8	16.8	13.8	15.0	15.0	15.2	14.7	-	-	-	-
10	16.0	13.6	15.0	15.0	15.2	16.6	11.4	17.0	13.4	11.4
12	16.1	15.8	15.0	14.8	15.2	15.4	-	-	-	-
14	16.0	16.2	15.0	14.7	15.3	14.0	10.0	15.3	11.2	11.3
	<u>O<sub>2</sub>, percent</u>									
2	4.2	2.6	2.2	6.2	5.1	6.4	6.4	5.8	6.3	7.2
4	2.4	4.6	2.1	5.5	5.2	7.6	-	-	-	-
6	2.1	5.3	3.4	3.8	4.5	2.7	8.8	2.0	6.7	5.4
8	1.9	5.4	4.3	4.0	4.2	4.5	-	-	-	-
10	3.4	5.6	3.9	4.2	3.9	2.7	8.0	1.1	5.6	7.9
12	2.9	3.2	4.1	4.5	3.9	3.8	-	-	-	-
14	2.7	2.9	4.0	4.6	3.8	5.7	7.0	2.5	7.2	8.2

(1) Distance in feet from boiler inside wall.

(2) Port number (typical).

TABLE A-16. FURNACE GAS COMPOSITION, MONTOUR BOILER 1

Traverse Distance(1)	118-Foot Level						96-Foot Level		
	1(2)	2	3	4	5	6	1-1/2	2	6
	<u>CO<sub>2</sub>, percent</u>								
2	8.6	10.2	12.2	14.0	12.8	12.8	5.6	10.2	8.2
4	8.4	9.4	-	-	-	-	9.6	10.8	6.4
6	4.8	3.2	13.7	14.2	13.4	12.7	9.3	10.4	7.4
8	8.4	12.4	-	-	-	-	8.6	10.6	8.6
10	7.2	12.0	15.0	13.4	13.2	13.2	12.1	8.3	7.7
12	6.8	12.2	-	-	-	-	8.0	9.2	8.6
14	8.4	12.0	14.3	14.0	13.8	13.6	11.2	8.2	9.6
	<u>O<sub>2</sub>, percent</u>								
2	10.8	6.8	6.3	5.0	5.9	6.0	14.0	9.4	11.9
4	11.4	8.7	-	-	-	-	9.8	8.8	13.4
6	16.4	16.2	4.9	4.4	5.6	6.1	10.5	9.6	13.0
8	11.6	6.6	-	-	-	-	11.4	9.0	11.0
10	13.2	7.4	4.4	5.0	5.4	5.8	7.3	11.8	12.5
12	13.2	7.0	-	-	-	-	12.0	10.8	11.2
14	11.6	7.0	4.9	5.0	5.0	5.4	8.0	11.8	10.8

(1) Distance in feet from boiler inside wall.

(2) Port number (typical).

APPENDIX B

Coal and Ash Analyses

TABLE B-1. COAL PROXIMATE ANALYSES, PERCENT, LABADIE 1

Date, 1977 & Mill	Sample Number	Proximate Analysis, percent			
		Moisture	Dry Basis		
			Ash	Volatile Matter	Fixed Carbon
8-11	A 101	3.75	12.72	36.01	51.27
	B 102	4.46	13.85	36.33	49.82
	C 103	4.48	13.38	36.54	50.08
	D 104	4.07	12.78	38.53	48.69
	E 105	3.10	14.20	36.55	49.25
	F 106	3.89	13.00	37.79	49.21
	360(1)	3.94	13.34	36.55	50.11
8-12	A 107	4.11	13.63	38.25	48.12
	B 108	10.22	14.15	32.96	52.89
	C 109	4.39	12.14	39.26	48.60
	D 110	4.17	12.22	39.01	48.77
	E 111	3.44	12.26	38.56	49.18
	F 112	4.70	11.82	40.45	47.73
	361(1)	3.71	12.30	37.86	49.84
8-13	A 113	3.02	12.55	38.87	48.58
	B 114	3.01	12.34	39.93	47.73
	C 115	2.63	12.02	37.99	49.99
	D 116	2.72	12.69	39.71	47.60
	E 117	4.01	12.08	39.41	48.51
	F 118	4.04	11.53	41.15	47.32
	362 (1)	4.14	12.01	39.62	48.37
8-17	A 291	7.49	13.12	38.51	48.37
	B 292	9.34	13.24	36.82	49.94
	C 293	8.48	13.93	55.02	31.05
	D 294	2.42	13.17	24.52	62.31
	E 295	8.83	13.05	36.78	50.17
	F 296	8.92	12.04	39.01	48.95
	363(1)	8.67	11.73	38.92	49.35
364(2)	3.7	12.63	38.68	48.69	

(1) Daily composite

(2) Test composite: 3.28% Sulfur, 12,468 Btu/lb dry

TABLE B-1 COAL PROXIMATE ANALYSES, PERCENT, LABADIE 4

Date, 1977	Sample Number	Proximate Analysis, percent			
		Moisture	Dry Basis		
			Ash	Volatile Matter	Fixed Carbon
9-12	A 156	4.82	10.85	39.55	49.60
	B 157	3.67	10.59	40.20	49.21
	C 158	3.14	11.03	38.34	50.63
	D 159	4.03	10.47	39.78	49.75
	E 160	4.37	10.51	39.73	49.76
	F 161	3.37	10.82	40.58	48.60
	365(1)	4.46	10.76	40.68	48.56
9-13	A 162	3.83	11.66	42.13	46.21
	B 163	3.91	11.64	40.59	47.77
	C 164	3.48	12.29	40.18	47.53
	D 165	3.50	10.55	41.73	47.72
	E 166	3.90	10.59	42.16	47.25
	F 167	4.45	10.53	39.81	49.66
	366(1)	4.26	12.44	39.88	47.68
9-14	A 168	4.29	12.46	39.24	48.30
	B 169	4.39	12.21	38.60	49.19
	C 170	4.43	12.96	37.63	49.41
	D 171	3.96	11.89	37.02	51.09
	E 172	3.15	12.93	39.05	48.02
	F 173	4.34	12.32	39.47	48.21
	367(1)	3.38	13.48	39.69	46.83
9-15	A 174	4.06	12.33	40.07	47.60
	B 175	4.22	12.19	41.09	46.72
	C 176	3.50	12.53	40.66	46.81
	D 177	4.08	11.71	40.63	47.66
	E 178	4.01	12.50	39.73	47.77
	F 179	4.26	12.11	40.48	47.41
	368(1)	2.86	14.23	37.43	48.34
369(2)	3.99	11.78	39.83	48.39	

(1) Daily composite.

(2) Test composite: 3.54 % Sulfur, 12,468 Btu/lb dry.

TABLE B-1 COAL PROXIMATE ANALYSES, MILL CREEK 1

Date, 1977	Sample Number	Proximate Analysis, percent			
		Dry Basis			
		Moisture	Ash	Volatile Matter	Fixed Carbon
10-11	A 404	3.71	13.22	39.61	47.17
	B 403	3.01	13.85	39.32	46.83
	C 402	3.16	13.19	39.13	47.68
	D 401	3.52	13.19	38.87	47.94
	530 (1)	2.98	16.39	37.26	46.35
10-12	A 408	2.97	16.09	38.01	45.90
	B 407	3.45	13.92	37.64	48.44
	C 406	3.56	13.51	37.79	48.70
	D 405	3.00	13.72	38.51	47.77
	531 (1)	3.02	17.01	35.81	47.18
10-13	A 412	2.99	16.29	37.33	46.38
	B 411	2.95	14.69	37.66	47.65
	C 410	3.05	16.49	35.64	47.87
	D 409	3.26	15.54	35.83	48.63
	532 (1)	4.60	11.31	40.55	48.14
10-14	A 416	2.82	16.86	37.48	45.66
	B 415	2.85	16.28	37.08	46.64
	C 414	3.68	16.40	38.63	44.97
	D 413	3.17	16.26	38.39	45.35
	533 (1)	4.55	12.75	40.86	46.39
	534 (2)	2.49	14.96	38.94	46.10

(1) Daily composite.

(2) Test composite: 4.15 % Sulfur, 12,289 Btu/lb dry

TABLE B-1. COAL PROXIMATE ANALYSES, CLIFFSIDE 5

Date, 1977	Sample Number	Proximate Analysis, percent			
		Dry Basis			
		Moisture	Ash	Volatile Matter	Fixed Carbon
11-1	A 601	.85	16.12	29.75	54.13
	B 602	1.20	16.21	29.46	54.33
	C 615	.95	15.01	30.59	54.40
	D 616	.91	15.03	30.43	54.54
	E 631	.89	15.22	30.76	54.02
	F 632	.89	15.99	30.20	53.81
	770 (1)	1.06	14.04	29.64	56.32
11-2	A 663	1.06	13.84	30.98	55.18
	B 664	.94	14.02	29.73	56.25
	C 648	1.03	13.86	31.37	54.77
	D 647	1.07	13.95	30.89	55.16
	E 634	1.27	15.12	31.65	53.23
	F 633	1.20	13.63	31.00	55.37
	771 (1)	0.73	15.70	29.18	55.12
11-3	A 683	.95	15.30	30.32	54.38
	B 684	.95	15.45	30.57	53.98
	C 699	1.17	16.24	29.77	53.99
	D 700	1.12	15.57	30.62	53.81
	E 713	1.00	15.23	31.23	53.54
	F 714	1.05	15.22	30.76	54.02
	772 (1)	0.94	15.59	29.97	54.44
11-4	A 716	.95	15.16	30.73	54.11
	B 717	.88	17.35	29.87	52.78
	C 732	1.12	15.67	30.37	53.96
	D 733	1.02	15.91	29.82	54.27
	E 746	.97	15.73	29.83	54.44
	F 747 (1)	1.05	14.09	30.82	55.09
	773 (1)	0.96	15.71	30.86	53.43
	774 (2)	0.79	15.26	30.28	54.46

(1) Daily composite.

(2) Test composite; 1.23 percent Sulfur, 12,808 Btu/lb dry.

TABLE B-1 COAL PROXIMATE ANALYSES, PERCENT, MORGANTOWN 1

Date, 1978 & Mill	Sample Number	Proximate Analysis, percent			
		Moisture	Ash	Dry Basis	
Volatile	Fixed Carbon				
5-2	A 901	2.49	13.08	22.76	64.16
	B 902	1.68	13.84	24.15	62.01
	C 903	2.62	15.63	23.72	60.65
	D 904	2.16	14.65	23.18	62.17
	E 905	1.97	14.96	22.62	62.42
	980(1)	2.14	14.34	23.27	62.29
5-3	A 948	1.14	12.36	23.97	63.67
	B 949	1.39	13.20	26.34	60.46
	C 950	1.33	13.85	26.33	59.82
	D 951	1.33	13.88	26.22	59.90
	E 952	1.20	13.33	26.56	60.11
	981(1)	1.20	12.95	26.63	60.42
982(2)	0.87	13.84	25.01	61.15	

(1) Daily composite

(2) Test composite: 1.40% Sulfur, 12,933 Btu/lb

TABLE B-1 COAL PROXIMATE ANALYSES, PERCENT, MONTOUR 1

Date, 1978 & Mill	Sample Number	Proximate Analysis, percent			
		Moisture	Ash	Dry Basis	
Volatile	Fixed Carbon				
5-16	A 1007	0.78	15.26	24.29	60.45
	B 1008	0.29	13.00	25.16	61.84
	C 1009	0.58	14.95	24.47	60.58
	D 1010	0.21	15.64	24.50	59.86
	E 1011	0.26	14.01	25.07	60.92
	F 1012	0.34	13.29	25.57	61.14
1080(1)	0.25	14.77	25.04	60.19	
5-17	A 1051	0.25	14.55	25.15	60.30
	B 1052	0.27	14.48	25.07	60.45
	C 1053	0.38	13.71	24.83	61.46
	D 1054	0.27	16.70	24.46	58.84
	E 1055	0.40	14.62	25.05	60.33
	F 1056	0.39	14.28	25.02	60.70
1081(1)	0.52	14.66	24.91	60.43	
5-18	A 1057	0.57	14.33	24.85	60.82
	B 1058	0.52	14.21	24.83	60.96
	C 1059	0.28	13.39	25.34	61.27
	D 1060	0.38	16.84	24.35	58.81
	E 1061	0.39	14.53	24.91	60.56
	F 1062	0.38	14.04	25.12	60.84
1082(1)	0.46	14.53	24.64	60.83	
1083(2)	0.28	14.62	25.33	60.05	

(1) Daily composite

(2) Test composite: 1.06% Sulfur, 13,231 Btu/lb.

TABLE B-2.COAL ULTIMATE ANALYSES,  
PERCENT, LABADIE 1

Sample No.	360	361	362
Ash	13.7	12.7	12.5
Hydrogen	5.16	5.10	5.25
Carbon	67.3	68.0	67.4
Sulfur	2.99	3.41	3.41
Nitrogen	1.44	1.16	1.24
Oxygen	9.37	9.65	10.27

TABLE B-2.COAL ULTIMATE ANALYSES,  
PERCENT, LABADIE 4

Sample No.	365	366	367	368
Ash	11.0	11.6	15.0	13.0
Hydrogen	5.06	5.38	5.19	5.51
Carbon	69.2	69.0	68.5	68.6
Sulfur	3.41	3.50	3.73	3.84
Nitrogen	1.35	1.26	1.35	1.46
Oxygen	9.91	9.21	6.28	7.56

TABLE B-2 COAL ULTIMATE ANALYSES  
PERCENT, MILL CREEK 1

Sample No.	530	531	532	533
Ash	14.10	14.85	16.36	17.43
Hydrogen	5.11	5.20	4.90	5.05
Carbon	67.42	68.41	68.57	65.43
Nitrogen	1.49	1.18	1.45	1.21
Sulfur	4.29	4.29	4.21	4.12
Oxygen	7.59	6.07	4.51	6.76

TABLE B-2 COAL ULTIMATE ANALYSES,  
PERCENT, CLIFFSIDE 5

Sample No.	770	771	772	773
Ash	15.54	14.11	15.55	15.87
Hydrogen	4.63	4.94	4.83	4.61
Carbon	71.40	73.23	72.02	71.24
Nitrogen	1.45	1.25	1.41	1.21
Sulfur	1.42	1.03	1.16	1.34
Oxygen	5.56	5.44	5.03	5.73

TABLE B-2 COAL ULTIMATE ANALYSES,  
MONTOUR 1, PERCENT

Ash	14.55
Hydrogen	4.64
Nitrogen	1.34
Sulfur	1.06
Oxygen	4.33
Carbon	74.08

Sample No. 1083 - 13,231 Btu/lb

TABLE B-2 . COAL ULTIMATE ANALYSES,  
MORGANTOWN 1, PERCENT

Ash	13.88
Hydrogen	4.62
Carbon	72.78
Nitrogen	1.42
Sulfur	1.40
Oxygen	5.90

Sample No. 982 - 12,933 Btu/lb

TABLE B-3. COAL SCREEN ANALYSES, LABADIE 1

Sample No.	Mill	U. S. Standard mesh size					
		+50	+100	+200	+325	-200	-325
113	A	-	6.8	25.6	46.7	74.4	53.3
114	B	-	6.2	27.3	48.6	72.8	51.4
115	C	-	13.4	37.6	58.0	62.4	42.0
116	D	-	3.3	19.3	42.4	80.7	57.6
117	E	-	13.1	37.8	60.5	62.2	39.5
118	F	-	15.9	42.7	64.6	57.4	35.4
	Average	-	10.0	31.7	53.5	68.3	46.5
362	Composite	-	10.0	31.1	42.0	68.3	58.0

TABLE B-3 . COAL SCREEN ANALYSES, CLIFFSIDE 5

Sample No.	Mill	U. S. Standard screen size					
		+50	+100	+200	+325	-200	-325
663	A	-	15.7	38.6	58.2	61.4	41.9
664	B	-	13.5	33.1	56.3	66.9	43.7
648	C	-	13.7	37.7	57.6	62.3	42.4
647	D	-	17.4	40.2	58.8	59.8	41.2
634	E	-	13.1	33.9	53.9	66.1	46.1
633	F	-	7.5	24.9	57.1	75.2	42.9
	Average	-	13.5	34.7	57.0	65.3	43.0
771	Composite	-	13.4	34.6	46.6	65.4	44.6
716	A	-	16.2	39.3	50.9	60.7	49.1
717	B	-	14.0	33.6	48.2	66.5	51.8
732	C	-	13.5	37.2	52.8	62.8	47.2
733	D	-	14.9	37.2	50.3	62.7	49.7
746	E	-	12.9	34.3	45.6	65.7	54.4
747	F	-	10.4	31.5	47.7	68.5	52.4
	Average	-	13.7	35.5	49.2	64.5	50.8
773	Composite	-	14.0	33.2	36.7	66.8	63.3

TABLE B-3. COAL SCREEN ANALYSIS, MORGANTOWN 1 CUMULATIVE PERCENT

Sample No.	Mill	U. S. Standard screen size					
		+50	+100	+200	+325	-200	-325
948	A	1.7	6.8	24.3	52.0	75.7	48.0
949	B	2.2	7.4	17.8	40.9	82.2	59.1
950	C	0	2.4	14.4	43.1	85.6	56.9
951	D	0	0.5	7.9	33.0	92.1	67.0
952	E	0	0.7	8.0	36.7	92.0	63.3
	Average	0.8	3.6	14.5	41.1	85.5	58.9

TABLE B-3 . COAL SCREEN ANALYSES, LABADIE 4

Sample No.	Mill	U. S. Standard screen size					
		+50	+100	+200	+325	-200	-325
162	A	-	12.0	33.8	55.1	66.2	44.9
163	B	-	12.0	36.6	59.2	63.5	40.8
164	C	-	7.8	24.5	46.1	75.5	53.9
165	D	-	22.6	53.0	73.6	47.0	26.4
166	E	-	9.2	34.0	58.0	66.0	42.0
167	F	-	9.8	32.2	55.1	67.8	43.9
	Average	-	12.3	35.7	58.0	64.3	42.0
366	Composite	-	12.9	36.4	48.3	63.6	51.7
174	A	-	14.5	38.0	60.1	62.0	39.9
175	B	-	15.6	44.1	66.8	55.9	33.2
176	C	-	8.7	28.1	51.1	71.9	48.9
177	D	-	18.4	47.8	70.0	52.2	30.0
178	E	-	9.9	45.7	60.5	64.3	39.5
179	F	-	15.5	42.3	65.1	57.6	34.9
	Average	-	13.8	39.4	62.3	60.6	37.7
368	Composite	-	13.8	39.0	49.7	61.0	50.3

TABLE B-3. COAL SCREEN ANALYSES, MILL CREEK 1

Sample No.	Mill	U. S. Standard screen size					
		+50	+100	+200	+325	-200	-325
404	A	-	8.6	36.1	60.6	63.9	39.4
403	B	-	14.0	39.1	57.7	60.9	42.3
402	C	-	5.7	30.6	57.0	69.4	43.0
401	D	-	11.1	33.8	50.9	66.2	49.1
	Average	-	9.9	34.9	56.6	65.1	43.4
530	Composite	-	10.3	34.7	44.4	65.3	55.6
416	A	-	5.6	25.5	60.7	74.5	39.3
415	B	-	9.7	28.9	60.3	71.1	39.7
414	C	-	3.9	21.8	46.3	78.2	53.7
413	D	-	7.8	26.7	55.5	73.3	44.5
	Average	-	6.8	25.7	55.7	74.3	44.3
533	Composite	-	6.5	23.4	38.8	76.6	61.2

TABLE B-3. COAL SCREEN ANALYSIS, MONTOUR 1 CUMULATIVE PERCENT

Sample No.	Mill	U. S. Standard screen size					
		+50	+100	+200	+325	-200	-325
1051	A	0	1.4	12.3	39.8	87.7	60.2
1052	B	0	4.0	18.0	50.0	82.0	50.0
1053	C	1.0	7.1	25.4	47.8	74.6	52.2
1054	D	0	0	1.2	21.4	98.8	78.6
1055	E	0	5.0	27.0	55.0	73.0	45.0
1056	F	0	1.9	12.8	36.6	87.2	63.4
	Average	0.2	3.2	16.1	41.8	83.9	58.2

TABLE B-4. ASH FUSION TEMPERATURES, F, LABADIE 1

Sample number	360	361	362	364
Oxidizing atmosphere				
Initial deformation	2320	2320	2320	2220
Softening	2440	2400	2400	2400
Hemisphere	2520	2500	2480	2420
Fluid	2540	2540	2500	2480
Reducing Atmosphere				
Initial Deformation	2020	1700	1700	2020
Softening	2180	2200	2120	2140
Hemisphere	2240	2240	2180	2220
Fluid	2300	2400	2320	2300

TABLE B-4. ASH FUSION TEMPERATURES, F LABADIE 4

Sample number	365	366	367	368	369
Oxidizing atmosphere					
Initial deformation	2320	2340	2340	2380	2380
Softening	2380	2400	2420	2500	2400
Hemisphere	2480	2440	2460	2520	2440
Fluid	2540	2520	2520	2540	2500
Reducing atmosphere					
Initial deformation	1700	1980	1980	2000	1980
Softening	2120	2040	2100	2120	2060
Hemisphere	2220	2200	2260	2300	2120
Fluid	2240	2240	2280	2320	2260

TABLE B-4. COAL ASH FUSION TEMPERATURES, F  
MILL CREEK 1

Sample number	530	531	532	533	534
Oxidizing atmosphere					
Initial deformation	2120	2120	2520	2300	2280
Softening	2400	2680	2680	2460	2360
Hemisphere	2500	2720	2740	2480	2380
Fluid	2520	2760	2760	2520	2420
Reducing atmosphere					
Initial deformation	1940	2400	2540	2020	1940
Softening	2100	2520	2600	2100	2040
Hemisphere	2240	2700	2680	2220	2140
Fluid	2260	2780	2720	2260	2200

TABLE B-4. COAL ASH FUSION TEMPERATURES, F, CLIFFSIDE 5

Sample number	770	771	772	773	774
Oxidizing atmosphere					
Initial deformation	2600	2300	2300	2560	2540
Softening	2780	2360	2380	2640	2560
Hemisphere	2700	2440	2460	2700	2620
Fluid	2720	2500	2520	2720	2640
Reducing Atmosphere					
Initial deformation	2560	2240	2240	1920	2020
Softening	2600	2500	2480	2020	2560
Hemisphere	2680	2620	2620	2140	2620
Fluid	2720	2660	2660	2160	2680

TABLE B-4. ASH FUSION TEMPERATURES, F,  
MORGANTOWN 1

	Oxidizing	Reducing
Initial deformation	2570	2460
Softening	2680	2530
Hemisphere	2700	2560
Fluid	2720	2650

Sample No 982

TABLE B-4 ASH FUSION TEMPERATURES, F,  
MONTOUR 1

	Oxidizing	Reducing
Initial deformation	2660	2460
Softening	2720	2530
Hemisphere	2740	2540
Fluid	2760	2660

Sample No 1083

TABLE B-5. ASH ANALYSES OF COAL COMPOSITE SAMPLES, LABADIE 4

Sample No.	360	361	362	365	366	367	368
Wt. % Ash	13.4	12.6	12.1	10.7	11.2	12.5	12.9
SiO <sub>2</sub>	54.3	52.8	53.3	52.4	52.2	51.7	50.3
Al <sub>2</sub> O <sub>3</sub>	20.3	19.2	19.1	19.4	19.8	18.9	19.1
TiO <sub>2</sub>	1.02	0.96	0.98	1.00	1.04	.94	0.92
Fe <sub>2</sub> O <sub>3</sub>	15.3	17.8	18.0	18.6	19.6	20.3	21.1
MgO	1.15	1.08	1.16	1.02	1.05	0.94	1.08
CaO	4.54	5.06	4.45	4.51	3.23	4.25	4.47
Na <sub>2</sub> O	0.65	0.62	0.62	0.75	0.60	0.62	0.52
K <sub>2</sub> O	2.49	2.29	2.30	2.20	2.34	2.29	2.40
P <sub>2</sub> O <sub>5</sub>	0.18	0.16	0.16	0.08	0.11	0.11	0.11

TABLE B-5. ANALYSES OF ASH IN COAL COMPOSITE SAMPLES, PERCENT, MILL CREEK 1

Sample No.	530	531	532	533	534
Percent ash	13.7	14.6	16.2	16.9	15.0
SiO <sub>2</sub>	44.1	49.5	47.2	47.8	45.6
Al <sub>2</sub> O <sub>3</sub>	17.8	17.7	18.1	19.0	18.5
TiO <sub>2</sub>	0.90	0.89	0.92	0.93	0.93
Fe <sub>2</sub> O <sub>3</sub>	27.4	26.5	23.0	21.6	24.5
MgO	1.00	1.03	1.10	1.15	0.99
CaO	5.67	6.45	5.70	6.06	6.26
Na <sub>2</sub> O	0.52	0.41	0.52	0.51	0.44
K <sub>2</sub> O	2.40	2.39	2.64	2.69	2.59
P <sub>2</sub> O <sub>5</sub>	0.14	0.15	0.19	0.20	0.19

TABLE B-5. ANALYSES OF ASH IN COAL COMPOSITE SAMPLES, PERCENT, CLIFFSIDE 5

Sample No.	770	771	772	773	774
Percent ash	15.7	14.1	15.6	15.8	15.3
SiO <sub>2</sub>	55.4	54.8	55.9	54.4	55.0
Al <sub>2</sub> O <sub>3</sub>	25.6	26.7	26.0	25.4	26.5
TiO <sub>2</sub>	1.24	1.25	1.29	1.20	1.25
Fe <sub>2</sub> O <sub>3</sub>	11.1	10.2	9.92	11.6	10.4
MgO	1.41	1.45	1.45	1.61	1.39
CaO	1.11	1.27	1.34	1.51	1.16
Na <sub>2</sub> O	0.52	0.75	0.51	0.48	0.48
K <sub>2</sub> O	3.54	3.52	3.61	3.61	3.61
P <sub>2</sub> O <sub>5</sub>	0.13	0.19	0.19	0.16	0.16

TABLE B-5. ANALYSES OF ASH IN COAL, PERCENT, MORGANTOWN 1

Sample No.	980	981	982
Percent ash	14.1	13.3	13.7
SiO <sub>2</sub>	50.2	52.0	51.0
Al <sub>2</sub> O <sub>3</sub>	28.3	26.5	27.4
TiO <sub>2</sub>	1.45	1.37	1.43
Fe <sub>2</sub> O <sub>3</sub>	13.7	14.5	14.1
MgO	1.14	0.98	1.09
CaO	1.72	1.44	1.63
Na <sub>2</sub> O	0.27	0.24	0.26
K <sub>2</sub> O	2.66	2.68	2.66
P <sub>2</sub> O <sub>5</sub>	0.53	0.37	0.47

TABLE B-5. ANALYSES OF ASH IN COAL COMPOSITE SAMPLES, PERCENT, MONTOUR 1

Sample No.	1080	1081	1082	1083
Percent ash	14.8	14.2	13.4	14.7
SiO <sub>2</sub>	53.6	54.5	54.6	54.3
Al <sub>2</sub> O <sub>3</sub>	28.0	27.7	27.8	27.8
TiO <sub>2</sub>	1.36	1.36	1.38	1.36
Fe <sub>2</sub> O <sub>3</sub>	8.45	7.87	7.71	7.97
MgO	1.14	1.14	1.12	1.12
CaO	4.12	4.11	4.12	4.10
Na <sub>2</sub> O	0.33	0.32	0.32	0.33
K <sub>2</sub> O	2.69	2.71	2.65	2.68
P <sub>2</sub> O <sub>5</sub>	0.34	0.28	0.31	0.31

TABLE B-6. FLY ASH ANALYSES, PERCENT, LABADIE 4

Sample No.	Coal	Economizer Hoppers				ESP Hoppers			
	369	373	374	375	376	378	379	381	382
SiO <sub>2</sub>	51.8	47.4	50.0	49.7	48.1	52.6	52.8	52.7	52.16
Al <sub>2</sub> O <sub>3</sub>	19.2	16.5	18.7	18.4	17.8	20.8	20.4	20.7	20.6
TiO <sub>2</sub>	1.00	0.86	0.98	0.98	0.91	1.05	1.04	1.04	1.02
Fe <sub>2</sub> O <sub>3</sub>	19.9	22.5	19.8	19.5	21.4	16.5	17.7	17.2	17.9
MgO	1.04	0.98	1.01	1.02	0.98	1.11	1.04	1.04	1.05
CaO	4.07	9.32	6.83	7.66	8.26	4.70	4.04	4.15	4.11
Na <sub>2</sub> O	0.53	0.35	0.46	0.46	0.38	0.55	0.57	0.57	0.55
K <sub>2</sub> O	2.30	1.78	2.07	2.10	2.04	2.49	2.43	2.46	2.50
P <sub>2</sub> O <sub>5</sub>	0.11	0.29	0.17	0.22	0.17	0.17	0.01	0.11	0.14

TABLE B-6. FLY ASH ANALYSES, PERCENT, MILL CREEK 1

Sample No.	Economizer Hoppers					ESP Hoppers				
	535	536	537	538	Avg.	540	541	542	543	Avg.
SiO <sub>2</sub>	41.8	44.0	41.5	42.4	42.1	47.7	46.3	47.9	47.3	47.5
Al <sub>2</sub> O <sub>3</sub>	17.3	17.5	16.9	17.8	17.5	20.3	19.9	20.6	20.2	20.2
TiO <sub>2</sub>	0.84	0.88	0.81	0.86	0.85	0.99	0.94	0.98	0.97	0.97
Fe <sub>2</sub> O <sub>3</sub>	28.3	26.2	28.5	26.6	27.2	21.5	22.0	19.9	20.8	21.1
MgO	0.91	0.94	0.94	0.96	0.94	1.08	1.05	1.10	1.08	1.08
CaO	7.92	7.34	8.67	9.69	8.41	5.09	6.32	5.66	5.95	5.62
Na <sub>2</sub> O	0.44	0.39	0.37	0.45	0.41	0.44	0.41	0.54	0.48	0.47
K <sub>2</sub> O	2.20	2.24	2.15	2.28	2.22	2.82	2.75	2.99	2.89	2.86
P <sub>2</sub> O <sub>5</sub>	0.27	0.54	0.16	0.16	0.28	0.20	0.21	0.23	0.22	0.21

TABLE B-6. FLY ASH ANALYSES, PERCENT, CLIFFSIDE 5

Sample No.	ECONOMIZER HOPPERS				ESP - A HOPPERS				ESP-B HOPPERS			
	775	776	777	778	780	781	782	783	785	786	787	788
SiO <sub>2</sub>	54.4	54.4	54.3	55.5	53.2	53.1	52.7	52.0	53.7	53.3	53.4	53.0
Al <sub>2</sub> O <sub>3</sub>	27.00	27.7	27.3	27.5	27.7	28.4	28.2	27.8	27.3	28.0	27.9	27.6
TiO <sub>2</sub>	1.26	1.22	1.22	1.29	1.31	1.32	1.34	1.27	1.28	1.28	1.26	1.20
Fe <sub>2</sub> O <sub>3</sub>	10.3	9.82	11.1	10.0	10.4	9.98	10.0	10.7	10.5	10.2	9.98	10.5
MgO	1.42	1.40	1.48	1.36	1.46	1.43	1.49	1.63	1.45	1.40	1.42	1.55
CaO	1.13	1.13	1.29	1.25	1.23	1.28	1.55	1.77	1.25	1.28	1.49	1.63
Na <sub>2</sub> O	0.53	0.48	0.48	0.50	0.56	0.58	0.59	0.54	0.55	0.55	0.54	0.53
K <sub>2</sub> O	3.75	3.63	3.72	3.61	3.95	3.88	3.80	3.99	3.81	3.74	3.66	3.78
P <sub>2</sub> O <sub>5</sub>	1.53	0.18	0.13	0.16	0.18	0.22	0.24	0.22	0.19	0.23	0.26	0.24

TABLE B-7 ASH CONTENT OF COAL  
SCREEN FRACTIONS, LABADIE 1

		Coal weight percent	Ash content, percent
+100	--	10.12	10.76
+140	-100	9.30	9.34
+200	-140	10.33	12.89
+325	-200	4.75	8.79
--	-325	65.50	13.43

Sample No. 364      Avg 12.6

TABLE B-7. ASH CONTENT OF COAL  
SCREEN FRACTIONS, LABADIE 4

		Coal weight percent	Ash content, percent
+100	--	12.97	11.45
+140	-100	10.88	9.69
+200	-140	9.62	9.22
+325	-200	5.23	8.89
--	-325	61.30	14.26

Sample No. 369      Avg 11.8

TABLE B-7 ASH CONTENT OF COAL  
SCREEN FRACTIONS, MILL CREEK 1

		Coal weight percent	Ash content, percent
+100	--	8.62	12.42
+140	-100	9.24	11.73
+200	-140	5.95	9.26
+325	-200	3.70	10.58
--	-325	72.48	16.09

Sample No. 534      Avg 15.0

TABLE B-7. ASH CONTENT OF COAL  
SCREEN FRACTIONS, CLIFFSIDE 5

		Coal weight percent	Ash content, percent
+100	--	14.05	14.31
+140	-100	9.78	13.22
+200	-140	8.96	12.37
+325	-200	2.24	12.84
--	-325	64.97	16.29

Sample No. 774      Avg 15.3

TABLE B-7. ASH CONTENT OF COAL  
SCREEN FRACTIONS, MORGANTOWN 1

		Coal weight percent	Ash content, percent
+50	--	0.7	25.6
+100	-50	3.0	19.2
+325	-100	22.7	12.2
--	-325	73.6	13.9

Sample No 982      Avg: 13.8

TABLE B-7. ASH CONTENT OF COAL  
SCREEN FRACTIONS, MONTOUR 1

		Coal weight percent	Ash content, percent
+50	--	0.5	19.8
+100	-50	3.7	18.7
+325	-100	36.0	15.7
--	-325	59.8	12.8

Sample No. 1083      Avg 14.6

TABLE B-8. ASH ANALYSES OF COAL SCREEN FRACTIONS  
LABADIE BOILER 4, PERCENT

	+100 Mesh	+140 -100 Mesh	+200 -140 Mesh	+325 -200 Mesh	-325 Mesh
Percent Ash	11.45	9.69	9.22	8.89	14.26
SiO <sub>2</sub>	52.0	50.5	49.3	47.2	53.2
Al <sub>2</sub> O <sub>3</sub>	18.8	18.6	18.8	19.0	20.3
Fe <sub>2</sub> O <sub>3</sub>	22.3	23.2	24.1	25.3	18.0
MgO	0.91	0.92	0.95	0.98	1.08
CaO	3.25	4.08	4.59	4.85	4.36
Na <sub>2</sub> O	0.47	0.49	0.52	0.53	0.57
K <sub>2</sub> O	2.17	2.17	2.19	2.18	2.40
P <sub>2</sub> O <sub>5</sub>	0.15	0.10	0.10	0.11	0.14
Tcv	2540	2470	2380	2270	2450
Slag viscosity					
2600 F	100	70	54	40	160
2300 F	1100	780	590	420	1600

Sample No. 369

TABLE B-8. ASH ANALYSES OF COAL SCREEN FRACTIONS,  
CLIFFSIDE 5

	+100 Mesh	+140 -100 Mesh	+200 -140 Mesh	+325 -200 Mesh	-325 Mesh
Percent Ash	14.21	13.22	12.37	12.34	16.29
SiO <sub>2</sub>	56.0	56.6	54.0	55.5	55.7
Al <sub>2</sub> O <sub>3</sub>	25.2	24.6	27.1	26.0	25.5
TiO <sub>2</sub>	1.28	1.22	1.24	1.19	1.19
Fe <sub>2</sub> O <sub>3</sub>	11.7	11.4	11.5	10.1	10.3
MgO	1.13	1.20	1.20	1.48	1.49
CaO	0.97	0.85	0.95	1.03	1.02
MnO	0.065	0.050	0.040	0.045	0.045
SrO	0.087	0.087	0.104	0.079	0.077
BaO	0.116	0.156	0.175	0.199	0.207
Na <sub>2</sub> O	0.49	0.48	0.53	0.52	0.51
K <sub>2</sub> O	2.89	3.23	3.06	3.76	3.79
P <sub>2</sub> O <sub>5</sub>	0.19	0.16	0.16	0.16	0.16
Tcv	2410	2430	2390	2410	2420
Slag Viscosity					
2600 F	830	900	780	1000	980
2300 F	6300	7000	5200	6800	6800

Sample No. 774

TABLE B-8. ASH ANALYSES OF COAL SCREEN FRACTIONS,  
MONTOUR 1

	+50 Mes'	+100 -50 Mesh	+325 -100 Mesh	-325 Mesh
Percent Ash	19.8	18.7	15.7	12.8
SiO <sub>2</sub>	56.8	55.1	52.3	55.4
Al <sub>2</sub> O <sub>3</sub>	28.5	28.1	28.1	26.8
TiO <sub>2</sub>	1.33	1.32	1.37	1.38
Fe <sub>2</sub> O <sub>3</sub>	6.1	8.3	9.5	7.4
MgO	0.977	0.901	0.926	1.17
CaO	3.07	3.00	4.68	4.05
MnO	0.041	0.034	0.034	0.038
SrO	0.051	0.053	0.079	0.070
BaO	0.071	0.071	0.097	0.100
Na <sub>2</sub> O	0.37	0.30	0.32	0.37
K <sub>2</sub> O	2.55	2.46	2.29	2.79
P <sub>2</sub> O <sub>5</sub>	0.29	0.30	0.32	0.35
Tcv	2460	2420	2380	2410
Slag Viscosity				
2600 F	1700	1100	550	1000
2300 F	9100	6300	3400	6100

Sample No. 1083

TABLE B-8. ASH ANALYSES OF COAL SCREEN FRACTIONS,  
MORGANTOWN 1

	+50 Mesh	+100 -50 Mesh	+325 -100 Mesh	-325 Mesh
Percent Ash	25.6	19.2	12.2	13.9
SiO <sub>2</sub>	52.0	53.0	50.9	50.2
Al <sub>2</sub> O <sub>3</sub>	26.0	28.2	28.3	27.7
TiO <sub>2</sub>	1.27	1.30	1.39	1.40
Fe <sub>2</sub> O <sub>3</sub>	16.3	12.7	13.9	14.1
MgO	0.740	0.774	0.769	1.07
CaO	0.578	0.794	1.34	1.84
MnO	0.029	0.029	0.041	0.049
SrO	0.058	0.080	0.121	1.07
BaO	0.096	0.120	0.191	0.220
Na <sub>2</sub> O	0.25	0.27	0.30	0.29
K <sub>2</sub> O	2.40	2.47	2.40	2.56
P <sub>2</sub> O <sub>5</sub>	0.22	0.36	0.41	0.49
Tcv	2320	2390	2380	2360
Slag Viscosity				
2600 F	350	660	440	350
2300 F	2900	4500	3100	2520

Sample No. 982

TABLE B-8. ASH ANALYSES OF COAL SCREEN FRACTIONS,  
MILL CREEK 1

	+100 Mesh	+140 -100 Mesh	+200 -140 Mesh	+325 -200 Mesh	-325 Mesh
Percent Ash	12.42	12.06	11.36	11.25	14.76
SiO <sub>2</sub>	45.9	40.6	38.5	46.5	46.5
Al <sub>2</sub> O <sub>3</sub>	17.1	16.2	15.9	18.9	18.5
TiO <sub>2</sub>	0.861	0.861	0.856	0.924	0.918
Fe <sub>2</sub> O <sub>3</sub>	28.3	32.5	33.6	23.1	23.3
MgO	0.757	0.778	0.814	1.05	1.06
CaO	4.45	6.40	7.67	6.01	5.89
MnO	0.036	0.047	0.051	0.046	0.047
SrO	0.020	0.022	0.023	0.024	0.024
BaO	0.039	0.040	0.041	0.050	0.051
Na <sub>2</sub> O	0.374	0.363	0.365	0.499	0.464
K <sub>2</sub> O	2.15	2.10	2.09	2.71	2.99
P <sub>2</sub> O <sub>5</sub>	0.114	0.114	0.15	0.21	0.22
Tcv	2390	2220	2160	2260	2290
Slag Viscosity					
2600 F	27	9	6	41	41
2300 F	300	93	58	420	420

Sample No. 534

TABLE B-9. MINERAL DISTRIBUTION IN COAL SCREEN  
FRACTIONS, PERCENT, LABADIE 4

	Total		+140	+200	+325	
Coal	+100	-100	-140	-200	-325	
LTA	15.5	13.2	11.7	11.3	11.3	17.4
Quartz	20	25	25	25	30	30
Pyrite	20	30	30	30	35	20
Calcite	5	1-5	5	5	5	5
Gypsum	1-5	nd	nd	1-5	1-5	5-10
Kaolinite	20	15	20	15	15	15
Illite + MLC	25	25	20	25	15	25
FeSO <sub>4</sub>	1-5	1-5	1-5	1-5	1-5	1-5
Total	90	105	100	105	100	100

Sample 369

TABLE B-9. MINERAL DISTRIBUTION IN COAL SCREEN  
FRACTIONS, PERCENT, MILL CREEK 1

	Total		+140	+200	+325	
Coal	+100	-100	-140	-200	-325	
LTA, % of coal	18.7	14.7	14.7	14.1	19.6	20.7
Quartz	20	25	20	15	20	20
Pyrite	30	40	40	35	20	30
Calcite	10	5	5-10	10	5	5
Gypsum	1-5	1-5	0	1-5	1-5	1-5
Kaolinite	20	15	15	15	15	15
Illite + MLC	20	20	20	15	15	20
FeSO <sub>4</sub>	1-5	0	1-5	0	1-5	1-5
Total	100	105	100	90	80	90

Sample 534

TABLE B-9. MINERAL DISTRIBUTION IN COAL SCREEN  
FRACTIONS, PERCENT, CLIFFSIDE 5

	Total		+140	+200	+325	
Coal	+100	-100	-140	-200	-325	
LTA, % of coal	18.9	15.3	13.2	13.9	18.1	18.8
Quartz	20	20	25	20	20	20
Pyrite	7	5	10	10	5	5
Calcite	1-5	0	0	0	0	0
Gypsum	1-5	1-5	1-5	1-5	1-5	1-5
Kaolinite	20	25	25	20	20	20
Illite + MLC	40	45	45	50	30 <sup>(1)</sup>	45 <sup>(1)</sup>
FeSO <sub>4</sub>	5-10	1-5	1-5	1-5	5-10	5-10
Total	95	100	105	100	85	90

Sample 774

(1) Illite + Montmorillite

TABLE B-9. COAL MINERAL ANALYSES,  
PERCENT, MORGANTOWN 1

L. T. Ash	16.8
Quartz	15
Pyrite	10
Calcite	0
Gypsum	1-5
Kaolinite	30
Illite + MLC	30
FeSO <sub>4</sub>	0

Sample No 982

TABLE B-9. COAL MINERAL ANALYSES,  
PERCENT, MONTOUR 1

L. T. Ash	16.7
Quartz	15
Pyrite	5
Calcite	1-5
Gypsum	1-5
Kaolinite	35
Illite + MLC	35
FeSO <sub>4</sub>	0

Sample No. 1083

TABLE B-10. ASH CONTENT OF COAL  
DENSITY FRACTIONS, LABADIE 4

Sp. Gr.		Coal weight percent	Ash content, percent
Sink	Float		
--	1.30	26.47	1.90
1.30	1.40	34.17	4.00
1.40	1.50	22.88	10.35
1.50	1.60	5.26	17.5
1.60	--	11.22	52.0
--	1.60	90.36	8.27
1.60	2.00	5.06	21.73
2.00	2.80	3.19	64.6
2.80	--	1.39	60.0

Sample No. 369

TABLE B-10 ASH CONTENT OF COAL  
DENSITY FRACTIONS, MILL CREEK 1

Sp. Gr.		Coal weight percent	Ash content, percent
Sink	Float		
--	1.30	36.54	2.55
1.30	1.40	26.16	5.75
1.40	1.50	18.50	10.89
1.50	1.60	3.34	17.80
1.60	--	15.46	60.01
--	1.60	86.30	8.16
1.60	2.00	4.85	25.33
2.00	2.80	5.50	71.27
2.80	--	3.35	61.33

Sample No. 534

TABLE B-10 ASH CONTENT OF COAL  
DENSITY FRACTIONS, CLIFFSIDE 5

Sp. Gr.		Coal weight percent	Ash content, percent
Sink	Float		
--	1.30	51.43	2.55
1.30	1.40	22.02	5.35
1.40	1.50	14.54	11.30
1.50	1.60	4.03	19.35
1.60	--	7.98	64.25
--	1.60	83.55	6.73
1.60	2.00	8.37	24.28
2.00	2.80	6.93	84.51
2.80	--	1.15	69.31

Sample No. 774

TABLE B-10. ASH CONTENT OF COAL  
DENSITY FRACTIONS, MORGANTOWN 1

Sp. Gr.		Coal weight percent	Ash content, percent
Sink	Float		
--	1.60	87.2	6.0
1.60	2.00	5.4	33.9
2.00	2.80	5.9	73.8
2.80	--	1.5	67.1

Sample No 982

TABLE B-10. ASH CONTENT OF COAL  
DENSITY FRACTIONS, MONTOUR 1

Sp. Gr.		Coal weight percent	Ash content, percent
Sink	Float		
--	1.60	88.4	5.8
1.60	2.00	3.1	36.4
2.00	2.80	7.5	79.8
2.80	--	0.9	57.7

Sample No. 1083

TABLE B-11. ASH ANALYSES OF COAL DENSITY FRACTIONS, LABADIE 4

Sp Gr:	Float	1.30	1.40	1.50	1.60	--	1.60	2.00	2.80	--	Total
	Sink	0	1.30	1.40	1.50	1.60	0	1.60	2.00	2.80	coal
Percent ash		1.9	4.0	10.6	17.2	52.0	8.27	21.7	64.6	60.1	11.8
Percent of coal		26.5	34.2	22.9	5.26	11.2	90.4	5.06	3.19	1.39	100
SiO <sub>2</sub>		49.9	55.3	59.5	58.0	47.2	58.0	53.2	45.3	6.98	51.8
Al <sub>2</sub> O <sub>3</sub>		25.2	24.4	22.9	22.0	15.7	22.1	19.8	13.5	2.91	19.2
TiO <sub>2</sub>		3.23	2.26	1.20	0.80	0.47	1.30	0.69	0.38	0.32	1.00
Fe <sub>2</sub> O <sub>3</sub>		11.9	11.1	11.6	14.0	27.0	12.1	20.5	22.2	87.2	19.8
MgO		1.55	1.30	1.19	1.13	0.45	1.25	1.15	0.75	0.05	1.04
CaO		3.70	1.51	0.83	0.74	6.93	1.75	1.66	15.8	1.78	4.08
Na <sub>2</sub> O		1.43	0.98	0.57	0.44	0.37	0.65	0.42	0.34	0.31	0.53
K <sub>2</sub> O		2.99	3.12	3.06	2.83	1.83	2.76	2.36	1.47	0.06	2.30
P <sub>2</sub> O <sub>5</sub>		0.11	0.08	0.08	0.07	0.08	0.13	0.14	0.25	0.38	0.12
Tcv		2320	2410	2590	2580	2720	2590	2500	3200	2600	2500
Slag Viscosity											
2600 F		340	790	990	640	28	730	160	15	1	130
2300 F		5000	20000	29000	14000	140	17000	1600	70	3	1000

Sample No. 369

TABLE B-11. ASH ANALYSES OF COAL DENSITY FRACTIONS, MILL CREEK 1

Sp Gr:	Float	1.30	1.40	1.50	1.60	--	1.60	2.00	2.80	--	Total
	Sink	0	1.30	1.40	1.50	1.60	0	1.60	2.00	2.80	coal
Percent ash		2.55	5.75	10.9	17.8	60.0	8.16	23.3	71.3	61.3	15.0
Percent of coal		36.5	26.2	18.5	3.34	15.5	86.3	4.85	5.50	3.35	100
SiO <sub>2</sub>		50.8	54.2	54.4	52.9	40.8	54.6	49.5	48.1	6.19	45.5
Al <sub>2</sub> O <sub>3</sub>		24.5	24.3	23.0	21.0	14.3	23.1	21.1	16.4	3.02	18.5
TiO <sub>2</sub>		2.89	1.92	1.14	0.75	0.55	1.33	0.75	0.59	0.34	0.93
Fe <sub>2</sub> O <sub>3</sub>		12.9	12.2	15.1	19.4	30.4	13.6	21.8	12.9	88.3	24.5
MgO		1.30	1.26	1.18	1.10	0.85	1.30	1.17	1.09	0.02	0.99
CaO		2.87	1.57	1.11	1.15	10.0	2.11	2.26	17.7	1.59	6.25
Na <sub>2</sub> O		0.81	0.65	0.49	0.54	0.40	0.45	0.42	0.40	0.22	0.44
K <sub>2</sub> O		3.52	3.57	3.36	2.99	2.28	3.29	2.86	2.57	0.09	2.59
P <sub>2</sub> O <sub>5</sub>		0.20	0.19	0.15	0.12	0.17	0.22	0.23	0.29	0.25	0.19
Tcv		2320	2380	2390	2400	2500	2390	2260	2650	2530	2240
Slag viscosity											
2600 F		360	620	420	420	8	440	97	40	1	32
2300 F		2800	4800	3800	3800	73	7700	800	240	3	330

Sample No. 534

TABLE B-11 · ASH ANALYSES OF COAL DENSITY FRACTIONS, CLIFFSIDE 5

Sp Gr:	Float	1.30	1.40	1.50	1.60	--	1.60	2.00	2.80	--	Total
	Sink	0	1.30	1.40	1.50	1.60	0	1.60	2.00	2.80	coal
Percent ash		2.55	5.35	11.3	19.4	64.3	6.73	24.3	84.5	69.3	15.3
Percent of coal		51.4	22.0	14.5	4.03	7.98	83.6	8.37	6.93	1.15	100
SiO <sub>2</sub>		43.7	49.8	52.9	55.2	58.2	50.9	56.0	63.2	15.9	54.8
Al <sub>2</sub> O <sub>3</sub>		32.1	32.1	31.6	29.8	22.7	31.7	29.4	23.3	7.16	26.4
TiO <sub>2</sub>		2.22	1.80	1.49	1.41	1.02	1.64	1.36	0.90	0.99	1.25
Fe <sub>2</sub> O <sub>3</sub>		10.9	8.3	7.68	6.70	11.5	8.22	6.90	5.57	72.2	10.4
MgO		1.61	1.23	1.21	1.17	1.41	1.54	1.31	1.62	0.69	1.38
CaO		4.75	2.5	2.13	1.75	0.62	2.20	0.95	0.52	0.75	1.16
Na <sub>2</sub> O		0.76	0.74	0.65	0.54	0.55	0.55	0.39	0.38	1.04	0.50
K <sub>2</sub> O		2.79	2.64	2.70	2.90	4.15	3.11	3.46	4.40	0.95	3.63
P <sub>2</sub> O <sub>5</sub>		0.29	0.34	0.29	0.26	0.12	0.26	0.18	0.10	0.35	0.17
Tcv		2610	2570	2530	2490	2560	2540	2490	2800	2280	2400
Slag Viscosity											
	2600 F	220	870	1220	1800	940	930	2000	3200	1	920
	2300 F	1200	4000	5700	8700	8100	26000	100000	263000	3	6100

Sample No. 774

TABLE B-11. ASH ANALYSES OF COAL DENSITY FRACTIONS, MORGANTOWN 1

SP.GR.:	Float	1.60	2.00	2.80	-	Total
	Sink	-	1.60	2.00	2.80	Coal
Percent Ash		6.0	33.9	73.8	67.1	13.9
Percent of Coal		87.2	5.4	5.9	1.5	100
SiO <sub>2</sub>		48.0	54.7	62.3	5.3	50.9
Al <sub>2</sub> O <sub>3</sub>		33.9	31.7	26.3	4.9	27.3
TiO <sub>2</sub>		1.91	1.29	0.983	1.05	1.42
Fe <sub>2</sub> O <sub>3</sub>		8.3	6.9	5.4	86.1	14.1
MgO		1.24	0.925	0.801	0.276	1.09
CaO		2.84	0.755	0.780	0.331	1.63
Na <sub>2</sub> O		0.36	0.31	0.30	0.14	0.26
K <sub>2</sub> O		2.54	2.87	2.83	0.530	2.65
P <sub>2</sub> O <sub>5</sub>		0.66	0.35	0.24	0.49	0.47
Tcv		2660	2560	2600	3100	2600
Slag Viscosity						
	2600 F	740	2200	3700	1	550
	2300 F	3180	9400	23000	3	--

Sample No. 982

TABLE B-11. ASH ANALYSES OF COAL DENSITY FRACTIONS,  
MONTOUR 1

SP.GR.: Float	1.60	2.00	2.80	-	Total
Sink	-	1.60	2.00	2.80	Coal
Percent Ash	5.78	36.4	79.8	57.7	14.7
Percent of Coal	88.4	3.1	7.5	0.9	100
SiO <sub>2</sub>	51.7	56.7	60.3	12.2	54.3
Al <sub>2</sub> O <sub>3</sub>	34.9	32.0	23.6	6.7	27.8
TiO <sub>2</sub>	1.90	1.35	0.921	1.35	1.36
Fe <sub>2</sub> O <sub>3</sub>	4.27	4.59	3.88	75.08	7.97
MgO	1.01	0.804	1.07	0.797	1.12
CaO	2.66	1.38	5.97	2.08	4.10
Na <sub>2</sub> O	0.452	0.360	0.329	0.273	0.332
K <sub>2</sub> O	2.52	2.52	2.87	0.709	2.68
P <sub>2</sub> O <sub>5</sub>	0.37	0.22	0.27	0.32	0.31
Tcv	2700	2580	2610	2360	2400
Slag Viscosity					
2600 F	2200	3400	1600	1	860
2300 F	7100	13000	11000	3	22500

Sample No. 1083

TABLE B-12 ANALYSES OF ASH IN COAL, FURNACE SLAG,  
AND FLY ASH, PERCENT, LABADIE 4

Sample No.	Coal	Furnace Deposits (Elevation)				Fly Ash	
		38	90	120	138	Economizer	ESP.
	369	326	316	312	300	Avg.	Avg.
SiO <sub>2</sub>	51.8	54.0	54.0	53.9	51.3	48.9	52.5
Al <sub>2</sub> O <sub>3</sub>	19.2	18.9	18.8	19.1	18.7	17.9	20.6
TiO <sub>2</sub>	1.00	0.90	0.96	0.92	0.96	0.94	1.04
Fe <sub>2</sub> O <sub>3</sub>	19.9	19.2	19.0	19.4	22.1	20.7	17.4
MgO	1.04	1.03	1.03	1.04	1.03	1.00	1.06
CaO	4.08	3.38	3.40	2.95	3.35	7.92	4.26
Na <sub>2</sub> O	0.53	0.40	0.46	0.46	0.43	0.42	0.56
K <sub>2</sub> O	2.30	2.08	2.13	2.17	2.14	2.02	2.48
P <sub>2</sub> O <sub>5</sub>	0.12	0.11	0.10	0.09	0.07	0.21	0.11
Tcv	2480	2650	2670	2620	2520	2460	2400
Slag Viscosity							
2600 F	120	160	160	170	93	53	170
2300 F	1200	1800	1800	1800	1000	530	1600

TABLE B-12 ANALYSES OF ASH IN COAL, FURNACE SLAG,  
AND FLY ASH, PERCENT, MILL CREEK 1

Sample No.	Coal	Furnace Deposits (elevation)				Fly Ash	
		35	70	92	116	Economizer	ESP
	534	512	511	507	499	Avg	Avg
SiO <sub>2</sub>	45.5	49.6	50.2	50.7	49.4	42.4	47.4
Al <sub>2</sub> O <sub>3</sub>	18.5	19.3	18.9	19.6	19.2	17.4	20.2
TiO <sub>2</sub>	0.93	0.923	0.894	0.960	0.958	0.850	0.971
Fe <sub>2</sub> O <sub>3</sub>	24.5	19.5	19.2	19.8	19.4	27.4	21.1
MgO	0.99	1.06	1.02	1.12	1.11	0.937	1.08
CaO	6.25	6.58	6.74	5.31	6.67	8.41	5.62
Na <sub>2</sub> O	0.44	0.358	0.374	0.395	0.404	0.414	0.471
K <sub>2</sub> O	2.59	2.42	2.43	2.59	2.58	2.22	2.86
P <sub>2</sub> O <sub>5</sub>	0.19	0.15	0.14	0.15	0.17	0.28	0.21
Tcv	2240	2360	2430	2380	2360	2200	2230
Slag Viscosity							
2600 F	32	76	81	92	74	14	60
2300 F	330	750	810	930	730	140	590

TABLE B-12 ANALYSES OF ASH IN COAL, FURNACE SLAG,  
AND FLY ASH, PERCENT, CLIFFSIDE 5

	Coal	Furnace Deposits (elevation)				Fly Ash	
		38	90	115	138	Economizer	ESP
Sample No.	774	763	760	757	750	Avg	Avg
SiO <sub>2</sub>	54.8	55.8	56.6	55.1	54.6	54.5	52.8
Al <sub>2</sub> O <sub>3</sub>	26.4	24.8	23.6	25.5	25.8	27.0	27.8
TiO <sub>2</sub>	1.25	1.17	1.17	1.21	1.14	1.25	1.28
Fe <sub>2</sub> O <sub>3</sub>	10.4	11.9	12.1	11.2	11.3	10.2	10.3
MgO	1.38	1.56	1.46	1.54	1.67	1.39	1.51
CaO	1.16	0.94	0.78	0.99	1.10	1.20	1.44
Na <sub>2</sub> O	0.50	0.45	0.42	0.48	0.46	0.50	0.55
K <sub>2</sub> O	3.63	3.66	3.59	3.56	3.80	3.63	3.82
P <sub>2</sub> O <sub>5</sub>	0.17	0.092	0.10	0.11	0.11	0.15	0.22
Tcv	2400	2400	2460	2390	2380	2400	2410
Slag Viscosity							
2600 F	920	740	770	810	740	930	790
2300 F	6100	5600	6300	5800	5200	6000	4800

TABLE B-12 ANALYSES OF ASH IN COAL, FURNACE SLAG,  
AND FLY ASH, PERCENT, MORGANTOWN 1

	Coal	Furnace Deposits (elevation)				Fly Ash	
		32	68	95	121	Economizer	ESP
Sample No.	982	953	957	959	961	984	985
SiO <sub>2</sub>	50.9	49.7	50.0	50.8	44.5	50.0	49.9
Al <sub>2</sub> O <sub>3</sub>	27.3	23.6	25.7	26.1	23.9	26.6	28.3
TiO <sub>2</sub>	1.42	1.07	1.23	1.28	1.17	1.37	1.46
Fe <sub>2</sub> O <sub>3</sub>	14.0	21.5	19.2	16.8	25.7	17.5	13.9
MgO	1.09	0.80	0.81	0.87	0.79	0.73	1.06
CaO	1.63	0.59	0.89	1.05	0.95	0.86	1.67
Na <sub>2</sub> O	0.26	0.18	0.20	0.26	0.23	0.25	0.26
K <sub>2</sub> O	2.65	2.33	2.36	2.44	2.05	2.21	2.54
P <sub>2</sub> O <sub>5</sub>	0.47	0.12	0.17	0.24	0.23	0.24	0.53
Tcv	2600	2240	2270	2300	2200	2310	2380
Slag Viscosity							
2600 F	550	140	190	280	50	250	370
2300 F	high	1370	1680	2290	530	2070	2560

TABLE B-12 ANALYSES OF ASH IN COAL, FURNACE SLAG,  
AND FLY ASH, PERCENT, MONTOUR 1

	Coal	Furnace Deposits (elevation)				Fly Ash		
		34	87	96	118	Econ.	ESP A	ESP B
Sample No.	1083	1067	1066	1065	1064	1085	1086	1087
SiO <sub>2</sub>	54.3	49.6	54.7	53.8	15.6	51.3	52.9	53.2
Al <sub>2</sub> O <sub>3</sub>	27.8	24.5	25.7	27.2	8.9	23.5	26.6	27.6
TiO <sub>2</sub>	1.36	1.15	1.26	0.997	0.462	1.15	1.29	1.35
Fe <sub>2</sub> O <sub>3</sub>	8.0	16.8	10.2	9.2	69.9	13.7	9.7	8.9
MgO	1.12	0.951	1.05	0.994	0.557	1.08	1.13	1.08
CaO	4.10	4.21	4.02	4.06	3.08	6.14	5.13	4.49
Na <sub>2</sub> O	0.332	0.233	0.275	0.262	0.473	0.265	0.290	0.330
K <sub>2</sub> O	2.68	2.25	2.57	2.44	0.347	2.46	2.60	2.63
P <sub>2</sub> O <sub>5</sub>	0.31	0.16	0.17	0.49	0.19	0.22	0.27	0.27
Tcv	2400	2250	2360	2380	2300	2280	2350	2380
Slag Viscosity								
2600 F	860	160	600	690	1	200	490	650
2300 F	610	1300	4300	4400	3	1700	3300	4000

APPENDIX C

Results of Preliminary Screening of Units

TABLE C-1. RESULTS OF PRELIMINARY SCREENING OF UNITS

Builder	Utility/Unit	Rating, MW	Coal(s)	Slagging Tendency	Load		Furnace Pressure	Access for Sampling	Comments (Reasons for Dropping from Further Consideration)
					Day	Night			
B&W	Dayton P&L Stuart No. 4	600	Various similar E. Ky & WV coals; could segregate 1 or 2 coals for test	No slagging problems	Full	Low	PF	Limited	Except for PF, good nonslagging test unit
B&W	Allegheny Power Hatfield Ferry No. 3	550	Various WV, Ky, & Pa coals; segregation very difficult	No slagging problem; avoid earlier problem by limiting one coal	Full	3/4	PF	Good	Coal highly variable
B&W	Allegheny Power Ft. Martin	550	Two coals: (1) SW. Va or Ky and (2) WV or Pa; could segregate	No slagging problem	Full	3/4	PF	Limited	Except for PF, good nonslagging test unit
B&W	Georgia Power Harlee Branch	500	Several similar E. Ky coals; could segregate one for test	No slagging problem; ESP limits load to 96% of rating	Full	Full	PF	Limited	ESP limits may obscure slagging, probably not good test unit
B&W	AEP Muskingum River No. 5	595	Ohio strip mine coal, one mine (maybe two seams)	Derated due to erosion; otherwise would expect slagging	Full	Low	PF (20 in)	--	Derating obscures nor- mal slagging of unit
B&W	AEP Cardinal	600	Various coals - Ohio, WV, and maybe Pa; segregation not practical	Slagging limits load to 92% of rating	Full	Low	PF	--	Highly variable coal
B&W	Detroit Edison Monroe No. 1	750	Ohio strip mine plus spot purchase; could segregate Ohio coal for test	Slagging limits load to 90% of rating	Full	Full	BD	Limited	Good slagging test unit
B&W	Duke Power Belews Creek No. 1 and No. 2	1100	SW. Va; consistent supply	Severe slagging	--	--	BD	--	Very large unit; diffi- cult to test; otherwise good slagging unit
B&W	Consumers Power Campbell No. 2	386	Two seams of Ohio strip mine coal; no segregation possible	Severe slagging limits load to 83% of rating (unique unit)	--	--	BD	Some	Somewhat unique furnace; small for rating
B&W	East KY Power Co-op Cooper No. 2	233	Similar E. Ky coals (although different seams); no segregation possible	No slagging problem	Full	1/2	PF (19 in)	Limited	Except for PF, good nonslagging test unit
B&W	Toledo Edison Bay Shore No. 4	225	Two Ohio and one Ky coals; segregation of one coal possible, but difficult	No slagging problem; operates at 103% of rating	Full	1/2	BD	Some	Possibly good nonslagging test unit
B&W	Carolina P&L Ashville No. 2	200	Various SW. Va, E. Ky, and Tenn coals; no segregation possible	No slagging problem	Full	1/2	PF	--	Coal highly variable

TABLE C-1. (Continued)

Builder	Utility/Unit	Rating, MW	Coal(s)	Slagging Tendency	Load		Furnace Pressure	Access for Sampling	Comments (Reasons for Dropping from Further Consideration)
					Day	Night			
CE	Pennsylvania Electric Keystone	900	Mostly Pa coal (mine mouth plant); some trucked coal	Severe slagging	Full	--	PF	Limited	Except for PF, possibly good slagging test unit
CE	Pennsylvania Electric Conemaugh	900	Mostly Pa coal (mine mouth plant); some trucked coal	Severe slagging	Full	--	PF	Limited	Ditto
CE	TVA Bull Run	900	Similar coals from three E. Ky mines; segregation not possible	Severe slagging	Full	--	PF	Limited	Ditto
CE	Duke Power Marshall No. 4	647	Variable coal; 50% SW. Va, rest from many sources	No slagging problem	Full	Low	BD	Good	Highly variable coal
CE	Duke Power Cliffside No. 5	600	Similar coal from many E. Ky mines; no segregation possible	No slagging problem	Full	Low	BD	Good	Ditto
CE	Union Electric Labadie No. 1	600	Three similar Illinois coals; two can be segre- gated	Some slagging problems; unit derated	Full	Full	BD	Good	Good slagging test unit
CE	Illinois Power Baldwin No. 3	600	Three similar Illinois coals; one coal could be segregated (with diffi- culty)	Some slagging problems	Full	1/2	BD	Good	Ditto
CE	VEPCO Mt. Storm	553	Similar WV coals; no segregation possible	No slagging problem	Full	Full	2 PF (40 in) 1 BD	Limited	Possible nonslagging test unit
CE	Indianapolis P&L Petersburg No. 3	532	Highly variable S. Ind strip mine coal	Some slagging problems	Full	--	BD	Limited	Highly variable coal
CE	Duquense Lighting Cheswick No. 1	525	Highly variable coal; 30% Pa deep mine, 70% strip mine	No slagging problem	Full	--	BD	Limited	Ditto
CE	Kentucky Utilities Ghent	511					BD		
CE	Detroit Edison Trenton Channel No. 9	500	Two very different coals; blended for SO <sub>2</sub> control	No slagging problem	Full	--	BD	--	Highly variable coal
CE	Florida Power Crystal River	500	Ky coal	No slagging problem	Full	--	PF	Limited	Except for PF, candidate nonslagging test unit
CE	Indianapolis P&L Elemer W. Stout No. 7	420	Highly variable S. Ind strip mine coal	Some slagging problems	Full	--	BD	Good	Highly variable coal

TABLE C-1. (Continued)

Builder	Utility/Unit	Rating, MW	Coal(s)	Slagging Tendency	Load		Furnace Pressure	Access for Sampling	Comments (Reasons for Dropping from Further Consideration)
					Day	Night			
CE	Louisville G&E Mill Creek No. 1 and No. 2	350, 321	W. Ky coal	Severe slagging; limits load	Full	--	BD	Good	Good slagging test unit
CE	Louisville G&E Cane Run No. 6	250	W. Ky coal	Severe slagging	--	--	BD	--	Ditto
CE	New England Power Brayton Point No. 2	238					BD		
CE	Potomac Electric Morgantown No. 1 and No. 2	575	30% coal, 70% oil	No slagging problems now	Full	--	BD	Good	May be candidate for field test in late 1977 when firing 100% coal
CE	Detroit Edison St. Clair No. 7	500	Western coal	--	--	--	BD	--	Western coal
CE	Kansas P&L Lawrence No. 5	420	Western coal	--	--	--	BD	--	Ditto
CE	Minnesota P&L Clay Boswell No. 3	334	Western coal	--	--	--	BD	--	Ditto
CE	Northern States Power Sherburne No. 1	680	Western coal	--	--	--	BD	--	Ditto
CE	Wisconsin P&L Columbia No. 1	527	Western coal	--	--	--	BD	--	Ditto
CE	Consolidated Edison Arthur Kill No. 3	500	Oil	--	--	--	BD	--	Oil fired
CE	Pennsylvania P&L Martins Creek No. 3 and No. 4	850	Oil	--	--	--	BD	--	Ditto
CE	Potomac Electric Chalk Point No. 3	660	Oil	--	--	--	BD	--	Ditto

APPENDIX D

Slag Viscosity Calculations

## APPENDIX D

### SLAG VISCOSITY CALCULATIONS

It is possible to calculate slag viscosity characteristics from composition of coal ash, and viscosity data are useful in evaluating the potential for disposition problems in boiler furnaces. In this report, the value of the Temperature of Critical Viscosity ( $T_{CV}$ ), the viscosity at 2600 F, and the viscosity at 2300 F have been calculated for ash compositions for ash samples taken from various points in boiler furnaces, for test coals, and for coal density fractions of test coals. The calculated viscosity data provide an integrated way of assessing the effects of the variations in ash composition found among various coal and ash samples.

#### Temperature of Critical Viscosity, $T_{CV}$

The temperature of critical viscosity is that temperature at which the viscosity properties of the molten slag change on cooling from those of a Newtonian fluid to those of a Bingham plastic. As a slag is cooled, the logarithm of its viscosity increases linearly with decreasing temperature. At some point the progression deviates from a straight line and viscosity tends to increase more rapidly as temperature is decreased. The point at which this deviation takes place has been termed "The temperature of critical viscosity" ( $T_{CV}$ ) and is believed to be the temperature where solid phases start to crystallize from the melt.

The method of Hoy, Roberts, and Wilkins<sup>(D-1)</sup> has been used in this report for calculating  $T_{CV}$ . This method is as follows:

1. Normalize ash composition so that:

$$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} = 100$$

2. Calculate  $T_{CV}$ :

$$T_{CV}, \text{ }^\circ\text{C} = 2990 - 1470\left(\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}\right) + 360\left(\frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}\right)^2 - 14.7(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO}) + 0.15(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO})^2$$

## Slag Viscosity

A calculation method developed by W. T. Reid was used for calculation of slag viscosity at 2600 F. This method is as follows:

1. Calculate "Silica Percentage", as

$$\text{Silica percentage} = \frac{100\text{SiO}_2}{\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO}}$$

2. Calculate slag viscosity at 2600 F using the following equation:

$$\text{Log, Viscosity at 2600 F} = (0.05784)(\text{Silica Percentage}) - 1.8452$$

The calculation method of Watt and Fereday<sup>(D-2,3)</sup> was used for calculation of slag viscosity at 2300 F. The procedure for this calculation is:

1. Normalize  $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO}$  to 100
2. Calculate constant  $M = 0.00835 \times \% \text{SiO}_2 + 0.00601 \times \% \text{Al}_2\text{O}_3 - 0.109$
3. Calculate constant  $C = 0.0415 \text{SiO}_2 + 0.0192 \text{Al}_2\text{O}_3 + 0.0276 \text{Fe}_2\text{O}_3 + 0.0160 \text{CaO} - 3.92$
4. Calculate slag viscosity at 2300 F (1260 C) using the following equation:

$$\text{Log, viscosity at 2300 F} = \frac{10^7 M}{(T-150)^2} + C$$

Where T = temperature °C, = 1260

Viscosity = poise

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D-1. H. R. Hoy, A. G. Roberts, and D. M. Wilkins, Inst. Gas Engrs. Comm. 672, London, (Nov. 1964).

D-2. J. D. Watt and F. Fereday, "The Flow Properties of Slags Formed from the Ashes of British Coals: Part 1. Viscosity of Homogeneous Liquid Slags in Relation to Slag Composition," Journal of the Institute of Fuel, XLII, No. 338 (March 1969) pp 99-103.

D-3. Same as above, "Part 2. The Crystallizing Behaviour of the Slags" - No.339 (April 1969) pg 131-134.