Task 3.11 - Fuel Quality Advisor

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For
U.S. Department of Energy
Office of Fossil Energy
Federal Energy Technology Center
Morgantown Site
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street
P. O. Box 9018
Grand Forks, North Dakota 58202-9018

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Lignite Predictive Model

© Copyright 1995 Energy & Environmental Research Center
University of North Dakota
PO Box 9018
Grand Forks, North Dakota 58202-9018
Telephone: (701) 777-5000
Fax: (701) 777-5181
www.eerc.und.nodak.edu

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SUBTASK 3.11 - FUEL QUALITY ADVISOR

1.0 INTRODUCTION

The objective of the Fuel Quality Advisor (FQA) project was to create a generalized software package capable of advising operations, purchasing, environmental, and maintenance personnel in making decisions related to the use of coal in electricity generation facilities. The specific goals for this project work included the following:

- Develop a standardized computer shell to integrate existing and future algorithms
- Develop a strategy for integrating the shell with future databases and boiler models
- Integrate the current ash transformation and deposition algorithms into the shell
- Generate algorithms for coal handleability through experimentation and integrate them into the code
- Enhance the current ash transformation algorithms for low-NO_x and entrained gasification through laboratory experimentation and integrate available full-scale results into the code

The program was divided into four primary thrust areas: development of the computerized shell and interface; development of the coal handleability advisor; enhancement of ash formation algorithms; and the enhancement of ash fouling algorithms. Accomplishments in each of these four areas are described in detail below.

2.0 DEVELOPMENT OF FUEL QUALITY ADVISOR

The purpose of the Fuel Quality Advisor is to bundle several existing computer models with a Windows™ graphical user interface. This interface controls entry into each of the models and provides a unified and efficient interface to aid users in moving around among different segments of the FQA. The following features and advantages have been utilized in the creation of the advisor:

- A single executable user interface that can start all models without regard to program location
- A consistent visual display for ease of learning and using the computer models
- A Help facility that can describe each model along with the requirements for that model
- Shortcuts such as hot keys to improve the speed and acceptance for advanced users
- Tool bar icons that will give the user a set of tools for running the models
- A packaging system for the creation of both DOS and Windows programs

2.1 Construction of Shell/Interface

The computer interface was designed to connect each of the three models (coal handleability, ash formation, and ash deposition) to a single execution environment. One of the strengths of this system is the ability to run multiple scenarios with each of the models. A user can easily change one or more of the inputs and rerun the model with the new data. Each of the models has a similar look and feel, which aids in learning the system. Details of the system are covered in Section 3.

2.2 Coal Handleability

The coal handleability model rates the dust handling for coal by making a correlation between type of coal, particle size distribution, and moisture content. Early attempts were made to use maceral content to help group the various lignite, subbituminous, and bituminous coals. However, maceral data were inconclusive and varied dramatically within each region. The as-received moisture content relative to the coal's original bed moisture content was the main factor in determining the overall coal handleability indices. A slacking index was used to further enhance the indices. The slacking index was based upon information compiled by the Bureau of Mines for various ranks of coal.

2.3 Ash Formation

The ash transformation model predicts the particle-size and composition distribution (PSCD) of the entrained ash reaching the convective pass of a utility boiler. The entrained ash PSCD is predicted from the distribution of the inorganics in the coal. Computer-controlled scanning electron microscopy (CCSEM) (1), x-ray fluorescence (XRF), and ultimate analysis are used to characterize the coal. The CCSEM analysis is also combined with a locked/liberated particle analysis (to determine if the individual mineral grains are located within a coal matrix or are free mineral grains) and ZAF data reduction of the compositions (2). The ZAF data reduction produces compositions free of the effects of atomic number (Z), x-ray absorption (A), and x-ray fluorescence (F). A mass balance is compiled on the coal by comparing the CCSEM and XRF data. The resultant balance provides the compositions of the minerals with their associations to the coal, organically associated constituents, and submicron particles. The minerals are divided into two data sets: those locked within a coal particle and those liberated from the coal matrix. The locked minerals are coalesced, on a frequency basis, in a random fashion with other mineral and submicron particles as well as those organically associated constituents that are expected to condense during the combustion of a coal particle. The coalescence produces intermediate, locked fly ash particles. The liberated minerals do not undergo a coalescence step. Both the intermediate locked particles and liberated minerals are then reacted with those constituents which stay in the vapor phase during the early stages of combustion. During the coalescence and vapor-nucleation steps, the formation of submicron fly ash is predicted. After these steps are completed, three different data sets are formed: locked fly ash, liberated fly ash, and submicron fly ash particles. The three data sets are characterized and combined on a mass basis, giving a distribution of the ash composition as a function of size.

Three coals of different rank were tested in a drop-tube furnace under low- NO_x and conventional conditions. These test results were integrated into the ash transformation model, which is covered in Section 5.

2.4 Ash-Fouling Algorithm

A series of ash deposition algorithms have been developed at the Energy & Environmental Research Center (EERC) over the last 5 years. These algorithms are in various forms and at various levels of sophistication. The various codes have been combined into a single ash deposition algorithm for use in all aspects of ash fouling. The general algorithm combines four fundamental principles of deposition: 1) deposit growth, 2) strength development, 3) thermal properties, and 4) deposit removal. Each of these principles is discussed in detail in Section 6 with respect to its implementation in the code.

3.0 DEVELOPMENT OF COMPUTERIZED SHELL AND INTERFACE

FQA is a compilation of computer models under a single user-friendly graphical interface in the Microsoft® Windows™ environment. This system is introduced by a splash screen (Figure 1) containing a graphical image of the FQA title and the EERC logo. A splash screen is a screen that remains visible for only a few seconds. The FQA main screen (Figure 2) will appear with buttons for the selection of a model to be executed. After a model has been selected either by the bitmapped buttons or through the pull-down menu, the program will enter the execution of that

Figure 1. Initial "About" splash screen incorporated into the user interface.

Figure 2. FQA main screen.

model. The Help system, which is being developed concurrently with the graphical system, explains the details needed to execute each model.

3.1 Requirements

FQA will run on a 486 or higher personal computer equipped with an SVGA video adapter with a minimum of 800×600 resolution and Windows™ Version 3.1 or higher. It requires a minimum of 8 MB of RAM to operate. A 3.5-in. high-density (1.44-MB) disk drive and at least 20 MB (3 MB to load and 17 MB to run) of free memory on a hard drive are required to install and run the FQA package. The package consists of 1) the FQA program, which contains the user interface and the three models; 2) coal analysis and boiler parameter files; and 3) an INSTALL program. DOS-based systems must have a WIN 32s upgrade.

3.2 Models

The main program will be separated into three different models: Coal Handleability (Figure 3), Ash Transformation (Figure 4), and Ash Deposition (Figure 5).

3.3 Operation

FQA is a user-friendly interface designed to bundle several existing computer models with a Windows™ graphical user interface. FQA contains three major computer programs: Coal Handleability Model, Ash Transformation Model (ATM), and Ash Deposition Model (ADM). The coal handleability model predicts the dust-handling characteristics for various coal types. The

Figure 3. Coal Handleability main screen.

Figure 4. Ash Transformation main screen.

Figure 5. Ash Deposition main screen.

ash transformation model program predicts the PSCD of the entrained ash reaching the convective pass of a utility boiler. The ash deposition model program predicts the ash deposition and strength development potentials of the ash, thermal resistance due to deposition on the heat-exchange tubes, and the effectiveness of sootblowers to remove the deposits in a convectional, cyclone, fluidized-bed, and boiler that has low- NO_x burners or staged low- NO_x combustion capabilities. All models are based on theory and a combination of laboratory-, pilot-, and full-scale test data. All outputs from the ADM model are on a relative basis and are intended to be used for comparative purposes.

The automated installation will place all required files and examples into the proper user-defined directories. A new group will be generated with the FQA icon placed inside. The look and feel of each model in FQA is similar so that training time in each of the models can be minimized. Each model will ask for a series of inputs required to calculate the particular models results. The Ash Transformation model will generate a parameter file that can be used by the deposition model.

4.0 DEVELOPMENT OF COAL HANDLEABILITY ADVISOR

The low-rank coal (LRC) upgrading technologies under development include evaporative and nonevaporative drying and mild pyrolysis and gasification. An obstacle affecting their development is the stability of the product with regard to dusting, moisture reabsorption, and spontaneous combustion. Because stability phenomena are often given only minor attention, devising improved stability-testing methods has been deemed a necessary and complementary component in the successful demonstration of upgrading technologies (3). Previous efforts to determine stability on a

laboratory scale include various test methods such as the tumble, drop-shatter, and dust box tests. However, no single test has been available to address the quality of coals from attrition, coal weathering (slacking), shattering, and dusting properties of the fuel. The need for a system to address each of these categories exists, since one of the most common plant retrofits is that of coal receiving and handling for fuel switching and blending with western coals.

Friability testing, either the American Society for Testing and Materials (ASTM) drop-shatter test or tumbler test, has determined the LRCs to be the least friable of the coals. Table 1 summarizes friability indices for various ranks of coal measured after tumbling the coal for 3 hours (4, 5). Even though LRCs are reported to be less friable, they show a pronounced

TABLE 1

Average Friability Values of Various Coal Ranks	
Coal Type	Friability, %
Anthracite	33
Low- and Medium-Volatile Bituminous	70
High-Volatile Bituminous	43
Subbituminous A	30
Subbituminous B	20
Lignite	12

tendency to disintegrate on exposure to the weathering conditions that are not simulated in ASTM procedures. This effect was first reported by Parry in 1941 when a sample of subbituminous coal was air-dried in a coal bin (6). The results show an increase of 34% in friability after air drying 10 days and a further increase to a total of a 138% increase after 20 days of air drying. As these results indicate, slacking, like the handling of a friable coal, causes the formation of an excessive amount of fine material at the expense of the coarser sizes, thus decreasing the value of the coal for most uses. Slacking indices of 5% or less characterize bituminous coals, whereas values for lignite approach 100% (7).

The EERC, in an effort to establish new standards for dried products, has used various known methods and developed new ones to evaluate the propensity of lump western coals, raw and dried, to produce dust in relation to coal-handling problems (8, 9). A conveyor test loop was designed to assess the friability and dust issues associated with handling solid fuels. Various time interval samples can be run through the system to simulate a specific transfer distance and loadout. The conveyor system offers a method to continuously monitor dust emissions and assess various dust suppression additives without conducting a full-scale field test. Establishing this system will provide an important link between research and commercial applications and extend EERC capabilities to better evaluate product integrity of upgraded fuel products.

4.1 Objectives

The objective of this area is to establish indices for dust-handling characteristics for various coal types and how they are impacted by current dust suppression methods (e.g., containment

methods, stockpiling, dust collection devices, or suppression additives). The results from the test program have been integrated into the overall FQA algorithm. The objectives were as follows:

- To develop improved methods for evaluating the physical stability of raw and dried coal samples
- To correlate ASTM with modified procedures and understand their relationship and their appropriateness to real-world applications

4.2 Experimental Procedures – Maceral Analysis

Various size-classified coal samples were prepared and analyzed by The Pennsylvania State University (Penn State) and the EERC to determine their macerals contents. Coal samples were collected and sized from tumbling tests reported in the previous semiannual report. Each of the coals samples were then ground to -50 mesh and distributed to the appropriate laboratories. Maceral analysis was performed on two lignite samples at the EERC based on experience with classifying lignitic characteristics. Two coals were evaluated, Knife River (lignite) and Illinois No. 6 (bituminous). Preliminary inspection indicated that samples were sized well below that required for an ASTM D2799 analysis and that the sample surfaces would require a fresh polish. Owing to the particle size (averaging $< 50 \mu\text{m}$) and dispersion of coal particles within the briquettes, the procedure used for maceral analysis was modified. The maceral analysis performed at Penn State was based on a point count of 1000 points, 500 from each of two freshly polished surfaces. Thus the samples were polished, 500 readings taken, and a new surface ground and polished for a second set of 500 readings. Also, identification of macerals that are dependent on relative differences in reflectance (i.e., vitrinite, semifusinite, and fusinite) was made more difficult by the particle size and could contribute to some minor variation in the results. Results are reported on a mineral matter-free basis.

4.3 Accomplishments – Maceral Analysis

Tables 2 and 3 summarize the Knife River lignite maceral analysis obtained from Penn State and the EERC. According to Penn State scientists, lignitic coals are normally evaluated using procedures developed for brown coals. The particle size made an accurate distinction between different huminite macerals impractical; consequently, Table 2 contains only a total huminite value. The as-received Knife River sample had less total huminite and more inertinite and liptinite group macerals than the tumbled sample. The results indicate that upon tumbling, the total reactive components are concentrated from 95.7% to 98.1%, and the total inert components are reduced from 4.3% to 1.9%. The total inertinite content does not show an increase in the tumbled samples until the -50-mesh fraction listed in Table 3. This correlates well with other results, which have indicated that the inertinite maceral is one of the most friable and is concentrated in the dust (10). For the samples in Table 2, qualitative analysis indicated the principal huminite maceral was ulminite, with lesser concentrations, in decreasing order, of humodetrinite, corpohuminite, and gelenite. The minerals observed during analysis were mostly clays, intimately mixed with the organic fraction, rutilated quartz, and minor pyrite. The analysis from Penn State did not include mineral analysis, but the EERC results in Table 3 show the minerals are concentrated in the fine fraction, as expected.

Tables 4 and 5 contain maceral analysis performed at Penn State on four Illinois No. 6 samples. The maceral composition for the samples was fairly consistent. The vitrinite maceral, the most abundant component, remained relatively unchanged from the tumbling, ranging between 88.7% and 87.5% among all samples. Table 4 indicates the fusinite was reduced as a result of tumbling. For the as-received sample, particles of clay minerals, pyrite, and carbonates were observed as individual particles and intimately mixed with the organic fraction. The $\frac{1}{2}$ in. $\times$ $\frac{3}{8}$ in. tumbled sample showed the most variation in maceral composition within the set, having slightly more liptinite (sporinite, resinite, and cutinite) and less inertinite than the other samples. In addition, clays and carbonates were observed in more relative abundance than pyrite, both as individual particles and mixed with the organic fraction.

4.4 Coal Handling Algorithm

The EERC then began to identify whether the maceral information could be used as an indicator for coal handability and grouping. Literature indicated no clear distinction between coal types (11,12). Large variability was even indicated for coal from the same mine. Therefore, efforts to develop of algorithm to be used for the computer model, focused back on the as-received moisture content relative the coal bed moisture content. Also the correlation of slacking to coal rank was identified by the Bureau of Mines as a key component. In fact an inverse relationship was determined between coal friability and the slacking phenomenon. Coal particle size was also identified as a key component to coal handling. Each of these components—moisture, slacking, friability, and particle size—affected dust and fines generation during coal test-loop testing conducted at the EERC. Based on the results of these tests and results reported in the literature, the EERC developed a formula for calculating a coal handling index.

The index is most sensitive to change in as-received moisture content. The index is completed for a range of values to characterize the coal relative to coal rank, coal blend, friability, moisture content, and the coal's tendency to weather.

The output from the computer program will indicate to the user whether the coal being considered has good, reasonable, or problem handling characteristics. It also issues comments on when to consider dust containment or suppression systems.

4.5 Conclusions

Maceral analysis performed on lignite samples indicated that fusinite, sporinite, and micrinite were reduced in particle size as a result of tumbling the coal sample. Pyrite and other mineral forms were also reduced in size. Maceral analysis performed on Illinois No. 6 samples indicated that fusinite and sporinite were reduced in particle size as a result of tumbling the coal sample.

The coal handling index was developed based on EERC coal test log data and data generated by the Bureau of Mines. This index will serve as an initial indicator of coal handling properties. Once the user has selected coal (or coal blend, the best method of determining coal handling would be to complement the model by conducting pilot or demonstration testing.

4.6 Coal Handleability Results

See Table 6 for coal handleability results.

TABLE 2

Knife River Maceral Analysis, vol%, mineral matter free

Analysis Report: Knife River, -1/2 in. × 3/8 in. as-received sample

Reactive		
Huminite		
Total Huminite		92.9
Reactive Semifusinite	0.7	
Sporinite	1.6	
Resinite	0.4	
Cutinite	0.1	
Total Reactive Components		95.7
Inert		
Fusinite	1.3	
Inert Semifusinite	1.3	
Macrinite	0.0	
Micrinite	1.7	
Inertodetrinite	0.0	
Sclerotinite	0.0	
Mineral Matter	ND ¹	
Total Inert Components		4.3
	Total	100.0

Analysis Report: Knife River, -1/2 in. × 3/8 in. tumbled sample

Reactive		
Huminite		
Total Huminite		96.5
Reactive Semifusinite	0.2	
Sporinite	0.9	
Resinite	0.5	
Cutinite	0.0	
Total Reactive Components		98.1
Inert		
Fusinite	0.4	
Inert Semifusinite	0.3	
Macrinite	0.0	
Micrinite	1.0	
Inertodetrinite	0.0	
Sclerotinite	0.2	
Mineral Matter	ND ¹	
Total Inert Components		1.9
	Total	100.00

¹ Not determined.

TABLE 3

Knife River EERC Maceral Analysis Report

Macerals	-50-mesh, tumbled		$\frac{3}{8}$ in. $\times$ 50-mesh, tumbled	
	Counts	vol%	Counts	vol%
Humotelinite	201	38.0	255	48.2
Humodetrinite/Humocollinite	237	44.8	179	33.8
Total Huminite	438	82.8	434	82.0
Sporinite	1	0.2	0	0.0
Cutinite	0	0.0	0	0.0
Resinite	2	0.4	0	0.0
Liptodetrinite	0	0.0	0	0.0
Total Liptinite	3	0.6	0	0.0
Fusinite	2	0.4	4	0.8
Semifusinite	12	2.3	4	0.8
Sclerotinite	0	0.0	0	0.0
Inertodetrinite	10	1.9	2	0.4
Total Inertinite	24	4.5	10	1.9
Pyrite	3	0.6	1	0.2
Other Minerals	67	12.7	7	1.3
Total Minerals	70	13.2	8	1.5
Total	535	101.1	452	85.4

TABLE 4

Illinois No. 6 Maceral Analysis, vol%, mineral matter free			
Analysis Report: Illinois No. 6, -1/2 in. × 3/8 in. as-received sample			
Reactive			
Vitrinite			
Total Vitrinite			88.0
Reactive Semifusinite	1.3		
Sporinite	2.3		
Resinite	0.3		
Cutinite	0.1		
Total Reactive Components			92.0
Inert			
Fusinite	3.6		
Inert Semifusinite	2.7		
Macrinite	0.0		
Micrinite	1.3		
Inertodetrinite	0.4		
Sclerotinite	0.0		
Mineral Matter	ND ¹		
Total Inert Components			8.0
	Total		100.0
Analysis Report: Illinois No. 6, -1/2 in. × 3/8 in. tumbled sample			
Reactive			
Vitrinite			
Total Vitrinite			88.8
Reactive Semifusinite	1.1		
Sporinite	4.0		
Resinite	0.3		
Cutinite	0.1		
Total Reactive Components			94.2
Inert			
Fusinite	1.6		
Inert Semifusinite	2.3		
Macrinite	0.0		
Micrinite	1.7		
Inertodetrinite	0.2		
Sclerotinite	0.0		
Mineral Matter	ND ¹		
Total Inert Components			5.8
	Total		100.0

¹ Not determined.

TABLE 5

Illinois No. 6 Maceral Analysis, vol%, mineral matter free			
Analysis Report: Illinois No. 6, -3/8 in. × 50 mesh tumbled sample			
Reactive			
Vitrinite			
Total Vitrinite			87.5
Reactive Semifusinite	1.1		
Sporinite	2.9		
Resinite	0.3		
Cutinite	0.3		
Total Reactive Components			92.1
Inert			
Fusinite	3.1		
Inert Semifusinite	2.3		
Macrinite	0.0		
Micrinite	1.5		
Inertodetrinite	1.0		
Sclerotinite	0.0		
Mineral Matter	ND ¹		
Total Inert Components			7.9
	Total		100.0
Analysis Report: Illinois No. 6, -50 mesh tumbled sample			
Reactive			
Vitrinite			
Total Vitrinite			88.3
Reactive Semifusinite	1.3		
Sporinite	2.3		
Resinite	0.3		
Cutinite	0.0		
Total Reactive Components			92.2
Inert			
Fusinite	3.9		
Inert Semifusinite	2.6		
Macrinite	0.0		
Micrinite	0.8		
Inertodetrinite	0.5		
Sclerotinite	0.0		
Mineral Matter	ND ¹		
Total Inert Components			7.8
	Total		100.0

¹ Not determined.

TABLE 6

Coal Type	Coal Handleability Results			
	As-Received Moisture	Equilibrium Moisture	Particle Size Distribution	Coal Handling Results
Anthracite	0.05	0.05	2" × 0"	Good handling
Low-Med.	0.05	0.1	-200 mesh	Problem handling
High Vol.	0.15	0.15	2" × 0"	Good handling
Sub A	0.23	0.23	2" × 0"	Good handling
Sub B	0.2	0.25	¼" × 0"	Potential problem handling
Lignite	0.35	0.35	¼" × 0"	Reasonable handling
Anthracite	0.05	0.05	2" × 0"	Good handling
Low-Med.	0.1	0.1	2" × 0"	Good handling
High Vol.	0.1	0.15	¼" × 0"	Potential problem handling
Sub A	0.18	0.23	2" × 0"	Reasonable handling
Sub B	0.25	0.25	2" × 0"	Good handling
Lignite	0.25	0.35	¼" × 0"	Problem handling

5.0 ENHANCEMENT OF ASH FORMATION ALGORITHMS

5.1 Introduction

The effects of combustion conditions on coal ash formation and deposition characteristics were investigated using a drop-tube furnace. A North Dakota Beulah lignite coal, Black Thunder subbituminous coal, and Illinois No. 6 bituminous coal were burned under conventional and low- NO_x combustion conditions. The resulting entrained ash and fouling deposits were sampled and analyzed to characterize their physical and chemical properties. The information from these tests and analyses was used to compare the ash formation and fouling deposition characteristics produced from the conventional and low- NO_x combustion of coals of varying rank. The results of these comparisons will be used for modeling ash transformations.

5.2 Experimental

The three test coals (Beulah lignite, Black Thunder subbituminous, and Illinois No. 6 bituminous) were pulverized to a particle-size distribution consistent with standard utility boiler practice (i.e., 70%–80% of the coal particles < 200 mesh). Ash formation and deposition tests were conducted in an optical drop-tube furnace (ODTF), depicted in Figure 6, using conventional and staged low- NO_x combustion conditions. During the conventional combustion tests, coals were fed with 50% excess air and heated to an initial temperature of 1530°C before passing through a cooler-temperature regime of 1200°C. To simulate low- NO_x conditions, the coals were fed into the furnace using a N_2 primary gas and an air- N_2 secondary gas and heated to an initial temperature of 1330°C before passing through a maximum temperature regime of 1430°C and a final, lower-temperature regime of 1200°C. The lower temperature and slower mixing of fuel and air extended the burning time and significantly reduced both the thermal and fuel NO_x , while maintaining an acceptable level of carbon burnout. Compared in Figure 7 are the furnace temperature profiles and gas flows for conventional and low- NO_x combustion conditions.

Figure 6. Schematic of the ODTF.

Figure 7. Comparison of gas flows and temperature profiles used in the ODTF to simulate conventional and staged low-NO_x combustion conditions.

A quench probe shown in Figure 8 was attached to the bottom of the ODTF to cool the fly ash before collection. A filter assembly was attached to the exit of the quench probe to collect bulk particulate samples. Samples of size-fractionated ash were collected using a U.S. Environmental Protection Agency Southern Research Institute five-stage multicyclone (EPAFSC). During several tests, the EPAFSC was used in conjunction with a scanning mobility particle sizer to determine the size distribution of the submicron ash fraction. Baseline tests, however, indicated that the concentration of contaminate submicron particles was too great to produce reliable results. Most of the contaminate particles, >70% by volume, were <0.1 μm in diameter. As an alternative, several samples of bulk ash were mounted on vitreous carbon substrates using a modified version of a freeze-dry dispersion method (13) and then analyzed using CCSEM to determine the size and chemical composition of individual microparticles ranging from 0.1 to 100 μm in average diameter. Approximately 1000 particles were analyzed in selected samples using CCSEM.

Deposits were formed in the ODTF on a deposition probe that simulates an actual boiler tube. Expendable sample coupons were attached to the probe and maintained at temperatures corresponding to boiler heat-transfer surfaces, 350° to 540°C. An insulating refractory constrictor was used to accelerate the gas flow and entrained ash onto the deposit probe. The crushing strengths of the deposits were determined. The resulting deposits were also analyzed using a scanning electron microscope point count method (SEMPC) described by Galbreath et al. (14).

5.3 Results

5.3.1 Ash Formation Tests

The ash formation test matrix and ODTF operating conditions are summarized in Table 7. Entrained ash was produced using relatively long residence times ranging from 3.9 to 5.2 seconds. Several tests at shorter residence times of 0.2 and 0.5 seconds were also conducted on the Black

Figure 8. Schematic of the fly ash quench probe.

TABLE 7

Operating Parameters for Drop-Tube Furnace Ash Formation Tests

Coal	Conditions	Furnace Temperatures, °C				Residence Time, s	Excess Air, %	Gas Carbon Conversion, %	Initial Thermal NO _x , ppm	Total NO _x , ppm
		Furnace 1	Furnace 2	Furnace 3	Furnace 4					
Black Thunder	Conventional	1100	1530	1450	1230	3.9	53	NA ¹	34.6	143.4
Black Thunder	Conventional	1100	1530	1450	1230	3.9	53	NA	34.3	147.4
Black Thunder	Low-NO _x	800	1330	1430	1230	4.1	52	99.3	2.2	97.1
Black Thunder	Low-NO _x	800	1330	1430	1230	4.1	53	NA	7.7	97.9
Black Thunder	Conventional	1100	1530	1450	1230	0.2	50	62.5	17.1	55.6
Black Thunder	Conventional	1100	1530	1450	1230	0.5	54	82.2	15.9	64.5
Black Thunder	Low-NO _x	800	1330	1430	1230	0.2	51	91.2	3.0	10.0
Black Thunder	Low-NO _x	800	1330	1430	1230	0.5	50	61.1	2.4	36.6
Black Thunder	Conventional	1000	1530	1450	1200	5.0	51	NA	NA	NA
Black Thunder	Low-NO _x	800	1330	1430	1200	5.2	51	NA	NA	NA
Illinois No. 6	Conventional	1100	1530	1450	1230	3.9	49	96.0	34.5	175.9
Illinois No. 6	Conventional	1100	1530	1450	1230	3.9	52	85.0	14.3	158.7
Illinois No. 6	Low-NO _x	800	1330	1430	1230	4.1	50	93.0	2.9	112.7
Illinois No. 6	Low-NO _x	800	1330	1430	1230	4.1	64	91.3	3.2	116.6
Illinois No. 6	Conventional	1000	1530	1450	1200	5.0	52	84.4	16.8	139.3
Illinois No. 6	Conventional	1000	1530	1450	1200	5.0	52	NA	NA	NA
Illinois No. 6	Low-NO _x	800	1330	1430	1200	5.2	52	90.1	3.43	108.7
Illinois No. 6	Low-NO _x	800	1330	1430	1200	5.2	52	NA	NA	NA
Beulah	Conventional	1100	1530	1450	1230	3.9	53	92.5	32.0	121.0
Beulah	Conventional	1100	1530	1450	1230	3.9	58	100.8	32.9	122.3
Beulah	Low-NO _x	800	1330	1430	1230	4.1	54	89.8	3.7	71.7
Beulah	Low-NO _x	800	1330	1430	1230	4.1	54	100.5	4.0	85.4
Beulah	Conventional	1000	1530	1450	1200	5.0	50	88.3	16.2	103.8
Beulah	Conventional	1000	1530	1450	1200	5.0	50	NA	NA	NA
Beulah	Low-NO _x	800	1330	1430	1200	5.2	50	91.3	3.65	77.3
Beulah	Low-NO _x	800	1330	1430	1200	5.2	50	NA	NA	NA

¹ Not analyzed.

Thunder coal. The simulated low-NO_x combustion conditions reduced NO_x by about 50% relative to conventional combustion while maintaining a relatively high degree of gas carbon conversion (Table 7).

Presented in Figure 9 are the multicyclone ash collection results for the ODTF tests. These results indicate that the Black Thunder coal produced the coarsest ash. In addition, combustion conditions most significantly affected the size distribution of the Black Thunder ash, whereby the ash produced under low-NO_x conditions was coarser relative to the ash generated during conventional combustion. The particle-size distributions of the Beulah and Illinois No. 6 coal ashes are similar, and combustion conditions appear to have had very little effect.

The fine-particle fractions (0.1- to 10- μ m diameter) of the ashes were investigated in detail using CCSEM. Particle-size distributions presented in Figure 10 indicate that combustion conditions greatly affected the formation of fine ash for the lower-rank Beulah and Black Thunder coals, but not for the Illinois No. 6 bituminous coal. The morphology of particles in the fine ash fractions was examined using scanning electron microscopy. The ashes produced from the conventional combustion of coal consist primarily of discrete spherical particles, as exemplified in Figure 11. Particle agglomerates, however, are characteristic of the low-NO_x Beulah and Black Thunder fine ashes, as illustrated in Figure 12. The agglomeration is the result of sintering between individual ash particles. Apparently the lower oxygen fugacity and extended combustion duration associated with low-NO_x test conditions enhance the sintering propensity of individual fine ash particles in the lower-rank coals. The fine ash fractions of the Beulah and Black Thunder coals produced using the low-NO_x combustion conditions are coarser because of the enhanced coalescence, as indicated in Figure 10. The predominant particle morphology was similar for the conventional and low-NO_x Illinois No. 6 fine ash fractions, that is, individual spherical particles.

Chemical analysis of individual ash particles indicates that the fine ash fractions are composed of very diverse particle-type assemblages, as shown in Table 8. The Beulah fine ash fraction is composed primarily of sodium and calcium aluminosilicate (Na-Al-Si and Ca-Al-Si) phases, which is consistent with the high concentrations of organically bound sodium and calcium that is available in ND lignite coals to react with clays during combustion. Likewise, the predominance of calcium aluminosilicate (Ca-Al-Si), calcium aluminate (Ca-Al), and calcium carbonate, hydroxide, or oxide [(Ca)CO₃, OH, or O] phases in the Black Thunder fine ash is consistent with the relatively high concentrations of organically bound calcium that is available in Powder River Basin subbituminous coals to react with mixed clays and kaolinite during combustion or to vaporize and condense. The Illinois No. 6 fine ash is composed largely of aluminosilicate (Al-Si), sodium aluminosilicate (Na-Al-Si), and mixed aluminosilicate [(Ca, Mg, Fe)-Al-Si] particle types. The different combustion conditions (conventional and low-NO_x) used to produce the fine ash fractions appear to have had a negligible effect on phase proportions.

5.3.2 Ash Deposition Tests

Deposits were produced in the ODTF under conventional and low-NO_x fouling conditions. The operating parameters used during the ash deposition tests are presented in Table 9. The deposits are largely amorphous; however, small crystals with chemical compositions consistent with the minerals clinopyroxene, melilite, plagioclase, and quartz have been identified. A total of 250 randomly selected locations on each of the deposit samples were chemically analyzed using a scanning electron microscope to assess compositional homogeneity. In addition, the crushing strengths of the deposits were determined.

Figure 9. Comparison of particle-size distributions for the Black Thunder, Illinois No.6, and Beulah, ND lignite ashes produced using conventional and low-NO_x combustion conditions.

Figure 10. Comparison of particle-size distributions for the Black Thunder, Illinois No. 6, and Beulah ND lignite fine ash fractions produced using conventional and low- NO_x combustion conditions.

Figure 11. Secondary electron images of the Black thunder fine ash fraction produced under low- NO_x combustion conditions.

Figure 12. Secondary electron image of the Beulah fine ash fraction produced using conventional combustion conditions.

An examination of the effect of low- NO_x conditions on the strength and chemistry of deposits formed under high-temperature fouling conditions was performed. Deposits of Beulah lignite and Illinois No. 6 bituminous coals were produced under conventional and low- NO_x conditions.

Crushing strengths for the deposits were determined in duplicate at ambient temperature after the deposits were grown, removed from the furnace, and cooled. Values of crushing strength at the base, midpoint, and top of the deposits are summarized in Table 10, along with average values for the duplicate tests. Although there is considerable scatter in the data, the Beulah deposit formed under conventional combustion conditions has a generally higher crushing strength than the Illinois No. 6 deposit formed under corresponding conditions. Under low- NO_x conditions, the strengths of the Beulah and Illinois No. 6 deposits are much more similar, except for the very weak base of the Illinois No. 6 deposit. Comparison of the Beulah deposits show that while the bases are similar in strength, the middle and upper portion formed under conventional conditions is somewhat harder than the deposit formed under low- NO_x conditions. The scatter in the data for the Illinois No. 6 deposits makes comparison difficult, but it appears that the two deposits are of roughly similar strength. Unburned carbon levels in the coal combustion ash did not appear to be of high enough concentration to impact deposit strength.

Point-by-point viscosities were calculated using a modified Urbain method with the VISCALC program developed at the EERC for silicate phases at a temperature of 1100°C . These average viscosities are given in Table 11. Although the average viscosity of the Beulah deposits are significantly less than those for the Illinois No. 6 deposits, there is little difference between the viscosity of the lower bottom and upper top sections of the deposits. In addition, there is

TABLE 8

Fine-Ash-Phase Proportions, frequency %

	Beulah		Black Thunder		Illinois No. 6	
	Conventional	Low NO _x	Conventional	Low NO _x	Conventional	Low NO _x
SiO ₂	1.7	3.2	5.3	5.1	6.4	8.1
Na-Al-Si	11.8	17.4	ND ¹	ND	17.6	14.2
Ca-Al-Si	24.0	19.1	19.6	20.8	1.8	1.7
K-Al-Si	ND	ND	ND	ND	2.4	2.2
Fe-Al-Si	ND	ND	ND	ND	1.2	1.3
(Ca,Mg,Fe)-Al-Si	3.5	1.8	4.5	8.7	17.5	13.3
Al-Si	0.4	ND	25.1	19.9	31.6	27.6
Na-Si	ND	ND	ND	0.9	ND	ND
Ca-Si	0.5	0.2	ND	ND	0.1	ND
Fe-Si	0.1	ND	0.8	ND	0.1	0.2
Si-Rich	1.7	2.0	3.6	6.6	5.2	4.5
Ca-Al	0.2	0.6	16.5	9.6	ND	ND
(Ca,Mg,Fe)CO ₃ , OH, or O	1.1	2.6	23.4	16.6	1.1	0.8
Al ₂ O ₃	0.3	ND	ND	ND	ND	0.1
FeO _x	0.2	0.3	0.6	0.3	0.1	0.1
Na ₂ SO ₄	ND	ND	ND	2.1	ND	ND
CaSO ₄	0.3	0.4	ND	3.0	1.4	0.1
S-Rich	3.7	3.8	0.6	0.6	1.8	4.1
(Na,K)Cl	ND	ND	ND	ND	ND	0.1
Cl-Rich	0.3	1.1	ND	3.0	0.1	0.2
P-Rich	0.2	0.4	ND	0.3	ND	ND
Na-Rich	ND	ND	ND	2.4	ND	ND
Unclassified	50.0	48.9	0.0	0.0	11.6	21.4

¹ND = Not detected.

TABLE 9

Operating Parameters for Drop-Tube Furnace Fouling Tests

Coal	Conditions	Furnace Temperatures, °C				Residence Time, s	Excess Air, %
		Furnace 1	Furnace 2	Furnace 3	Furnace 4		
Beulah	Conventional	1000	1530	1450	1200	3.5	50
Beulah	Low-NO _x	800	1330	1430	1200	3.6	50
Illinois No. 6	Conventional	1000	1530	1450	1200	3.5	51
Illinois No. 6	Low-NO _x	800	1330	1430	1200	3.6	52

TABLE 10

FQA Deposit Crushing Strengths

	Beulah		Illinois No. 6	
	Conventional	Low-NO _x	Conventional	Low-NO _x
Test 1				
Deposit Base	522	531	126	95
Deposit Middle	779	596	371	614
Deposit Top	985	806	778	806
Average	762	644	425	505
Test 2				
Deposit Base	500	636	170	95
Deposit Middle	1298	677	718	675
Deposit Top	934	408	1056	466
Average	911	574	648	412
Average Base	511	584	148	95
Base Standard Deviation	16	74	31	0
Average Middle	1039	637	545	645
Middle Standard Deviation	367	57	245	43
Average Top	960	607	917	636
Top Standard Deviation	36	281	197	240
Overall Average	836	609	537	459
Standard Deviation	105	50	158	66

TABLE 11

FQA Deposit Viscosities

Deposits	Average Viscosity		Average Viscosity, log 10 poise	Standard Deviation
Beulah	Conventional Deposit	Bottom	3.62	1.59
Beulah	Conventional Deposit	Top	3.77	1.18
Beulah	Low-NO _x Deposit	Bottom	3.45	1.61
Beulah	Low-NO _x Deposit	Top	3.43	1.44
Illinois No. 6	Conventional Deposit	Bottom	5.78	1.85
Illinois No. 6	Conventional Deposit	Top	5.95	1.98
Illinois No. 6	Low-NO _x Deposit	Bottom	6.10	1.75
Illinois No. 6	Low-NO _x Deposit	Top	5.98	1.80

little difference between the average viscosities of deposits formed under conventional and under low-NO_x conditions.

Mineral phases inferred from the point SEMPC chemical analyses and the bulk chemistry of the deposits are shown in Table 12. Both the Beulah and Illinois No. 6 deposits are dominated by mixed silica-alumina phases. The Beulah deposit contains significant albite, anorthite, and montmorillonite, and the Illinois No. 6 deposit quartz, iron oxide, and montmorillonite. Both deposits also contain minor amounts of other minerals, as well as other unclassified material. It should be noted that each analysis point corresponds to 0.8% of a mineral species. The bulk chemistry of the Beulah deposit is primarily SiO₂, Al₂O₃, and CaO, and the Illinois No. 6 deposit SiO₂, Al₂O₃, and Fe₂O₃, reflecting the composition of the coal ash. Again, very little difference is seen between deposits formed under conventional and under low-NO_x conditions, either in the mineralogy or the bulk chemistry. It appears that the deposit mineralogy and chemistry are dictated by the coal ash composition, with the combustion environment (conventional or low-NO_x conditions) having little or no effect.

5.4 Ash Formation Model Results

The data produced from the ash formation tests were used in enhancing the ash formation model to include low-NO_x boiler conditions. To reproduce the increase in coarse particles observed with low-NO_x conditions, the coalescence frequency of the locked minerals was increased along with a decrease in the fragmentation of the mineral particles. Figure 13 compares the predicated results of the particle-size distributions (PSD) for the Black Thunder coal for both conventional and low-NO_x combustion conditions. The predicted low-NO_x combustion conditions produced a coarser PSD than the corresponding ash produced under conventional combustion conditions, matching the experimental results.

TABLE 12

FQA Deposit Analysis

Mineral, frequency %	Beulah				Illinois No. 6			
	Conventional	Conventional	Low-NO _x	Low-NO _x	Conventional	Conventional	Low-NO _x	Low-NO _x
	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top
Aluminum Oxide	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0
Iron Oxide	2.4	1.6	3.2	3.2	6.3	8.8	3.2	4.0
Mixed Oxide-Rich	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0
Pyrite	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mixed Sulfur-Rich	1.6	0.0	2.4	0.0	2.4	0.8	0.8	0.0
Calcite	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
Ankerite	0.8	0.0	0.0	0.8	0.0	0.0	0.0	0.0
Mixed Carbon-Rich	3.2	1.6	1.6	3.2	0.8	0.8	0.8	0.0
Quartz	1.6	0.8	1.6	0.8	9.4	12.0	11.2	11.2
Albite	12.0	8.8	12.8	8.8	0.0	0.0	0.8	0.0
Anorthite	19.2	23.2	8.8	14.4	6.3	2.4	8.0	8.8
Kaolinite	0.0	0.0	0.0	0.0	3.9	2.4	1.6	0.8
Altered Kaolinite	1.6	2.4	3.2	1.6	0.0	0.8	0.8	0.8
Illite	0.8	0.8	0.8	0.8	11.8	7.2	11.2	10.4
Montmorillonite	12.0	21.6	0.8	20.0	28.3	29.6	24.8	34.4
Pyroxene	0.8	0.0	1.6	0.8	0.0	0.0	0.0	0.0
Wollastonite	2.4	2.4	2.4	1.6	0.0	0.0	0.8	0.0
Calcium Silicate	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0
Dicalcium Silicate	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0
Gehlenite	0.8	0.0	1.6	2.4	0.0	0.0	0.0	0.0
Akermanite	0.0	0.0	1.6	2.4	0.0	0.0	0.0	0.0

Continued . . .

Table 12 (continued)

Mineral, frequency %	Beulah				Illinois No. 6			
	Conventional	Conventional	Low-NO _x	Low-NO _x	Conventional	Conventional	Low-NO _x	Low-NO _x
Spurrite	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0
Mixed Silicon-Rich	34.4	30.4	39.2	28.8	29.9	35.2	36.0	26.4
Other	5.6	4.8	10.4	6.4	0.8	0.0	0.0	3.2
Bulk Composition, wt %								
SiO ₂	36.9	40.3	34.4	35.1	53.6	54.4	58.9	56.4
Al ₂ O ₃	17.4	18.7	18.0	17.4	20.5	18.8	21.8	20.3
Fe ₂ O ₃	9.9	8.4	9.3	10.6	13.7	17.3	7.4	10.8
TiO ₂	0.8	0.7	0.7	1.1	0.9	0.9	1.0	1.4
P ₂ O ₅	0.2	0.2	0.4	0.3	0.0	0.0	0.0	0.0
CaO	20.7	18.7	23.8	21.4	6.3	4.0	5.3	5.3
MgO	6.7	5.7	6.8	7.4	0.8	0.9	0.9	0.9
Na ₂ O	4.3	5.3	4.0	4.7	1.4	1.4	2.1	2.4
K ₂ O	0.6	0.8	0.6	0.7	1.6	1.8	1.9	1.9
SO ₃	1.6	0.4	1.4	0.5	0.9	0.3	0.4	0.1
ClO	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1
Cr ₂ O ₃	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
BaO	0.6	0.6	0.4	0.7	0.1	0.1	0.1	0.1

*Each point analyzed equals 0.8%.

Figure 13. Comparison of ash formation model predicated particle-size distributions for the Black Thunder coal using conventional and low- NO_x combustion conditions.

5.5 Conclusions

An important finding from the tests is that the fine ash fraction ($< 10 \mu\text{m}$) produced by burning the lower-rank Beulah ND lignite and Black Thunder subbituminous coals under low- NO_x conditions is coarser than the corresponding ash produced under conventional combustion conditions. The lower partial pressure of oxygen and extended combustion duration associated with the low- NO_x combustion conditions promotes the sintering of individual ash particles to form agglomerates. This agglomeration effect was insignificant for the Illinois No. 6 bituminous ash.

6.0 ENHANCEMENT OF ASH FOULING ALGORITHMS

The fouling algorithm contains four major areas: deposit growth, strength development, thermal properties, and deposit removal. Each of these areas is covered in detail in the following sections.

6.1 Deposit Growth

The first function of the deposit growth submodel is to organize the ash by size into three ash categories. The code will utilize the data produced from the ash formation algorithms as discussed later. The particle-size and composition distribution (PSCD) of the ash is divided into six size and seven composition bins, for a total of 42 different bins of ash particles. The first ash category includes ash particles less than 5 microns in diameter, which makes up the initial layer. All ash particles less than 10 microns are included in the second category, used in modeling the

downstream deposit. Downstream deposits are formed by impaction from the recirculation eddies passing around the heat-exchange tubes. As the gas stream passes around the tube, those particles that do not inertially impact (generally less than 10 microns) get caught in the recirculation eddies of the gas stream and are impacted into the downstream side of the tube surface, as shown in Figure 14. The last ash category forming the upstream deposit includes all the size and composition bins.

As discussed previously, the three primary modes of fouling deposit growth are inertial and eddy impaction; vapor-phase and small-particle diffusion; and thermophoresis/electrophoresis. The inner layer, formed by small-particle diffusion and thermophoretic/electrophoretic forces, comprises primarily vapors and particles less than 5 microns that traverse through the boundary layer surrounding the tube and deposit. Which particles actually deposit depends upon the flow characteristics around the heat-exchange tubes. At higher temperatures and faster gas velocities, the inner layer is enriched in vapor-phase species and remains loosely bound, while at lower temperatures and lower velocities, the enrichment tends to shift to particles in the less-than-5-micron range. In both cases, the inner layer plays a role in the eventual formation of massive upstream deposits.

$$DR_t = \frac{V_g^2}{T_g} \times R_r \times M_{ash} \times \frac{\delta}{A_d} \quad [1]$$

Both the downstream and inner layer deposition rates (DR_t), where t is the type of deposit layer—downstream (d) or initial (i)—are calculated from the following equation:

EERC SA11802.CDR

Figure 14. Downstream deposition.

Potential deposition mass is the fraction of total mass in the respective ash categories described previously for initial and downstream deposition. Total ash is the total mass of ash passing through the convective pass.

The massive upstream deposits form primarily by inertial impaction onto the surface of the deposit. The deposit surface can be captive or noncaptive. The larger particles become separated from the gas stream as it flows around the tubes. The particles impact the surface and either stick or deflect off, depending upon their sticking ability and the captive surface of the tube. As massive deposits grow, the surface temperature of the deposit increases, developing a highly captive surface that will capture most of the impacting particles. As the deposit grows, it commonly becomes more aerodynamic, thus minimizing the amount of ash that impacts the surface.

The upstream deposition function is separated into three subfunctions, as shown in Figure 15. The sticking fraction subfunction determines the deposit potential, which is the fraction of the total ash in the path of the heat-transfer surface that sticks. A cutoff particle viscosity is calculated by using the values from the inertial impaction subfunction (IEF). If the particle viscosity is less than the cutoff viscosity, Equation 2, that particle is added to the sticking fraction.

$$DP = \alpha \times \frac{M_p}{100} \times IEF \quad [2]$$

Figure 15. Components of the deposit growth model.

The impact efficiency value is a combination of two values: the impact efficiency strike (IES) and the impact efficiency velocity (IEV). The IES value (0 to 1) is the fraction of ash that will strike the tube, and the IEV value (0 to 1) is used to determine whether the particle has sufficient kinetic energy to rebound off or stick to the tube surface. The upstream deposition function goes through each ash particle-size fraction using the gas stream temperature and determines the impaction efficiency value for each size fraction and the cutoff particle viscosity. Summing all of the size bins, a cumulative sticking fraction (SF) value (0 to 1) can be determined. The cumulative sticking fraction is then used in Equation 3 to determine the upstream deposition rate.

$$DR_u = \frac{M_{ash}}{A_b} \times SF \times 2 \times Rad_{t_o} \quad [3]$$

6.2 Strength Development

Strength development is generally the result of one of two sintering mechanisms: silicate- or sulfate-based. The low viscosities necessary for silicate-based sintering are commonly attributed to higher temperatures and lower-melting-point phases such as sodium aluminosilicates. Some of the reduction in melting point happens after deposition, when interaction of the deposited material and gas-phase species forms low-melting-point phases. Sintering develops over time as low-viscosity material flows and fills the pores of a deposit. Decreasing the numbers or size of the pores in the deposit increases strength. The larger the quantity of liquid phase, the higher the potential for sintering and generating hard deposits.

Sulfate-based sintering is attributed to the filling of deposit pores by sulfation of the alkaline and alkaline-earth components in the deposit. Sulfates are generally unstable and decompose above 1850°F (1000°C), but form very rapidly at temperatures slightly below this decomposition temperature. The crossover temperature range from rapid sulfation to decomposition is narrow and can be crossed in some areas of the boiler as a result of load swings.

Both silicate- and sulfate-based strengths are determined for each deposit. The silicate strengths are a function of the viscosity and particle size of the deposited materials and the time duration of deposition. Equation 4 determines a silicate variable that is a function of the deposit potential, particle diameter, and particle viscosity.

$$Sil_v = DP \times D_p \times \mu_p \quad [4]$$

The silicate variable is summed for all of the particle-size bins for that particular deposit type. For example, using Equation 5, the silicate variable for a downstream deposit strength would sum the ash size bins less than 10 microns.

$$\overline{Sil_v} = \frac{\Sigma Sil_v}{\Sigma DP} \quad [5]$$

The cumulative silicate variable is divided by the total deposit potential, producing a weighted average silicate variable. The average silicate variable is the unitless time needed to achieve a completely sintered deposit. The silicate strength of the deposit at that time interval is determined using Equation 6.

$$\text{Str}_{\text{sil}} = 1 - \left(\frac{1}{(t+1)^{\text{sil}_v}} \right)^{\text{sil}_w} \quad [6]$$

The silicate strength is summed over all of the deposit layers present. The longer a deposit has time to sinter, the higher the silicate strength. The weighted average silicate strength (Str_{sil}), Equation 7, is the sum of each deposit layer strength multiplied by that deposit layer's respective mass, divided by the total deposit mass. The weighted average silicate strength is an index value, from 0 to 1, with 1 being the maximum silicate strength.

$$\overline{\text{Str}_{\text{sil}}} = \frac{\sum(\text{Str}_{\text{sil}} \times M_L)}{M_{\text{dep}}} \quad [7]$$

The sulfate strength, Equation 8, is a function of composition and is assumed to reach maximum strength immediately. The PC factors 1 and 2 in the equation are calibration numbers the EERC has obtained from previous projects. Sulfation strengths are set to zero if the temperature is above the sulfate decomposition temperature.

$$\text{Str}_{\text{sulf}} = \frac{\frac{\text{Na}_2\text{O} + \text{MgO} + \text{K}_2\text{O} + \text{CaO}}{\text{Si}_2\text{O}} \times \text{PCF}_1 - \text{PCF}_2}{C_{\text{sulf}}} \quad [8]$$

The sulfate strength is divided by a constant to produce a sulfate strength index number, from 0 to 1. Both sulfate and silicate strength mechanisms can occur at the same location. Figure 16 shows how the sulfate and silicate strength curves may intersect. The greatest strength determined from the two functions is chosen as the strength for that deposit layer (Str_{depL}) at that time interval. An average deposit strength ($\text{Str}_{\text{depave}}$) can be determined by summing the strength multiplied by the deposit layer mass and divided by the total deposit mass.

6.3 Thermal Properties

The thermal properties submodel is a collection of functions that support the other submodels. The thermal properties of the deposits depend upon the thickness, temperature, and physical sintered state of the deposit. Because of the changing temperature and sintered state throughout the thickness of a deposit, as well as its growth and removal, the thermal properties are not constant and require multiple iterations throughout the running of the FOULER model. Since the deposition rates and compositions of the upstream and downstream deposit are different, the thermal property calculations are considered separately for each half of the heat-exchange tube.

Figure 16. Strength development curve.

The main thermal property submodel is the heat-transfer function, which is responsible for the determination of the heat-transfer value through the deposit. The change in heat transfer is due to the convection and conduction through the gas stream, deposit, tube, and steam. Figure 17 shows the components of the heat-transfer function, along with a relative temperature drop through an upstream deposit. The forced convection heat-transfer rate, q''_{conv} , occurs at the boundary layer between the gas stream and the deposit surface. The forced convection value is dependent upon surface geometry and flow conditions and several fluid properties, which include density, viscosity, thermal conductivity, and specific heat. The thermal property submodel contains several fluid property functions, which are documented in the FOULER code. Once the fluid parameters are determined, a subfunction determines whether the flow at the boundary layer is turbulent or laminar. Depending upon the flow characteristics and average convection coefficient, h_{conv} , q''_{conv} is determined. The conductive heat-transfer rate, q''_{cond} , through the deposit and tube is dependent upon thermal conductivity, temperature, and thickness of each layer. Determination at the convection heat-transfer rate through the steam is similar to solving the forced convection of the gas stream. The heat equation for the heat-transfer through the deposit is given in Equation 9.

The deposit thermal conductivity is based on laboratory measurements of ash thermal conductivity. The conductivity of ash is nearly independent of the chemical composition, but is strongly dependent on the degree of sintering. Further, the ash conductivity exhibits hysteresis: once heated to a point where sintering occurs, the ash on cooling has a higher thermal conductivity than the original unsintered ash.

Figure 17. Heat transfer through deposit.

$$q = \frac{T_{\text{gas}} - T_{\text{steam}}}{\frac{1}{2\pi \text{Rad}_t L h_{st}} + \frac{\ln\left(\frac{\text{Rad}_{t_o}}{\text{Rad}_{t_i}}\right)}{2\pi L K_t} + \sum \frac{\ln\left(\frac{\text{Rad}_{dn}}{\text{Rad}_{dn-1}}\right)}{2\pi L K_{dn}} + \frac{1}{2\pi \text{Rad}_{ds} L h_g}} \quad [9]$$

6.4 Deposit Removal

The deposit removal algorithm accounts for thermal shedding, sootblowing, and gravity shedding. The removal characteristics of the deposit are calculated based on the deposit growth and strength development. The removal indices have a value from 0 to 1, with 1 being complete removal. The sootblowing and load drop models are applied only at the time intervals supplied by the input data. The largest removal index is selected for each time interval.

Thermal shedding occurs when a utility drops load, resulting in a temperature change in the boiler. Because of the different thermal expansion value of the ash deposit and the steam tube, the result is shear fracture in the deposit. The difference in thermal expansion can be correlated to the density of the deposit. The change in temperature and the strength of the deposit are the main variables in determining the thermal-shedding index.

Gravity shedding is common in the backpass regions of a utility boiler where strength development is low, but deposition is high. This form of deposit removal is correlated to the

strength:mass ratio of the deposit. The gravity-shedding index is a function of the deposit strength and weight. Unlike load shedding and sootblowing, gravity shedding is possible at every time interval, since shedding occurs as the weight of the deposit becomes greater than the strength.

The amount of removal due to sootblowing is calculated by comparing the strength of the deposit with the shear stress applied to the deposit by a retractable sootblower as a function of the blowing medium, pressure, nozzle angle, and spacing between sootblowers.

6.5 Ash Fouling Algorithms Results

The fouling algorithms have been tested in other projects for conventional pulverized coal, cyclone, and fluidized bed utility boilers. A great deal of experimentation, sampling, and analysis on full-scale and pilot-scale tests has been conducted. The predicated results have compared well with the experimentally measured and full-scale sampling results.

Comparisons of upstream and downstream deposit strengths for a lignite and a bituminous coal, using the same conventional pc-fired boiler configuration, are shown in (Figure 18). As expected, the deposits show a higher strength than the upstream deposits. The lignite coal also had a higher deposit strength than the bituminous deposits. The lignite coal has a higher deposit mass, especially the upstream deposit (Figure 19), compared to the bituminous coal under the same operational conditions.

Figure 18. Comparison of predicted lignite and bituminous deposit strength.

Figure 19. Comparison of a lignite and bituminous predicted deposit mass.

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APPENDIX A

VARIABLES DEFINITION LIST

VARIABLES DEFINITION LIST

A_d	=	Total cross-sectional area available for ash deposition, ft^2
A_t	=	Cross-sectional area of the convective pass, ft^2
C_{sulf}	=	Sulfate constant
D_p	=	Particle diameter, microns
DP	=	Deposit potential mass of ash that sticks to the tube, lb
DR_t	=	Low-temperature deposition rate, $\text{lb}/(\text{ft}^2 \text{ hr})$
DR_u	=	Upstream deposition rate, $\text{lb}/(\text{ft}^2 \text{ hr})$
h_{conv}	=	Average convection coefficient, $\text{Btu}/(\text{ft}^2 \text{ hr} \cdot ^\circ\text{F})$
h_g	=	Heat-transfer coefficient of the gas, $\text{Btu}/(\text{ft}^2 \text{ hr} \cdot ^\circ\text{F})$
h_{st}	=	Heat-transfer coefficient of the steam, $\text{Btu}/(\text{ft}^2 \text{ hr} \cdot ^\circ\text{F})$
IEF	=	Inertial impaction subfunction—fraction of ash that will strike the tube
K_{down}	=	Average downstream deposit thermal conductivity
K_{dn}	=	Thermal conductivity of deposit layer, $\text{Btu}/(\text{ft}^2 \text{ hr} \cdot ^\circ\text{F})$
K_t	=	Thermal conductivity of tube, $\text{Btu}/(\text{ft}^2 \text{ hr} \cdot ^\circ\text{F})$
K_{up}	=	Average upstream deposit thermal conductivity
L	=	Unit length of 1 ft
M_{ash}	=	Total ash, lb/hr
M_{dep}	=	Total deposit mass
M_L	=	Deposit layer mass
M_p	=	Mass percent for a specific particle size
PCF_1	=	PC Sulfate Factor 1
PCF_2	=	PC Sulfate Factor 2
q	=	Heat-transfer rate, Btu/hr
q''_{cond}	=	Conductive heat-transfer rate
q''_{conv}	=	Forced convection heat-transfer rate
Rad_{ds}	=	Outer deposit radius
Rad_{max}	=	Maximum radius of ellipse, in.
Rad_{min}	=	Minimum radius of ellipse, in.
Rad_t	=	Outside radius of tube, ft
Rad_i	=	Inside radius of tube, ft
$R_{\text{dn}1}$	=	Deposit layer radius n, ft
$R_{\text{dn}-1}$	=	Next deposit layer radius n-1, ft
R_{dt}	=	Total deposit radius
SF	=	Cumulative sticking fraction, 0 to 1
Sil_v	=	Silicate variable
S_{rc}	=	Silicate reference constant
$\text{Str}_{\text{depavg}}$	=	Average deposit strength
Str_{depl}	=	Strength of individual deposit layer
Str_{sil}	=	Silicate strength
Str_{sulf}	=	Sulfate strength
T_g	=	Gas temperature stream, R
T_{gas}	=	Temperature of the gas stream, $^\circ\text{F}$
T_{dn}	=	Deposit layer temperature, $^\circ\text{F}$
$T_{\text{dn}-1}$	=	Next deposit layer temperature, $^\circ\text{F}$
T_{douter}	=	Temperature of outermost deposit layer

T_{steam}	=	Temperature of the steam, °F
V_g	=	Gas velocity, ft/s
α	=	Angle factor
δ	=	Potential deposition mass fraction
μ_p	=	Particle viscosity, poise

Fuel Quality Advisor Operation Manual

Version 1.0

Fuel Quality Advisor

© Copyright 1995 Energy & Environmental Research Center
University of North Dakota
PO Box 9018
Grand Forks, North Dakota 58202-9018
Telephone: (701) 777-5000
Fax: (701) 777-5181
www.eerc.und.nodak.edu

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FQA OPERATION MANUAL

1.0 INTRODUCTION

Fuel Quality Advisor (FQA) is a user-friendly interface designed to bundle several existing computer models with a Windows™ graphical user interface. FQA contains three major computer programs: Coal Handleability Model, Ash Transformation Model (ATM), and Ash Deposition Model (ADM). The coal handleability model predicts dust-handling characteristics for various coal types. The ash transformation model predicts the particle-size and composition distribution (PSCD) of the entrained ash reaching the convective pass of a utility boiler. The ash deposition model predicts the ash deposition and strength development potentials of the ash, thermal resistance due to deposition on the heat-exchange tubes, and the effectiveness of sootblowers to remove the deposits in a convectional, cyclone, fluidized-bed, and low-NO_x boiler. All models are based on theory and a combination of laboratory-, pilot-, and full-scale test data. All outputs from the ADM model are on a relative basis and are intended to be used for comparative purposes.

FQA has been developed by the Energy & Environmental Research Center (EERC), a research, consulting, and development organization affiliated with the University of North Dakota in Grand Forks, North Dakota. The EERC is recognized as an international leader in low-rank coal research, providing energy and environmental research and consulting services for public and private clients in the United States and abroad. Additional information about the EERC is available by calling (701) 777-5000 or by visiting the EERC Web site at www.eerc.und.nodak.edu.

2.0 SYSTEM AND SOFTWARE REQUIREMENTS

FQA will run on a 486 or higher personal computer equipped with a SVGA video adapter with a minimum of 800 × 600 resolution and Windows™ Version 3.1 or higher. It requires a minimum of 8 MB of RAM to operate properly. A 3.5-in. high-density (1.44-MB) disk drive and at least 20 MB (3 MB to load and 17 MB to run) of free memory on a hard drive are required to install and run the FQA package. The package consists of 1) the FQA program, which contains a user interface and the three models; 2) coal analysis and boiler parameter files; and 3) an INSTALL program. DOS-based systems must have a WIN 32s upgrade.

3.0 INSTALLATION

FQA is designed to be installed anywhere on a hard drive. A user-defined directory will contain the subdirectories \ANALYSIS and \RESULTS, which are created during installation. To install FQA, use the following step-by-step procedure:

1. Insert the FQA installation disk into a 3.5-in. disk drive.
2. Specify the 3.5-in. drive as the current drive by typing *a:* or *b:* and pressing ENTER.
3. With Windows™ 3.1 or higher systems, type *setup* and press ENTER.

4.0 COAL HANDLEABILITY

The coal handleability model rates the dust handling properties for coal by making a correlation between type of coal, particle size distribution, and moisture content. The moisture content is the main factor relative to the coal's original bed moisture content to determine the overall coal handleability indices. A slacking index was used to further enhance the indices. The slacking index was based upon information compiled by the Bureau of Mines for various ranks of coal.

4.1 Input for Coal Handleability Model

Input for the handleability model consists of a selecting the coal type (anthracite, low-medium-volatile bituminous, high-volatile bituminous, subbituminous, and lignite), as-received moisture percent, equilibrium moisture percent, particle-size distribution, and coal ash percent.

4.2 Data Output

The index is completed for a range of values to characterize the coal relative to coal rank, coal blend, friability, moisture content, and the coal's tendency to weather. The index is most sensitive to change in as-received moisture content.

The output from the computer program will indicate to the user whether the coal being considered has good, reasonable, or problem handling characteristics. It also issues comments on when to consider dust contaminant or suppression systems.

5.0 ASH TRANSFORMATION MODEL

The ash transformation model predicts the PSCD for the entrained ash reaching the convective pass of a utility boiler. The entrained-ash PSCD is predicted from the distribution of the inorganics in the coal.

5.1 Input File Format for Ash Transformation Model

Input to ATM consists of coal analysis results determined by computer-controlled scanning electron microscopy (CCSEM)¹ and standard American Society for Testing and Materials (ASTM) proximate, ultimate, and coal ash chemical analysis methods as listed in Table 1. The CCSEM method provides quantitative information on the distribution of various elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Fe, and Ba) among the mineral constituents of coal, whereas ASTM methods provide information on the bulk chemical composition and combustion characteristics of coal. The combination of these analysis data provides a more comprehensive basis for predicting the combustion performance characteristics of a pulverized coal.

¹ The CCSEM method of coal mineral analysis was originally developed in the late 1970s and early 1980s by Lee and others' (1) and Huggins and others (2, 3). The method and its applications in coal mineral research were reviewed recently by Skorupska and Carpenter (4).

TABLE 1

FQA Coal and Sorbent Analysis Input Parameters

Method	Parameter(s)	Unit	File Extensions
CCSEM	Elemental mineral compositions	wt%, mineral basis	.ccs
Proximate	Moisture, volatile matter, fixed C, and ash	wt%, as-received	.ult
Ultimate	H, total C, N, S, O, and ash	wt%, as-received	.ult
Coal Chemical Composition	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , TiO ₂ , P ₂ O ₅ , CaO, MgO, Na ₂ O, and K ₂ O	wt%, ash basis	.xrf
Sorbent Chemical Composition	SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃ , TiO ₂ , CaO, MgO, Na ₂ O, K ₂ O, SO ₃ , and CO ₂	wt%, ash basis	.bed

Note: The coal analysis parameters indicated in Table 1 and the boiler specifications and operating conditions indicated in Table 3 must be organized into ASCII files. Most database, spreadsheet, and word-processing programs can produce ASCII files.

5.1.1 CCSEM Mineral Analysis Results

The CCSEM mineral analysis section consists of either two or three different magnification files. The highest magnification will be 800 × and will be present only with a three-file analysis. The 240× magnification file will be either the three-file analysis medium-magnification file or the two-file analysis high-magnification file. The lowest magnification is the 50× file. Each file has 27 columns and a varying number of rows. The columns have the following definitions: particle number, chemical type, x-ray count, Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe, Ba, Ti, x-coordinate, y-coordinate, average diameter, maximum diameter, minimum diameter, perimeter, shape factor, frame number, and excluded/included. The composition is expressed in normalized elemental weight percent.

5.1.2 Coal Proximate and Ultimate Analysis Results

The standard ASTM proximate and ultimate analysis results are reported on an as-received basis in a single column, as indicated below, in the following order: hydrogen, carbon, nitrogen, sulfur, oxygen, and ash.

6.05

54.78

0.97

0.46

32.50

5.23

5.1.3 Ash Coal Chemical Analysis

The chemical composition of coal ash (in wt%) on a sulfur-free basis is also tabulated in a single column, as indicated below, in the following order: SiO_2 , Al_2O_3 , Fe_2O_3 , TiO_2 , P_2O_5 , CaO , MgO , Na_2O , and K_2O , for example:

53.30

24.80

16.60

0.08

0.10

1.30

1.10

0.10

2.10

5.2 Data Output

The ATM produces two output files: Combo Ash File and Convective Pass Ash File. The Combo Ash File contains a table with 34 different ash classifications and six particle-size bins. Classification of an ash particle is based on various weight and molar ratios. Particle size is dependant upon the aerodynamic size. The values in weight percents are totaled both horizontally for the each classification phase and vertically for each size range.

Table 2 is an example of a Combo Ash File. In this example, the quartz classification has 4.71 weight percent of ash in the 3-10- μm size range. Below this table, there is breakdown of the bulk composition into nine different size and type bulk compositions. The nine different bulk compositions are that of the nucleated ash, overall ash bulk composition (< 1.0- μm ash, 1.0-3.0- μm ash, 3.0-10.0- μm ash, 10.0-30.0- μm ash, 30.0-50.0- μm ash, > 50.0- μm ash), and the bulk composition of the entrained ash. The first section is the nucleated fly ash composition, which is the ash formed from the organically associated minerals originally in the coal matrix. The second section is the overall bulk composition of the fly ash.

Sections 4-9 are a breakdown of the oxide compositions by size range, with the corresponding weight percent present in that size range. The size segregation section shows the weight percent distribution of the entrained ash. The last section is the bulk composition of the entrained ash. The convective pass ash file is the input for the ash deposition model. It contains the same bulk composition and size distribution as the Combo Ash File, but in a more compact manner, providing information to be read as an input file for the ash deposition model.

TABLE 2

Combo Ash File Output Example

Entrained Fly Ash Predicted from Advanced Coal Analysis							
AERO. DIAMETER	0.0-1.0	1.0-3.0	3.0-10.0	10.0-30.0	30.0-50.0	Unused	Total
QUARTZ	0.00	0.83	4.71	2.20	0.00	0.00	7.75
IRON OXIDE	0.00	0.27	1.48	0.62	0.53	0.00	2.90
PERICLASE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RUTILE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ALUMINA	0.00	0.00	0.05	0.00	0.00	0.00	0.05
CALCITE	0.00	0.15	0.29	4.12	0.00	0.00	4.56
DOLOMITE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ANKERITE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KAOLINITE	0.02	0.46	2.31	0.17	0.00	0.00	2.95
MONTMORILLONITE	0.00	0.04	0.04	0.08	0.00	0.00	0.16
K AL-SILICATE	0.06	0.22	1.11	0.75	0.00	0.00	2.14
FE AL-SILICATE	0.00	0.01	2.13	7.88	0.00	0.00	10.01
CA AL-SILICATE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NA AL-SILICATE	0.00	0.00	0.02	0.00	0.00	0.00	0.02
ALUMINOSILICATE	0.00	0.00	0.01	0.57	0.00	0.00	0.58
MIXED AL-SILICATES	0.00	0.00	0.01	0.53	0.00	0.00	0.55
FE SILICATE	0.00	0.00	0.03	0.62	0.18	0.00	0.83
CA SILICATE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA ALUMINATE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PYRITE	0.18	1.13	4.63	9.57	2.43	0.00	17.95
PYRRHOTITE	0.00	0.00	0.05	1.82	0.14	0.00	2.02
OXIDIZED PYRRHOTITE	0.00	0.00	0.04	0.41	0.09	0.00	0.55
GYPSUM	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BARITE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
APATITE	0.00	0.00	0.04	0.00	0.00	0.00	0.04
CA AL-P	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KCL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GYPSUM/BARITE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GYPSUM/AL-SILICATE	0.00	0.00	0.04	0.00	0.00	0.00	0.04
SI-RICH	0.03	0.01	0.07	1.50	0.00	0.00	1.62
CA-RICH	0.08	0.00	0.57	0.77	0.00	0.00	1.41
CA-SI RICH	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UNKNOWN	0.34	0.51	10.13	26.95	0.15	0.00	38.09
TOTAL	0.70	3.63	27.79	58.56	3.53	0.00	94.23

Continued . . .

Table 2 (continued)

NUCLEATED FLY ASH AVERAGE COMPOSITION(OXIDES)

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.90	2.60	21.60	54.90	0.00	0.00	0.00	3.70	0.00	16.20	0.00	0.00

BULK COMPOSITION OF FLYASH AS OXIDES,

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.3	1.1	12.9	35.2	0.2	21.4	0.1	1.3	7.4	19.7	0.0	0.3

BULK COMPOSITION OF < 1.0-MICRON ASH,

WEIGHT PERCENT 5.91

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
1.0	2.4	20.4	50.9	0.1	3.9	0.0	3.6	1.3	16.2	0.0	0.1

BULK COMPOSITION OF 1.0-3.0-MICRON ASH,

WEIGHT PERCENT 4.21

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.7	0.8	12.2	43.9	0.3	21.0	0.2	2.0	4.6	14.0	0.0	0.4

BULK COMPOSITION OF 3.0-10.0-MICRON ASH,

WEIGHT PERCENT 27.79

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.3	1.0	12.9	40.2	0.3	19.0	0.1	1.1	4.5	20.3	0.0	0.3

BULK COMPOSITION OF 10.0-30.0-MICRON ASH,

WEIGHT PERCENT 58.56

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.2	1.0	12.9	32.5	0.2	22.0	0.1	1.2	9.8	19.8	0.0	0.4

BULK COMPOSITION OF 30.0-50.0-MICRON ASH,

WEIGHT PERCENT 3.53

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.0	0.8	3.5	8.4	0.0	59.4	0.0	0.1	0.0	27.7	0.0	0.0

BULK COMPOSITION OF NOT USED MICRON ASH,

WEIGHT PERCENT 0.00

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

After size segregation in box:

0.0-1.0-micron Ash	6.12
1.0-3.0-micron Ash	4.36
3.0-10.0-micron Ash	28.81
> 10.0-micron Ash	60.70

BULK COMPOSITION OF ENTRAINED ASH

NA2O	MGO	AL2O3	SIO2	P2O5	SO3	CL2O7	K2O	CAO	FE2O3	BAO	TIO2
0.3	1.1	13.3	36.3	0.2	20.0	0.1	1.4	7.5	19.4	0.0	0.3

6.0 ASH DEPOSITION MODEL

The ash deposition model (ADM) predicts the effects of operational conditions and coal switching or blending on the fouling rate in the convective pass. ADM is based on both theory and a combination of laboratory- and pilot-scale and field test data.

ADM predicts both growth and removal of fouling deposits through the interaction of several submodels: Deposit Growth, Strength Development, Thermal Properties, Deposit Removal, and Sootblower Effectiveness. These submodels interact to produce outputs based on time for deposit mass, strength, resistivity, removal rates, and sootblowing effectiveness.

6.1 Input File Format for Ash Deposition Model

Input to the ADM consists of an ash file produced by the ash transformation model and a boiler parameter file. The ash file provides the PSCD of the ash entering the convective pass. The boiler file contains the boiler type, operating conditions, and boiler configuration. The type of boiler on which the ash file is based and the type of boiler parameter file must coincide; for example, both files must be for low-NO_x conditions. Table 3 gives ADM boiler input parameters.

6.1.1 Boiler Parameter File

The required format of a boiler file (.boi) is shown below. The first row gives the boiler file version number. The second row indicates the type of boiler. The name of the boiler is on the following line. The fourth row indicates the number of convective pass banks in the boiler. There is a maximum limit of 12 boiler banks allowed in the convective pass. The following rows are descriptions of each bank. The next 20 rows consist of boiler rank specifications. The last 19 are operating input parameters. It is important to note that if a value is changed, a whole number must remain as a whole number, and nondecimal numbers must remain in the original format, including unit. For example, to change the height of the tube bank in the Primary Superheater Bank 2, it must be changed from 38.0 feet to 40.0 feet, not 38.0 to 40 feet. To increase the number of banks in the convective pass, add the respective number of columns after the bank description; also change the "Number of Banks" value and add to the bank description rows. The following is an exact example of a boiler parameter file:

FQA Boiler Version 1.0

Cyclone

Heskett Station Unit 2

4 Number of banks

Bank 1 Description: High-Temp Superheater

Bank 2 Description: Primary Superheater Bank 1

Bank 3 Description: Primary Superheater Bank 2

Bank 4 Description: Economizer

47	47	47	36	Number of tube rows, perpendicular to gas flow
10	10	10	72	Number of tubes per row, parallel to gas flow
14.5	38.0	38.0	14.5	Height of tube bank, ft
9.94	9.94	9.94	3.25	Center to center between rows, perpendicular to gas flow, in.
4.97	4.97	4.97	3.25	Center to center between rows, parallel to gas flow, in.
2.25	2.5	2.5	2.0	Tube outside diameter, in.
2.0	2.25	2.25	1.75	Tube inside diameter, in.
13.0	13.0	13.0	13.0	Tube thermal conductivity, Btu/hr-ft-F
1	1	1	0	Sootblowers: 0 = no, 1 = yes

0	0	0	0	Sootblower medium: 0 = steam, 1 = air
0	0	0	0	SB angle: 0 = 90° 1 = 10° -10° lag, degrees from perpendicular
8.0	8.0	8.0	8.0	Length of sootblower insertion, ft
200.0	200.0	200.0	200.0	Pressure asserted by sootblower, psi
0.15	0.15	0.15	0.15	Sootblower insertion speed, ft/s
8.0	8.0	8.0	8.0	Distance between upstream sootblowers, ft
8.0	8.0	8.0	8.0	Distance between downstream sootblowers, ft
758.0	717.0	626.0	550.0	Temperature after load shift, each bank °F
858.0	817.0	726.0	660.0	Gas temperature in that section, °F
836.0	790.0	706.0	466.0	Steam temperature, °F
1419.0	1419.0	1419.0	1419.0	Steam pressure, psi
8.0	Sootblower increments, hr			
12.0	Load drop interval, hr			
12.0	Bed gas velocity, ft/s			
11.11	CO ₂ percent, volume %			
0.016	SO ₂ percent, volume %			
69.88	N ₂ percent, volume %			
3.68	O ₂ percent, volume %			
0.0	CO percent, volume %			
15.31	H ₂ O percent, volume %			
29.9	Barometric pressure, in. Hg			
7080.0	Coal HHV, Btu/lb			
0.27	Fly ash fraction or ash split			
53.0	Coal burn rate, full load coal consumption, ton/hr			
2.0	Calcium-to-sulfur ratio			
2.39	Ultimate analysis sulfur, as received, wt %			
0	Using a bed sorbent, dolomite or limestone: 1 = yes, 0 = no			
1500.0	Bed temperature, °F			
40.0	Box width, ft			
25.0	Box depth, ft			

6.1.2 Sorbent Coal Chemical Analysis

A sorbent composition is needed only if a fluidized-bed boiler is being used. The chemical composition of sorbent ash (in wt%) is also tabulated in a single column, as indicated below, in the following order: SiO₂, Al₂O₃, Fe₂O₃, TiO₂, CaO, MgO, Na₂O, K₂O, SO₃, and CO₂, for example:

2.96
0.78
0.42
0.03
51.77
2.77
0.06
0.32
0.21
40.68

TABLE 3

ADM Boiler Input Parameters

Parameter	Unit or Available Options
Number of Steam Tube Rows, perpendicular to gas flow	No. for each heat-exchange bank
Number of Steam Tubes per Row, parallel to gas flow	No. for each heat-exchange bank
Height of Steam Tube Bank	ft
Center to Center Between Steam Tube Rows, perpendicular to gas flow	in.
Center to Center Between Steam Tube Rows, parallel to gas flow	in.
Steam Tube Outside Diameter	in.
Steam Tube Inside Diameter	in.
Steam Tube Thermal Conductivity	Btu/hr-ft-°F
Sootblowers	0 = no, 1 = yes
Sootblower Media	0 = steam, 1 = air
Sootblower Angle	0 = 90°, 1 = 10° to -10 lag
Length of Sootblower Insertion	ft
Pressure Asserted by Sootblower	psi
Sootblower Insertion Speed	ft/s
Distance Between Upstream Sootblowers	ft
Distance Between Downstream Sootblowers	ft
Gas Temperature After Load Shift	°F
Gas Temperature in That Section	°F
Steam Temperature	°F
Steam Pressure	psi
Sootblower Intervals	hr
Load Drop Interval	hr
Bed Gas Velocity	ft/s
CO ₂	volume%
SO ₂	volume%
N ₂	volume%
O ₂	volume%
CO	volume%
H ₂ O	volume%
Barometric Pressure	in. of Hg
Coal HHV	Btu/lb
Fly Ash Fraction*	(Bottom ash/fly ash) split
Coal Burn Rate, Full Load Coal Consumption	ton/hr
Calcium-to-Sulfur Ratio	unitless (lb/lb)
Bed Sorbent	0 = no, 1 = yes
Box Width	ft
Box Depth	ft

* The variable name "fly ash fraction" has a default value of 0.8. A pulverized coal-fired (dry bottom) with low- to medium-volatile bituminous coals 2.0 to 0.3, high-volatile bituminous coals 0.2 to 0.3, and subbituminous and lignites 0.3 to 0.5 as bottom ash.

6.2 Data Output

The results generated from the ADM program are all relative to a given data set. They are not intended to be quantitative amounts, but rather relative indices. The output from ADM produces a deposition rate, strength value, and deposit resistance value for upstream and downstream deposits and sootblower effectiveness. Deposition is given an index value (0-100) for average unit of mass deposited per hour. The strength is given an index value between 0 and 100. The sootblower effectiveness index accounts for thermal shedding, sootblowing, and gravity shedding. Sootblower effectiveness is expressed as a percentage, with 100% being complete removal of the deposits.

7.0 FQA OPERATION

This application was designed and written to simplify the running of a combination of coal handleability, ash transformation, and ash fouling models. This will allow the user to pick a coal and look at the handling qualities, ash generation, and fouling potential from one software package. This package was designed to be consistent throughout each of the models to reduce training time.

Like other WindowsTM applications, FQA appears in a Program Manager group as an icon that can be started simply by double-clicking with the mouse on the icon. This action will activate the introduction screen followed by the main program window (Figure 1), which has several buttons to transfer the user to the model needed. Each model runs independently, with the ATM generating output that in turn can be used as input into ADM.

7.1 Coal Handleability

This model starts with a listbox of coal types available and an empty listbox where the coal types selected will be displayed (see Figure 2). After one or two coal types have been selected, the Continue button should be pushed, and the model will ask for the blending percentage, if needed. The model will then inquire about the particle-size distribution, equilibrium moisture, and the as-received moisture. With this information, the model is ready to determine the coal-handling characteristics by pressing the Show index button. The model will display a phase that will indicate the handleability of the coal. Many scenarios can be run with a change to the particle-size distribution, the coal type, or even the percentage blend of each of the coal types.

7.2 Ash Transformation

This model starts with an informational screen that identifies the data files selected and the master file name (see Figure 3). The model requires the input data files to be selected before the model can run, and to accomplish this, the Command Menu is used. The following sections describe each of the pull-down items.

7.2.1 File

The options under this menu are used to manipulate only the master run file. The **New** option will reset all the input files for the current run situation. The **Open** option will open a preexisting run situation. The **Save** option will save the current fields of information to the current

Figure 1. Main screen.

Figure 2. Coal Handleability screen.

Figure 3. Ash Transformation main screen.

master run file. The **Save As** option will save the current fields of information to a user-specified master run file. The **Exit** option will terminate the program.

7.2.2 Run

The options under this menu are used to run the actual ash transformation model. The **Execute** option will run the ash transformation model with the current master run information. The program will not allow the user to continue if any data files are missing or if a master filename has not been selected. After the run, control is transferred to the **Output** menu item **Table** option to display the output.

7.2.3 Data

The options under this menu are used to enter data through input screens. The Coal Input option prompts the user for two or three CCSEM, XRF, Prox/Ult data files and a boiler type (Figure 4). The Browse button allows the user to select a file from anywhere on the disk. The OK button is used to accept the data input and return to the main window with updated values in the fields of information. The Cancel button is used to exit the input screen and return to the main window, with no modification to the fields of information.

7.2.4 Output

The option under this menu is used to view the table of results. The **Table** option allows the user to view results from a previous run. The Open button will load an existing data set from a previous run. The Quit button will return the user to the main window.

Load Coal input files

The Number of CCSEM magnifications Files

☒ Three files ☐ Two files

CCSEM Input Files

50x CCSEM :

240x CCSEM :

800x CCSEM :

XRF Input File

XRF :

Prox/Ult Input File

Prox/Ult :

Boiler Type

Boiler :

Figure 4. Coal input screen.

7.2.5 *Help*

The options under this menu are used to help the user with the details of the program. The **Contents** option will take you to the help file, which describes the use of the program. The **About** option will give the user information about the model's authors and sponsors.

7.2.6 *Toolbar*

The Toolbar items are used as a shortcut for options that are found under the pull-down menu system. The toolbar items currently available are (from left to right) the **New** option under the **File** pull-down menu, which will reset all the parameters. The second toolbar item is the **Open** option under the **File** pull-down menu, which will open an existing master run file. The third toolbar item is the **Save** option under the **File** pull-down menu, which will save the current inputs to the master run file. The last toolbar item is the **Contents** option under the **Help** pull-down menu, which will go to the standard help system.

7.3 *Ash Deposition*

This model starts with an informational screen that identifies the data files selected and the master file name (see Figure 5). The model requires the input data files to be selected before the model can run, and to accomplish this, the Command Menu is used. The following sections describe each of the pull-down items.

7.3.1 *File*

The options under this menu are used to manipulate only the master run file. The **New** option will reset all the input files for the current run situation. The **Open** option will open a preexisting run situation. The **Save** option will save the current fields of information to the current master run file. The **Save As** option will save the current fields of information to a user-specified master run file. The **Exit** option will terminate the program.

7.3.2 *Run*

The options under this menu are used to run the actual ash deposition model. The **Execute** option will run the ash deposition model with the current master run information. The program will not allow the user to continue if any data files are missing or if a master filename has not been selected. After the run, control is transferred to the **Output** menu item **Table** option to display the output.

7.3.3 *Data*

The options under this menu are used to enter data through input screens. The **Inputs** option prompts the user for a convective pass ash file and a boiler file (Figure 6). The Browse button allows the user to select a file from anywhere on the disk. The OK button is used to accept the data input and return to the main window with updated values in the fields information. The Cancel button is used to exit the input screen and return to the main window, with no modification to the fields of information.

Figure 5. Ash Deposition main screen.

Figure 6. Inputs screen.

7.3.4 Output

The option under this menu is used to view the table of results (see Figure 7). The **Table** option allows the user to view results from a previous run. The **Open** button will load an existing data set from a previous run. The **Quit** button will return the user to the main window.

7.3.5 Help

The options under this menu are used to help the user with the details of the program. The **Contents** option will take you to the Help file, which describes the use of the program. The **About** option will give the user information about the model's authors and sponsors.

7.3.6 Toolbar

The Toolbar items are used as a shortcut for options that are found under the pull-down menu system. The toolbar items currently available are (from left to right) the **New** option under the **File** pull-down menu, which will reset all the parameters. The second toolbar item is the **Open** option

	Upstream Mass	Upstream Strength	Downstream Mass	Downstream Strength	Thermal Resistance	Sootblower Effectiveness
Bank 1	34.5	7.6	5.2	6.8	30.8	62.4
Bank 2	17.0	8.3	5.2	7.3	19.1	69.7
Bank 3	16.8	8.3	5.1	7.3	19.6	70.0
Bank 4	14.3	7.1	11.5	10.8	43.6	84.0

D:\SOURCE\FQA\run1.cpo

Open Quit

Figure 7. Convective Pass output screen.

under the **File** pull-down menu, which will open an existing master run file. The third toolbar item is the **Save** option under the **File** pull-down menu, which will save the current inputs to the master run file. The last toolbar item is the **Contents** option under the **Help** pull-down menu, which will go to the standard help system.

8.0 REFERENCES

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